4-4-2017

Terahertz Plasmonic Devices

Mustafa Karabiyik

Department of Electrical and Computer Engineering, Florida International University, mkara006@fiu.edu

DOI: 10.25148/etd.FIDC001789

Follow this and additional works at: <http://digitalcommons.fiu.edu/etd>

Recommended Citation

Karabiyik, Mustafa, "Terahertz Plasmonic Devices" (2017). *FIU Electronic Theses and Dissertations*. 3185.
<http://digitalcommons.fiu.edu/etd/3185>

This work is brought to you for free and open access by the University Graduate School at FIU Digital Commons. It has been accepted for inclusion in FIU Electronic Theses and Dissertations by an authorized administrator of FIU Digital Commons. For more information, please contact dcc@fiu.edu.

FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

TERAHERTZ PLASMONIC DEVICES

A dissertation submitted in partial fulfillment of

the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

ELECTRICAL ENGINEERING

by

Mustafa Karabiyik

2017

To: Interim Dean Ranu Jung
College of Engineering and Computing

This dissertation, written by Mustafa Karabiyik, and entitled Terahertz Plasmonic Devices, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

Ismail Guvenc

Yesim Darici

Irene Calizo

Shakrat Khizroev

Nezih Pala, Major Professor

Date of Defense: April 4 2017

The dissertation of Mustafa Karabiyik is approved.

Interim Dean Ranu Jung
College of Engineering and Computing

Andrés G. Gil
Vice President for Research and Economic Development
and Dean of the University Graduate School

Florida International University, 2017

© Copyright 2017 by Mustafa Karabiyik

All rights reserved.

ACKNOWLEDGMENTS

First, I would like to express gratitude to my advisor and mentor, Dr. Nezih Pala, for giving me the opportunity to work on an exciting project for my doctoral dissertation. I am also thankful for his encouragement and support in developing my research skills and personality through the many opportunities provided during my time at FIU.

I would like to thank the members of my dissertation committee Dr. Shakrat Khizroev, Dr. Ismail Guvenc, Dr. Irene Calizo, and Dr. Yesim Darici, for agreeing to be my dissertation committee, and for their valuable inputs towards my dissertation research. I thank the Department of Electrical and Computer Engineering, for the logistical support. I would like to acknowledge the funding sources that made this work possible: teaching assistantship from the Department of Electrical and Computer Engineering, National Science Foundation and Qatar National Research Fund. The devices I have fabricated at Oak Ridge National lab would not be possible without Scott Retterer, Dayrl Briggs and Kevin Lester

I take this opportunity to also thank all the members of the INSYST Lab Raju Sinha, Burak Gerislioglu, Arash Ahmediwand, Fahmida Alam, Chowdhury Al-Amin, Phani Kiran Vabbina and other graduate students that worked along with me at Electrical Engineering and AMERI, Patrick Roman, Kevin Luongo and Alexander Franco. Many thanks to my dearest friends who have supported me and stood by me through the hardest times of this journey, Erkan E. Arslan, Christopher R. Lashway, Serkan Kaya, Aparajitah Singh, Khalid Sayeed Pasha, Krystine Pimentel, Mark Stone, Emre Babali, Ahmet Ceran and Derya Kara.

Finally, I could not have come this far without the unconditional love, support, patience and blessings from my family in Turkey. Many thanks to my father, Kemali Karabiyik, mother, Semiha Karabiyik and sisters, Binnur Col, Aynur Kokcu and Fadime Demirkiran my father in law, Ahmet Ozcan, mother in law Nejla Ozcan.

I would like to thank my wife Emine Ozcan Karabiyik and my daughter Mina Nesibe Karabiyik for always standing by me, laughing with me and crying with me. I love them both with all my heart. My wife has been in the same course as I was and it was not an easy and pleasant way. They both deserve a PhD title along with me.

ABSTRACT OF THE DISSERTATION

TERAHERTZ PLASMONIC DEVICES

By

Mustafa Karabiyik

Florida International University, 2017

Miami, Florida

Professor Nezih Pala, Major Professor

Terahertz (THz) devices are designed to operate from 0.1-10 THz. The THz spectra have unique properties such as penetration through soft materials and reflecting from hard materials, which make THz technologies, a prime candidate for imaging. Plasmons are longitudinal charge oscillations in carrier rich materials. Plasmons can be generated over the channel of transistors inducing a voltage between the source-drain when conditions are satisfied. In this thesis, plasmonic devices operating in the THz region have been studied both theoretically and experimentally investigating GaN/AlGa_N and Graphene based transistors.

First, we report on a detailed study of dispersion properties of uniform grating gate THz plasmonic crystals, asymmetric dual grating gate plasmonic crystals and with symmetry-breaking defect-like cavities in order to understand the physics behind THz plasmons. For the first time, we defined the dispersion of plasmons in terms of effective plasmonic index. By adding an additional grating on top of the grating gate with a different

periodicity, doubles the amount of absorption. Plasmons can be excited when polarization is perpendicular to the gate. We then showed focusing and exciting of THz plasmons polarization independent using circular grating lenses. Sub-micron THz ring resonators are presented showing THz guiding in plasmonic waveguides.

So far, resonant sensing has been observed only at cryogenic temperatures since electron mobility is high enough at low temperatures to sustain resonant plasmonic excitation at the channel of the detector. Recently, graphene attracted the attention of the researchers because of its high mobility at room temperature. Room temperature detection has been attempted and achieved, however the detectors have very small responsivity with non-resonant behavior since the graphene is sandwiched and fabrication of such detectors in large scale is impossible with the methods used. Here, we present a resonant room temperature detection of THz with upside down free standing graphene FETs having more than a 400 quality factor, a record high number in the field which is up to 50 times higher than GaN detectors and hundreds of responsivity values with a maximum around 400 V/W which is record high for graphene (10,000 times higher than previously reported graphene detector).

TABLE OF CONTENTS

CHAPTER	PAGE
1. Introduction to Terahertz Technologies.....	1
1. Terahertz Spectrum and Its Properties	1
2. Terahertz Sources and Detectors	2
3. Contribution of This Work.....	8
4. References	11
2. Theoretical Background.....	15
2.1 Plasma Wave Physics	15
2.2 Plasmons in FETs	24
2.3 Electrical Responsivity	26
2.4 References	32
3. Numerical Analysis.....	33
3.1 FDTD Theory.....	33
3.2 Numerical Analysis of Absorption and Dispersion Characteristics	34
3.3 Dispersion Calculation.....	37
3.4 References	39
4. Plasmon Excitation and Dispersion of Plasmons.....	40
4.1 Plasmons in Grating Gate FETs.....	40
4.2 Plasmons in Linearly Integrated FETs.....	43
4.3 Dispersion of Symmetrical Gratings.....	48
4.3.1 Theory	49
4.3.2 Dispersion of Grating Gate FETs	51
4.3.3 Dispersion of a Cavity	56
4.4 Dispersion of Asymmetrical Gratings	60
4.4.1 Dispersion of Asymmetric Dual Grating Gate FETs.....	62
4.4.2 Absorption and Terahertz Responsivity.....	66
4.5 References.....	66
5. Ratchet Effect In two-Layer Grating Systems	71
5.1 Theory and Analytical Approach.....	72
5.2 Effect of Phase Shift on Absorption and Mode Distribution.....	79
5.3 References.....	83
6. Circular Grating Terahertz Plasmonics.....	84
6.1 Circular Lens Structure	84
6.2 Lensing Effect.....	85
6.3 Analytical Approach	87
6.4 Effect of Mobility and Duty Cycle on Lensing	89
6.5 References.....	92

7. Ring Resonator Terahertz Plasmonics	93
7.1 Circular Ring Resonator Structure	93
7.2 Electromagnetic Profile of Plasmons and Resonant Frequencies	95
7.3 Comparison of Different Materials and Resonant On Chip Filter	99
7.4 References	102
8. Experimental Methods	104
4.1 Device Fabrication	104
4.2 Device Characterization	109
8.2.1 Electrical Characterization	109
8.2.2 Optical Characterization	110
9. Experimental Results for Graphene Terahertz Plasmonics	114
9.1 Physical and Electronical Properties	114
9.2 Terahertz Response Characteristics	117
9.3 Polarization Dependence of Terahertz Response	120
9.4 References	125
10. Conclusion	126
VITAE	129

LIST OF FIGURES

CHAPTER	PAGE
Figure 1.1: The electromagnetic frequency spectrum. [1] Reprinted with permission as per license or document.....	1
Figure 1.2: Antenna coupled exfoliated graphene channel THz detector operating at room temperature. [27] Reprinted with permission as per license or document	6
Figure 2.1: Real part, ϵ_1 and imaginary part, ϵ_2 for silver calculated from Drude model and experimentally extracted data by Palik [1,4].....	17
Figure 2.2: Electric field intensity profile of a SPP propagating at the metal dielectric interface [1].....	19
Figure 2.3: Surface plasmon dispersion relation for silver-air interface and dispersion of light in air [1].....	21
Figure 2.4: Electric and magnetic field distributions of SPPs propagating at the metal-dielectric interface and Cross section view from the x-z plane, of electric and magnetic field distributions of SPP propagation at the metal-dielectric interface[1].....	22
Figure 2.5: Schematic representations of grating coupler [1].....	24
Figure 2.6: a) The representation of ungated and gated plasmons. The gated second mode is presented under the gate. The directions of the electric fields are shown with arrows, b) fundamental mode, c) third mode.....	25
Figure 2.7: Schematically representation of an 2DEG FET with gate, source and drain contacts	27
Figure 3.1: Screen shot from the FDTD simulation set up. Gold is indicated with yellow and 2DEG is indicated with gray. Blue material is GaN at upper side of the 2DEG and AlGa _N is at lower side of the 2DEG. Right and left boundaries are periodic. Upper and lower boundaries are absorbing layer each separated at least half of the highest wavelength. A broad band source illuminates the structure. Absorption is calculated from reflection and transmission.....	35
Figure 3.2: Comparison of published experimental data with the simulated data. a) Transmission spectrum of AlGa _N /GaN grating gate FET detectors [4]. b) Simulation result for ref [4] c) Transmission spectrum of graphene micro ribbons [3]. d) Simulated result for ref [3]. The simulation showed good agreement with the results and parameters values of the experiments. Reprinted with permission as per license or document.....	36

Figure 4.1: Room temperature absorption spectra of AlGaIn/GaN and Graphene grating gate FET structures with $L=1.5\mu\text{m}$ $W=1.15\mu\text{m}$, $N_s=7.5\times 10^{12}\text{ cm}^{-2}$. The inset shows the cross section of the structure. (i) Graphene, (ii) AlGaIn/GaN	41
Figure 4.2: Absorption spectra of graphene with different mobilities. $L=1.5\mu\text{m}$ $W=1.15\mu\text{m}$, $N_s=7.5\times 10^{12}\text{ cm}^{-2}$. (i) $\mu = 3000\text{ cm}^2/\text{V.s}$ (ii) $\mu = 15000\text{ cm}^2/\text{V.s}$ (iii) $\mu = 40000\text{ cm}^2/\text{V.s}$	42
Figure 4.3: Absorption spectra of graphene grating gate FET structure with different carrier concentrations. $L=1.5\mu\text{m}$ $W=1.15\mu\text{m}$, $\mu=15000\text{ cm}^2/\text{V.s}$. (i) $N_s = 3.6\times 10^{12}\text{ cm}^{-2}$ (ii) $N_s = 8.3\times 10^{12}\text{ cm}^{-2}$ (iii) $N_s = 1.5\times 10^{13}\text{ cm}^{-2}$	43
Figure 4.4: Cross-sectional view of Graphene based Linearly integrated FET (LFET)....	44
Figure 4.5: Absorption spectrum of the LFET array Graphene based device for different gate widths (L_G) with $L_{SD}=3\mu\text{m}$ at room temperature. (i) $L_G=2\mu\text{m}$ (ii) $L_G=1.5\mu\text{m}$ (iii) $L_G=1\mu\text{m}$ (iv) $L_G=0.4\mu\text{m}$	44
Figure 4.6: Simulation result of the Graphene LFET device showing two FET elements and the propagation of the first mode (a) and second mode (2) where the high electric field intensity is shown in red, zero electric field intensity is shown in blue.....	45
Figure 4.7: Absorption spectra of graphene LFETs with different mobilities. (i) $\mu = 3000\text{ cm}^2/\text{V.s}$ (ii) $\mu = 15000\text{ cm}^2/\text{V.s}$ (iii) $\mu = 40000\text{ cm}^2/\text{V.s}$	46
Figure 4.8: Absorption spectra of graphene LFET structure with different carrier concentrations. (i) $N_s = 3.6\times 10^{12}\text{ cm}^{-2}$ (ii) $N_s = 8.3\times 10^{12}\text{ cm}^{-2}$ (iii) $N_s = 1.5\times 10^{13}\text{ cm}^{-2}$..	47
Figure 4.9: (a) Schematic representation of a grating gate plasmonic device showing the unit cell, gated-ungated regions and layered structure. (b) Effective indices of plasmons in gated and ungated regions of the device calculated by using FDTD simulations	49
Figure 4.10: Dispersion curves of grating gate 2D plasmonic devices. The blue solid line is the analytical dispersion and circled points are the calculated points by FDTD method. Grating gate device with (a)-(b) 200 nm gate length and 800 nm slit length, (c) 500 nm gate length and 500 nm slit length, (d) 800 nm gate length and 200 nm slit length. (a) shows the plasmonic excitation heat map in logarithmic scale where red indicated high level plasmonic excitation and blue indicates low level plasmonic excitation.....	52
Figure 4.11: Electric field distributions ($ E ^2$) at different wave vectors, energies and geometries. Red indicates the high electric fields and blue indicates the low electric field. (a) and (b) are modes for the 200 nm gate length and 800 nm slit length device at 3.3 THz and 3.9 THz consecutively with momentum close to zero. (c), (d), (e) and (f) are modes for the grating gate device with 800 nm gate length and 200 nm slit	

length. The momentum is $0.5 \, 2\pi/\text{period}$, at 3.5 THz for (c) and 4.8 THz for (d). The momentum is $0.5 \, 2\pi/\text{period}$, at 3 THz for (e) and 4.5 THz for (f). The momentum is $0.125 \, 2\pi/\text{period}$, at 3.5 THz for (g) and 3.8 THz for (h).....54

Figure 4.12: Electric field distributions in a unit cell that is cross section from the middle of the AlGaIn region shown in green and analytical results are shown in blue.....57

Figure 4.13: (a) Dispersion curve of grating gate 2D plasmonic devices with cavities in red and analytically calculated cavity modes in blue. Grating gate device geometry has 900 nm gate length and 100 nm slit length. (b) Schematic representation of a grating gate plasmonic device unit cell with cavity with semi-infinite crystal on either side is shown. The cavity region is presented with a different color over the 2DEG. $|E|^2$ of the corresponding branches are shown. (c) Electric field distributions in a unit cell that is cross section from AlGaIn region shown in red and analytical results are shown in blue58

Figure 4.14: (a) Numerically calculated effective indices of plasmons at gated and ungated regions. (b) The mode profiles of gated and ungated plasmons at 2 THz. The inset is the extended ungated mode profile. The different material regions are separated with dashed black lines. The right most region is considered as gate for gated modes and air for ungated modes.....61

Figure 4.15: Schematic representation of an asymmetric grating gate plasmonic device showing the unit cell and the gated-ungated regions where the width of gated region 1 is 900 nm, width of ungated region 1 is 250 nm, width of gated region 2 is 400 nm and width of ungated region 2 is 450 nm. The unit cell width is 2 μm . The dielectric above the 2DEG is set to AlGaIn and below is set to GaN.....62

Figure 4.16: (a-l) Normalized Electric field distributions ($|E|^2$) at different wave vectors and energies. The modes on the left are zero momentum plasmonic modes; the modes on the right are half reciprocal lattice vector momentum plasmons. Red indicates the high electric fields and blue indicates the low electric field. The corresponding momentum-energy is indicated on the graph in blue letters. (m) The calculated dispersion of ADGG HEMT where x-axis is the momentum of the grating....64

Figure 4.17: (a) The absorption comparisons of a uniform grating with 900 nm gate width and 100 nm slit width and the asymmetric grating gate structure discussed in this paper. (b) Calculated absorption of the incident plane wave over the device, y-axis in log scale and Calculated THz response of the device in y-axis log scale66

Figure 5.1: Schematic representation of (a) grating gate and (b) coupler grating gate plasmonic devices with semi-infinite crystal on either side. The ungated region has an effective index of n_a and gated region has an effective index of n_b . The unit cell of each configuration is shown. Plasmon dispersion of (c) single grating gate and (d) coupler grating gate devices where $\lambda=L_a+L_b$. Red regions represents the propagating plasmons while blue regions represents the dissipating plasmons. Dispersion of the baseline grating gate device shown in Fig.6.1 (c) presents several band gaps opened at

zero momentum and in Brillion zones. Here the coupling of the light from free space is achieved by the Fourier harmonics of the grating gate. When an additional grating gate is introduced on top of the first one with a π phase shift, the unit cell changes as shown in Fig. 6.1 (b) and reciprocal lattice vector reduces to half. This results in formation of band gaps at half momentum of the original reciprocal lattice as shown in Fig. 6.1 (d). The bands are mirror folded from the center of the Fig. 6.1. (c), this also results in excitation of additional modes at zero momentum	73
Figure 5.2: (a) The effective index of plasmons, (b) effective gate length derived empirically, (c) dispersions of plasmons, simulation in red, calculation in blue are shown	77
Figure 5.3: (a) The absorption spectrum of single grating gate and double grating gate devices when the THz light is incident over the system to excite the plasmons at zero momentum. (b) The absorption normalized according to 2π phase shift. Red regions represent the observation of new plasmonics modes as the phase shift modulates	79
Figure 5.4: Phase shift dependence of a resonant plasmonic mode induced by the upper grating. Normalized electric field intensity is considered	80
Figure 5.5: Plasmon electric field $ E ^2$ distributions at zero momentum for double grating gate devices. First 6 modes are shown form (a) to (f) with and increasing mode number	81
Figure 5.6: The absorption spectrum of single grating gate and double grating gate devices when the THz light is incident over the system to excite the plasmons at zero momentum	82
Figure 6.1: (a) THz plasmonic concentrators with concentric circular gratings. (b) The cross section of the AlGaIn/GaN devices passing from the center of the circular grating structure.(c) Cross section of the graphene devices	85
Figure 6.2: (a) Electric field density under the central ring and under the outer rings. The total electric fields under the central and outer rings are divided by the total are of the rings. (b) Electric field density ratio under the central ring to the electric field intensity under the outer rings. The ratio gives the strength of the electric field confined at the central ring compared to the outer rings	86
Figure 6.3: (a) Simulated electric field mode distribution for the fundamental mode in between the grating and 2DEG,(b) second mode, (c) Electric field intensity from the diameter parallel to the polarization of the incident THz radiation for the fundamental mode, x-axis is the pixel in simulation	87
Figure 6.4:.(a) Calculated electric field intensity of the fundamental mode in between the circular grating and 2DEG, (b) second mode, (c) summation of modes from 1 to 5. (d) Relative electric field intensity on the diameter parallel to the polarization of the incident radiation (i) numerical simulation (ii) analytical calculation using Eq. 7.1 is shown	88

Figure 6.5: (a) Normalized electric field intensity under the central disc vs. frequency for different duty cycle of circular gratings. (b) Total electric field profile for 87% duty cycle, (c) 60% duty cycle and (d) 33% duty cycle	89
Figure 6.6: (a) Intensity vs. frequency of the graphene circular grating devices with different relaxation times of electrons in the channel. (b) Total electric field distribution of the circular gratings for plasma collision frequency of 1 THz (c) 3 THz (d) 5 THz.....	91
Figure 7.1: (a) Split ring resonator placed on top of GaN/AlGaIn heterojunction substrate mesa structure. (b) The cross section of the resonator device	94
Figure 7.2: (a) Electric field intensity vs. frequency for the 1.4 μm outer ring and 1.15 μm inner ring in between the ring and 2DEG, absorption spectrum on the left scale; the maximum coupling of incident radiation is around 1.5 THz which is the third mode. The electric field distribution of fundamental mode at 0.5 THz is shown.....	96
Figure 7.3: Electric field intensity profile under the ring. The electric fields are normalized where black represents the high electric field and white represents the low electric field, (a) for the 2nd mode, (b) for the 3rd mode and (c) for the 9th mode	96
Figure 7.4: Normalized electric field intensity in between the ring and 2DEG vs. frequency for different electron concentrations for the 1.4 μm outer ring and 1.15 μm inner ring geometry. The different electron concentrations represent different applied gate voltages applied over the half rings. The resonant modes with electron concentrations of $6 \times 10^{12} \text{ cm}^{-2}$, $7.5 \times 10^{12} \text{ cm}^{-2}$ and $9.5 \times 10^{12} \text{ cm}^{-2}$ are shown	98
Figure 7.5: The normalized electric field intensity vs. frequency for different ring geometries where R_{out} is 3 μm , R_{in} is 2.5 μm and is 1.4 μm , R_{in} is 1.15 μm for each split ring geometries.....	99
Figure 7.6: Normalized electric field intensities for different materials.....	101
Figure 7.7: (a) Device model for THz split ring resonator to couple the THz plasmons to the waveguide, (b) one of the resonant mode of the split ring resonator integrated with the waveguide	102
Figure 8.1: SEM image of the grating gate structure fabricated with EBL at Oak Ridge Nat. Lab. The slit width is 177nm and gate width is 495 nm.....	106
Figure 8.2: Microscope images of the circular grating gate structure before and after oxygen plasma etch to remove graphene over desired areas	108
Figure 8.3: Images of the packaged devices ready for measurement, (a) angle dependent measurement packaging at ambient conditions, (b) sample clamped with probes where probes are contacting with the pads and keeping the sample steady, (c) sample glued over the ceramic hip holder and wire bonded from the pads to chip holder	108

Figure 8.4: Tools used for electrical characterization, (a) semiconductor parameter analyzer HP 4156A, (b) probe station for contacting contact pads of a device by using microscope and micro manipulator probes	109
Figure 8.5: Schematic representation of the experimental set up and sample connection and wiring.....	111
Figure 8.6: The images of the tools used to measure THz response of the detectors.....	113
Figure 9.1: SEM images of the devices. (a) The SEM image of a circular grating gate device. The total device size is 1.6 mm by 1.6 mm including antennas and pads. Left antenna is the source side of the device, shown in S, while right antenna is the drain side of the device, shown in D and the bottom pad is connected to the gate, shown in G. (b) A zoomed in SEM image of the device showing the active graphene region. Graphene area is presented in green color where outer boundaries are dashed. Source of the device is the surrounding thick outer circle, source width is 3 μm , drain is the center circle, drain width is 8 μm . Gates are circular and connected to each other. The gate width is 1 μm and gate slit width is 200 nm. (c) SEM image of the device from the cross section after cleaving the device. Free standing graphene is circled. Gate metal is 50 nm thick and oxide is 30 nm thick	114
Figure 9.2: Process flow and graphene properties. (a) SEM image of the graphene on copper foil. Individual grains can easily be identified. (b) 2-dimensional micro Raman map of the device. Graphene is observed in blacked dashed area as patterned. The heat map shows the ratio between 2D band and G band (2D/G) which gives the information about how many graphene layers are stacked. Higher numbers more than 1.5 is assumed to be single layer and lower numbers less than 1.5 is assumed to be multi-layer. The map indicates that the graphene consist of multi grain and mostly single layer graphene. A small portion of the graphene is few layers. The ratio is not uniform over the device which indicates, the device will consist of multi-electron concentration graphene grains. (c) The graph shows the Raman spectrum at point p1 where the ratio 2D/G is one of the highest which indicates single layer graphene. (d) The graph shows the Raman spectrum at point p2 where the ratio 2D/G is lower which indicates few more layers graphene	115
Figure 9.3: Electrical and responsivity properties of the device. (a) The channel current as a function of source-drain voltage. The current flows over the graphene active region that behaves as a channel. (b) Channel current and gate leakage current as a function of gate voltage while channel voltage is kept at a constant 50 mV. (c) The responsivity of the device as a function of the temperature	116
Figure 9.4: Responsivity measurements at different channel and gate voltages. (a) Responsivity at different gate voltages. (b) Responsivity at different channel voltages. (c) Responsivity at different gate voltages detailed. (d) Responsivity at different channel voltages detailed	118

Figure 9.5: Responsivities as function of channel or gate voltage at different frequencies. (a) Responsivity and channel current as a function of channel voltage at 363 GHz resonant mode. (b) Responsivity ($V=R=(x^2+y^2)^{1/2}$ of signal) as a function of gate voltage at different frequencies. (c) Responsivity ($V=X$ of signal) as a function of gate voltage at different frequencies.....	119
Figure 9.6: Normalized response as a function of incident polarization angle. (a) Schematic representation of the device showing the incident Terahertz field polarization and rotation direction which is in clockwise. (b) Polar plot of normalized response at resonant frequency 304.5 GHz at room temperature and ambient pressure as a function of polarization direction	121
Figure 9.7: Second generation detector and its Normalized response as a function of incident polarization angle and frequency. The sample is rotated from 0 to 350 degrees with 10 degree steps. At each angle, response is measured. The azimuthal angle of the graph is polarization direction and from inner ring to outer ring is the frequency of the incident THz field from 280 GHz to 380 GHz. The heat map is in logarithmic scale	122
Figure 9.8: Second generation detector and its Normalized response as a function of incident polarization angle at resonant frequency. The sample is rotated from 0 to 350 degrees with 10 degree steps. At each angle, response is measured.....	123
Figure 9.9: (a) High responsivity linear grating device. (b) Simulation result for a graphene FET with lower electron concentration compared to the graphene FETs discussed in chapter 5. The plasma frequency is set to 4×10^{13} rad/s.	123

LIST OF ACRONYMS & ABBREVIATIONS

THZ	Terahertz
GHz	Gigahertz
Hz	Hertz
HEMT	High Electron Mobility Transistor
FET	Field Effect Transistor
GaN	Gallium Nitride
AlGaN	Aluminium Gallium Nitride
2DEG	2 Dimensional Electron Gas
MRI	Magnetic Resonance Imaging
mmW	millimetre Wave
UV	Ultra Violet
ADGG	Asymmetric Double Grating Gate
SEM	Scanning Electron Microscope
RIE	Reactive Ion Etching
FPA	Focal Plane Array
EBL	Electron Beam Lithography
EBE	Electron Beam Evaporation
ORNL	Oak Ridge National Laboratory
CNMS	Center for Nanophase Material Synthesis
AMERI	Advanced Material Research Laboratory
DI	De Ionized Water
PMMA	Poly methyl methacrylate
TM	Transverse Magnetic
TE	Transverse Electric
Al ₂ O ₃	Aluminium Oxide

BWO	Backward Wave Oscillator
TDS	Time Domain Spectrometer
QCL	Quantum Cascade Laser
FWHM	Full Width Half Maximum
NEP	Noise Equivalent Power
STJ	Superconducting Tunneling Junction
PML	Perfectly Matching Layer
FDTD	Finite Difference Time Domain

CHAPTER 1

Introduction to Terahertz Technologies

1.1. Terahertz Spectrum and Its Properties

While visible to infrared and microwave to radio waves have been extensively studied, research in the Terahertz (THz) region was lagged. [1] THz devices are considered to operate from 0.1 THz to 10 THz, which is in between infrared and microwave region in the spectrum. Fig. 1.1 represents where THz frequencies fall into in the electromagnetic spectrum. The lower frequency side of the THz region which is referred as millimeter waves (mmW) is mainly used for communication from satellites to mobile phones and wireless data transfer. Even medical imaging is made possible by utilizing this region such as magnetic Resonance Imaging (MRI). The higher frequency side of the THz region starts from infrared, which can be used for infrared imaging to fiber optical communication, and extends beyond the visible and ultraviolet (UV) frequencies. Much

Figure 1.1: The electromagnetic frequency spectrum. [1] Reprinted with permission as per license or document.

higher frequencies such as X-ray is being extensively used in medical imaging to structural defect analysis to crystal structure analysis.

The THz spectrum has unique and elusive properties which makes it attractive for imaging and sensing applications. Physics, biology, chemistry, medicine, astronomy, defense and security all utilize the THz spectrum. The energies of the THz frequencies are very low so that it is not high enough to ionize or break the bonds of biological tissues. The THz waves can penetrate into soft materials such as paper, fabric, plastic and leather but it cannot penetrate materials like metal, and the human body, which makes them perfect for security monitoring applications. The advantage of the THz spectrum over millimeter waves in security monitoring is the resolution, since the resolution is limited with wavelength used for imaging. In THz frequencies, wavelength is at the order of tens and hundreds of microns, which provide better resolution. The energy of the rotational modes of many molecules such as DNA [2], proteins [3], and explosives [4] coincide with the energy of the THz frequencies, which lets THz devices to distinguish materials due to their specific fingerprints within the THz spectrum. The THz frequencies are strongly absorbed by water and water vapor, which makes THz spectrum capable of giving the information of hydration state [5] and they can indicate the water condition of the tissue. THz devices are also used to track the defects hidden inside bulky materials that are transparent to THz such as plastic components [6].

1.2. Terahertz Sources and Detectors

THz imaging and spectroscopy techniques broadly could be classified into two groups. The first one is THz Time Domain Spectroscopy (TDS) and the other one is Backward

Wave Oscillator (BWO) spectroscopy are two common imaging techniques in THz applications. Both BWO and TDS systems are table-top experimental set ups and they require precise alignment to perform high yield experiments. These systems also tend to be expensive. Cost of a BWO system is around \$120,000 while a TDS system is \$70,000. Both systems are very bulky that require high power and large space. These systems generate THz wavelengths and then tend to measure transmission spectra or reflection spectra to acquire the optical properties of the material. The detectors used in BWO systems are not sensitive to the incident wavelength and they are broad band detectors. The detector is generally a bolometer, a pyroelectric detector or a Golay cell. The price of the detectors ranges from \$4,000 to \$15,000. Detectors used in TDS systems are generally silicon detectors. The sensing mechanism is the polarization rotation phenomena of the pulsed laser inside a non-linear crystal, mixed with generated THz radiation. This phenomenon is known as the Pockel's effect [7]. A femtosecond laser which is an expensive tool is used to generate terahertz and as well as sensing it. There is no way to tune the sensing wavelength of the detector for both systems. The measurement times of both systems are at the order of minutes. The detection time is long to get a significant signal-to-noise ratio. Another approach for the THz sensing is direct detection, where the incident THz light is upon a detecting device, and results in a measurable response. Available direct detection technologies with key parameters are summarized in Table 1.2.

Another technique in terahertz sensing is using continuous wave emitters such as free electron laser or quantum cascade lasers. The power of free electron laser can reach up to

20W and it's a coherent source while the power from a quantum cascade laser can range from tens of mW to hundreds of mW and they need to operate at cryogenic temperatures. The free electron laser is the bulkiest among all terahertz sources (requires a room space) while the quantum cascade lasers are compact such as few millimeters on a chip. But, the required cryogenic system makes them bulkier.

Nowadays, the most sensitive THz detectors are Golay cells, pyroelectric detectors, bolometers and Schottky diodes. They are not portable, very slow, and not tunable. Schottky diodes, as the most serious contender for the devices investigated in this study, can reach very low noise equivalent power (NEP) and high responsivity at millimeter waves. However, their responsivity drops orders of magnitude (to $<10^3$ V/W) at frequencies greater than 1 THz [22]. Moreover, Schottky diodes are not tunable for the wavelength detected.

Detector Type	NEP (W/Hz ^{1/2})	Responsivity (V/W)	Resp. time (sec)	Op. Tmp. (K)	Size	Tunable
Bolometers ^[8,9]	10^{-16} – 10^{-13}	10^5 – 10^7	10^{-3} – 10^{-2}	≤ 4.2	Large	No
Hot-e microbolometers ^[10,11]	10^{-19} – 10^{-17}	10^9	10^{-8}	≤ 0.3	Compact	No
STJ detectors ^[12]	10^{-16}	10^9	10^{-3}	≤ 0.8	Compact	No
Golay cells ^[13]	10^{-10}	10^5	10^{-2}	300	Large	No
Pyroelectric detectors ^[14]	10^{-10}	10^5	10^{-2}	240-350	Medium	No
Schottky diodes ^[15,16,17]	10^{-12}	10^3	10^{-12}	10-420	Compact	No
Plasmonic HEMTs ^[18,19]	10^{-10}	10^3	10^{-10}	10-420	Compact	YES
Antenna graphene FET ^[27]	10^{-7}	0.01		300	Compact	NO
Graphene Plasmonic Devices	10^{-10}	10^3		65-310	Compact	YES

Table 1.2: Comparison of THz direct detection technologies.

The THz detection by grating gate coupled field effect transistor (FET) detectors are able to operate at room temperatures in a broad band or narrow band manner. [20,21] Recently, a THz detector able to acquire real time video monitoring has been achieved at room temperature. [22] This focal plane array (FPA) camera utilizes from a circular antenna coupled FET detector and the detector is not at a tunable. The FET detector used is a silicon detector, which is also sensitive to visible light, but the wavelength was filtered from visible light by placing a high resistive silicon lens in front of the optical path. Novel ideas and approaches in tunable compact detection in the THz range are demonstrated successfully for resonant detection at low cryogenic temperatures. [23] These detectors are plasmonic sensors, which utilize excitation of plasmons on the two dimensional electron gas (2DEG) channel, which creates a DC bias between the source and drain of the transistor. [24] The THz plasmonic detectors require a cryogenic cooling system to maintain the properties of the 2DEG, such as high carrier mobility and high carrier concentration. The resonant plasmonic THz detectors require high carrier mobility over the channel (more than $10000 \text{ cm}^2/\text{Vs}$ depending on the electron effective mass) and sufficient carrier concentration (at the order of 10^{11} to 10^{13} cm^{-2}). The room temperature resonant detection of sub-THz frequencies has been achieved at 0.6 THz that utilize from a GaAs/AlGaAs heterojunction transistor, but the detector is not tunable and the gate length is just 250 nm, which is quite challenging for fabrication. [25] Recently, graphene has emerged as a material suitable for THz plasmonic applications due to its high carrier mobility and right amount of carrier concentration [26,27,]. These two properties create the basis for high quality factor THz plasmonic cavities at room temperature. Tunable THz metamaterials with patterning of graphene have been developed for wide band

Figure 1.2: Antenna coupled exfoliated graphene channel THz detector operating at room temperature. [27] Reprinted with permission as per license or document.

plasmonic excitation. [26] A room temperature exfoliated graphene THz FET detector is achieved to operate from 0.4 THz to 1.4 THz where THz waves are coupled by using logarithmic antennas as seen in Fig. 1.2. [27]. The responsivity of the devices was at the order of 0.04 V/W maximum and it was not a resonant response. Using exfoliated graphene is not suitable for mass fabrication for focal plane array applications. The coupling mechanism is an antenna coupler and it is different than a grating coupler which makes the device hundreds of microns in size which is around 700 μm diameter. Later, there have been other efforts to fabricate graphene THz devices but their responsivity was low, not resonant but rather quite broad band. [28,29] There is a tremendous effort in order to develop an ideal resonant terahertz detector working at ambient conditions with very high responsivity, and fast response time. No such detector has been demonstrated yet. Since it has been realized that graphene can sustain very high mobility values at room temperature with the right amount of electron concentrations to support plasmonic terahertz oscillations, there is an ongoing effort to fabricate the high mobility graphene

terahertz detectors. In order to excite strong terahertz plasmons, a grating gate is a necessity to compensate the momentum of the incoming radiation. Fabrication of devices with gate electrodes requires an insulating dielectric layer between the channel and the gate which causes the graphene to be sandwiched between the substrate and oxide layer. Such a treatment dramatically reduces the graphene mobility since the carriers are affected by the materials above and below the graphene. The graphene mobility drastically depends on the substrate and dielectric material. While graphene on silicon dioxide can have mobilities of $3300 \text{ cm}^2/\text{Vs}$ [30], graphene over boron nitride can have $24,000 \text{ cm}^2/\text{Vs}$ mobility [31] and freestanding graphene can have $200000 \text{ cm}^2/\text{Vs}$ mobility. [32,33,34] But, when an insulating material is deposited over the graphene to fabricate an FET, the mobility decreases dramatically in some cases only few hundreds which is even less than the silicon mobility. This problem has been waiting for to be solved, how one can have a grating gated transistor while sustaining high mobility values of graphene. We have overcome this issue by reversing the regular transistor structure and saving graphene from being sandwiched and leaving it suspended over desired regions. This will give the control of gate while maintaining high mobility. At gated region, the graphene will be over the oxide while on ungated regions, graphene will be suspended on air. Such a transistor can reach very high mobility values with the proper graphene treatment.

Aside from the experimental works mentioned above, the theoretical understanding of plasmons in FETs is also critical. The physics behind the plasmonic THz response has been in focus for a long time with new theories and approaches are developed in the

literature. [35,36] The gated region of a FET supports gated plasmons where electromagnetic fields are confined in between the 2DEG and the gate, while ungated plasmons with a different dispersion law are observed in the ungated region of a FET. In the case of periodically spaced gates, the grating gate supplies the necessary momentum to excite the plasmons compensating the momentum mismatch between the THz light in free space and plasmons.

In order to understand the physical properties of THz plasmons in FETs, the dispersion relations have been developed for gated 2DEG structures and ungated 2DEG structures as well as a combination of these two structures into a lattice with one-dimensional (1D) translational symmetry, known as a 1D plasmonic crystal. The gated or ungated plasmon dispersions for isolated gated and ungated regions neglect the coupling between these regions. [37] Recent studies have shown that the dispersion can be solved for plasmonic crystals, but the presented solutions are either an analogy to electrical circuits or to electronic wave solutions. [38] Recently, highly sensitive terahertz detectors based on asymmetric dual-grating gate (ADGG) HEMTs have been demonstrated with 25kV/W record high responsivity [39] but the plasmon dispersion in such structures has not been studied.

1.3. Contribution of This Work

This thesis outlines a new theoretical and experimental approach to investigate the THz light-plasmon interactions in various FET structures at room temperatures and cryogenic temperatures. We theorized, designed, fabricated and characterized various multi-size and multi-geometry detectors and experimentally demonstrate frequency dependent THz

detection. Engineering applications in THz imaging and detection are demonstrated by using the fabricated detectors. The detectors have the following important advantages, which make the devices the prime candidate for future THz on a chip application over the conventional THz detection techniques:

- i. Tunable by voltage – -10 to 10 volts
- ii. Compact on a chip – 50 μm size of each pixel
- iii. Room temperature operations and cryogenic operations– 65° K to 300° K
- iv. No moving optical components – no time delay or lenses are required
- v. Suitable for focal plane array (FPA) applications – millions can be fabricated on a chip

These advantages make the proposed devices the prime candidate for future THz on chip applications.

In the past, resonant sensing has been observed only at cryogenic temperatures since electron mobility is high enough at low temperatures to sustain resonant plasmonic excitation at the channel of the detector [40]. Only high electron mobility semiconductor field effect transistors were able to sustain resonant plasmonic detection. Room temperature detection has been attempted and achieved, however the detectors have very small responsivity with non-resonant behavior since the graphene is sandwiched and fabrication of such detectors in large scale is impossible with the method used. Here, we present resonant room temperature THz detection by novel free standing graphene-based flipped FETs with the quality factor $Q > 400$ and responsivity ~ 400 V/W. These are record-breaking numbers as the demonstrated quality factor is up to 50 times higher than the ones reported for GaN detectors and the demonstrated responsivity is 10,000 times higher than the previously reported graphene detector responsivity. Also we have come up

with a new idea to excite plasmons that are independent from the incident angle. By redesigning the gate, source and drain geometry, we were able to fabricate structures that can sustain plasmonic excitation at every incident angle.

Apart from THz detection, we have designed new geometries that can sustain THz plasmonic excitation in a ring resonator configuration. We have shown that that split ring resonator structures can be used to guide THz into deep sub-wavelength down $\lambda/200$ and achieve relatively higher quality factors than grating gate devices by plasmonic confinement which can be used for THz detection, filtering and possibly for THz on-chip-spectrometer. Moreover, ring resonator modes supported by system can be tuned with an applied voltage to gratings.

We have designed circular gratings that can sustain plasmons independent of the incident THz polarization. Plasmonic modes excited by incident THz radiation are concentrated into $\lambda/180$ area localized under the central disc. Electric field intensity under the central point is found to be orders of magnitude larger than the outer grating area. Optimal geometries for enhanced radiation coupling and plasmon focusing are investigated. Plasmonic lens modes supported by system has the advantage of tunability by an applied voltage to gratings. The large field enhancement by plasmonic confinement presents the potential for sub-wavelength imaging.

Finally, we have reported on a detailed study of dispersion properties of grating gate THz plasmonic devices and with symmetry-breaking defect-like cavities. Our numerical and analytical results suggest that the dispersion of plasmons can be presented in terms of an effective plasmonic index. The results suggested that long know classical dispersion for

plasmons was not complete and partially wrong since it includes approximations. We have suggested a complete resonant mode calculation for grating gate devices.

1.4. References

1. Ferguson, B., & Zhang, X. C. (2002). Materials for terahertz science and technology. *Nature materials*, 1(1), 26-33.
2. Markelz, A. G., Roitberg, A., & Heilweil, E. J. (2000). Pulsed terahertz spectroscopy of DNA, bovine serum albumin and collagen between 0.1 and 2.0 THz. *Chemical Physics Letters*, 320(1), 42-48.
3. Walther, M., Fischer, B., Schall, M., Helm, H., & Jepsen, P. U. (2000). Far-infrared vibrational spectra of all-trans, 9-cis and 13-cis retinal measured by THz time-domain spectroscopy. *Chemical Physics Letters*, 332(3), 389-395.
4. Liu, H. B., Chen, Y., Bastiaans, G. J., & Zhang, X. C. (2006). Detection and identification of explosive RDX by THz diffuse reflection spectroscopy. *Optics Express*, 14(1), 415-423.
5. Mittleman, D. M., Jacobsen, R. H., & Nuss, M. C. (1996). T-ray imaging. *IEEE Journal of selected topics in quantum electronics*, 2(3), 679-692.
6. Hor, Y. L., Federici, J. F., & Wample, R. L. (2008). Nondestructive evaluation of cork enclosures using terahertz/millimeter wave spectroscopy and imaging. *Applied Optics*, 47(1), 72-78.
7. Kippelen, B., Meerholz, K., & Peyghambarian, N. (1996). Ellipsometric measurements of poling birefringence, the Pockels effect, and the Kerr effect in high-performance photorefractive polymer composites. *Applied Optics*, 35(14), 2346-2354.
8. Richards, P. L. (1994). Bolometers for infrared and millimeter waves. *Journal of Applied Physics*, 76(1), 1-24.
9. QMC Instruments, <http://qmciworks.ph.qmw.ac.uk/QMCI/qmc.html>
10. L. Kuzmin, M. Fominsky, A. Kalabukhov, D. Golubey, and M. Tarasov, "Capacitively coupled hot-electron nanobolometer with SIN tunnel junctions," presented at Proceedings of SPIE - The International Society for Optical Engineering, Waikaloa, HI, United States, (2002).

-
11. Kuzmin, L. S., Fominsky, M., Kalabukhov, A., Golubev, D., & Tarasov, M. (2003, February). Capacitively coupled hot-electron nanobolometer with SIN tunnel junctions. In *Astronomical Telescopes and Instrumentation* (pp. 217-226). International Society for Optics and Photonics.
 12. Ariyoshi, S., Otani, C., Dobroiu, A., Sato, H., Kawase, K., Shimizu, H. M., ... & Matsuo, H. (2006). Terahertz imaging with a direct detector based on superconducting tunnel junctions. *Applied physics letters*, 88(20), 203503.
 13. QMC Instruments, <http://qmcworks.ph.qmw.ac.uk/QMCI/qmc.html>.
 14. Spectrum Detector Inc., "THz pyroelectric detector datasheet", 2007, <http://www.spectrumdetector.com/pdf/datasheets/THZ.pdf>
 15. Chahal, P., Morris, F., & Frazier, G. (2005). Zero bias resonant tunnel Schottky contact diode for wide-band direct detection. *IEEE electron device letters*, 26(12), 894-896.
 16. Hesler, J. L., & Crowe, T. W. (2007, September). NEP and responsivity of THz zero-bias Schottky diode detectors. In *Infrared and Millimeter Waves, 2007 and the 2007 15th International Conference on Terahertz Electronics. IRMMW-THz. Joint 32nd International Conference on* (pp. 844-845). IEEE.
 17. Kazemi, H., Nagy, G., Tran, L., Grossman, E., Brown, E. R., Gossard, A. C., ... & Zimmerman, J. D. (2007, June). Ultra sensitive ErAs/InAlGaAs direct detectors for millimeter wave and THz imaging applications. In *Microwave Symposium, 2007. IEEE/MTT-S International* (pp. 1367-1370). IEEE.
 18. Antonov, A. V., Gavrilenko, V. I., Demidov, E. V., Morozov, S. V., Dubinov, A. A., Lusakowski, J., ... & Golaszewska, K. (2004). Electron transport and terahertz radiation detection in submicrometer-sized GaAs/AlGaAs field-effect transistors with two-dimensional electron gas. *Physics of the Solid State*, 46(1), 146-149.
 19. Kachorovskii, V. Y., & Shur, M. S. (2008). Field effect transistor as ultrafast detector of modulated terahertz radiation. *Solid-State Electronics*, 52(2), 182-185..
 20. Dyakonov, M. I., & Shur, M. S. (1996). Plasma wave electronics: novel terahertz devices using two dimensional electron fluid. *IEEE Transactions on Electron Devices*, 43(10), 1640-1645.
 21. Rebeiz, G. M. (1992). Millimeter-wave and terahertz integrated circuit antennas. *Proceedings of the IEEE*, 80(11), 1748-1770.

-
22. Sherry, H., Grzyb, J., Zhao, Y., Al Hadi, R., Cathelin, A., Kaiser, A., & Pfeiffer, U. (2012, February). A 1kpixel CMOS camera chip for 25fps real-time terahertz imaging applications. In Solid-State Circuits Conference Digest of Technical Papers (ISSCC), 2012 IEEE International (pp. 252-254). IEEE.
 23. El Fatimy, A. S. ; Teppe, F. ; Knap, W. ; Veksler, D.B. ; Rumyantsev, S. ; Shur, M.S. ; Pala, N. ; Gaska, R. ; Fareed, Q. ; Hu, X. ; Seliuta, D. ; Valusis, G. ; Gaquiere, C. ; Theron, D. ; Cappy, A. "Terahertz detection by GaN/AlGaIn transistors" Electronics Letters Vol. 42 issue 23 1342-1343 (2016).
 24. El Fatimy, A., Tombet, S. B., Teppe, F., Knap, W., Veksler, D. B., Rumyantsev, S., ... & Hu, X. (2006). Terahertz detection by GaN/AlGaIn transistors. Electronics Letters, 42(23), 1342-1343.
 25. Teppe, F., Knap, W., Veksler, D., Shur, M. S., Dmitriev, A. P., Kachorovskii, V. Y., & Rumyantsev, S. (2005). Room-temperature plasma waves resonant detection of sub-terahertz radiation by nanometer field-effect transistor. Applied Physics Letters, 87(5), 052107.
 26. Ju, L., Geng, B., Horng, J., Girit, C., Martin, M., Hao, Z., ... & Wang, F. (2011). Graphene plasmonics for tunable terahertz metamaterials. Nature nanotechnology, 6(10), 630-634.
 27. Vicarelli, L., Vitiello, M. S., Coquillat, D., Lombardo, A., Ferrari, A. C., Knap, W., ... & Tredicucci, A. (2012). Graphene field-effect transistors as room-temperature terahertz detectors. Nature materials, 11(10), 865-871.
 28. Muraviev, A. V., Rumyantsev, S. L., Liu, G., Balandin, A. A., Knap, W., & Shur, M. S. (2013). Plasmonic and bolometric terahertz detection by graphene field-effect transistor. Applied Physics Letters, 103(18), 181114.
 29. Cai, X., Sushkov, A. B., Jadidi, M. M., Nyakiti, L. O., Myers-Ward, R. L., Gaskill, D. K., ... & Drew, H. D. (2015). Plasmon-enhanced terahertz photodetection in graphene. Nano letters, 15(7), 4295-4302.
 30. Dorgan, V. E., Bae, M. H., & Pop, E. (2010). Mobility and saturation velocity in graphene on SiO₂. Applied Physics Letters, 97(8), 082112.
 31. Kim, S. M., Hsu, A., Park, M. H., Chae, S. H., Yun, S. J., Lee, J. S., ... & Dresselhaus, M. (2015). Synthesis of large-area multilayer hexagonal boron nitride for high material performance. Nature communications, 6.
 32. Du, X., Skachko, I., Barker, A., & Andrei, E. Y. (2008). Approaching ballistic transport in suspended graphene. Nature nanotechnology, 3(8), 491-495.

-
33. Bao, W., Liu, G., Zhao, Z., Zhang, H., Yan, D., Deshpande, A., ... & Lau, C. N. (2010). Lithography-free fabrication of high quality substrate-supported and freestanding graphene devices. *Nano Research*, 3(2), 98-102.
34. Geim, A. K., & Novoselov, K. S. (2007). The rise of graphene. *Nature materials*, 6(3), 183-191.
35. Aizin, G. R., & Dyer, G. C. (2012). Transmission line theory of collective plasma excitations in periodic two-dimensional electron systems: Finite plasmonic crystals and Tamm states. *Physical Review B*, 86(23), 235316.
36. Rozhansky, I. V., Kachorovskii, V. Y., & Shur, M. S. (2015). Helicity-driven ratchet effect enhanced by plasmons. *Physical review letters*, 114(24), 246601.
37. Popov, V. V., Polischuk, O. V., & Shur, M. S. (2005). Resonant excitation of plasma oscillations in a partially gated two-dimensional electron layer. *Journal of applied physics*, 98(3), 033510.
38. Kachorovskii, V. Y., & Shur, M. S. (2012). Current-induced terahertz oscillations in plasmonic crystal. *Applied Physics Letters*, 100(23), 232108.
39. Kurita, Y., Ducournau, G., Coquillat, D., Satou, A., Kobayashi, K., Boubanga Tombet, S., ... & Otsuji, T. (2014). Ultrahigh sensitive sub-terahertz detection by InP-based asymmetric dual-grating-gate high-electron-mobility transistors and their broadband characteristics. *Applied Physics Letters*, 104(25), 251114.
40. Ryzhii, V., Satou, A., Otsuji, T., & Shur, M. S. (2008). Plasma mechanisms of resonant terahertz detection in a two-dimensional electron channel with split gates. *Journal of Applied Physics*, 103(1), 014504.

CHAPTER 2

Theoretical Background

In this chapter, we will describe the theory that is necessary to understand the operation of the THz plasmonic devices. This chapter first gives a summary of the optical properties of plasmons in metals and then in FETs.

2.1. Plasma Wave Physics

Optical properties of metals can be explained by using plasma model also known as Drude Model Mustafa K. MSc thesis. [1] In this model, the free electron gas interacts with fixed positive ion atom cores. Electron-electron interactions are neglected. Free electron gas responds to the applied electric field which defines the optical properties of metals. Oscillation of electrons is damped since electron-core collisions occur with a characteristic collision frequency $\gamma=1/\tau$ at the order of hundreds of THz depending on the electron concentration, where τ is mean free time of free electron gas. τ is generally of the order of 10^{-14} s at room temperature.

Equation of motion for an electron gas which is affected by an external electric field can be written as

$$m\ddot{x} + m\gamma\dot{x} = -eE \quad (2.1)$$

where m is the electron mass, e is unit charge and E is the electric field. The solution of the differential equation Eq. 2.1 can be solved by assuming $x(t)=x_0e^{-i\omega t}$ which results

$$x(t) = \frac{e}{m(\omega^2 + i\gamma\omega)} E(t) \quad (2.2)$$

Polarization (P) induced by the electron displacement is $P=nex$ and takes the following form

$$P = \frac{ne^2}{m(\omega^2 + i\gamma\omega)} E \quad (2.3)$$

The dielectric displacement (D) is $\epsilon_0 E + P$ and can be written as

$$D = \epsilon_0 \left(1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}\right) E \quad (2.4)$$

where $\omega_p^2 = ne^2/\epsilon_0 m$ is called plasma frequency of the free electron gas. The resulting dielectric function for the free electron gas can be expressed as

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \quad (2.5)$$

The real and imaginary parts of $\epsilon(\omega)$ where $\epsilon(\omega) = \epsilon_1(\omega) + i\epsilon_2(\omega)$ are

$$\epsilon_1(\omega) = 1 - \frac{\omega_p^2 \tau^2}{1 + \omega^2 \tau^2} \quad (2.6a)$$

$$\epsilon_2(\omega) = \frac{\omega_p^2 \tau}{\omega(1 + \omega^2 \tau^2)} \quad (2.6b)$$

Figure 2.1: Real part, ϵ_1 and imaginary part, ϵ_2 for silver calculated from Drude model and experimentally extracted data by Palik [4,1].

The model defined above is known as the Drude model [2]. For example, parameters for silver are; $\gamma\hbar=0.06\text{eV}$ and $\omega\hbar=7.9\text{eV}$, for gold; $\gamma\hbar=0.18\text{eV}$ and $w\hbar=8.5\text{eV}$ [3]. When $w_p < w$, metals can sustain their metallic behavior, but, for large frequencies near w_p , and with $w\tau \gg 1$, results in negligible damping, and real part of $\epsilon(w)$ becomes dominant and dielectric function of the undamped free electron plasma becomes

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2} \quad (2.7)$$

Fig. 2.1 shows the real ϵ_1 and imaginary ϵ_2 parts of dielectric function for silver metal calculated using Drude model and results are compared with experimental data given by Palik [4]. The dielectric function is shown as a function of the energy in eV. Theoretical ϵ_1 changes sign from negative to positive after the theoretical plasma frequency $\omega_{p\text{-theory}}$. For energies above $\omega_{p\text{-theory}}$, metal becomes transparent to the applied electric field so that electrons cannot respond to the externally applied electric field. Drude model can define the optical properties of metals for energies until transitions between electronic bands.

For some noble metals used in plasmonic applications like copper, silver and gold, interband transitions start occurring around 2 eV [5] and Drude model fails for higher energies. Since there are no interband transitions in THz region and the plasma frequency of the 2DEG is very low compared to metals, Drude model is in good agreement with experimental results.

To understand the properties of plasmons we need to calculate the energy-momentum relation known as dispersion of surface plasmons. Plasmons are charge oscillations confined at the metal dielectric interface. Starting with Helmholtz equations at a metal-dielectric interface with constant dielectric permittivity and with proper boundary conditions, plasmon dispersion relations can be derived. By referring to the coordinate system in Fig. 2.2, wave propagation at the metal-dielectric interface can be defined. The dielectric permittivity is constant in the xy plane and changes at $z=0$. When $z>0$, the dielectric permittivity is ϵ_1 and when $z<0$, the dielectric permittivity is ϵ_2 . The wave propagation direction is x-axis.

Starting with the wave equation

$$\nabla^2 E - \frac{\epsilon}{c^2} \frac{\partial^2 E}{\partial t^2} = 0 \quad (2.8)$$

and assuming E field is harmonic

$$E(r, t) = E(r) e^{-i\omega t} \quad (2.9)$$

We get Helmholtz equation

$$(\nabla^2 + k_0^2 \epsilon)(E, H) = 0 \quad (2.10)$$

Figure 2.2: Electric field intensity profile of a SPP propagating at the metal dielectric interface. [1]

where k_0 ($k_0 = \omega/c$) is the momentum of wave in free space. For a wave propagating along the x-axis and for transverse magnetic (TM) modes, following assumptions can be made

$$E(r, t) = E(z)e^{i\beta x} \quad (2.11a)$$

$$H(r, t) = H(y)e^{i\beta x} \quad (2.11b)$$

where β is the propagation constant along the x-axis. When we insert Eq. 2.1 to 2.2 results in

$$\frac{\partial^2 E(z)}{\partial z^2} + (k_0^2 \epsilon - \beta^2)E(z) = 0 \quad (2.12a)$$

$$\frac{\partial^2 H(y)}{\partial y^2} + (k_0^2 \epsilon - \beta^2)H(y) = 0 \quad (2.12b)$$

The field components, when $z > 0$ can be defined as

$$H_y(z) = A_2 e^{i\beta x} e^{-k_2 z} \quad (2.13a)$$

$$E_x(z) = iA_2 \frac{1}{\omega \epsilon_0 \epsilon_2} k_2 e^{i\beta x} e^{-k_2 z} \quad (2.13b)$$

$$E_z(z) = -A_2 \frac{\beta}{\omega \epsilon_0 \epsilon_2} k_2 e^{i\beta x} e^{-k_2 z} \quad (2.13c)$$

The field components, when $z < 0$ can be defined as

$$H_y(z) = A_1 e^{i\beta x} e^{-k_1 z} \quad (2.14a)$$

$$E_x(z) = iA_1 \frac{1}{\omega \varepsilon_0 \varepsilon_1} k_1 e^{i\beta x} e^{-k_1 z} \quad (2.14b)$$

$$E_z(z) = -A_1 \frac{\beta}{\omega \varepsilon_0 \varepsilon_1} k_1 e^{i\beta x} e^{-k_1 z} \quad (2.14c)$$

where k_1 and k_2 are positive. Continuity at boundary conditions at $z=0$ results in

$$A_1 = A_2 \quad (2.15a)$$

$$\frac{k_2}{k_1} = -\frac{\varepsilon_2}{\varepsilon_1} \quad (2.15b)$$

$$k_1^2 = \beta^2 - k_0^2 \varepsilon_1^2 \quad (2.15c)$$

$$k_2^2 = \beta^2 - k_0^2 \varepsilon_2^2 \quad (2.15c)$$

The above equations are satisfied only if ε_1 and ε_2 has opposite signs. Since ε_1 is always positive (because it is dielectric), this condition is satisfied at a specific frequency interval from zero to plasma frequency, because, only at this interval, ε_2 is negative. If we solve these equations, we derive the dispersion relation for plasmons as

$$k_P = \frac{\omega}{c} \sqrt{\frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2}} \quad (2.16)$$

where $\beta=k_P$ and $k_0=\omega/c$. k_P is always larger than k_0 , which implies that light in free space cannot directly excite plasmons since they have different k values. This situation is known as the momentum mismatch. Dielectric permittivity is constant over a wide range of wavelengths for dielectrics compared to the metals and dielectric permittivity of metals changes dramatically for visible light. When $\varepsilon_1=-\varepsilon_2$, the singularity point is obtained. The singularity is

$$\omega_{SP} = \frac{\omega_p}{\sqrt{1 + \epsilon_2}} \quad (2.17)$$

This specific frequency is called the surface plasmon resonance frequency.

Fig. 2.3 shows the dispersion of plasmons for silver-air interface. Plasmons bound to the interface are the curve below the light line up to surface plasmon resonance frequency at 3.7 eV. Bound plasmons are confined at the metal dielectric interface propagating along the interface. In the bound mode regime, momentum of light in air is less than the momentum of plasmons for the same energies. Because, plasmon are collective oscillations of free electrons and photons, plasmons are hybrid waves that have both electron and photon parts. The momentums of electrons are larger than the momentum of light in free space with the same energy. This effect causes a momentum miss match. The difference in momentum prevents the excitation of plasmons when light in air is incident over the metal surface. To compensate the momentum miss match, the momentum of light should be enhanced.

Figure 2.3: Surface plasmon dispersion relation for silver-air interface and dispersion of light in air.

Electric and magnetic field distribution of plasmons propagation at metal dielectric interfaces for TM polarization is shown in Fig. 2.4. Electric fields are generated by positive and negative charge oscillations on the surface of the metal. H field has a component only parallel to the interface. E field has both parallel and perpendicular field components to the interface. Perpendicular components of the E field in the two media are in opposite directions and parallel components of the E field in the two media are in the same direction. Boundary conditions require the continuity of $E_{//}$ and $D_{\perp}$ according to Maxwell's equations. The continuity of $D_{\perp}$ is satisfied for positive values of ϵ_1 and negative values of ϵ_2 a condition that is only satisfied for metal-dielectric interfaces below plasmon frequency and this indicates, plasmons exists only at the metal-dielectric interfaces. H fields should be divergence free and that indicates the absence of magnetic monopoles. The end points of the H field lines should be in the same direction. For a transverse electric field (TE) mode solutions, boundary condition for the continuity of $H_{//}$ cannot be satisfied because the H field directions are in opposite directions at the metal dielectric interface and as a result of this TE polarized plasmons cannot be excited at the metal dielectric interfaces. [6]

Figure 2.4: Electric and magnetic field distributions of SPPs propagating at the metal-dielectric interface and Cross section view from the x-z plane, of electric and magnetic field distributions of SPP propagation at the metal-dielectric interface. [1]

The wavelength of the plasmons is the wavelength of the charge distributions on the surface. Real part of dispersion defines the wavelength of plasmons and imaginary part of dispersion defines the loss and the propagation length of plasmons. Real part of the plasmon dispersion is

$$k_{P-real} = k_0 \sqrt{\frac{\epsilon_d \epsilon_{m1}}{\epsilon_d + \epsilon_{m1}}} \quad (2.18)$$

where ϵ_{m1} is the real part of dielectric function of the metal and ϵ_d is the dielectric function of dielectric. Plasmon wavelength can be expressed as

$$\lambda_P = 2\pi/k_{P-real} \quad (2.19)$$

$$\lambda_P = \lambda_0 \sqrt{\frac{\epsilon_d + \epsilon_{m1}}{\epsilon_d \epsilon_{m1}}} \quad (2.20)$$

Wavelength of the plasmon is smaller than the wavelength of light in free space which enables to study optics below the light diffraction limit called sub-wavelength optics. Wavelength of light in air can be reduced depending on the momentum difference between light in free space and plasmons. [7]

Plasmons cannot be excited without overcoming momentum mismatch between light in free space and plasmons as we have proved. Methods like grating coupling or prism coupling to excite plasmons is necessary to compensate the mismatch [8]. There are also other methods like the use of trench scatterers, charged particle impact and near field couplers [6]. Prism coupling and grating coupling is the most common ways to excite plasmons.

In grating couplers, grating surfaces can compensate the missing momentum by adding momentum to the incident light induced by the periodicity of the grating. Grating coupler allows to excite plasmons when light is incident from above the grating or below the grating. According to Fig. 2.5, plasmons can be excited using grating coupler when the condition is satisfied

$$k_P = k_0 \sin(\theta) \pm mG \quad (2.21)$$

where G ($G=2\pi/a$) is the reciprocal lattice vector of the grating and m is the order of diffraction and a is the period of the grating.

2.2. Plasmons in FETs

The plasmonic detection of the THz radiation is based on the excitation of plasma oscillations in the 2DEG channels of FET structures by the incoming THz light. FETs support two different types of plasma oscillations. The first one is the plasma oscillations in the gated region of the 2DEG channel. If an infinite perfect conductive plane is located at a distance d from the infinite 2DEG, and the conducting plane is close enough to 2DEG (*i.e.* $kd \ll 1$), then the dispersion relation is given by

Figure 2.5: Schematic representations of grating coupler. [1]

$$\omega_p = k \sqrt{(e^2 N d / m^* \epsilon_0 \epsilon_1)} \quad (2.22a)$$

where ω_p is the frequency, k is the wave vector of the plasma wave, N is the sheet carrier density, e is the electron charge, m^* is the effective mass of electron, ϵ_0 is the dielectric permittivity, and ϵ_1 is the dielectric constant of the insulator separating the 2D electron layer from the perfectly conductive plane. The second type of plasma oscillations exist in ungated regions. For negligible electron scattering in 2D electron gas, the dispersion relation for ungated plasma oscillations in an infinite homogenous 2D electron sheet is

$$\omega_p = \sqrt{k} \sqrt{(e^2 N d / m^* \epsilon_0 \bar{\epsilon})} \quad (2.22b)$$

where $\bar{\epsilon}$ is the effective dielectric function, which depends on the geometry of the structure. [9]

The charge distributions for gated plasmonic modes are presented in Fig.2.6. Total charge is conserved within the gate metal and 2DEG. Two couple of plus and minus charge is

Figure 2.6: a) The representation of ungated and gated plasmons. The gated second mode is presented under the gate. The directions of the electric fields are shown with arrows. b) fundamental mode, c) third mode.

observed in first mode, four couple for second mode and six couple for the third mode.

Plasmon dispersion in a gated graphene can be formally written in the same form as in a conventional semiconductor structure with substituting the effective electron mass by the “relativistic” effective mass m_F resulting in

$$\omega = q \sqrt{N_s \frac{V_f^2 e^4}{\hbar^2 \epsilon^2}} \quad (2.23)$$

where N_s is the sheet carrier concentration, d is the distance between the graphene channel and the gate metal, ϵ is the permittivity, q is the plasmon wavevector, which is determined by the grating gate period L , $q=2\pi/L$ ($n = 1,2,3\dots$). [10]

2.3. Electrical Responsivity

The equations describing 2DEG are the relationship between the carrier concentration and gate voltage swing, the equation of motion, and the continuity equation. The concentrations, n_s in the channel depends on gate-channel voltage, $U=U_{gc}(x)-U_T$, and

$$n_s = CU/e \quad (2.24)$$

where C is the gate capacitance per unit area and $U_{gc}(x)$ is the gate-channel voltage, U_T is the threshold voltage. Eq. 2.24 represents gradual channel approximation. [11,12] that is valid when potential variation in the scale of the channel is much greater than the gate-channel separation.

Figure 2.7: Schematically representation of an 2DEG FET with gate, source and drain contacts.

Euler equation of motion is defined as

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \frac{e}{m} \frac{\partial U}{\partial x} + \frac{v}{r} = 0 \quad (2.25)$$

where $\partial U / \partial x$ is the longitudinal electric field in the channel, $v(x,t)$ is the local electron velocity, and m is the effective electron mass. The last term is to represent electron collision with impurities and phonons. Eq. 2.25 must be solved with continuity equation that can be written as

$$\frac{\partial U}{\partial t} + \frac{\partial(Uv)}{\partial x} = 0 \quad (2.26)$$

When the boundary conditions, for detection mode operation for an FET shown in Fig. 2.7, are

$$U(0, t) = U_0 + U_a \cos(\omega t) \text{ for } x = 0 \text{ on source side} \quad (2.27)$$

$$J(L, t) = U_0 + U_a \cos(\omega t) \text{ for } x = L \text{ on drain side} \quad (2.28)$$

where U_0 is the dc gate-source voltage, $U_{ac}=U_a\cos(\omega t)$ is the external ac voltage induced between the gate and source by the incident illumination, and $j=CUv$ is the electron current per unit width. To solve Eq. 2.25 and 2.26,

$$v = v_{ta} + v_1 + v_2 + \dots \quad (2.29)$$

$$U = U_{ta} + U_1 + U_2 + \dots \quad (2.30)$$

where v_{ta} and U_{ta} are time averaged electron velocity and channel potential, and v_n, U_n vary in time and frequency $n\omega$. Eq. 2.25 and 2.26 are nonlinear equations and different harmonics are coupled. If U_a is small, v_1, U_1 are proportional to U_a^2 , etc. the first order in U_a , we get the equations as

$$\frac{\partial v_1}{\partial t} + \frac{\partial u_1}{\partial x} + \frac{v_1}{r} = 0 \quad (2.31)$$

$$\frac{\partial u_1}{\partial t} + s^2 \frac{\partial v_1}{\partial x} = 0 \quad (2.32)$$

Where $u_1=eU_1/m$ and $s=(eU_0/m)^{1/2}$ is the plasma wave velocity. Keeping the second order time independent terms, we get

$$\frac{d}{dx} \left(u_{ta} + \frac{\langle v_1^2 \rangle}{2} \right) + \frac{v_{ta}}{r} = 0 \quad (2.33)$$

$$\frac{d}{dx} (s^2 v_{ta} + \langle u_1 v_1 \rangle) = 0 \quad (2.34)$$

$u_{ta}=eU_{ta}/m$ and angular brackets represent time averaging over $2\pi/\omega$ period. The boundary conditions for Eq. 2.31-34 follow from Eq. 2.27 and

$$u_1(0) = \frac{e}{m} U_a \cos(\omega t) \quad (2.35)$$

$$u_{ta}(0) = \frac{e}{m} U_a \quad (2.36)$$

$$v_{ta}(L) = v_1(L) = 0 \quad (2.37)$$

For the boundary conditions in Eq. 2.36 and 2.37, the integration of Eq. 2.33 and 2.34 with respect to x results in

$$\Delta u = u_{ta}(L) - u_{ta}(0) = \frac{1}{2} \langle v_1^2(0) \rangle - \frac{1}{\tau} \int_0^L v_{ta} dx \quad (2.38)$$

$$v_{ta} = -\frac{\langle v_1 v_2 \rangle}{s^2} \quad (2.39)$$

To find an explicit expression for the dc detector response, Δu , we must solve Eq. 2.31 and 2.32 for u_1 and v_1 with the boundary conditions given by Eq. 2.35 and 2.37 and substitute the solutions into Eq. 2.38 and 2.39. The solutions for v_1 and u_1 that are proportional to $\exp(ikx-i\omega t)$, we get the dispersion equation as

$$\omega^2 + i\frac{\omega}{\tau} + s^2 k^2 = 0 \quad (2.40)$$

The dispersion relation for plasma waves becomes

$$k = \pm k_0 = \pm \frac{\omega}{s} \sqrt{1 + \frac{i}{\omega\tau}} \quad (2.41)$$

Then, the solution to Eq. 2.31 and 2.32 is given by

$$u_1 = \text{Re}[(C_1 e^{ik_0 x} + C_2 e^{-ik_0 x}) e^{i\omega t}] \quad (2.42)$$

$$v_1 = \text{Re} \left[\frac{w}{k_0 S^2} (C_1 e^{ik_0 x} + C_2 e^{-ik_0 x}) e^{i\omega t} \right] \quad (2.43)$$

The C_1 and C_2 constants are found from the boundary conditions

$$C_1 = \frac{u_a}{1 + e^{2ik_0 L}} \quad (2.44)$$

$$C_2 = \frac{u_a}{1 + e^{-2ik_0 L}} \quad (2.45)$$

where $u_a = U_a/m$. Using Eq. 2.38, 2.39 and 2.41 to 45 yields the detector response $\Delta U = m\Delta u/e$ that is the constant source-drain voltage induced by external ac field

$$\frac{\Delta U}{U_0} = \frac{1}{4} \left(\frac{U_a}{U_0} \right)^2 f(\omega) \quad (2.46)$$

where

$$f(w) = 1 + \beta - \frac{1 + \beta \cos(2k'_o L)}{\sinh^2(k''_o L) + \cos^2(k'_o L)} \quad (2.47)$$

β is

$$\beta = \frac{2w\tau}{\sqrt{1 + (\omega\tau)^2}} \quad (2.47)$$

and k'_o and k''_o are the real and imaginary parts of k_0 derived from

$$k'_o = \frac{\omega}{8} \sqrt{\frac{\sqrt{1 + (\omega t)^{-2}} + 1}{2}} \quad (2.48)$$

$$k'_o = \frac{\omega}{8} \sqrt{\frac{\sqrt{1 + (\omega t)^{-2}} - 1}{2}} \quad (2.49)$$

When $\omega\tau \gg 1$, the damping of the plasmons are small. In this case, $\beta=2$, $k'_o/\omega s$, $k''_o=1/2\tau$ and

$$f(w) = \frac{3\sinh^2(L/2s\tau) + \sin^2(wL/s)}{\sinh^2(L/2s\tau) + \cos^2(wL/s)} \quad (2.50)$$

For a short sample, $s\tau/L \gg 1$, $f(w)$ exhibits sharp resonances as $\omega_0 = \pi s/2L$ and its odd harmonics. In this case, in the vicinity of the resonance frequencies, when $|\omega - n\omega_0| \ll \omega_0$, where $n=1, 3, 5, 7, \dots$, we find from Eq. 2.50 that

$$f(\omega) = 4 \left(\frac{s\tau}{L} \right)^2 \frac{1}{4(\omega - n\omega_0)^2 \tau^2 + 1} \quad (2.51)$$

The factor $s\tau/L$, that determines the quality factor of the plasmons, can be in the range from 10 to 100 in AlGaAs/GaAs HEMTs. Eq. 2.51 indicates that the 2DEG in a FET can be used for resonant electromagnetic detection.

2.4. References

1. Karabiyik, M. (2010). Fabrication, characterization and simulation of plasmonic cavities (Master dissertation, Bilkent University).
2. Maier, S. A. (2007). Plasmonics: fundamentals and applications. Springer Science & Business Media.
3. <http://www.wave-scattering.com/drudefit.html>
4. Palik, E. D. (1998). Handbook of optical constants of solids (Vol. 3). Academic press.
5. Fox, M. (2006) Optical Properties of Solids, Oxford University Press.
6. Zakharian, A. R., Moloney, J. V., & Mansuripur, M. (2007). Surface plasmon polaritons on metallic surfaces. Optics express, 15(1), 183-197.
7. Palik, E. D. (1998). Handbook of optical constants of solids (Vol. 3). Academic press.
8. Fleischmann, M., Hendra, P. J., & McQuillan, A. J. (1974). Raman spectra of pyridine adsorbed at a silver electrode. Chemical Physics Letters, 26(2), 163-166.
9. Popov, V. V., Shur, M. S., Tsymbalov, G. M., & Fateev, D. V. (2007). Higher-order plasmon resonances in GaN-based field-effect transistor arrays. International Journal of High Speed Electronics and Systems, 17(03), 557-566.
10. Karabiyik, M., Al-Amin, C., & Pala, N. (2013). Graphene-Based Periodic Gate Field Effect Transistor Structures for Terahertz Applications. Nanoscience and Nanotechnology Letters, 5(7), 754-757.
11. Dyakonov, M., & Shur, M. (1993). Shallow water analogy for a ballistic field effect transistor: New mechanism of plasma wave generation by dc current. Physical review letters, 71(15), 2465.
12. Shur, M. S. (1996) Introduction to Electronic Devices. New York, NY: Wiley.

CHAPTER 3

Numerical Analysis

3.1. FDTD Theory

In order to gain further insight to the physics of THz plasmons, propagation and excitation, we can numerically solve the paraxial wave equation. There are numerous ways to achieve this. Finite difference time domain (FDTD) is one of the most powerful techniques for solving Maxwell's equations with proper boundary conditions. The description and formulation of this iterative method was described in Ref. [1]:

In our numerical analysis, the THz plasmonic structure is located in a computation window frame. The computation window is divided by a three dimensional grid and each of these cell are called the Yee cell. The size of these grids, Δx , Δy , Δz , are set to be small enough that they do not change drastically from one to the neighboring one. For a stable converging solution, the condition that

$$\sqrt{(\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2} > c\Delta t = \sqrt{\frac{1}{\epsilon\mu}} \times \Delta t \quad (3.1)$$

has to be satisfied.

In a two dimensional homogeneous medium along one axis, in this case it is z-axis, ϵ and μ is constant along z-axis and $J=0$, no current, the electromagnetic fields for transverse magnetic (TM) can be written in difference iterative form

$$E_z^{n+1}(i, j) = E_z^n(i, j) + Z \frac{\Delta\tau}{\Delta x} [H_y^{n+1/2}(i + 1/2, j) - H_y^{n+1/2}(i - 1/2, j)] \quad (3.2)$$

$$-Z \frac{\Delta\tau}{\Delta y} [H_x^{n+1/2}(i, j + 1/2) - H_x^{n+1/2}(i, j - 1/2)]$$

$$H_x^{n+1/2}(i, j + 1/2) = H_x^{n-1/2}(i, j + 1/2) + \frac{1}{Z} \frac{\Delta\tau}{\Delta y} [E_z^n(i, j + 1) - E_z^n(i, j)]$$

$$H_y^{n+1/2}(i + 1/2, j) = H_y^{n-1/2}(i + 1/2, j) + \frac{1}{Z} \frac{\Delta\tau}{\Delta x} [E_z^n(i + 1, j) - E_z^n(i, j)]$$

where $Z=(\mu/\epsilon)^{1/2}$, $\Delta\tau=c\Delta t$, c is the speed of light, t is the simulation time and Δt is the time step, n is the time iteration, i is the vector component along the x-axis and j is the vector component along the y-axis. The eq. 3.2 is solved iteratively for given initial conditions. Initial conditions are generally pulsed sources.

3.2. Numerical Analysis of Absorption and Dispersion Characteristics

A commercial FDTD simulation tool Lumerical was used to investigate the electromagnetic field profile of the plasmons and the plasmonic absorption spectra of the studied devices at THz frequencies [2]. Typical simulation setups used for absorption and dispersion analysis in our studies are presented in Fig.3.1a and b, respectively. For absorption studies, the modes were excited with a broad-band plane wave source whereas a dipole source was used for dispersion calculations. In both cases, the polarization was perpendicular to the plane of the structure. The source bandwidth was selected based on the investigated structures and the targeted spectrum. Longer temporal the pulse width generates narrower bandwidth. The plasmons are excited when the momentum and energy of the incident wave match to the plasmons'. Reflection and transmission

monitors were placed at above and below the devices to calculate their absorption spectrum and an electric field monitor was placed around the channel to calculate the excitation spectrum of the plasmons. Periodic Bloch boundary conditions are applied to each side of the devices which turn the structure effectively an infinite array of the studied devices.

The 2D electron layers in the AlGaIn/GaN hetero-interface and the graphene layer were defined as plasma layers with specific plasma frequencies and collision frequencies extracted from the experimental results reported in the literature. [3,4] Per the following equations, plasma frequency is the measure for electron concentration and plasma collision time is the measure for electron mobility in the plasma layer:

$$\omega_p = \sqrt{\frac{n_e e^2}{m^* \epsilon}} \quad (3.3)$$

$$\mu = e\tau/m^* \quad (3.4)$$

where m^* effective mass and ϵ being permittivity of the material where electrons are present. The electron mobility is $\mu = q\tau/m$ where e is elementary charge, τ is average scattering time and m is the effective mass of the electrons. Here, τ defines the plasma collision frequency in simulations once the mobility and effective mass is known.

The plasma frequency used in GaN simulations is 360×10^{12} rad/s and the plasma collision frequency was 1×10^{12} rad/s. Physically, plasma frequency depends on the doping level of the AlGaIn in a GaN device, because, the electrons in the doped AlGaIn layer migrate to form a 2DEG channel at the heterointerface because of the conduction band

Figure 3.1: Screen shots from the FDTD simulation setups for (a) absorption and (b) dispersion calculations. gate is indicated with yellow in a and gray in b and 2DEG is indicated with gray. Blue material is GaN at upper side of the 2DEG and AlGaN is at lower side of the 2DEG. Right and left boundaries are periodic. Upper and lower boundaries are absorbing layer each separated at least half of the longest wavelength. A broad band source illuminates the structure. Absorption is calculated from reflection and transmission.

discontinuity. At the hetero-interface, conduction band of the GaN layer is below the fermi level forming a quantum well which is filled with the electrons from the doped AlGaN layer. The thickness of this quantum well defines the thickness of the plasma layer which was set to 5nm in the simulations. The mobility of the GaN devices dramatically depends on the temperature. As the temperature decreases, the mobility increases from $1000 \text{ cm}^2/\text{Vs}$ at room temperature to $40000 \text{ cm}^2/\text{Vs}$ at 4 K. [5] Such a high mobility value which can be attained at cryogenic temperatures is necessary in order to excite high quality factor plasmons and to properly distinguish the plasmonic modes. For low mobility values, the modes are broadened and cannot be individually resolved since the full width half maximum of frequency represents the lifetime of the plasmons.

The same approach is also valid for graphene. For graphene, the mobility dramatically depends on the doping level because of scattering with impurities of carriers during their transport in the channel. In Ref. [6], the dependence of mobility over temperature and

carrier concentration are reported in detail. The metals used for gate electrodes are either gold or titanium which have well defined electrical and optical parameters in the THz frequency range. These parameters and our simulation methods have been validated by numerically reproducing the experimental results both for graphene and GaN/AlGaN devices reported in the literature (Fig. 3.2).

The simulations were terminated when the total electric field converges down to the electric field that is 5 to 6 orders of magnitude smaller than the initial electric field value. Custom codes for data analysis were used to calculate absorption and transmission spectra of the structures. The mesh size was sufficiently small to match experimental data for structures with small features.

In the dispersion studies, the data is recorded for several different k vectors that are added to the Bloch boundary conditions with the largest k vector being half of the reciprocal lattice of the unit cell. Incident wave spectrum was selected to cover wide THz range. The electric field profiles for each simulation were extracted to calculate the total electric field at each frequency and momentum value and mapped over a 2D graph by a custom code. It should be noted that due to the use of periodic boundary conditions, the presented results are for an infinite array of the unit cell described here.

Figure 3.2: Comparison of published experimental data with the simulated data. a) Transmission spectrum of AlGaIn/GaN grating gate FET detectors [4]. b) Simulation result for ref [4] c) Transmission spectrum of graphene micro ribbons [3] . d) Simulated result for ref [3]. The simulation showed good agreement with the results and parameters values of the experiments. Reprinted with permission as per license or document.

3.3. References

1. Yee, K. (1966). Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *IEEE Transactions on antennas and propagation*, 14(3), 302-307.
2. Lumerical Solutions, Vancouver, Canada.
3. Ju, L., Geng, B., Horng, J., Girit, C., Martin, M., Hao, Z., ... & Wang, F. (2011). Graphene plasmonics for tunable terahertz metamaterials. *Nature nanotechnology*, 6(10), 630-634.
4. Muravjov, A. V., Veksler, D. B., Popov, V. V., Polischuk, O. V., Pala, N., Hu, X., ... & Shur, M. S. (2010). Temperature dependence of plasmonic terahertz absorption in grating-gate gallium-nitride transistor structures. *Applied Physics Letters*, 96(4), 042105.
5. Smorchkova, I. P., Elsass, C. R., Ibbetson, J. P., Vetury, R., Heying, B., Fini, P., ... & Mishra, U. K. (1999). Polarization-induced charge and electron mobility in AlGaIn/GaN heterostructures grown by plasma-assisted molecular-beam epitaxy. *Journal of applied physics*, 86(8), 4520-4526.
6. Hwang, E. H., & Sarma, S. D. (2008). Acoustic phonon scattering limited carrier mobility in two-dimensional extrinsic graphene. *Physical Review B*, 77(11), 115449.

CHAPTER 4

Plasmon Excitation and Dispersion of Plasmons

4.1. Plasmons in Grating Gate FETs

The structures investigated in this section consist of graphene layers on sapphire substrates as shown in the inset in Fig. 4.1 and comparison of the devices with GaN based devices. Titanium grating gates are placed on 17 nm thick SiO₂ layer deposited on graphene. Different gate period, L, and gate finger length, W, combinations were studied.

A short channel with high sheet carrier concentration acts as a resonant cavity for the plasma waves with the fundamental frequency of ω_0 and its harmonics. An incoming electromagnetic radiation excites plasma waves in such a channel. When $\omega_0\tau \gg 1$ (τ is the momentum relaxation time) the resonant condition is satisfied. The electron energy dispersion in undoped graphene is linear $E = \hbar V_F k$ with k being the electron momentum and V_F being the 2D Fermi velocity, which is a constant for graphene ($V_F = 10^8$ cm/s). The linear electron energy spectrum implies zero effective electron mass in graphene. The electron “inertia” in massless graphene is described by a fictitious “relativistic” effective mass $m_F = \hbar V_F / v_F^2$, where E_F is the Fermi energy. Electron relaxation rate in graphene with electron mobility μ can be estimated as $1/\tau = e/\mu m_F$. Therefore, $\omega_0\tau \gg 1$ is satisfied for frequencies above 2 THz even for low mobility graphene with $\mu = 1600$ cm²/Vs. Plasmon dispersion in a gated graphene can be formally written in the same form

Figure 4.1: Room temperature absorption spectra of AlGaIn/GaN and Graphene grating gate FET structures with $L=1.5\mu\text{m}$ $W=1.15\mu\text{m}$, $N_s=7.5\times 10^{12}\text{ cm}^{-2}$. The inset shows the cross section of the structure. (i) Graphene, (ii) AlGaIn/GaN.

as in a conventional semiconductor structure with substituting the effective electron mass by the “relativistic” effective mass m_F resulting in

$$w = q^4 \sqrt{N_s \frac{2V_f^2 e^4 d^2}{\hbar^2 \epsilon^2}} \quad (4.1)$$

where N_s is the sheet carrier concentration, d is the distance between the graphene channel and the gate metal, ϵ is the permittivity, q is the plasmon wavevector, which is determined by the grating gate period L , $q=2\pi/L$ ($n = 1, 2, 3, \dots$).

Room temperature operation is a crucial aspect for the practicality of the THz devices for many practical applications like medical imaging, security and sensing. In Fig. 4.1 we compare the room temperature absorption spectra of Graphene and AlGaIn/GaN grating gate devices with the same geometrical parameters. The graphene devices present a well pronounced resonant absorption peaks corresponding to the fundamental mode and first

Figure 4.2: Absorption spectra of graphene with different mobilities. $L=1.5\mu\text{m}$ $W=1.15\mu\text{m}$, $N_S=7.5\times 10^{12}\text{ cm}^{-2}$. (i) $\mu = 3000\text{ cm}^2/\text{V.s}$ (ii) $\mu = 15000\text{ cm}^2/\text{V.s}$ (iii) $\mu = 40000\text{ cm}^2/\text{V.s}$.

three harmonics in the 1 – 8 THz range. The resonant frequencies are in agreement with the calculated values using the Eq. 4.1.

The modulation depth in the absorption spectrum of the periodic gated FET structures is also controlled by the carrier scattering rate in the channel. The lower scattering rate in graphene compared to GaN/AlGaN heterostructure devices allows clear absorption peaks with large modulation depth. Effect of the scattering rate in graphene is presented in Fig. 4.2. For lower mobilities (curve i and ii) contribution of Drude absorption at the background is visible. As the mobility increases, modulation depth increases as especially at higher frequency modes.

An important advantage of the grating gate devices is tunability of the resonant absorption frequencies though controlling the charge concentration by the applied gate voltage. Fig. 4.3 clearly shows the shift of the resonant frequencies by the charge carrier concentration as expected from the Eq. 4.1. It should be noted that the plasmon frequency

Figure 4.3: Absorption spectra of graphene grating gate FET structure with different carrier concentrations. $L=1.5\mu\text{m}$ $W=1.15\mu\text{m}$, $\mu=15000\text{ cm}^2/\text{Vs}$. (i) $N_s = 3.6 \times 10^{12}\text{ cm}^{-2}$ (ii) $N_s = 8.3 \times 10^{12}\text{ cm}^{-2}$ (iii) $N_s = 1.5 \times 10^{13}\text{ cm}^{-2}$.

in graphene exhibits different dependence on the gate voltage ($\sim N_s^{1/4}$) as compared with gated plasmons in conventional semiconductor structures ($\sim N_s^{1/2}$).

4.2. Plasmons in Linearly Integrated FETs

We investigated linearly integrated FET arrays (LFETs) which consists of graphene layers on sapphire substrates as channel layer. LFETs are composed of a periodic gate structure on top of Graphene which allows tunable detection under applied bias. In the structure, the periodic source and drain patterns make ohmic contacts with the Graphene sheet while the gate is separated from Graphene by SiO_2 for plasma wave propagation confinement between the metal gate and Graphene. In the analysis, A Graphene sheet is placed on a SiO_2 substrate with periodic palladium (Pd) gratings on top of Graphene. A 10 nm Silicon Dioxide (SiO_2) layer is placed on top of Graphene to create the cavity for plasma wave propagation. Additionally, periodic gate fingers of Titanium (Ti) are placed on top of SiO_2 . Fig. 4.4 shows the cross sectional views of the investigated device.

Figure 4.4: Cross-sectional view of Graphene based Linearly integrated FET (LFET).

Because of the long momentum relaxation time of Graphene and high mobility at room temperature (300 K), very clear resonant modes appear in the absorption spectrum. Fig.4.5 shows the Graphene THz LFET detector with different gate dimensions and a source-drain distance of 3 μm . Looking at the figure, the size of the cavity under the gate

Figure 4.5: Absorption spectrum of the LFET array Graphene based device for different gate widths (L_G) with $L_{SD}=3\mu\text{m}$ at room temperature. (i) $L_G=2\mu\text{m}$ (ii) $L_G=1.5\mu\text{m}$ (iii) $L_G=1\mu\text{m}$ (iv) $L_G=0.4\mu\text{m}$.

with length L_G changes the resonant modes and smaller L_G supports higher frequency first mode. Fig.4.6 shows the electric field profile of two FET elements of the Graphene LFET device with the plasma wave of the first mode propagating under the gate. It is apparent that the relatively long SiO_2 side air-interface in the FET elements allows the energy of the plasma wave to reradiate and accordingly lower the modulation depth of the resonant modes.

The results of the simulation were compared to the analytical results using Eq. 4.1 for the resonant frequencies. For the LFET devices under consideration, the wavelength $\lambda=2L_G$ and the wave vector $k=2\pi n/L_G$. This means that the first mode has a propagating plasma wave of a half wavelength under the gate contact. The simulated results matched the analytical equation with an error reaching 5 % for higher order modes in small gate dimensions. These errors are caused by the simplification of the plasma equation used and other non-ideal effects.

Figure 4.6: Simulation result of the Graphene LFET device showing two FET elements and the propagation of the first mode (a) and second mode (2) where the high electric field intensity is shown in red, zero electric field intensity is shown in blue.

It is noted that the Graphene under analysis has a mobility of $2390 \text{ cm}^2/\text{V.s}$, carrier concentration of $1.5 \times 10^{13} \text{ cm}^{-2}$ and a momentum relaxation time of $25 \times 10^{-14} \text{ sec}$. This is a reasonable practical value corresponding to defects in the Graphene sheet [1]. Higher quality and less defective Graphene with higher mobility values would result in a deeper modulation depth of the modes in the absorption spectrum. In order to show the effects of the mobility on the operation of the device, higher mobility values of 10000 and 40000 $\text{cm}^2/\text{V.s}$ [2] which were previously measured, are used. Figure 4.7 shows the change in the Graphene LFET device response with mobility. Increasing the mobility significantly enhances the quality factor of the resonant absorption modes and increases the modulation depth because of the lower value of energy loss, caused by scattering effects, in the Graphene channel.

The modulation depth in the absorption spectrum of the periodic gated FET structures is also controlled by the carrier scattering rate in the channel. The lower scattering rate in

Figure 4.7: Absorption spectra of graphene LFETs with different mobilities. (i) $\mu = 3000 \text{ cm}^2/\text{V.s}$ (ii) $\mu = 15000 \text{ cm}^2/\text{V.s}$ (iii) $\mu = 40000 \text{ cm}^2/\text{V.s}$.

Figure 4.8: Absorption spectra of graphene LFET structure with different carrier concentrations. (i) $N_s = 3.6 \times 10^{12} \text{ cm}^{-2}$ (ii) $N_s = 8.3 \times 10^{12} \text{ cm}^{-2}$ (iii) $N_s = 1.5 \times 10^{13} \text{ cm}^{-2}$.

graphene devices allows clear absorption peaks with large modulation depth. Effect of the absorption rate in graphene is presented in Fig. 4.7. For lower mobilities (curve i) contribution of Drude absorption at the background is visible. As the mobility increases, modulation depth increases as especially at higher frequency modes. The slight background increase with the frequency is due to the decrease of the reflection spectra (not shown).

An important advantage of the LFET plasmonic THz devices is tunability of the resonant absorption frequencies though controlling the charge concentration by the applied gate voltage. Fig. 4.8 clearly shows the shift of the resonant frequencies by the charge carrier concentration. It should be noted that the plasmon frequency in graphene exhibits different dependence on the gate voltage ($\sim N_s^{1/4}$) as compared with gated plasmons in conventional semiconductor structures ($\sim N_s^{1/2}$).

4.3. Dispersion of Symmetrical Gratings

In this section, we report on a detailed study of dispersion properties of grating gate THz plasmonic devices and with symmetry-breaking defect-like cavities. Here we present the description of the plasmonic crystal dispersion relation that is framed in the context of the optical properties of the THz plasmons. Our numerical and analytical results suggest that the dispersion of plasmons can be presented in terms of an effective plasmonic index. The dispersion relations of plasmons in a 2D electron gas (2DEG) capped with periodic grating gates have energy band gaps in the Brillouin zones. Depending on the wave vector, the plasmons can have symmetrical, anti-symmetrical and asymmetrical charge distributions. Breaking the translational symmetry of the plasmonic crystal lattice by changing the electron concentration of the 2DEG under a single gate line in every n^{th} gate induces a cavity state. The induced cavity state supports multiple cavity modes inside the band gap. The plasmons in such perturbed plasmonic crystal are tightly confined and cavities are weakly coupled. The presented results suggest that the cavity states might be used for creating localized plasmonic bands of resonant frequencies for resonant THz detectors using plasmonic crystals.

4.3.1. Theory

A 1D plasmonic crystal as seen in Fig. 4.9 (a) is a 1D periodic structure that consists of two different regions with different effective indices of n_1 and n_2 resulting in two different plasmon wave velocities. This produces plasmonic band gaps due to scattering of plasma waves at the interfaces between the two regions, provided that the Bragg condition is satisfied

Fig. 4.9: (a) Schematic representation of a grating gate plasmonic device showing the unit cell, gated-ungated regions and layered structure. (b) Effective indices of plasmons in gated and ungated regions of the device calculated by using FDTD simulations.

$$k_p = G/2 \quad (4.2)$$

where k_p is the momentum of the plasmons and $G = 2\pi/L$ is the reciprocal lattice vector, with L is the period of the grating. [3] The non-identical effective indices result from differences in plasmon screening in the gated and ungated regions of the THz plasmonic structure, and depend on the excitation frequency, structure geometry, and the refractive index of the intrinsic semiconductor material in which the 2DEG is embedded.

Kachorovskii and Shur have shown that the plasmonic crystal dispersion relation can be solved for the case of two different gated regions with non-identical wave velocities. [4] The effective index of the plasmons describes the velocity of the plasmons; the analogy was made by considering that the plasmons have two different velocities in ungated and gated regions. The ungated region has an effective index of n_a while the gated region has an effective index of n_b . This case can be converted into an optical formalism by representing the plasmon wave velocity at ungated region ‘a’ as $S_a = c/n_a$ and the plasmon wave velocity at gated region ‘b’ as $S_b = c/n_b$ where c is speed of light. Rewriting Eq. (2) of 16 in this notation, we obtain

$$k(f) = \frac{1}{L_a + L_b} \arccos \left[\cos \frac{2\pi f L_a n_a}{c} \cos \frac{2\pi f L_b n_b}{c} - \frac{n_a^2 + n_b^2}{2n_a n_b} \sin \frac{2\pi f L_a n_a}{c} \sin \frac{2\pi f L_b n_b}{c} \right] \quad (4.3)$$

where f is the frequency, L_a and L_b are the length of gated and ungated region.

To calculate the effective indices of the plasmons, a modal source is placed in the direction of plasmon propagation and possible modes are calculated. When a plasmonic mode is excited, a high electric field is recorded with the monitors. This is repeated for different frequencies and only plasmonic modes are selected and corresponding effective indices are calculated. The effective indices are shown in Fig. 4.9 (b) are shown for gated and ungated plasmons. The gated plasmons are highly confined between the gate and the 2DEG which makes the effective index high and they have a linear behavior. This linear behavior is consistent with previous prediction of dispersion of gated plasmons. The effective index starts from 150 and goes as high as 240. The effective indices of ungated plasmons have a nonlinear behavior and it starts from the index close to the AlGaIn index and goes up to 180. This effect arises from the mode to be tighter over the 2DEG and index of plasmons are highly affected by the surrounding material index. Such high plasmonic indices require momentum matching techniques and they indicate high wavelength shrinking. The conventional prism coupling method cannot be used for matching the momentum of plasmons for THz plasmonic devices. Only grating coupler that have a period around 150 times higher than the wavelength of incident light can compensate the momentum mismatch between light in free space and plasmons.

4.3.2. Dispersion of Grating Gate FETs

In this section, the dispersion of plasmons in grating gate devices is studied. The device model is considered as a GaN/AlGa_N HEMT device. The mobility used is the high electron mobility at low cryogenic temperatures, typically below liquid nitrogen temperatures of 4 K, in order to excite high quality factor plasmons and distinguish plasmonic modes properly. If the mobility is too low, the modes are broadened in energy and cannot be individually resolved.

Three grating geometries are studied. One has a 200 nm gate length with an 800 nm slit length, and the other has an 800 nm gate length with a 200 nm slit length, the other one has 500 nm gate and slit width. The gate-channel separation is 30 nm in all geometries. Both geometries are presented in Fig. 4.10. Fig. 4.10 (b), (c) and (d) compares the analytical and numerical dispersion. The dispersion of plasmons calculated using FDTD method is shown in Fig. 4.10 (a). The peak points are extracted using a custom Matlab code and Fig. 4.10 (b) is obtained. Eq. 4.3 is used along with effective indices of plasmons in order to calculate the analytical dispersion. All dispersions are in good agreement with analytical calculations, except the mismatch at lower frequencies. The effective indices are calculated via FDTD mode calculation method by taking the cross section of gated and ungated regions. The gated modes at lower frequencies are highly screened by the gate and mode is tightly confined over the AlGa_N region. Higher frequency modes tend to be closer to 2DEG with less screening creating a less gate effect. This causes a dramatic index modulation of the low frequency modes, which is not considered in the analytical calculation. The dispersion curves of the grating gated

devices show that a band gap is opened up in several energy bands. There are no propagating plasmonic modes with purely real crystal wave vectors within the band gap.

Plasmon Bragg scattering in the periodic structure results in both forward and backward traveling waves that interfere constructively to form a standing wave profile. Plasmons with momentum of $G/2$ interfere constructively in the structure forming two standing wave profiles with different energies at the band edges. The minima of the high energy standing wave form in the lower effective index region, E_+ and the maxima of the low energy standing wave occur in the high index region E_- . Plasmons with energies in between the forbidden energy bands interfere destructively and plasmon propagation is not allowed along the structure. [5] Hence, a band gap is formed, known as the plasmonic

Figure 4.10: Dispersion curves of grating gate 2D plasmonic devices. The blue solid line is the analytical dispersion and circled points are the calculated points by FDTD method. Grating gate device with (a)-(b) 200 nm gate length and 800 nm slit length, (c) 500 nm gate length and 500 nm slit length, (d) 800 nm gate length and 200 nm slit length. (a) shows the plasmonic excitation heat map in logarithmic scale where red indicated high level plasmonic excitation and blue indicates low level plasmonic excitation.

band gap. The ungated cavity and gated cavity form one larger compound cavity, and they cannot be considered as two isolated cavities adjacent to each other. They are strongly coupled as seen from the plasmonic field profile in Fig. 4.11 (a) and (b).

The energy of the E_+ and E_- modes is related to the distortion in the electric field lines. This distortion depends on the gated and ungated region effective index contrast. The band gap span also depends on this effective index contrast. Therefore, as the grating gate length increases, we expect for the band gap to be widened as seen in Fig. 4.10. [6] Fig. 4.11 (a) is an example for E_- where the mode is localized around the gated region and (b) is an example for E_+ where the mode is localized around the ungated region.

Fig. 4.11 shows the electric field distributions of different frequency-momentum configurations. Fig. 4.11 (c) and (d) are an example for anti-symmetric mode at zero momentum and (e) and (f) are an example for symmetric mode. While the field distribution in half momentum of reciprocal vector is symmetric, the field distribution at momentum 0.125 of reciprocal lattice is asymmetric. There are intensity differences between the peaks. The charge distributions for symmetrical modes (e) and (f), asymmetrical modes (g) and (h) are shown that have comparable sizes of charge signs with the amount of charge.

At zero momentum, the case for space light coupling to the plasmonic system, only anti-symmetrical modes can be excited. The band splitting cannot be observed. Only E_- or E_+ makes constructive interference at zero momentum. The plasmon intensity drops to zero for each branch at the band edges as seen in Fig. 4.10 (a).

The electric field within each medium is a summation of an incident plane wave and a reflected plane wave. The electric field in the α layer of the n^{th} unit cell can be presented by a column vector

$$\begin{pmatrix} a_n^\alpha \\ b_n^\alpha \end{pmatrix} \quad (4.4)$$

The distribution of typical electric field components can be written in an alternating

Figure 4.11: Electric field distributions ($|E|^2$) at different wave vectors, energies and geometries. Red indicates the high electric fields and blue indicates the low electric field. (a) and (b) are modes for the 200 nm gate length and 800 nm slit length device at 3.3 THz and 3.9 THz consecutively with momentum close to zero. (c), (d), (e) and (f) are modes for the grating gate device with 800 nm gate length and 200 nm slit length. The momentum is $0.5 \, 2\pi/\text{period}$, at 3.5 THz for (c) and 4.8 THz for (d). The momentum is $0.5 \, 2\pi/\text{period}$, at 3 THz for (e) and 4.5 THz for (f). The momentum is $0.125 \, 2\pi/\text{period}$, at 3.5 THz for (g) and 3.8 THz for (h).

periodic medium

$$E_n^\alpha(x) = a_n^\alpha e^{ik_\alpha(x-nL)} + b_n^\alpha e^{-ik_\alpha(x-nL)} \quad (4.5)$$

with

$$k_\alpha = 2\pi f c / n_\alpha \quad (4.5)$$

The column vectors are dependent to each other and they are related through the boundary conditions at the interfaces. After imposing the boundary conditions as continuity of E and $\partial E / \partial x$ at the interface results in

$$\begin{pmatrix} a_n^\alpha \\ b_n^\alpha \end{pmatrix} = \begin{pmatrix} D & -B \\ -C & A \end{pmatrix}^n \begin{pmatrix} a_0^\alpha \\ b_0^\alpha \end{pmatrix} \quad (4.6)$$

where

$$A = e^{-ik_l L_a} \left[\cos k_h L_b - \frac{1}{2} i \left(\frac{k_h}{k_l} - \frac{k_l}{k_h} \right) \sin k_h L_b \right] \quad (4.7a)$$

$$B = e^{-ik_l L_a} \left[-\frac{1}{2} i \left(\frac{k_h}{k_l} - \frac{k_l}{k_h} \right) \sin k_h L_b \right] \quad (4.7b)$$

$$C = e^{-ik_l L_a} \left[\frac{1}{2} i \left(\frac{k_h}{k_l} - \frac{k_l}{k_h} \right) \sin k_h L_b \right] \quad (4.7c)$$

$$D = e^{-ik_l L_a} \left[\cos k_h L_b - \frac{1}{2} i \left(\frac{k_h}{k_l} - \frac{k_l}{k_h} \right) \sin k_h L_b \right] \quad (4.7d)$$

This method is explained deeper in ref. [7,30]. By using transfer matrix method described from Eq. 4.4 to 4.7d, the electric field intensity of the plasmons can be calculated. Fig.

4.12 shows the simulation results and analytical calculations for the mode at Fig. 4.11 (c). They are in good agreement by following the same trend.

4.3.3. Dispersion of a Cavity

Cavity states can also emerge in plasmonic crystal structures where there is breaking of the translational symmetry. In the case of grating gate devices, a cavity element may be introduced into the periodic structure by applying a non-identical gate voltage to one grating element that changes the electron concentration underneath. Such cavities can localize plasmons due to the wave velocity change upon reflection. In Fig. 4.13 (b), we show a cavity structure that is achieved by applying a voltage in every 9 elements periodically to the grating gate elements. [8,9,10,11] For an isolated cavity, the cavity state is dispersionless. For cavities that are in close proximity of each other, plasmonic modes can couple to each other. Coupling of such cavities shows dispersion. When cavities are in close proximity and they are coupled, the dispersion obtained from the analog of the tight binding approximation is;

$$\omega(k) = \alpha[1 + \beta\cos(kl)] \quad (4.8)$$

where l , α , β , k are superperiodicity (cavity to cavity distance) of the cavities, resonance frequency of individual cavity, coupling factor and momentum of plasmons respectively. [12]. The resonance condition is given by

$$\delta = (2n+1)(\lambda_p/4) \quad (4.7c)$$

where δ is the phase shift added to the plasmons while traveling over the cavity element, n is the order of the cavity resonance and a positive integer starting from zero, λ_p is the wavelength of the plasmon.

Setting l , 9 μm , α , 1.7 THz and 3.1 THz for 2 different cavity modes, β , -0.001, we get the dispersion shown with blue line in Fig. 4.13 (a). The mode is tightly localized and coupling between the cavities is very low.

Figure 4.12: Electric field distributions in a unit cell that is cross section from the middle of the AlGaIn region shown in green and analytical results are shown in blue.

To study the formation of cavities in plasmonic crystals with broken translational symmetry, we used a model where an electron concentration of 90% of the surrounding 2DEG occurs below every 9th gate. Experimentally, a grating structure with different electron concentration can be achieved by applying a voltage to the corresponding gates in a super periodic manner. It might also occur due to the variations of the threshold voltage from a gated region to a gated region. Fig. 4.13 (a) shows the dispersion relation for a grating gate device with a 900 nm gate length and a 100 nm slit length. The horizontal axis is the plasmon momentum and the vertical axis is the plasmon frequency. The dispersion is only shown in and near the first band gap because a cavity state is

Figure 4.13: (a) Dispersion curve of grating gate 2D plasmonic devices with cavities in red and analytically calculated cavity modes in blue. Grating gate device geometry has 900 nm gate length and 100 nm slit length. (b) Schematic representation of a grating gate plasmonic device unit cell with cavity with semi-infinite crystal on either side is shown. The cavity region is presented with a different color over the 2DEG. $|E|^2$ of the corresponding branches are shown. (c) Electric field distributions in a unit cell that is cross section from AlGaIn region shown in red and analytical results are shown in blue.

expected to be observed within this band gap. A dispersionless mode is observed at 1.7 THz in contrast to Fig. 4.10. (d) where it is absent. The additional plasmonic mode is the first excited cavity mode within the band gap. The corresponding electric field distributions at a momentum of 0.5 of the grating are shown for two branches and the cavity mode in Fig. 4.13 (b).

Optical cavities that localize light in the forbidden band gap can be obtained by breaking the symmetry of a photonic crystal.[13,14] High transmission bands at frequencies within

the band gap of the photonic crystal can be achieved.[15] New electromagnetic modes in the cavities are created due to the constructive interference of the photons for wavelengths within the cavity region.

Fig. 4.13 (b) shows the electric field distributions of the plasmonic modes for each corresponding plasmonic mode branch at the band edge. The blue regions on the graph show the plasmon electric field distribution minima while the red regions represent the maxima. A plasmonic cavity state is created around 1.7 THz. The gap can be identified in between 1 THz and 1.8 THz. From Fig. 4.13, it is clear that the slope of the cavity state defines a standing wave since the derivative of the dispersion is zero corresponding to the zero group velocity, which is the indication of a standing wave profile.

The group velocity of the cavity state indicates that, for our configuration, the cavities are weakly coupled.

To see how plasmonic cavity mode localizes at the cavity structures, the electric field intensity profiles of the cavity mode have been simulated. The electric field intensity distribution is shown in Fig. 4.13 (b) C_1 for the first cavity mode supported by the structure. The field distributions show that the electric field peaks are located within the cavity regions, which are excited at the resonant frequencies supported by the cavity structure. The resonant modes are widely distributed over the uniform grating side while creating an interference pattern that is the highest at the center of the uniform grating region. By controlling the electron concentration of the cavity structure, the resonance condition can be tuned as we discussed in pervious section. The analytical calculations

for Electric field are performed by using ref. [16] They show good agreement as well as seen in Fig. 4.13 (c).

4.4. Dispersion of Asymmetrical Gratings

We report on numerical study of dispersion properties and frequency dependent absorption characteristics of asymmetric dual grating gate Terahertz (THz) plasmonic crystals. The study shows that the dispersion relations of plasmons in a 2-dimensional electron gas (2DEG) capped with asymmetric dual grating gates have energy band gaps in the Brillion zones. Depending on the wave vector, the plasmons can have symmetrical, anti-symmetrical and asymmetrical charge distributions that are different from the ones for uniform gratings case. Plasmons in the studied plasmonic crystal exhibit both tightly confined/weakly-coupled behavior and propagating/strongly-coupled behavior depending on the plasmonic modes. The responsivity of the plasmonic detector based on asymmetric dual grating gate does not monotonically decrease with the frequency, which is in contrast to the responsivity of uniform grating THz detectors.

The dispersion characteristics of plasmons reveal many important properties of the plasmons such as the localization of the plasmons, the electric field profile distribution, the group velocity etc. The charge distribution along the channel of the FET is especially important since they contribute to THz detection. Unlike uniform grating gate devices, ADGG HEMT device architecture has a geometry that cannot sustain a symmetric charge distribution. An asymmetric charge distribution can create a net dipole moment along the channel and result in a higher THz response. The THz-induced DC voltage response can be calculated by integrating the induced electric field distribution along the channel. Therefore, understanding the field and charge distribution in the device and their effect on responsivity would allow design of better performing THz detectors. In this study we also investigated the absorption spectrum of the device since the response of the detector strongly depends on the absorption. The presented analyses of the plasmonic crystal dispersion are based on the optical properties of the THz plasmons in 2D cavities which are obtained using FDTD method.

Figure 4.14: (a) Numerically calculated effective indices of plasmons at gated and ungated regions. (b) The mode profiles of gated and ungated plasmons at 2 THz. The inset is the extended ungated mode profile. The different material regions are separated with dashed black lines. The right most region is considered as gate for gated modes and air for ungated modes.

Figure 4.15: Schematic representation of an asymmetric grating gate plasmonic device showing the unit cell and the gated-ungated regions where the width of gated region 1 is 900 nm, width of ungated region 1 is 250 nm, width of gated region 2 is 400 nm and width of ungated region 2 is 450 nm. The unit cell width is 2 μm . The dielectric above the 2DEG is set to AlGaN and below is set to GaN.

4.4.1. Dispersion of Asymmetric Dual Grating Gate FETs

The effective index of a resonant mode is a combination of gated and ungated plasmon effective indices since they are coupled and cannot be separated from each other. When we consider a uniform grating gate device with a very short gate where the limit of the gate length goes to zero, the effective index a resonant mode will be close to ungated mode. Conversely, in the long gate device where the limit of the gate goes to the periodicity, the effective index of the mode will be closer to the gated effective index of the plasmons. So, the effective index of a resonant mode is expected to be in the region between the gated effective index and ungated effective index shown in Fig. 4.14 (a). Also, for the short gates the effective index will be smaller compared to the longer gates. The effective indices (Fig. 4.14 (a)) are calculated via FDTD mode calculation method by taking the cross section of the gated and the ungated regions. The mode profiles of the plasmons for gated and ungated regions are shown in Fig. 4.14 (b) for 2 THz. The gated plasmonic modes at lower frequencies are highly screened by the gate and tightly confined over the AlGaN region. Higher frequency modes tend to be closer to 2DEG

with less screening resulting in smaller gate effect, which causes a dramatic index difference at lower frequencies. This effect can be observed in Fig. 4.14 (a), as the frequency increases, the effective index difference between the gated mode and ungated mode decreases. The effective index of plasmons under the gate is 15 times higher than the ungated plasmons at 1 THz.

Fig. 4.16 shows the plasmonic dispersion characteristics calculated using FDTD method. The x -axis represents the plasmon momentum Γ_x in x direction where Γ_x at 0.5 is $G/2=n\pi/L$, G is the reciprocal lattice vector ($2\pi/L$), n is an integer; L is the unit cell length. The peak points are extracted using a custom code. The dispersion curves for the grating gated devices show that a band gap is opened up in several energy bands in which there are no propagating plasmons. The resulting dispersion curves are not similar to the uniform grating dispersion curves like having cavity like standing wave bands. [17].

A periodic structure causes Bragg scattering of plasmons. This scattering results in forward and backward traveling waves, which forms a standing wave due to their constructive interference. If plasmon momentum is half of the reciprocal lattice vector G or 0, plasmons interfere constructively in the structure forming two standing wave profiles with different energy levels at the band edges. The high energetic plasmon standing wave profile, E_+ , tends to localize over the lower index region, and the low energetic plasmon standing wave profile, E_- , tends to localize over the high index region. This is a result of the splitting of the bands at Brillion zones. If the energy of the plasmons falls between these two energy levels, plasmons interfere destructively

Figure 4.16: (a-l) Normalized Electric field distributions ($|E|/2$) at different wave vectors and energies. The modes on the left are zero momentum plasmonic modes; the modes on the right are half reciprocal lattice vector momentum plasmons. Red indicates the high electric fields and blue indicates the low electric field. The corresponding momentum-energy is indicated on the graph in blue letters. (m) The calculated dispersion of ADGG HEMT where x-axis is the momentum of the grating.

resulting in no propagation along the structure [18]. This behaviour of plasmons causes formation of a band gap, which is known as the plasmonic band gap.

Fig. 4.16 (c) is an example for E_+ for which the mode is localized around the gated region 1 and (b) is an example for E_- for which the mode is localized around the gated region 2. Since the gated region 1 is wider than the gated region 2, the mode in the gated region 1 has a tighter confinement than the one in the gated region 2, which results in higher screening of plasmons and higher effective index of plasmons in the gated region 1.

The plasmonic mode distribution in Fig. 4.16 (b) has maxima under the gated region 1 while the maximum in Fig. 4.16 (c) is under the gated region 2. The modes corresponding to the 2nd branch (Fig. 4.16 (m)) are shown in Fig. 4.16 (a) and (g). The mode starts at gated region 1 and ends up in the gated region 2. Considering that the derivative of dispersion (dw/dk) is the group velocity, this branch corresponds to propagating plasmons with a non-zero group velocity and the mode maxima changes its location as the momentum changes. The 3rd branch has a semi-propagating behavior as its derivative (dw/dk) is smaller than the one of the 2nd branch. Hence, the mode profile at the lower side of the branch (point (b) in Fig. 4.16 (m)) is localized in the gated region 1 (Fig. 4.16 (b)) and as the momentum increases the mode profile does not totally relocate to the gated region 2. Instead, it partially shifts to the gated region 2. The same behavior is also observed for the 5th (Fig 4.16. (d) to (j)) and 6th (Fig 4.16. (e) to (k)) branches. Therefore, these plasmonic modes are weakly coupled localized modes. The 4th branch shows the same properties with the 2nd branch. The mode starts at the gated region 1 and totally shifts to the gated region 2 from (c) to (i). So these modes are the strongly coupled

Figure 4.17: (a) The absorption comparisons of a uniform grating with 900 nm gate width and 100 nm slit width and the asymmetric grating gate structure discussed in this paper. (b) Calculated absorption of the incident plane wave over the device, y-axis in log scale and Calculated THz response of the device in y-axis log scale.

plasmonic modes. The observed behaviors of the branches are completely different than the ones for uniform grating gate devices [16,19,20].

The asymmetrical unit cell results in a non-uniform plasmonic mode distribution along the channel, which causes non-uniform charge distribution with dipoles along the channel. The unit cell behaves as a net dipole source and creates a potential difference between its two ends. Therefore, the entire device with several unit cell behaves like a collection of serially connected voltage sources which could yield high responsivity for an incident THz wave.

4.4.2. Absorption and Terahertz Responsivity

We also calculated the absorption and response of the periodic device using FDTD method. Since we use Bloch boundary conditions, the structure can be considered as infinite number of unit cells. A perpendicular plane wave source was set up to illuminate the device from the top along with a monitor at the back of the source to record the

reflected wave, another monitor at the bottom of the device buried inside the GaN layer to record the transmitted wave. We monitored the electric field in the 2DEG and integrated it along the x direction, (along the 2DEG channel) to calculate the voltage response of periodic structure. Fig. 4.17 (a) shows the THz absorption of the periodic structure as a function of incident wave frequency. The corresponding resonant plasmons distributions are shown in Fig. 4.16 a-f respectively. The momentum of the incident wave is set to zero in the direction of the grating momentum, and hence, the parallel component of the incident wave is zero. Seven different resonant modes are observed in the absorption spectrum with different amplitudes the maximum of which reached to 30%. This behavior is quite different from typical absorption spectra for a uniform grating gate device where the absorption of the fundamental mode is the highest and absorption decreases with increasing mode number [21]. Fig. 4.17 (b) also shows the response of the device for the same spectral range along with the absorption in semi-log scale. There is a correlation between the THz response and the absorption, as the absorption increases, the response also increases. The responsivity of one unit cell can reach higher than 10 kV/W; which is in agreement with the experimentally measured value of 25 kV/W for a similar ADGG HEMT [21].

The non-uniform responses and absorptions of the resonant modes are caused by the asymmetric unit cell. In a grating gate device, the absorption depends on the dissipation losses and radiative losses of the modes [22]. The dissipation loss is proportional with the frequency, as the frequency increases, the dissipation loss increases, and the radiative loss is proportional to the gate length to slit length ratio, as the ratio decreases, radiation loss

increases [23]. The two different gate length results in different amount of radiative loss and each plasmonic mode has different amount plasmonic confinement under the gate 1 and gate 2 which results in a different amount of radiative loss in each mode. Such a behavior causes non-uniform amount of absorption as a function of frequency. Fig. 4.17 (b) also presents a comparison of the absorption of the ADGG device to a symmetric gate device.

4.5. References

-
1. Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., ... & Firsov, A. A. (2004). Electric field effect in atomically thin carbon films. *science*, 306(5696), 666-669.
 2. Chen, J. H., Jang, C., Xiao, S., Ishigami, M., & Fuhrer, M. S. (2008). Intrinsic and extrinsic performance limits of graphene devices on SiO₂. *Nature nanotechnology*, 3(4), 206-209.
 3. Karabiyik, M., Sinha, R., Al-Amin, C., Dyer, G. C., Pala, N., & Shur, M. S. (2014, May). Dispersion studies in THz plasmonic devices with cavities. In *SPIE Sensing Technology+ Applications* (pp. 91020K-91020K). International Society for Optics and Photonics.
 4. Kachorovskii, V. Y., & Shur, M. S. (2012). Current-induced terahertz oscillations in plasmonic crystal. *Applied Physics Letters*, 100(23), 232108.
 5. Barnes, W. L., Preist, T. W., Kitson, S. C., & Sambles, J. R. (1996). Physical origin of photonic energy gaps in the propagation of surface plasmons on gratings. *Physical Review B*, 54(9), 6227.
 6. Fischer, B., Fischer, T. M., & Knoll, W. (1994). Dispersion of surface plasmons in rectangular, sinusoidal, and incoherent silver gratings. *Journal of applied physics*, 75(3), 1577-1581.
 7. Bayindir, M., Temelkuran, B., & Ozbay, E. (2000). Tight-binding description of the coupled defect modes in three-dimensional photonic crystals. *Physical Review Letters*, 84(10), 2140.

-
8. Dyer, G. C., Aizin, G. R., Preu, S., Vinh, N. Q., Allen, S. J., Reno, J. L., & Shaner, E. A. (2012). Inducing an incipient terahertz finite plasmonic crystal in coupled two dimensional plasmonic cavities. *Physical review letters*, 109(12), 126803.
 9. Dyer, G. C., Vinh, N. Q., Allen, S. J., Aizin, G. R., Mikalopas, J., Reno, J. L., & Shaner, E. A. (2010). A terahertz plasmon cavity detector. *Applied Physics Letters*, 97(19), 193507.
 10. Dyer, G. C., Preu, S., Aizin, G. R., Mikalopas, J., Grine, A. D., Reno, J. L., ... & Allen, S. J. (2012). Enhanced performance of resonant sub-terahertz detection in a plasmonic cavity. *Applied Physics Letters*, 100(8), 083506.
 11. Davoyan, A. R., Popov, V. V., & Nikitov, S. A. (2012). Tailoring terahertz near-field enhancement via two-dimensional plasmons. *Physical review letters*, 108(12), 127401.
 12. Yariv, A., Xu, Y., Lee, R. K., & Scherer, A. (1999). Coupled-resonator optical waveguide: a proposal and analysis. *Optics letters*, 24(11), 711-713.
 13. Yablonovitch, E., Gmitter, T. J., Meade, R. D., Rappe, A. M., Brommer, K., & Joannopoulos, J. D. (1991). Donor and acceptor modes in photonic band structure. *Physical Review Letters*, 67(24), 3380.
 14. Dyer, G. C., Aizin, G. R., Allen, S. J., Grine, A. D., Bethke, D., Reno, J. L., & Shaner, E. A. (2013). Induced transparency by coupling of Tamm and defect states in tunable terahertz plasmonic crystals. *Nature Photonics*, 7(11), 925-930.
 15. Yeh, P., Yariv, A., & Hong, C. S. (1977). Electromagnetic propagation in periodic stratified media. I. General theory. *JOSA*, 67(4), 423-438.
 16. Skorobogatiy, M., & Yang, J. (2009). *Fundamentals of photonic crystal guiding*. Cambridge University Press.
 17. Anwar, M. F., Crowe, T. W., & Manzur, T. (2014). Terahertz Physics, Devices, and Systems VIII: Advanced Applications in Industry and Defense. In *Proc. of SPIE Vol (Vol. 9102, pp. 910201-1)*.
 18. Barnes, W. L., Preist, T. W., Kitson, S. C., & Sambles, J. R. (1996). Physical origin of photonic energy gaps in the propagation of surface plasmons on gratings. *Physical Review B*, 54(9), 6227.
 19. Aizin, G. R., & Dyer, G. C. (2012). Transmission line theory of collective plasma excitations in periodic two-dimensional electron systems: Finite plasmonic crystals and Tamm states. *Physical Review B*, 86(23), 235316.

-
20. Dyer, G. C., Aizin, G. R., Allen, S. J., Grine, A. D., Bethke, D., Reno, J. L., & Shaner, E. A. (2013). Induced transparency by coupling of Tamm and defect states in tunable terahertz plasmonic crystals. *Nature Photonics*, 7(11), 925-930.
21. Kurita, Y., Ducournau, G., Coquillat, D., Satou, A., Kobayashi, K., Boubanga Tombet, S., ... & Otsuji, T. (2014). Ultrahigh sensitive sub-terahertz detection by InP-based asymmetric dual-grating-gate high-electron-mobility transistors and their broadband characteristics. *Applied Physics Letters*, 104(25), 251114.
22. Popov, V. V., Fateev, D. V., Polischuk, O. V., & Shur, M. S. (2010). Enhanced electromagnetic coupling between terahertz radiation and plasmons in a grating-gate transistor structure on membrane substrate. *Optics express*, 18(16), 16771-16776.
23. Popov, V. V., Polischuk, O. V., Teperik, T. V., Peralta, X. G., Allen, S. J., Horing, N. J. M., & Wanke, M. C. (2003). Absorption of terahertz radiation by plasmon modes in a grid-gated double-quantum-well field-effect transistor. *Journal of applied physics*, 94(5), 3556-3562.

CHAPTER 5

Ratchet Effect In Two-Layer Grating Systems

In this chapter, how a two layer grating structure responds to incident THz field is discussed. The Ratchet effect is observed as described in the literature. Momentum matching is a critical requirement to excite plasmonic oscillations in a high carrier concretion medium, such as 2DEG channel of semiconductor heterostructures or graphene. This requirement is typically satisfied by periodic gate metals (grating gate) and only the plasmons with momentum of the grating gate could be excited since the momentum of incident wave is orders of magnitude smaller than the grating momentum. Here, we present a new method to excite the plasmons in a plasmonic crystal with momentum different than the grating gate momentum by adding an additional grating on top of the grating gate with a different periodicity which enhances the momentum of incident light. While the single layer grating gate excites zero momentum plasmons have asymmetrical (with even number of maxima) charge density distribution, the proposed double layer grating gate allows excitation of plasmons with symmetrical (with odd number maxima) charge distribution. The proposed double grating gate plasmonic crystals provide better understanding of EM wave-plasmon coupling and pave the way to demonstrate advanced THz plasmonic detectors with better tunability and improved responsivity.

5.1. Theory and Analytical Approach

The coupling efficiency of single gate plasmonic devices to THz radiation is weak due to small active region of these devices. To mitigate this problem, grating gate couplers on a large active region and linearly integrated Field Effect Transistor (FET) arrays with high integration density are proposed. [1,2] Structures with grating gate couples are also known as plasmonic crystals. Momentum of an incident THz radiation is two orders of magnitude smaller than the plasmons excited in a high carrier concentration 2D channel. Grating gate over the channel compensates the necessary momentum for excitation of the plasmons. The excited plasmons in such a system can only take the momentum values of $G=n\pi/\lambda$, where G is the reciprocal lattice vector, n is the order of diffraction and λ is the period of the grating gate. The excited plasmonic modes have an anti-symmetrical charge distribution and even numbers of minima-maxima of charge concentration. Resonant absorption of incident THz radiation in such structures can only be achieved by excitation of plasmons by matching the momentum of plasmons and incident radiation. Recently, dispersion of plasmons have been extensively studied which revealed extraordinary behaviors such as plasmons at zero momentum have zero group velocity while plasmons with quarter momentum of the period have non-zero group velocity. Moreover, plasmons with zero momentum have zero dipole moment and non-zero momentum plasmons can have a net dipole moment. Here we present a new method to excite zero momentum and odd number of maxima symmetrical THz plasmons in a plasmonic crystal, which opens up new possibilities in THz plasmonics.

Figure 5.1: Schematic representation of (a) grating gate and (b) coupler grating gate plasmonic devices with semi-infinite crystal on either side. The ungated region has an effective index of n_a and gated region has an effective index of n_b . The unit cell of each configuration is shown. Plasmon dispersion of (c) single grating gate and (d) coupler grating gate devices where $\lambda = L_a + L_b$. Red regions represents the propagating plasmons while blue regions represents the dissipating plasmons. Dispersion of the baseline grating gate device shown in Fig. 6.1 (c) presents several band gaps opened at zero momentum and in Brillion zones. Here the coupling of the light from free space is achieved by the Fourier harmonics of the grating gate. When an additional grating gate is introduced on top of the first one with a π phase shift, the unit cell changes as shown in Fig. 6.1 (b) and reciprocal lattice vector reduces to half. This results in formation of band gaps at half momentum of the original reciprocal lattice as shown in Fig. 6.1 (d). The bands are mirror folded from the center of the Fig. 6.1. (c), this also results in excitation of additional modes at zero momentum.

A 1D plasmonic crystal shown in in Fig. 5.1 (a) is a periodic structure repeating itself in one direction and consists of two different regions with different effective plasmon refractive indices of n_a and n_b resulting in two different plasmon wave velocities. This results in plasmonic band gaps in dispersion due to scattering of plasma waves at the interfaces between the two regions, provided that the Bragg condition is satisfied $k_p = G/2$

where k_P is the momentum of the plasmons and G is the reciprocal lattice vector.[3] As the plasmons propagate along the plasmonic crystal, they will be affected by two different media, in gated and ungated regions. The refractive indices of these two regions and the plasmon mode distributions are different from each other which results in observation of two different effective refractive indices. The non-identical effective refractive indices result from differences in plasmon screening in the gated and ungated regions of the structure, and it depends on the frequency, structure geometry, and the refractive index of the material in which the 2DEG is embedded.

Kachorovskii and Shur have shown that the plasmonic crystal dispersion relation can be solved for the case with two different gated regions with non-identical wave velocities.[4] Effective indices for the plasmons define the velocity of the plasmons. A similar approach could be used to study the different plasmon velocities in gated and ungated regions. In this case, dispersion relation could be found using an optical formalism by representing the plasmon wave velocity at ungated region ‘a’ as $S_a=c/n_a$ and the plasmon wave velocity at gated region ‘b’ as $S_b=c/n_b$ where c is speed of light and n_a and n_b are the effective indices at ungated and gated regions, respectively. Then, an optical description of the plasmonic system describing plasmonic modes can be given as:

$$k(f) = \frac{1}{L_a + L_b} \arccos \left[\cos \frac{2\pi f L_a n_a}{c} \cos \frac{2\pi f L_b n_b}{c} - \frac{n_a^2 + n_b^2}{2n_a n_b} \sin \frac{2\pi f L_a n_a}{c} \sin \frac{2\pi f L_b n_b}{c} \right] \quad (6.1)$$

where f is the frequency, L_a and L_b are the length of gated and ungated region. This equation is analogous to the one for light dispersion in Bragg reflectors.

The characteristic matrix $M(\Lambda)$ for multilayer structure is expressed as

$$M(\Lambda) = \prod_{i=1}^4 \begin{bmatrix} \cos\delta_i & -i\sin\delta_i/\eta_i \\ -i\eta_i\sin\delta_i & \cos\delta_i \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (5.2)$$

The dispersion relation is defined as

$$K = \frac{1}{L} \arccos \frac{m_{11} + m_{22}}{2} = \frac{1}{L} \arccos D \quad (5.3)$$

where D is

$$D = -\frac{1}{2n_a n_b n_c n_d} \dots$$

$$\begin{aligned}
& \dots \left(\sin \left[\frac{wL_a n_1}{c} \right] n_a^2 \left(\sin \left[\frac{wL_b n_2}{c} \right] n_c \left(-\sin \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_c \right. \right. \right. \\
& + \cos \left[\frac{wL_c n_3}{c} \right] \cos \left[\frac{wL_d n_4}{c} \right] n_d \Bigg) \\
& + \cos \left[\frac{wL_b n_2}{c} \right] n_b \left(\cos \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_c + \cos \left[\frac{wL_d n_4}{c} \right] \sin \left[\frac{wL_c n_3}{c} \right] n_d \Bigg) \Bigg) \\
& + \sin \left[\frac{wL_a n_1}{c} \right] n_b n_d \left(\cos \left[\frac{wL_b n_2}{c} \right] n_c \left(\cos \left[\frac{wL_d n_4}{c} \right] \sin \left[\frac{wL_c n_3}{c} \right] n_c \right. \right. \\
& + \cos \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_d \Bigg) \\
& + \sin \left[\frac{wL_b n_2}{c} \right] n_b \left(\cos \left[\frac{wL_c n_3}{c} \right] \cos \left[\frac{wL_d n_4}{c} \right] n_c - \sin \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_d \Bigg) \Bigg) \\
& + \cos \left[\frac{wL_a n_1}{c} \right] n_a \left(\sin \left[\frac{wL_b n_2}{c} \right] n_b^2 \left(\cos \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_c \right. \right. \\
& + \cos \left[\frac{wL_d n_4}{c} \right] \sin \left[\frac{wL_c n_3}{c} \right] n_d \Bigg) \\
& + \sin \left[\frac{wL_b n_2}{c} \right] n_c n_d \left(\cos \left[\frac{wL_d n_4}{c} \right] \sin \left[\frac{wL_c n_3}{c} \right] n_c + \cos \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_d \Bigg) \\
& + \cos \left[\frac{wL_b n_2}{c} \right] n_b \left(\sin \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_c^2 - 2 \cos \left[\frac{wL_c n_3}{c} \right] \cos \left[\frac{wL_d n_4}{c} \right] n_c n_d \right. \\
& \left. \left. + \sin \left[\frac{wL_c n_3}{c} \right] \sin \left[\frac{wL_d n_4}{c} \right] n_d^2 \right) \right) \Bigg) \Bigg) \tag{5.5}
\end{aligned}$$

Figure 5.2: (a) The effective index of plasmons, (b) effective gate length derived empirically, (c) dispersions of plasmons, simulation in red, calculation in blue are shown.

Fig.5.1 (a) and (b) shows the baseline and proposed double layer grating gate plasmonic crystals, respectively. The grating gate periodicity is $1 \mu\text{m}$ in both devices, gate length is $0.9 \mu\text{m}$ and gate separation is $0.1 \mu\text{m}$. The coupler grating gate in the proposed structure has the same gate length with $2 \mu\text{m}$ periodicity. The unit cell of the baseline device is $1 \mu\text{m}$, while the proposed device has a unit cell of $2 \mu\text{m}$. The dispersions of the plasmons are shown in Fig. 5.1 (c) for the baseline grating gate in 1(d) for coupler grating gate devices. The dispersion relations calculated analytically and numerically are in good agreement as described in detail in previous chapters.

When there is a coupler grating, it behaves as a coupler by increasing the momentum of the incident light, while the grating gated region behaves as a medium where the plasmons propagate, the additional grating only contributes by enhancing the momentum of the incident light. Plasmons with zero momentum can be excited when the THz light is incident over the plasmonic crystal coupling from free space.

The coupler grating also introduces a cavity like mode where it overlaps with the ungated region of the grating gate underneath. It disturbs the periodicity of grating gate and modifies the dispersion. Instead of having a consecutive ungated and gated region for grating gate devices in the unit cell, the unit cell is modified to gated region one, gated region two, gated region one and ungated region. The branches at 1.9 THz and 2.2 THz in Fig. 5.1 (d) correspond to such cavity states behaving almost like a flat band which is the typical behavior of a standing wave cavity state.

Figure 5.3: (a) The absorption spectrum of single grating gate and double grating gate devices when the THz light is incident over the system to excite the plasmons at zero momentum. (b) The absorption normalized according to 2π phase shift. Red regions represent the observation of new plasmonics modes as the phase shift modulates.

Since the secondary unit cell modifies the unit cell to 4 parts, one needs to modify the 2 element dispersion Eq. 5.1 to 4 elements unit cell. By using the transfer matrix method (TMM), the dispersion is recalculated for the modified structure. From Eq. 5.2 to Eq. 5.4 we derive the dispersion. The dispersion equation takes a pretty long format as in Eq. 5.5. By using the effective gate length as shown in Fig. 5.2 (b) and effective index method as discussed in previous chapters, the dispersion calculated by the simulation and theory are in good agreement. The theory and simulation matched better for high frequency modes since at high frequencies, the effect of gate becomes smaller and modes are closer to the 2DEG.

5.2. Effect of Phase Shift on Absorption and Mode Distribution

In Fig. 5.3, the effect of phase shift in the coupler grating is presented. As the phase of the coupler grating compared to the grating gate increases to π , the absorption makes maxima and the decreases to zero as the phase goes to 2π because of the symmetry of the

structure. The maximum excitation of coupled modes are shown in Fig. 5.3 (a) and the normalized phase shift absorption is shown in Fig. 5.3 (b) which has a mirror fold symmetry from π phase shift. In order to excite the odd plasmonic modes, the grating should have a π phase shift because, the odd modes has a π phase shift from the even modes, that is why only even modes have been observed so far in experimental and theoretical/numerical studies. The modes that are excited with the grating coupler have to follow the phase of the grating. Electric field of the incident wave spatially modulated is

Figure 5.4: Phase shift dependence of a resonant plasmonic mode induced by the upper grating. Normalized electric field intensity is considered.

as follows [5]

$$E(t, x) = [1 + \hat{h}\cos(kx + \varphi)]e(t) \quad (5.6)$$

where $\hat{h}$ is the diagonal 2x2 matrix with diagonal components of $\hat{h}_x$ and $\hat{h}_y$, $e(t)=(e_x(t), e_y(t))$ is the in-plane oscillating vector that has the components depending on the polarization and φ is the phase shift. Fig. 5.4 shows the comparison of the simulation and the theory for the phase shift dependence on the E field intensity for the fundamental

mode. They clearly match. Here, they have mirror symmetry from pi phase shift as in Fig. 5.3 (b).

The absorption at resonance frequencies are defined as [6,7]

$$A_{n-res} = \frac{2\gamma_e\gamma_{rn}}{(\gamma_e + \gamma_{rn})^2} \left(1 - \frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}\right) \quad (5.7)$$

where γ_e is the dissipative damping, γ_{rn} is the radiative damping and ε is the substrate dielectric constant. The secondary grating changes the absorption levels of the resonant modes of the primary grating. For the first mode, it slightly suppresses the absorption and for the higher order modes, it dramatically increases the absorption levels such as almost 2, 3 and 4 times increase for 3rd, 4th and 5th modes consecutively. While γ_e is the same for single and double grating geometries, only γ_{rn} is changing when a secondary grating is

Figure 5.5: Plasmon electric field $|E|^2$ distributions at zero momentum for double grating gate devices. First 6 modes are shown from (a) to (f) with increasing mode number.

introduced. Since one in two parts of the slits in a unit cell is now covered by the secondary grating, the radiative damping is suppressed and this causes better absorption. Maximum Eq. 5.7 of is 0.5 which corresponds to a %50 percent absorption when $\gamma_e = \gamma_m$. Since we have high mobility values, γ_e is small which depends on electron scattering time. γ_m becomes smaller and gets closer to γ_e with the secondary grating and the absorption increases for the higher modes.

Fig. 5.5 shows the electric field distributions of plasmons excited at zero momentum.

Figure 5.6: The absorption spectrum of single grating gate and double grating gate devices when the THz light is incident over the system to excite the plasmons at zero momentum.

When looking at the total number of the electric field maxima in Fig. 5.5 (a), (c) and (e), they show odd number of modes and (b), (d) and (f) show even number of modes. Even modes can also be observed with single grating, but the odd modes can only be observed with coupler gratings. In Fig 5.5 (a), the fundamental mode shows an unusual behavior. Each grating gate in the unit cell is charged with a single charge at an instant. This behavior is like a capacitor and it can make possible to measure the responsivity like an

oscillating capacitor. While there will be positive charge under one gate, there will be negative charge on the other gate. For this purpose, each gate in unit cell needs to be connected in an interdigitated configuration in to two groups. Capacitance can be measured between the both ends.

5.3. References

1. Popov, V. V., Shur, M. S., Tsybalov, G. M., & Fateev, D. V. (2007). Higher-order plasmon resonances in GaN-based field-effect transistor arrays. *International Journal of High Speed Electronics and Systems*, 17(03), 557-566.
2. Popov, V. V., Pala, N., & Shur, M. S. (2012). Room temperature terahertz plasmonic detection by antenna arrays of field-effect transistors. *Nanoscience and Nanotechnology Letters*, 4(10), 1015-1022.
3. Karabiyik, M., Sinha, R., Al-Amin, C., Dyer, G. C., Pala, N., & Shur, M. S. (2014, May). Dispersion studies in THz plasmonic devices with cavities. In *SPIE Sensing Technology+ Applications* (pp. 91020K-91020K). International Society for Optics and Photonics.
4. Kachorovskii, V. Y., & Shur, M. S. (2012). Current-induced terahertz oscillations in plasmonic crystal. *Applied Physics Letters*, 100(23), 232108.
5. Rozhansky, I. V., Kachorovskii, V. Y., & Shur, M. S. (2015). Helicity-driven ratchet effect enhanced by plasmons. *Physical review letters*, 114(24), 246601.
6. Popov, V. V., Polischuk, O. V., Teperik, T. V., Peralta, X. G., Allen, S. J., Horing, N. J. M., & Wanke, M. C. (2003). Absorption of terahertz radiation by plasmon modes in a grid-gated double-quantum-well field-effect transistor. *Journal of applied physics*, 94(5), 3556-3562.
7. Popov, V. V., Fateev, D. V., Polischuk, O. V., & Shur, M. S. (2010). Enhanced electromagnetic coupling between terahertz radiation and plasmons in a grating-gate transistor structure on membrane substrate. *Optics express*, 18(16), 16771-16776.

CHAPTER 6

Circular Grating Terahertz Plasmonics

Devices those are able to Focus plasmons are proposed in visible and near infrared region by using metal structures [1]. The plasmonic focusing has also been achieved with several methods in THz but not in-plane deep sub-wavelength regime [2,3,4]. $\lambda/250$ has been achieved by tapered metal-plasmon tip [5]. In this paper, we propose a new design for plasmonic devices that has the capability of focusing the incident THz radiation into deep sub-wavelength volume independent of its polarization. Moreover, the resonant modes of the focused plasmons can be tuned by the applied voltage on the metallic gratings. The proposed devices can find applications in THz detection with the advantage of tunability and the proposed device can also solve the sub-wavelength imaging demand.

6.1. Circular Lens Structure

In plane THz plasmonic concentrator device consists of periodic concentric metallic rings placed on AlGaIn/GaN heterojunction substrate as presented in Fig. 6.1. The abrupt junction of the GaN/AlGaIn interface plane causes the creation of 2DEG on the interface. The periodicity in the radial direction compensates the momentum for excitation of the plasmons in between the metal and 2DEG. These plasmons obey the gated 2DEG plasmon dispersion. The outer edge of the outer most rings is assumed to be mesa etched which results in isolated cylindrical active region. This etched interface causes the reflection of the plasmons.

Figure 6.1: (a) THz plasmonic concentrators with concentric circular gratings. (b) The cross section of the AlGaIn/GaN devices passing from the center of the circular grating structure. (c) Cross section of the graphene devices.

The simulation results indicate that gated plasmons are excited under all the circular gratings. Plasmons propagate parallel to the direction of the electric field of the incident radiation. They interfere with each other forming a standing wave profile. The highest electric field intensity is observed under the central ring since, as plasmons propagate, the plasmonic intensity is concentrated under the central ring and expanded at the outer rings. The plasmons are reflected back from the outer boundaries of the circular mesa and the process continues as they attenuate. The quality factor of the plasmons should be higher than the number of the gratings, the plasmons excited at the outer rings can reach to the central ring before they attenuate and thereby contribute to the focusing. The electric field intensity is expected to be the highest at the central ring at the frequencies of the resonant plasmonic modes according to the focal effect of the structure.

6.2. Lensing Effect

Areal electric field density is calculated by dividing the total electric field within a region to its total area. Fig. 6.2 (a) shows the electric field densities of the central ring and outer rings as a function of frequency. At the resonant plasmonic modes, a peak in electric field density is observed and the electric field density under the central ring is much higher

Figure 6.2: (a) Electric field density under the central ring and under the outer rings. The total electric fields under the central and outer rings are divided by the total are of the rings. (b) Electric field density ratio under the central ring to the electric field intensity under the outer rings. The ratio gives the strength of the electric field confined at the central ring compared to the outer rings.

than that of the electric field intensity under the outer rings. The electric field intensity at the central point can be 6 orders of magnitude higher than that at the outer ring point where the polarization of incident radiation is perpendicular. The ratio of the electric field density under the central ring to the outer rings gives the compression ratio or field enhancement ratio. As the Fig. 6.2 (b) shows the electric field can be 80 times higher under the central ring which indicates plasmons can be concentrated up to 80 times higher intensity.

The electric field distribution of the fundamental mode is shown in Fig. 6.3 (a). Two electric field peak intensities are observed at the center of the structure. Those two peaks are a result of anti-symmetric nature of the gated plasmonic mode [6]. The electric field intensity on a line passing through the diameter that is parallel to the polarization of the incident radiation is shown in Fig. 6.3 (c). Two sharp and high electric field intensity peaks at 1.3 THz is observed near the center of the ring. The second mode shows four

Figure 6.3: (a) Simulated electric field mode distribution for the fundamental mode in between the grating and 2DEG, (b) second mode, (c) Electric field intensity from the diameter parallel to the polarization of the incident THz radiation for the fundamental mode, x-axis is the pixel in simulation.

peaks as seen in Fig. 6.3 (b) which is again because of the nature of the gated plasmons. The summation of all electric field distribution over the complete spectrum is shown in Fig. 6.4 (c). The total plasmonic interference pattern exhibits two peaks under the central ring that are very close to the central point of the ring. The distance between these two peaks is a few hundreds of nanometers. The plasmons are confined in between 2DEG and circular gratings. The confinement of plasmons is not just in 2D, the confinement is actually in 3D. Therefore, plasmons are highly concentrated under the central ring.

6.3. Analytical Approach

The 2D electric field distribution of the plasmons is presented in Eq. 6.1 in cylindrical coordinates. An analogy with the infinite quantum well is used to develop the equation. First sinusoidal term describes the mode confined under the individual grating. This term is like particle in a box wave equation. Exponential term defines the propagation or dissipation loss of the plasmons [7] as they propagate in the radial direction. Plasmons have a $1/r$ field distribution from the center [8] as they concentrate or dilute. The last

Figure 6.4: (a) Calculated electric field intensity of the fundamental mode in between the circular grating and 2DEG, (b) second mode, (c) summation of modes from 1 to 5. (d) Relative electric field intensity on the diameter parallel to the polarization of the incident radiation (i) numerical simulation (ii) analytical calculation using Eq. 7.1 is shown.

sinusoidal term is the contribution of the polarization effect of the incident radiation on the circular grating. The z dependence of the E field has $e^{-\alpha z}$ with different α values for different mediums [9] which is not included in the equation. Electric field distribution in cylindrical coordinates in 2D can be written as

$$E_n^2(r, \phi) = E_0^2 \sin^2\left(\frac{2n\pi r}{\lambda}\right) e^{-\frac{2r}{L_p}} \frac{1}{r^2} \sin^2(\phi) \quad (6.1)$$

where E_0 is the constant, n is the mode number, λ is the half period, L_{SPP} is the plasmon propagation length. The fundamental mode is calculated with $n=1$ and the results is presented in Fig. 6.4 (a). The highest intensity is observed under the central ring and 2 high electric field peaks are distinct. The second mode is calculated for $n=2$ and resulting electric field profile shows four high intensity peaks under the central ring as seen in Fig. 6.4 (b). The summation of electric field intensity distribution from mode 1 to mode 5 is

presented in Fig. 6.4 (c). The total electric field distribution reflects the actual grating structure assuming with high duty cycle. The model agrees with the simulation results.

6.4. Effect of Mobility and Duty Cycle on Lensing

The duty cycle (w/L) has a dramatic effect on the quality factor of the plasmonic modes. The electric field intensity under the central ring vs. frequency for different duty cycles is presented in Fig. 6.5 (a). Radiative damping strongly depends on relation between wavelength of the incident radiation and geometry of the structure and increases as the slit size gets smaller. Further decrease of the slit size makes radiative damping larger than dissipative damping which causes absorption rate starts decreasing. The radiative damping and dissipative damping should be close to each other in order to optimal absorption and propagation of THz as described before.

Graphene has high electron mobility characteristics at room temperature which makes it a

Figure 6.5: (a) Normalized electric field intensity under the central disc vs. frequency for different duty cycle of circular gratings. (b) Total electric field profile for 87% duty cycle, (c) 60% duty cycle and (d) 33% duty cycle.

very attractive material for THz plasmonic applications. We investigated the response of the graphene based circular gratings to the incident THz radiation by modulating the electron mobility of the graphene.

In our graphene lens design, a graphene layer is placed on a THz transparent substrate and covered by a thin layer of dielectric layer. On top of the thin dielectric layer, a circular grating structure is described as in GaN/AlGaN devices. Fig. 6.1 (c) is showing the cross section of circular grating structure.

The electron concentration is kept the same and the plasma collision frequency is modulated. As the plasma collision frequency increases, it corresponds to a decrease in plasma collision time or electron relaxation time. Mobility of the electrons depends on electron relaxation time. The mobility used in simulations are $2500\text{cm}^2/(\text{V.s})$ (CVD growth graphene on copper), $4500\text{cm}^2/(\text{V.s})$. (graphene on h-BN) $12500\text{cm}^2/(\text{V.s})$ (epitaxial growth graphene on SiC). The lower mobility causes the propagation loss to be dominant in the structure and lower the quality factor of the plasmons. Low quality factor prevents the hopping of plasmons from one grating to another and causes the loss of focusing ability of the circular grating structure. Fig.6.6 (a) shows the electric field density ratios as a function of the incident THz radiation. The high intensity peaks indicate the resonant plasmonic modes within the structure. As the mobility increases, the quality factor and the electric field intensity of the plasmons increases. The width of the first mode is decreasing with increasing mobility which indicates higher quality factor of the plasmonic mode. Total electric field distribution is shown in Fig. 6.6 (b) for the device with graphene with highest electron mobility. A focusing affect can be observed

Figure 6.6: (a) Intensity vs. frequency of the graphene circular grating devices with different relaxation times of electrons in the channel. (b) Total electric field distribution of the circular gratings for plasma collision frequency of 1 THz (c) 3 THz (d) 5 THz.

for the highest mobility graphene. As the mobility decreases down to $4500 \text{ cm}^2/(\text{V.s})$, the focusing affect decreases as seen in Fig.6.6 (c) and the field density ratio goes down by a factor of 4. As the mobility goes down to the value calculated with reverse engineering from the experimental data $2500 \text{ cm}^2/(\text{V.s})$, the focusing effect cannot be observed that can be understood from Fig.6.6 (d). All these mobility values can still be used a polarization independent plasmonic tunable THz sensing because even at low mobility at the order of $2000 \text{ cm}^2/(\text{V.s})$, THz plasmons can be excited but they are unable to propagate. The quality factor of the resonant modes can be improved with the increasing mobility of the graphene layer, high mobility graphene devices are reported up to mobility of $100000 \text{ cm}^2/(\text{V.s})$ [10].

6.5. References

1. Fu, Y., & Zhou, X. (2010). Plasmonic lenses: a review. *Plasmonics*, 5(3), 287-310.
2. Hu, B., & Wang, Q. (2010, December). Tunable terahertz plasmonic lens with external magnetic field. In *Photonics Global Conference (PGC)*, 2010 (pp. 1-3). IEEE.
3. Chen, M. K., Chang, Y. C., Yang, C. E., Guo, Y., Mazurowski, J., Yin, S., ... & Luo, C. (2010). Tunable terahertz plasmonic lenses based on semiconductor microslits. *Microwave and Optical Technology Letters*, 52(4), 979-981.
4. Scherger, B., Jördens, C., & Koch, M. (2011). Variable-focus terahertz lens. *Optics express*, 19(5), 4528-4535.
5. Zhan, H., Mendis, R., & Mittleman, D. M. (2010). Superfocusing terahertz waves below $\lambda/250$ using plasmonic parallel-plate waveguides. *Optics Express*, 18(9), 9643-9650.
6. Peralta, X. G., Allen, S. J., Wanke, M. C., Harff, N. E., Simmons, J. A., Lilly, M. P., ... & Eisenstein, J. P. (2002). Terahertz photoconductivity and plasmon modes in double-quantum-well field-effect transistors. *Applied Physics Letters*, 81(9), 1627-1629.
7. Steele, J. M., Liu, Z., Wang, Y., & Zhang, X. (2006). Resonant and non-resonant generation and focusing of surface plasmons with circular gratings. *Optics Express*, 14(12), 5664-5670.
8. Chang, S. H., Gray, S. K., & Schatz, G. C. (2005). Surface plasmon generation and light transmission by isolated nanoholes and arrays of nanoholes in thin metal films. *Optics Express*, 13(8), 3150-3165.
9. Maier, S. A. (2007). *Plasmonics: fundamentals and applications*. Springer Science & Business Media.
10. Hwang, E. H., & Sarma, S. D. (2008). Acoustic phonon scattering limited carrier mobility in two-dimensional extrinsic graphene. *Physical Review B*, 77(11), 115449.

CHAPTER 7

Ring Resonator Terahertz Plasmonics

In this section, we report on sub-wavelength THz plasmonic split ring resonators on 2 dimensional electron gas (2DEG) at AlGaIn/GaN hetero-interface and on oxide coated high mobility graphene. The investigated in this study guide THz electric field into deep sub-wavelength scale by plasmonic excitations. Propagation of a broadband pulse of EM waves was simulated by using a commercial FDTD simulation tool. The results show that split ring resonator structures can be used to guide THz into deep sub-wavelength down $\lambda/200$ and achieve relatively higher quality factors than grating gate devices by plasmonic confinement which can be used for THz detection, filtering and possibly for THz on-chip-spectrometer. Moreover, ring resonator modes supported by system can be tuned with an applied voltage to gratings.

7.1. Circular Ring Resonator Structure

We propose novel plasmonic ring resonators with the capability to guide THz radiation into deep sub-wavelength size with relatively higher quality factors with sustaining the periodic structure. The size of the proposed devices can be a few microns which is much smaller than the THz disc resonators consisting of dielectric [1] and dielectric-metal plasmonic [2] that are in centimeter and hundreds of micrometer size range reported in the literature. Moreover, the resonant modes of the guided plasmons can be tuned by the applied voltage on the metallic gratings. The proposed devices can find applications in

Figure 7.1: (a) Split ring resonator placed on top of GaN/AlGaN heterojunction substrate mesa structure. (b) The cross section of the resonator device.

THz filtering with the advantage of tunability. The proposed devices also prove that the THz plasmonic excitation can be achieved with split rings and THz plasmons can be guided in plasmonic waveguides with waveguide width of as low as $\lambda/1200$.

Our device design consists of a split ring placed on AlGaN/GaN heterojunction as seen in Fig. 7.1 (a). The abrupt junction of the GaN/AlGaN interface creates a 2DEG. The edges where the ring is placed is assumed to be mesa etched which results in isolated ring active region. The cross section passing from the center is presented on the Fig. 7.1 (b).

The modes are excited with a broad band plane wave source parallel to the plane of the structure. A reflection and transmission monitor is placed to calculate the absorption spectrum of the device. An electric field profile monitor is placed in between the 2DEG and split ring to record the electric field profile of the plasmons. The 2DEG is defined as a plasma layer with specific plasma frequency and collision frequency extracted from the experimental results as discussed before.[3] The simulation is automatically stopped when the total electric field converges down to a small electric field that is orders of magnitude smaller than the initial electric field.

7.2. Electromagnetic Profile of Plasmons and Resonance Frequencies

The electric field distributions at THz frequencies were investigated by FDTD simulations. The results show that plasmons are created in between the metal and the 2DEG as gated plasmons. The azimuthal periodicity of the split ring supplies the necessary momentum to excite the plasmons in the direction of propagation. The polarization of the incident radiation has to be perpendicular to the slit for the excitation of plasmon. [4] After the excitation of plasmons, they propagate in both directions perpendicular to the slit of the ring and form a standing wave profile. The supported modes cause the high electric field intensities to be observed under the ring. Fig. 7.2 (a) shows the electric intensity vs. frequency in between the ring and 2DEG and absorption spectrum for a split ring with 1.4 μm outer ring and 1.15 μm inner ring diameter. The highest absorption is observed for the plasmonic mode at 1.5 THz with 4% absorption. The envelope of the graph is a result of the competition of two loss mechanisms; radiative loss and dissipative loss. Dissipative loss is higher for lower frequencies while radiative loss is lower for lower frequencies and higher for higher frequencies. This relation results in an optimal excitation frequency. [5] The optimal excitation is observed at 1.5 THz. The optimal excitation also depends on the waveguide geometry, the quarter plasmon wavelength for 1.5 THz mode is the closest to the width of the waveguide. The quality factor of the plasmons can go up to 50 which is 2 times higher for the plasmons excited at the grating gate and linearly integrated FET devices at the same frequency. [6,7]

Figure 7.2: (a) Electric field intensity vs. frequency for the 1.4 μm outer ring and 1.15 μm inner ring in between the ring and 2DEG, absorption spectrum on the left scale; the maximum coupling of incident radiation is around 1.5 THz which is the third mode. The electric field distribution of fundamental mode at 0.5 THz is shown.

Normalized electric field intensity vs. frequency and absorption spectrum in between the grating and 2DEG of the same devices is shown in Fig. 7.2 (b). The electric field intensity exhibits a peak at the resonant plasmonic modes. Only the plasmon modes at specific THz frequencies results in that specific frequency to be observed under the rings. The fundamental mode has three high electric fields under the semicircle.

Figure 7.3: Electric field intensity profile under the ring. The electric fields are normalized where black represents the high electric field and white represents the low electric field, (a) for the 2nd mode, (b) for the 3rd mode and (c) for the 9th mode.

The electric field profile distribution of the modes is shown in Fig. 7.3. The second mode has three peaks of electric field intensity under the center of the half ring and two slightly lower peaks near the slit. The total charge over the 2DEG and the split ring has to be conserved. The electric field intensity at the central peak is higher than the other two neighboring electric fields, which shows that the charges distribution of the plasmonic mode is not uniform and to compensate the charge conservation, the charge at the central peak should be higher than the neighboring peaks. The high intensity peak can be observed in Fig. 7.3 (a) where the central electric field peak is higher than other two peaks. The non-uniform charge distribution arises from the split nature of the structure. The electric field of the incident radiation will cause the excitation of the plasmons from the two slits in phase, since the excitations are in phase, the charge under the upper and lower sides of the half ring will be the same. This results in the odd number of high intensity peak distribution of the plasmonic mode. When the charges under the lower and upper sides of the half ring are the same, the neighboring charge has to be opposite to conserve the total charge along the half ring. This effect can also be observed for the third mode where the two of the peaks has higher intensity than other three as seen in Fig. 7.3 (b).

Figure 7.4: Normalized electric field intensity in between the ring and 2DEG vs. frequency for different electron concentrations for the 1.4 μm outer ring and 1.15 μm inner ring geometry. The different electron concentrations represent different applied gate voltages applied over the half rings. The resonant modes with electron concentrations of $6 \times 10^{12} \text{ cm}^{-2}$, $7.5 \times 10^{12} \text{ cm}^{-2}$ and $9.5 \times 10^{12} \text{ cm}^{-2}$ are shown.

An applied voltage to the split rings will trigger the change of the electron concentration in the 2DEG. This allows the tunability of the resonant absorption frequencies. Since several (up to 14) modes are observed in a wide range of THz spectrum (0.1 to 5 THz), any small change in voltage applied to the half rings will cause the shift in modes covering the big portion of THz spectrum. An increase in the electron concentration over the channel due to the applied voltage causes the modes to shift to higher frequencies due to dispersion relation of the THz plasmons. Fig. 8.4 shows this shift for the electron concentrations of $6 \times 10^{12} \text{ cm}^{-2}$, $7.5 \times 10^{12} \text{ cm}^{-2}$ and $9.5 \times 10^{12} \text{ cm}^{-2}$. The higher energy shift in the modes can be seen by following up the resonant modes at the same electric field intensity level.

Figure 7.5: The normalized electric field intensity vs. frequency for different ring geometries where R_{out} is $3 \mu\text{m}$, R_{in} is $2.5 \mu\text{m}$ and is $1.4 \mu\text{m}$, R_{in} is $1.15 \mu\text{m}$ for each split ring geometries.

Fig. 7.5 compares the resonant modes of two rings with different geometries. As the diameter increases, the number of the modes within a frequency range increases and higher order modes can be excited. This is the same phenomenon of increasing the duty cycle in grating gate devices which results in increasing in the amplitude of the higher Fourier harmonics of the grating²¹ that increases the absorption amplitude of the resonant mode. The plasmon waveguide width, the radius of the ring and the slit width are the geometrical variables that affect the frequencies of the resonant plasmonic modes.

7.3. Comparison of Different Materials and Resonant On Chip Filter

We investigated the response of the graphene based split rings to the incident THz radiation. In our graphene ring design, a graphene layer is placed on a THz transparent substrate and covered by a thin layer of dielectric layer. On top of the thin dielectric layer, a split ring structure is described as in GaN/AlGaIn devices before. If we make an

analogy with the Fig. 7.1 (b), sapphire layer is replaced with of GaN layer, graphene layer is replaced with of 2DEG, HfO_2 layer is replaced with of AlGaIn layer and split ring structure is kept the same. Electron collision frequency and electron concentration used in our simulations are extracted from the data in reference as described before. Our simulation model is validated successfully by replicating the experimental data of THz transmission through graphene micro ribbons. The mobility used in simulations is $12500 \text{ cm}^2/(\text{V.s})$ (epitaxial growth graphene on SiC [8]).

Fig. 8.6 is showing the comparison of GaN and Graphene ring resonators. The response of the graphene devices are in a wider THz spectrum compared to the AlGaIn/GaN based devices due to its high mobility and electron concentration which arises from the dispersion relation of the gated plasmons. The increase in electron concentration will cause the higher energy shift of the modes like applying a positive voltage over the split ring as discussed before in previous sections. According to the dispersion of the plasmons in graphene, the resonant frequency has fourth root dependence on the electron concentration which causes smaller shift of the resonant modes to the applied gate voltage compared to the AlGaIn/GaN devices.

Figure 7.6: Normalized electric field intensities for different materials.

One potential application of the proposed split-ring resonator could be THz filters to select certain frequencies in a broad band radiation and guide them through a waveguide. To analyze such an application, a split ring resonator is integrated with a THz plasmonic waveguide. Since the plasmons are highly confined in between the 2DEG and the split ring, the waveguide and the ring resonator have to be in close proximity for a better coupling. Fig. 7.7 (a) presents the investigated design of split ring resonator integrated to a plasmonic waveguide. The plasmons excited over the split ring propagate over the ring, couple to the waveguide and propagate in the linear waveguide. The total electric field distribution is shown in Fig. 7.7 (b) for a resonant plasmonic mode supported by the structure. The electric field intensity on the linear waveguide is higher than the split ring resonator due to the accumulation of plasmons to linear waveguide. The applied voltage to the split ring and waveguide will cause to shift in the resonant mode and the output of the linear waveguide can be used as a tunable THz filter. There will be no need of active complicated components for THz filtering for the proposed device such as mirrors,

Figure 7.7: (a) Device model for THz split ring resonator to couple the THz plasmons to the waveguide, (b) one of the resonant mode of the split ring resonator integrated with the waveguide.

source-drain current flow or pulsed lasers. It is sufficient to place the structure in front of a broadband light source to filter the THz light. The applications of the filtered THz light can be utilized in a wide spectrum of applications such as on chip THz spectroscopy and THz detecting.

7.4. References

-
1. Preu, S., Schwefel, H. G. L., Malzer, S., Döhler, G. H., Wang, L. J., Hanson, M., ... & Gossard, A. C. (2008). Coupled whispering gallery mode resonators in the Terahertz frequency range. *Optics Express*, 16(10), 7336-7343.
 2. Wang, B., & Wang, G. P. (2006). Plasmonic waveguide ring resonator at terahertz frequencies. *Applied physics letters*, 89(13), 133106.
 3. Ju, L., Geng, B., Horng, J., Girit, C., Martin, M., Hao, Z., ... & Wang, F. (2011). Graphene plasmonics for tunable terahertz metamaterials. *Nature nanotechnology*, 6(10), 630-634.
 4. Popov, V. V., Shur, M. S., Tsymbalov, G. M., & Fateev, D. V. (2007). Higher-order plasmon resonances in GaN-based field-effect transistor arrays. *International Journal of High Speed Electronics and Systems*, 17(03), 557-566.

-
5. Popov, V. V., Fateev, D. V., Polischuk, O. V., & Shur, M. S. (2010). Enhanced electromagnetic coupling between terahertz radiation and plasmons in a grating-gate transistor structure on membrane substrate. *Optics express*, 18(16), 16771-16776.
 6. Anwar, M. F., Crowe, T. W., & Manzur, T. (2014). Terahertz Physics, Devices, and Systems VIII: Advanced Applications in Industry and Defense. In *Proc. of SPIE Vol* (Vol. 9102, pp. 910201-1).
 7. Karabiyik M., Al-Amin C., and Pala N., "Graphene-Based Periodic Gate Field Effect Transistor Structures for Terahertz Applications", *Nanoscience and Nanotechnology Letters*, Vol. 5, 1–4, (2013).
 8. Haydell Jr, M. W. (2012). Direct Writing of Graphene-based Nanoelectronics via Atomic Force Microscopy (No. USNA-TSPR-405). NAVAL ACADEMY ANNAPOLIS MD.

CHAPTER 8

Experimental Methods

8.1. Device Fabrication

Fabrications of the devices are performed in AMERI and Oak Ridge National Laboratory (ORNL) Center for Nanophase Material Synthesis (CNMS).

The process to fabricate a graphene device consists of multiple aligned layers using mask aligner and electron beam lithography (EBL) tools. A standard photoresist process is developed. NLOF2020 is used for some of the steps. Negative resists are ideal for metal lift off processes since they have negative side walls, in other words they give a nice undercut if processed properly. NLOF2020 is a negative resist with a thickness $1.6\text{ }\mu\text{m}$ when spun at 6000 rpm for 45 seconds. After the spin, the resist is baked at 110° C for 90 seconds and left for cooling down to room temperature over a heat bath. This layer is exposed for 4 seconds ($12.5\text{mW/cm}^2 \times 4\text{ seconds} = 50\text{ mJ/cm}^2$). Since it is a negative photoresist, a post exposure bake is necessary. The wafer is post baked for 90 seconds at the same 110° C and then left to cool down to room temperature over a heat bath. Then development with MF26A is performed for 20 seconds and deionized (DI) water is used to stop development. After the development, the resist is inspected under microscope for any defects, impurities, misalignments etc. The following step is a gentle oxygen plasma etch in reactive ion etching (RIE) tool called descum process. This step is necessary to remove any undeveloped or precipitated photoresist over the developed area. It also thins

the resist down. In RIE, the pressure is set to 400 mTorr, oxygen flow is set to 60 sccm and RF power is set to 100 W and etch time is set to 30 seconds. This should remove a thickness of 100 nm from the resist. The wafer is ready for etching or metal deposition and lift off. The resolution of this process can go down to 2 μm if a proper contact achieved during mask alignment procedure.

Masks are written with Hiedelberg direct laser writer. Then developed for one minute in 1:4 AZ400K:DI developer for 1 minute and washed with DI. Then they are inspected under microscope. A descum process as described above is performed after development. If they pass inspection, they are etched in chrome etchant until clear in desired areas. The etching time is around 3 minutes. The mask is then washed and loaded to RIE for oxygen plasma etching. 10 minute etch is performed as described above this time only oxygen flow is increased to 100 sccm. Mask is ready to be used.

For sub-micron features, electron beam lithography (EBL) is used. A process with 200 nm resolution has been developed. ZEP520A is used as the positive electron beam resist. This resist is very sensitive to ultraviolet (UV) and electron beam exposure. For this reason, the electron dissipation layer like thin 10 nm Chromium (Cr) layer has to be deposited under this resist, not above like PMMA. During electron beam evaporation (EBE) of Cr layer, the resist gets exposed and loses its electron beam resist characteristics. This is from the x-ray and UV generated during EBE. The wafer is first coated with 10 nm Cr with EBE. Then, the wafer is coated with ZEP520A at 6000 rpm for 45 seconds. The wafer is baked at 180° C for 2 minutes. The wafer is then patterned with JEOL7000 at 30 kV, 50 pA and 110 $\mu\text{C}/\text{cm}^2$ by using Nability software. The wafer is

developed in Xylenes for 1 minute and rinsed in isopropyl alcohol. The wafer is then dipped into 1:1 DI:Cr etchant 1020 for 50 seconds. The wafer is then etched in the same descum recipe mentioned above for 20 seconds. The wafer is ready for metal deposition and lift off. After gate metal is deposited with EBE, the wafer is then sonicated in acetone and then cleaned with isopropyl alcohol and DI water. After stripping the resist, it is time for a second Cr etching. The previous 50 second etching is repeated. A resulting pattern is shown in Fig. 8.1. A high duty cycle grating is fabricated successfully. The described process is a very robust process which can be used for many substrates unless the substrate is resistant to Cr etching. If the substrate is sensitive to Cr etching such as InP/InAlGaAs, PMMA resist should be used and Cr should be deposited on top of PMMA so that after exposure, and before development, Cr etching is necessary, and wafer surface can be protected with PMMA.

High resistive silicon wafer <100> (resistivity>10000 ohm) is used as a supporting

Figure 8.1: SEM image of the grating gate structure fabricated with EBL at Oak Ridge Nat. Lab. The slit width is 177nm and gate width is 495 nm.

substrate since terahertz can penetrate this material and prevent any absorption loss. Sapphire is also used for some devices. Quartz wafers are also used. First, alignment marks for mask aligner, electron beam lithography and gates are patterned with JEOL 6300 100 kV electron beam lithography tool, Ti/Au (10/40 nm) is deposited and lift off is performed. The wafer is coated with 25 nm of Al_2O_3 with atomic layer deposition tool. Then the wafer is patterned with mask aligner and oxide is etched with reactive ion etching tool on desired regions in order to make contact with the gate pads. Source and drains where graphene will make contact is patterned with EBL, Ti/Au (10/40 nm) is deposited and lift is performed. Gate and source-drain contact pads are patterned with mask aligner, a thick layer of Ti/Au (100/200 nm) is deposited for wire bonding and packaging purposes. Commercially available graphene from Graphene Supermarket is used. It is CVD grown graphene on copper foil. The size is 2 inch by 1 inch. PMMA is coated over the graphene grown side and then baked at 180°C for 1 minute. Wet etching of the copper film is performed in ferric chloride solution. PMMA supported graphene is left. It is then transferred to DI water for cleaning. Finally, it is transferred over the substrate to a desired patterned area. Graphene is then patterned with mask aligner and etched with oxygen plasma in RIE in order to form an active region for the devices. Fig. 8.2 shows the chip before and after the oxygen plasma etches. The developer is a basic solution and it deforms graphene over the developed regions and makes graphene easy to observe under microscope in which we can see the individual grains. The protective photoresist boundary can be observed. The graphene under the photoresist is protected. The wafer is then protected with photoresist and diced with dicing saw system. The wafer is cleaned, packaged and wire bonded on a carrier chip for electrical and

optical characterization purposes. The packaged device images are exhibited in Fig. 8.3. Since the samples are measured in different conditions, the way of packaging the samples required different methods

Figure 8.2: Microscope images of the circular grating gate structure before and after oxygen plasma etch to remove graphene over desired areas.

Figure 8.3: Images of the packaged devices ready for measurement, (a) angle dependent measurement packaging at ambient conditions, (b) sample clamped with probes where probes are contacting with the pads and keeping the sample steady, (c) sample glued over the ceramic hip holder and wire bonded from the pads to chip holder.

8.2. Device Characterization

The devices require first electrical characterization. Once they show transistor characteristics such as channel control by gate voltage, the detectors are then taken to optical characterization.

8.2.1. Electrical Characterization

The electrical characterizations are performed at first at room temperature using a 4 probe semiconductor parameter analyzer (SPA). The system is integrated to a probe station with microscope. The tools are shown in Fig. 8.4. The probes are manually controlled and contacted with the contact pads. First, source-drain current, and gate leak current is measured by sweeping drain voltage from negative values to positive values and keeping the gate floating at 0 V. If there is gate current at the comparable order with the channel current, device is set aside and a new one is measured until low gate current device is found. Then, the drain voltage is kept constant at a voltage value that is enough to derive few tens of micro amperes; the gate voltage is swept from negative to positive to observe

Figure 8.4: Tools used for electrical characterization, (a) semiconductor parameter analyzer HP 4156A, (b) probe station for contacting contact pads of a device by using microscope and micro manipulator probes.

minima in the channel current. This indicates the channel control via gate. Once a device passes all such requirements, the devices are loaded to the cryogenic head and electrical characteristics are again measured at room temperature and cryogenic temperatures since gate leak current is lower at lower temperatures. The measurements are performed via two Keithley source-meters in same configuration with 4 probe semiconductor analyzer. The same electrical characteristics are being searched. The Keithley source-meters are shown in Fig. 8.6 (a). The electrical characteristics of FETs are discussed in Chapter 9.

8.2.2. Optical Characterization

A tunable frequency backward Wave Oscillator (BWO) source that is integrated to an optical transmission set up is used to measure the THz transmission and response. The system is able to measure THz transmission from the samples in ranges from 180 to 380 and 550 to 1130 GHz when a tripler is added to the emission port, in two different configurations of the BWO. Response of the detector can be measured as a function of the frequency and temperature down to temperatures as low as 65° K by using the cryogenic system. The source is a narrow band emitter. The experimental set up schematics is shown in Fig. 8.5. The data is gathered using Lab view software. Sample in green color is positioned to the focal point of the THz field. The focal point is found by maximizing the transmission intensity at a specific frequency. The sample holder has a hole at the center and sample is mounted right over the hole, so THz can transmit through the sample while illuminating it as well. A pyro-electric THz sensor collects the transmission data. Once optics and sample is in place, the voltage induced across the sample channel is measured as a function of frequency. The source meters do not have to

Figure 8.5: Schematic representation of the experimental set up and sample connection and wiring.

be connected to the sample for zero channel bias measurements. If the response of the detector will be measured as a function of gate voltage or channel voltage, then they should be connected as presented in of the Fig. 8.5. The set up can also be used THz imaging purposes since an XYZ stage is integrated. The responsivity of the detectors are shown in chapter 9.

The measurement sequence is as follows;

1. Emission frequency from BWO is set.
2. Voltage to gate or channel is set.
3. Sample angle is set.
4. THz wave is chopped.

5. THz wave is collimated by the first lens.
6. THz wave is focused over the sample by the second lens.
7. A voltage signal is induced in the channel.
8. Signal is amplified via signal pre-amplifier.
9. Amplified signal is read via lock-in amplifier.
 - a. Voltage to gate or channel has been updated and steps 1-8 repeated.
 - b. Frequency is updated and steps 1-8 repeated.
 - c. Sample angle is updated and steps 1-8 repeated.

Steps a, b, c can be used to make different type of measurement. They can be used separately or together. Some of the measurements we used to measure response are as follows. Response can be measured at zero channel or gate bias; in this case, only frequency is swept. Frequency can be set constant and bias over the channel or gate or both can be swept. Frequency can be constant, frequency can be swept. Both frequency and angle can be swept.

The tools that are used to perform the optical characterization are shown in Fig. 8.6. The Keithley 2400 that is controlling the gate and the source-drain voltage, is shown in Fig. 8.6 (a), in (b) Thorlabs chopper controller, Signal Recovery 5113 pre-amp, SR830 DSP lock-in amplifier and Newport ESP300 motion controller are shown, in (c) BWO, chopper, cryogenic system which is out of the optical path, pyro-electric detector and sample holder mounted over the rotation motor are shown.

Figure 8.6: The images of the tools used to measure THz response of the detectors.

CHAPTER 9

Experimental Results for Graphene Terahertz Plasmonics

9.1. Physical and Electrical Characteristics

SEM images of our devices are shown and described in Fig. 9.1 (a-c). The shape of the grating is circular in order to decrease the effect of polarization of incident THz since only perpendicular polarization relative to the gratings can excite plasmons. A single

Figure 9.1: SEM images of the devices. (a) The SEM image of a circular grating gate device. The total device size is 1.6 mm by 1.6 mm including antennas and pads. Left antenna is the source side of the device, shown in S, while right antenna is the drain side of the device, shown in D and the bottom pad is connected to the gate, shown in G. (b) A zoomed in SEM image of the device showing the active graphene region. Graphene area is presented in green color where outer boundaries are dashed. Source of the device is the surrounding thick outer circle, source width is 3 μm, drain is the center circle, drain width is 8 μm. Gates are circular and connected to each other. The gate width is 1 μm and gate slit width is 200 nm. (c) SEM image of the device from the cross section after cleaving the device. Free standing graphene is circled. Gate metal is 50 nm thick and oxide is 30 nm thick.

Figure 9.2: Process flow and graphene properties. (a) SEM image of the graphene on copper foil. Individual grains can easily be identified. (b) 2-dimensional micro Raman map of the device. Graphene is observed in blacked dashed area as patterned. The heat map shows the ratio between 2D band and G band (2D/G) which gives the information about how many graphene layers are stacked. Higher numbers more than 1.5 is assumed to be single layer and lower numbers less than 1.5 is assumed to be multi-layer. The map indicates that the graphene consist of multi grain and mostly single layer graphene. A small portion of the graphene is few layers. The ratio is not uniform over the device which indicates, the device will consist of multi-electron concentration graphene grains. (c) The graph shows the Raman spectrum at point p1 where the ratio 2D/G is one of the highest which indicates single layer graphene. (d) The graph shows the Raman spectrum at point p2 where the ratio 2D/G is lower which indicates few more layers graphene.

device is shown in Fig. 9.1 (a), only active region is shown in Fig. 9.1 (b) and the cross section is shown in Fig 9.1 (c) where free standing graphene can be distinguished.

The Raman map was measured in order to understand the physical properties of the patterned graphene. The ratio between 2D band and G band is mapped. Fig. 2 (b) is the heat map of this ratio. The map indicates that many graphene grains are present on the

active region with varying sizes from 5 μm to 10 μm . The numbers of layers are mostly few layers of graphene. Fig. 2 (c), (d) are showing Raman spectrum at different points as indicated in the heat map. Such an active region material will have different electron and hole concentrations in each grain which will end up supporting different frequency THz

Figure 9.3: Electrical and responsivity properties of the device. (a) The channel current as a function of source-drain voltage. The current flows over the graphene active region that behaves as a channel. (b) Channel current and gate leakage current as a function of gate voltage while channel voltage is kept at a constant 50 mV. (c) The responsivity of the device as a function of the temperature.

plasmons. There will be multi modes supported by this system.

9.2. Terahertz Response Characteristics

The channel current as a function of the channel voltage is shown in Fig. 9.3 (a). The graph is nearly linear which means the contacts are ohmic contact. The gate control over the channel current is shown in Fig. 9.3 (b). The channel current can be controlled with an applied voltage while there is few orders of magnitude difference in gate current and channel current. The minimum channel current is observed at 1.2 V and this point is known as the charge neutrality point. Right side of this point channel is dominated with negative charges and left side is dominated with positive charges. The graphene is naturally p-type as understood from the graph because zero voltage is on the left side of the charge neutrality point. This is very typical with CVD grown graphene over the copper foil. Figure 3c is showing the responsivity of the device at different temperatures. There are many resonant responses at different frequencies. The responses are quite sharp compared to other plasmonic responses from visible to Terahertz regime. The quality factors are record high which ranges from 100 to 400 at 77 K. These quality factors can only be observed when the propagation loss is extremely low. This can only be observed when the mobility of the graphene is quite high. The reported mobility value for free standing graphene is at the order of 200,000 cm/Vs. The responsivity measurement is performed at 10 mT pressure. The responsivity is %40 lower at atmospheric pressure. The responsivity increases as the temperature drops because charge-phonon interactions decrease with temperature which has a critical role in mobility of the graphene. The variety of the resonant peaks arises from the multi grain structure of the graphene. Such a property results in different electron concentration and different layers and this effect

Figure 9.4: Responsivity measurements at different channel and gate voltages. (a) Responsivity at different gate voltages. (b) Responsivity at different channel voltages. (c) Responsivity at different gate voltages detailed. (d) Responsivity at different channel voltages detailed.

causes observation of multi modes all around the measured terahertz region via backward wave oscillator (BWO). All responsivity measurements are performed with lock-in amplifier at 85 Hz chopping frequency.

The responsivities in measurable spectrum (180 GHz-380 GHz) at different channel and gate voltages are shown in Fig. 9.4 (a-d). The response of the detector at resonant and non-resonant frequencies change with applied voltage either to the gate or to the channel. In an ordinary THz plasmonic detector, one would expect to observe shift in the response with applies voltage. In our case, the responsivity level of a resonant mode is either

increasing or decreasing. It is hard to claim it shifts because there are many peaks arising from different graphene properties. Even if a resonant peak shifts, we cannot really know where its new position is. In both voltage cases the peak position stays at the same frequency. This behavior can be observed in ungated plasmons or resonant peaks supported by the antenna. It is really hard to claim that the peaks shifts, but we can easily claim that they change with applied bias. If we were to have a single property graphene, it would be much easier for characterization.

Figure 9.5: Responsivities as function of channel or gate voltage at different frequencies. (a) Responsivity and channel current as a function of channel voltage at 363 GHz resonant mode. (b) Responsivity ($V=R=(x^2+y^2)^{1/2}$ of signal) as a function of gate voltage at different frequencies. (c) Responsivity ($V=X$ of signal) as a function of gate voltage at different frequencies.

At a resonant frequency at 363 GHz, the responsivity was measured as a function of the channel voltage. The resonance at 363 GHz was observed at 0 channel voltage before, which indicates when the channel voltage is swept, there should be some response measured at 0 V. Fig. 9.5 (a) shows this behavior. Since the sweep in gate voltage will not affect ungated part of the graphene, the resonance over suspended graphene side can be tuned with a bias applied to the source drain. The gate voltage also has an effect on the responsivity level. Fig. 9.5 (b) is showing the behavior of the response. Pretty much, for all the frequencies, the responsivity behavior is very similar; as the gate voltage increases, the response drops, then increases, then decreases, then increases and saturates. I do not have an explanation for this yet. Here needs to be explained. Similar behavior but not the same has been observed at the Ref. [1]. In order to understand this, I plotted the x of the signal, as expected, the phase of the signal changes which means signal x changes its sign from negative to positive and then negative to positive and saturates. It peaks at positive. The signal goes to zero at the opposite voltage value for the charge neutrality point. This was also observed in Ref. [1].

9.3. Polarization Dependence of Terahertz Response

There is a dramatic dependence on the incident THz polarization angle and the sample position. This was tricky, because polarization is in the same direction with antennas which may trick as antenna coupled plasmons cause response. It is not the case, because after closing the antennas with copper tape, we still observed the same response characteristics of the device.

Figure 9.6: Normalized response as a function of incident polarization angle. (a) Schematic representation of the device showing the incident Terahertz field polarization and rotation direction which is in clockwise. (b) Polar plot of normalized response at resonant frequency 304.5 GHz at room temperature and ambient pressure as a function of polarization direction.

Antenna does not have any significant effect on the response. The asymmetrical graphene active region causes the asymmetrical shape of the angle dependent response. These plasmons can be gate-coupled plasmons; the circular shape of the gates should partially eliminate the angle dependence of the response. Also, I measured the same device without the gates that has only graphene and antenna. I was not able to observe any resonant or non-resonant response. This means, the gated are necessary for resonant response and response do not arise from antenna and graphene. Also, if the responses were to arise from the resonant modes of the antenna, the band with of the antennas would not be this sharp. The angle dependence actually comes from material properties. At each angle value, different graphene grain is perpendicular to the gratings and incident THz light. We should observe resonant response at each frequency.. Fig. 9.6 (a) is showing the second generation devices with modified geometry. Logarithmic antenna is

Figure 9.7: Second generation detector and its Normalized response as a function of incident polarization angle and frequency. The sample is rotated from 0 to 350 degrees with 10 degree steps. At each angle, response is measured. The azimuthal angle of the graph is polarization direction and from inner ring to outer ring is the frequency of the incident THz field from 280 GHz to 380 GHz. The heat map is in logarithmic scale.

removed. We observed resonant response at every angle. The response should partially repeat at every 180 degrees. It is partially because the geometry is not perfectly azimuthal angle symmetrical. Fig. 9.6 (b) is showing this angle and frequency dependency. Many of the resonant modes have symmetrical responses at 180 degrees. This is another claim that responses arise from plasmonic excitation.

Figure 9.8: Second generation detector and its Normalized response as a function of incident polarization angle at resonant frequency. The sample is rotated from 0 to 350 degrees with 10 degree steps. At each angle, response is measured.

Fig. 9.8 (b) is showing the response of a linear grating as shown in Fig. 9.8 (a). The response is highly dependent on the incident angle. We always observe this shift in maximum response which arises from the physical position of the BWO tip. Since the response has a dramatic dependence on the angle, the plasmonic excitation should play the main role in response.

Figure 9.9: (a) High responsivity linear grating device. (b) Simulation result for a graphene FET with lower electron concentration compared to the graphene FETs discussed in chapter 5. The plasma frequency is set to 4×10^{13} rad/s.

Fig. 9.9 (a) shows responsivity of a device exhibiting high responsivity characteristics at room temperature and ambient pressure. If a single grain of the graphene is large on the device, the total area where plasmons are induced increases and results in higher responsivity. Fig. 9.9 (b) is showing a graphene FET identical to the experimental geometry. The absorption peaks are in the measured range. The line widths of the resonance frequencies are wider than experimentally observed, because we could not lower the mobility further because of divergence problems. Once the plasmons are excited, they should be absorbed and simulation should converge. Since, we have low material loss, simulation does not converge properly, and instead it diverges. The point to understand from this simulation is that, the resonance frequencies are in the experimentally observed region.

9.4. References

-
1. Vicarelli, L., Vitiello, M. S., Coquillat, D., Lombardo, A., Ferrari, A. C., Knap, W., ... & Tredicucci, A. (2012). Graphene field-effect transistors as room-temperature terahertz detectors. *Nature materials*, 11(10), 865-871.

CHAPTER 10

Conclusion

In this thesis, we explored a wide range of plasmonic structures both theoretically and experimentally. The 2D plasmonic crystal dispersion relation is presented in terms of the effective index of plasmons in two elements that form the primitive crystal unit cell. The dispersion of grating gated plasmonic structures shows band gaps at the Brillion zone boundaries. A cavity is induced by changing the electron concentration of a single gate stripe in every 9 gates embedded in a plasmonic crystal and the plasmonic cavity mode is observed in FDTD simulations. These results suggest that the cavity states might be used for creating narrow bands of resonant frequencies for resonant THz detectors using plasmonic crystals. We investigated the dispersion characteristics of an asymmetric dual-grating gate (ADGG) HEMT structure in detail using FDTD numerical methods. The dispersion of the structure presented several energy band gaps in which no propagation is allowed. The branches in the dispersion are completely different than the ones in dispersion of uniform grating devices. ADGG device can support tightly confined /weakly coupled behavior and propagating/strongly coupled plasmonic modes with asymmetrical charge distributions. This non-uniform charge distribution along the channel can result in high responsivity which makes the ADGG devices a promising candidate for tunable solid-sate THz plasmonic detectors.

A dual grating modifies the dispersion of the single grating structure and new plasmonic modes are observed in which such modes cannot be excited in single grating systems. The dual grating has to be with π phase shift in order to achieve maximum plasmon coupling. The coupling efficiency is doubled when a dual grating gate is introduced. Symmetrical charge oscillations with odd numbers are observed in the channel other than well-known anti-symmetrical charge oscillations with even number.

We analytically and numerically investigated circular gratings on GaN/AlGaN heterostructures and graphene with the capability of concentrating THz radiation into a region with $\lambda/180$ linear scale which translates to volumetric confinement of 3.8×10^8 . The response of the concentrator devices is polarization independent due to their cylindrical symmetry. The electric field distribution over 2DEG/graphene layer shows highest electric field intensity peaks under the central ring at resonant plasmonic modes that is a result of constructive interference of the plasmons. The focusing phenomena is strongly affected by the duty cycle where high duty cycled structures are able to focus plasmons better compared to the lower ones. Graphene active layer concentrator devices show higher quality factors for the plasmonic modes with their high mobility at room temperature which allows a more pronounced lens effect. Graphene devices with their potentially very high mobility could be effectively used for concentrators operating at room temperature in THz range as well as in the sub-THz range for many important applications. We have investigated split ring resonator for GaN/AlGaN and graphene based high electron mobility devices. The responses of the devices are in a wide spectral range of THz frequencies. The resonant modes can be controlled with an applied voltage

over the gates. The radius and the width of the ring can be used to passively to tune the resonant frequency. Increasing the radius of the ring causes higher order modes to be observed. Graphene active layer devices show resonance response to the incident radiation in a wider spectral range because of the dispersion relation and higher mobility at room temperature. A THz filter is based on split ring integrated with a linear waveguide is also investigated. The proposed devices can be used for applications of compact tunable THz filters and THz detectors.

We have achieved measuring resonant Terahertz room temperature detection using suspended graphene FETs. Because of material properties, we observed many resonant peaks. The circular geometry of the detector made possible for multi angle multi resonance detection. The amount of signal received from THz could be controlled with gate bias or source drain bias. Resonant modes are fading and coming back as the sample rotates depending on the grain location and electron concentration.

VITAE

MUSTAFA KARABIYIK

2003- 2008	B. Sc. Physics Department Bilkent University, Ankara, Turkey
2008- 2010	M. Sc. Physics Department Bilkent University, Ankara, Turkey
2011 -2017	Doctoral Candidate Florida International University, Miami, Florida

PUBLICATIONS AND PRESENTATIONS

1. Ahmadivand, A., Gerislioglu, B., Sinha, R., Karabiyik, M., & Pala, N. (2017). Optical Switching Using Transition from Dipolar to Charge Transfer Plasmon Modes in Ge₂Sb₂Te₅ Bridged Metallodielectric Dimers. *Scientific Reports*, 7.
2. Ahmadivand, A., Sinha, R., Karabiyik, M., Vabbina, P. K., Gerislioglu, B., Kaya, S., & Pala, N. (2017). Tunable THz wave absorption by graphene-assisted plasmonic metasurfaces based on metallic split ring resonators. *Journal of Nanoparticle Research*, 19(1), 3.
3. Ahmadivand, A., Sinha, R., Gerislioglu, B., Karabiyik, M., Pala, N., & Shur, M. (2016). Transition from capacitive coupling to direct charge transfer in asymmetric terahertz plasmonic assemblies. *Optics Letters*, 41(22), 5333-5336.
4. Sinha, R., Vabbina, P. K., Ahmadivand, A., Karabiyik, M., Gerislioglu, B., & Pala, N. (2016, October). Ultraviolet LED based compact and fast cortisol detector with ultra high sensitivity. In *SENSORS, 2016 IEEE* (pp. 1-3). IEEE.
5. Al-Amin, C., Karabiyik, M., & Pala, N. (2016). Fabrication of Graphene Field-effect Transistor with Field Controlling Electrodes to improve f_T. *Microelectronic Engineering*, 164, 71-74.
6. Al-Amin, C., Vabbina, P. K., Karabiyik, M., Sinha, R., Wang, C., & Pala, N. (2016). Bandgap engineering of single layer graphene by randomly distributed nanoparticles. *Journal of Materials Science: Materials in Electronics*, 27(7), 7454-7459.
7. Ahmadivand, A., Sinha, R., Vabbina, P. K., Karabiyik, M., Kaya, S., & Pala, N. (2016). Hot electron generation by aluminum oligomers in plasmonic ultraviolet photodetectors. *Optics express*, 24(12), 13665-13678.
8. Al-Amin, C., Karabiyik, M., Vabbina, P. K., Sinha, R., & Pala, N. (2016). Graphene FETs with Low-Resistance Hybrid Contacts for Improved High Frequency Performance. *Nanomaterials*, 6(5), 86.
9. Sinha, R., Karabiyik, M., Ahmadivand, A., Al-Amin, C., Vabbina, P. K., Shur, M., & Pala, N. (2016). Tunable, Room Temperature CMOS-Compatible THz Emitters Based on Nonlinear Mixing in Microdisk Resonators. *Journal of Infrared, Millimeter, and Terahertz Waves*, 37(3), 230-242.
10. Ahmadivand, A., Karabiyik, M., & Pala, N. (2015). Inducing multiple Fano resonant modes in split concentric nanoring resonator dimers for ultraprecise sensing. *Journal of Optics*, 17(8), 085104.
11. Vabbina, P., Choudhary, N., Chowdhury, A. A., Sinha, R., Karabiyik, M., Das, S., ... & Pala, N. (2015). Highly sensitive wide bandwidth photodetector based on internal photoemission in CVD grown p-type MoS₂/graphene Schottky junction. *ACS applied materials & interfaces*, 7(28), 15206-15213.

12. Ahmadivand, A., Karabiyik, M., & Pala, N. (2015). Fano-like resonances in split concentric nanoshell dimers in designing negative-index metamaterials for biological-chemical sensing and spectroscopic purposes. *Applied spectroscopy*, 69(5), 563-573.
13. Ahmadivand, A., Golmohammadi, S., Karabiyik, M., & Pala, N. (2015). Self-assembled silicon-based clusters to design efficient, fast, and controllable Fano switches. *Microwave and Optical Technology Letters*, 57(5), 1242-1246.
14. Ahmadivand, A., Golmohammadi, S., Karabiyik, M., & Pala, N. (2015). Fano resonances in complex plasmonic necklaces composed of gold nanodisks clusters for enhanced LSPR sensing. *IEEE Sensors Journal*, 15(3), 1588-1594.
15. Sinha, R., Karabiyik, M., Al-Amin, C., Vabbina, P. K., Güney, D. Ö., & Pala, N. (2015). Tunable room temperature THz sources based on nonlinear mixing in a hybrid optical and THz micro-ring resonator. *Scientific reports*, 5.
16. Al-Amin, C., Karabiyik, M., Vabbina, P. K., Sinha, R., & Pala, N. (2014). Field controlled RF Graphene FETs with improved high frequency performance. *Solid-State Electronics*, 95, 36-41.
17. Sinha, R., Karabiyik, M., Al-Amin, C., Vabbina, P. K., Shur, M., & Pala, N. (2014, May). Microdisk resonators for difference frequency generation in THz range. In *SPIE Sensing Technology+ Applications* (pp. 910208-910208). International Society for Optics and Photonics.
18. Karabiyik, M., Sinha, R., Al-Amin, C., Dyer, G. C., Pala, N., & Shur, M. S. (2014, May). Dispersion studies in THz plasmonic devices with cavities. In *SPIE Sensing Technology+ Applications* (pp. 91020K-91020K). International Society for Optics and Photonics.
19. Sinha, R., Karabiyik, M., Al-Amin, C., Vabbina, P. K., & Pala, N. (2014, March). Nonlinear optical resonators for tunable THz emission. In *SPIE OPTO* (pp. 898505-898505). International Society for Optics and Photonics.
20. Vabbina, P. K., Karabiyik, M., Al-Amin, C., Pala, N., Das, S., Choi, W., ... & Shur, M. (2014). Controlled synthesis of single-crystalline ZnO nanoflakes on arbitrary substrates at ambient conditions. *Particle & Particle Systems Characterization*, 31(2), 190-194.
21. Al-Amin, C., Vabbina, P. K., Karabiyik, M., Sinha, R., Pala, N., & Choi, W. (2013). Improving high-frequency characteristics of graphene FETs by field-controlling electrodes. *IEEE Electron Device Letters*, 34(9), 1193-1195.
22. Karabiyik, M., Al-Amin, C., & Pala, N. (2013). Deep sub-wavelength multimode tunable in-plane plasmonic lenses operating at terahertz frequencies. *IEEE Transactions on Terahertz Science and Technology*, 3(5), 550-557.
23. Karabiyik, M., Al-Amin, C., & Pala, N. (2013). Graphene-Based Periodic Gate Field Effect Transistor Structures for Terahertz Applications. *Nanoscience and Nanotechnology Letters*, 5(7), 754-757.
24. Karabiyik, M., Al-Amin, C., & Pala, N. (2013, May). Numerical analysis of terahertz plasmonic ring resonators. In *SPIE Defense, Security, and Sensing* (pp. 87160I-87160I). International Society for Optics and Photonics.
25. Karabiyik, M., Al-Amin, C., Das, S., Pala, N., & Choi, W. B. (2012, May). Subwavelength, multimode, tunable plasmonic terahertz lenses and detectors. In *SPIE Defense, Security, and Sensing* (pp. 83630L-83630L). International Society for Optics and Photonics.