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Plasma wave detection of terahertz radiation by silicon field effects transistors: Responsivity and noise equivalent power

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Si metal oxide semiconductor field effect transistors (MOSFETs) with the gate lengths of 120–300 nm have been studied as room temperature plasma wave detectors of 0.7 THz electromagnetic radiation. In agreement with the plasma wave detection theory, the response was found to depend on the gate length and the gate bias. The obtained values of responsivity ($\leqslant$200 V/W) and noise equivalent power ($\geqslant 10^{-10}$ W/Hz$^{0.5}$) demonstrate the potential of Si MOSFETs as sensitive detectors of terahertz radiation. © *2006 American Institute of Physics*.
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Dyakonov and Shur proposed using field effect transistors (FETs) as detectors of terahertz radiation.[1] When $\omega\tau \gg 1$, where ω is the frequency of the terahertz radiation and τ is the plasmon decay time, the transistor can operate as a resonant detector with resonances at the fundamental plasma frequency ω_0 and its odd harmonics ($\omega_0=\pi/(2L_g)\sqrt{(e^2 n_s)/(Cm)}$, where L_g is the gate length, n_s is the channel carrier concentration, C is the gate capacitance per unit area, e is the electron charge, and m is the effective mass). The resonance quality factor is $\omega\tau$. When $\omega\tau \ll 1$, the FET operates in a nonresonant regime and its response to the electromagnetic radiation above threshold is a decreasing function of the gate voltage swing, $V_g - V_t$, where V_g is the gate voltage and V_t is the threshold voltage.

Several additive mechanisms might determine the plasmon decay time. These mechanisms might include electron scattering by impurities and/or lattice vibrations,[1] viscosity of the electron fluid due to the electron-electron collisions,[1] the effect of ballistic transport,[2] and a possible effect of oblique plasma modes.[3] The detection of terahertz and subterahertz radiation by GaAs/AlGaAs,[4–7] InGaP/InGaAs/GaAs,[8] InGaAs/AlInAs,[9] and Si (Refs. 10 and 11) transistors has been already reported. Si based detectors operating at room temperature have an advantage of compatibility with mainstream complementary metal-oxide semiconductor (CMOS) technology. Although the experiments with subterahertz and terahertz sources in Refs. 10 and 11 demonstrated the possibility of terahertz detection by Si metal-oxide semiconductor field-effect transistors (MOSFETs), the data did not allow quantitative comparison with other existing terahertz detectors. In this letter, we report on responsivity and noise equivalent power (NEP) of Si MOSFETs and demonstrate that these transistors can be sensitive terahertz detectors operating at room temperature.

The n-channel silicon on insulator transistors had a 1.1 nm gate oxide with a 120 nm N^+ polycrystalline silicon gate. The test structures consisted of transistor arrays with common source and gate contacts and variable gate lengths. Transistors with the metal gate lengths of L_g=300, 200, and 120 nm have been studied. The gate width W was 10 μm for all the transistors. The threshold voltage extracted from the transfer current voltage characteristics at low drain bias was within the range of V_t=0.22–0.25 V for all devices.

The subterahertz radiation of frequency $f \approx 0.7$ THz was generated by a backward wave oscillator (BWO). The transistors were placed at a distance of ~26 mm from the BWO output cone [see Fig. 1(a) for the main dimensions]. Figures 1(b) and 1(c) show the wafer with transistors and bonded wires [Fig. 1(b)] and the configuration of the contact pads for a single transistor [Fig. 1(c)]. The power of the BWO radiation at given frequency was measured using a set of doped Si wafers with calibrated attenuation and a bolometer with calibrated responsivity. For the power measurement, the bolometer window, with a diameter of 20 mm, was positioned the same distance from the BWO output as the transistor was in the detector measurements. The power $P_t \approx 1$ mW measured this way was about one order of magnitude smaller than the value provided by the manufacturer. The response to the subterahertz radiation was measured as a dc voltage at the open drain with the source grounded.

Figure 2 shows the responsivity to 0.7 THz radiation as a function of the gate voltage V_g. The responsivity was esti-

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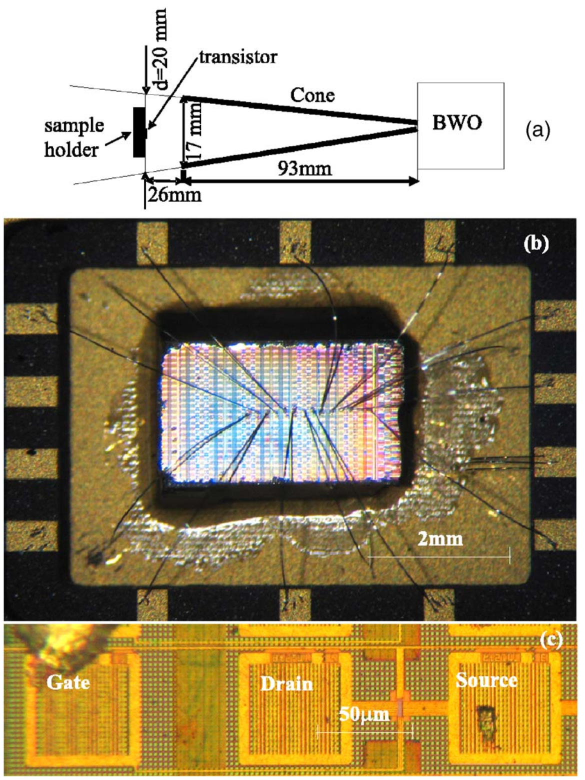

FIG. 1. (Color online) Schematic of the experimental setup (a), photo of the wafer in the sample holder with the bonding wires (b), and configuration of the contact pads of the transistor (c).

mated as $R_V=(\Delta u S_t)/(P_t S_a)$ where Δu is the induced dc drain voltage, P_t is the total power of the source, $S_t=\pi d^2/4$ [see Fig. 1(a)] is the radiation beam spot area, and S_a is the active area. Since the area of the transistor with the contact pads was smaller than the diffraction limited area $S_\lambda=\lambda^2/4$, the active area was taken equal to S_λ. Bonding wires [see Fig. 1(b)] might act as antennas for the terahertz radiation. This effect was not taken into account for the responsivity estimate.[12] As seen, the responsivity was a decreasing function of the gate voltage for $V_g>V_t$. This kind of the gate

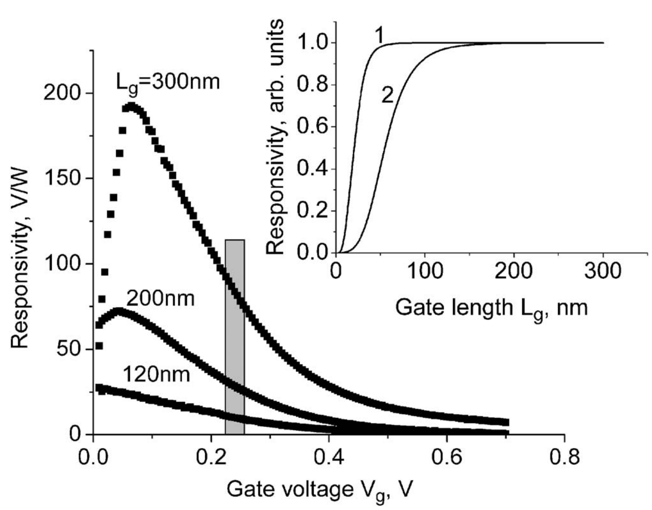

FIG. 2. Responsivity to 0.7 THz radiation as a function of the gate voltage for Si MOSFETs of different gate lengths, $T=300$ K (gray bar indicates the approximate range of the threshold voltages for different transistors). The inset shows the result of calculations of the maximum responsivity vs gate length. 1: $\tau=0.02$ ps ($\mu=200$ cm^2/V s), 2: $\tau=0.15$ ps ($\mu=1400$ cm^2/V s).

voltage dependence of the response was predicted by the theory[1,2] and was experimentally observed in Si FETs before.[10,11] The maximum value of the responsivity is comparable with that of commercial pyroelectric and Schottky diodes detectors, which is in the range of $\sim 10^2-10^5$ V/W.[13]

The upper limit for the plasmon decay time is the momentum relaxation time, which can be obtained as $\tau_m=\mu m/e=0.15$ ps taking the maximum electron mobility in Si ($\mu=1400$ cm^2/V s). Even with this value of τ the parameter $\omega\tau=0.66<1$. Since the actual mobility in the Si MOSFET channel is much smaller,[10,14] we expect the nonresonant detection in our experiments.

As shown in Ref. 15 the detector response due to the plasma wave excitation in the nonresonant regime is given by

$$\Delta u=\frac{eu_a^2}{4ms^2}\frac{\sinh^2 Q-\sin^2 Q}{\sinh^2 Q+\cos^2 Q}, \quad (1)$$

where $Q=\sqrt{\omega/(2\tau)}(L/s)$, $s^2=s_0^2(1+\exp(-(eU_0)/(\eta k_B T)))\ln(1+\exp((eU_0)/(\eta k_B T)))$, is the plasma wave velocity, $s_0=\sqrt{(\eta k_B T/m)}$, η is the ideality factor ($\eta=1.5$ for the transistors under study), U_0 is the gate-to-source voltage swing, and u_a is the ac source-to-gate voltage.

The inset in Fig. 2 shows the calculations of the maximum responsivity as a function the gate length for the relaxation times $\tau=0.02$ ps and $\tau=0.15$ ps, which correspond to the mobilities $\mu=200$ cm^2/V s (see Ref. 14 for the mobility measurements in Si transistors) and $\mu=1400$ cm^2/V s, respectively.

As seen, the theory predicts that the responsivity is constant for large gate lengths and decreases with the gate length below a certain value. The calculations predict the decrease of the signal to occur at shorter gate lengths than observed experimentally even assuming the maximum possible electron mobility in Si (curve 2 in the inset in Fig. 2). This discrepancy might be linked to the increase in the device absorption cross-section of the THz radiation with an increase in the gate length, which is not accounted for in our model.

One of the most important metrics for the detectors is the NEP. The NEP can be found as N/R_V, where N is the noise of the transistor in V/Hz$^{0.5}$ and R_V is the responsivity in V/W. Since detection was studied at zero drain bias the thermal noise $N=(4kTR_d)^{0.5}$ was the only source of noise of the transistor. Here R_d is the drain-to-source resistance, which can be extracted from the transfer current-voltage characteristics measured at low drain bias corresponding to the linear regime. At high gate voltage, the resistance R_d was in the range of a few hundred ohms and increased up to a $(1-2)\times 10^5$ Ω in the subthreshold region ($V_g<V_t$). Figure 3 shows the NEP calculated as N/R_V for the transistors whose characteristics are shown in Fig. 1. As seen, the transistors demonstrate a very low NEP at the gate voltages close to the threshold voltage V_t. In order to check our estimates, we measured the signal to noise ratio directly using a dynamic spectrum analyzer. The inset of Fig. 3 shows the spectral density for the detected signal and the noise measured simultaneously for the 300 nm gate length transistor at $V_g=0.3$ V. The dashed line shows the estimated noise $N^2=4kTR_{d,}\approx 10^{-17}$ V^2/Hz, which agrees well with the measured background noise level. The detected signal is seen as a peak at the sampling frequency of ~ 76 Hz. The spectrum

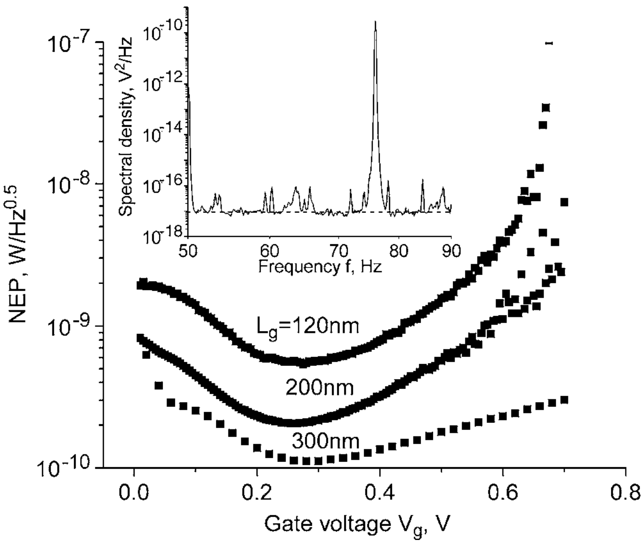

FIG. 3. Noise equivalent power as a function of the gate voltage for Si MOSFETs of different gate lengths, T=300 K. The inset shows the spectral density showing the detected signal and the background noise for the transistor with L_g=300 nm. V_g=0.3 V.

analyzer frequency window is ~0.15 Hz. Taking for the maximum of the peak of 3×10^{-10} V^2/Hz, we obtain the absolute value of the detected signal $\Delta u \approx 6.7$ μV. The actual power, which is incident on the diffraction limited spot size surrounding the detector is about $P_a \approx 200$ nW. Therefore, the responsivity and NEP are $R_V = \Delta V / P_a \approx 33$ V/W and $NEP = N/R_V \approx 10^{-10}$ W/Hz$^{0.5}$, respectively, in a reasonable agreement with the calculated values shown in Fig. 3. This value of the NEP is comparable to those for commercial detectors operating at room temperature such as Golay cells, pyroelectric detectors, microbolometers, and Schottky diodes.[13] In comparison with Golay cells, pyroelectric detectors, and microbolometers, the transistor plasma wave detectors should have an advantage of a much higher modulation frequency (the fast plasmon response was demonstrated experimentally in Ref. 5).

In conclusion, we have demonstrated that Si MOSFETs with the gate length of 120–300 nm can operate as sensitive nonresonant detectors of the terahertz radiation. The obtained values of the responsivity and NEP show that these detectors can compete with conventional terahertz detectors having the advantages of being compatible with the CMOS technology and potentially exhibiting much higher operating speed.

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