Far infrared emission and possibility of population inversion of hot holes in MQW InGaAs/GaAs heterostructures under real space transfer

V. Ya. Aleshkin†, A. A. Andronov†, A. V. Antonov†, N. A. Bekin†,
V. I. Gavrilenko†, I. G. Malkina‡, D. G. Revin†, E. A. Uskova‡,
B. N. Zvonkov‡, W. Knap¶, C. Skierbiszewski¶, J. Lusakowski¶
and S. Komiyama§

† Institute for Physics of Microstructures of Russian Academy of Sciences, GSP-105, Nizhny Novgorod, 603600, Russia
‡ Physical-Technical Institute of Nizhny Novgorod State University, Russia
¶ GES, Universite Montpellier 2-CNRS UMR5650, place E. Bataillon, 34095 Montpellier France
§ Department of Basic Sciences, Graduate School of Arts and Sciences, University of Tokyo, Komaba, Meguro-ku, Tokyo 153, Japan

Abstract. Far IR emission and current-voltage characteristics of hot holes in strained MQW $In_xGa_{1-x}As$/GaAs heterostructures at lateral charge transport are investigated. Highly nonequilibrium phenomena observed are shown to results from the real space transfer. The simple experimental criterion for the population inversion between barrier and quantum well states is put forward. The population inversion is shown to realize in "shallow" (with respect to the optical phonon energy) $In_xGa_{1-x}As$ quantum wells.

Introduction

Recently there has been considerable interest to the hot holes in strained multi-quantum-well (MQW) $In_xGa_{1-x}As$/GaAs heterostructures excited at lateral charge transport [1-6]. The interest is stimulated by the possibility to realize the hot carrier population inversion and the amplification of the far infrared (FIR) radiation under the real space transfer (RST) conditions. In the present paper the simple experimental criterion for the population inversion between barrier and quantum well states based on the figures obtained from the observed FIR emission and transport characteristics of hot holes is put forward.

1 Experimental

$In_xGa_{1-x}As$/GaAs MQW heterostructures with δ-layers of carbon at 50 Å apart from the boundaries of each InGaAs QW were grown by MOCVD on GaAs(001) substrates [1]. Pulsed electric field up to 2.5 kV/cm was applied to the structure via strip electric contacts deposited on the sample surface at $3 \div 4$ mm apart. Current-voltage (I–V) characteristics were investigated in wide temperature range $4.2 \div 300$ K. Hot hole FIR emission at $T = 4.2$ K was detected by photoresistor Ge:Ga ($\hbar\omega = 10 \div 25$ meV). Narrow band n-GaAs photodetector ($\hbar\omega = 4.2$ meV) was used for the investigation of the cyclotron emission of the hot carriers in high magnetic fields (normal to the plane of the heterostructure) up to 14 T.
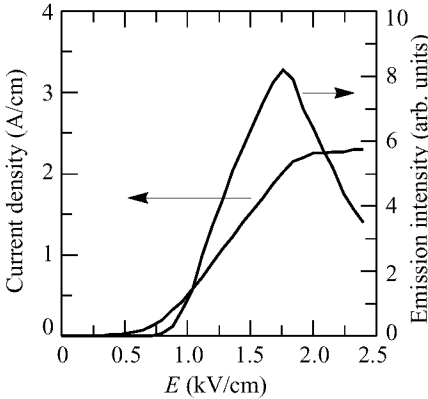
Fig. 1. Emission-voltage and current-voltage characteristics of the sample #2154 ($x = 0.11$, $d_{QW} = 47$ Å, $p_s = 2 \times 10^{11}$ cm^{-2}, $n_{QW} = 50$) at $T = 4.2$ K. Detector — Ge:Ga.
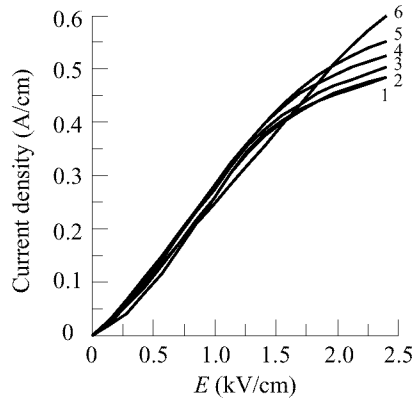
**Fig. 2.** Current-voltage characteristics of the sample #1947 ($x = 0.11$, $d_{QW} = 52$ Å, $p_s = 2 \times 10^{11}$ cm^{-2}, $n_{QW} = 20$) T, K: 1—4,2, 2—40, 3—60, 4—80, 5—100, 6—140.

2   Results and discussion

Current-voltage and emission-voltage characteristics of the sample #2154 with "shallow" (with respect to the optical phonon energy $\hbar\omega_0 = 37$ meV) QWs are given in Fig. 1. In this sample the calculated [1] position of the only hole subband hh1 in QW is 28 meV lower with respect to the edge of the valence band in the barrier. This figure is very closed to the binding energy of carbon acceptor in GaAs of 26 meV. Therefore at $T = 4.2$ K the holes may be frozen out at the impurities since the binding energy increases in the vicinity of QW. The steep rise of the current and the emission at $E > 0.3$ kV/cm results from the impact ionization of the impurities and the hole transfer from δ-layers into InGaAs QWs. At further increase of the electric field the saturation of current was observed at $E = 1.8 \div 2.5$ kV/cm resulted from hot hole escape from QWs to the barrier layers (i.e. RST) where the carrier mobility drop drastically due to the increase of the effective mass and to the strong ionized impurity scattering in δ-doped barriers. At the same fields the emission intensity reaches its maximum and then monotonously decreases with the electric field (Fig. 1). The cogent argument on the important role of RST in high electric fields is the behavior of I–V characteristics at higher temperatures. Fig. 2 shows I–V plots for the sample #1947 (similar to #2154) in between 4.2–140 K (cf. [3]). The saturation current increases with the rise of the temperature thus proving that the saturation is connected with the RST rather than with the optical phonon scattering as stated in [7].

The "shallow" QWs seems to be most suitable for the realization of the population inversion between barrier and well states [5, 6]. The key point of the inversion mechanism is the high effective carrier temperature in QWs (T_w) and the low one in the barriers (T_b). This results from the large difference in the carrier mobilities in the QWs and in the barriers. The theoretical criterion for the inversion [5, 6] can be expressed in the simplest form for rather reasonable case when not only the well but also barrier states are of 2D nature (that for example can take place if the barrier holes are confined
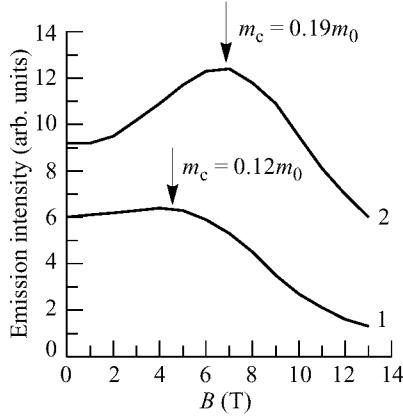
Fig 3. CR emission spectra for the sample #1842 ($x = 0, 22$, $d_{QW} = 81$ Å, $p_s = 2 \times 10^{11}$ cm^{-2}, $n_{QW} = 20$).

in the selfconsistent Coulomb potential at the δ-layers). In this case the occupation number ratio is given by the simple relation [6]

$$ p = \frac{n_b}{n_w} = \frac{T_w}{T_b} \exp\left(-\frac{\Delta}{T_w}\right). \tag{1} $$

For $T_w \approx \Delta$ and $T_w \gg T_b$ this formula gives the population inversion ($p > 1$). Direct information on the hot hole temperature in QWs was obtained from the measurements of CR emission (Fig. 3). In this experiment $\hbar\omega = 4.2$ meV is too small for the inter-subband or barrier-well transitions; so the observed radiation results from the cyclotron resonance (CR) emission in QWs with the maximum corresponding to the resonant magnetic field $H = \omega c m_c / e$ (m_c is the cyclotron hole mass). As one can see from Fig. 3 the maximum on curve 1 at $E = 110$ V/cm corresponds to the effective cyclotron mass of $0.12m_0$ while at $E = 840$ V/cm the maximum is shifted to $0.19m_0$. According to the calculated energy-momentum law (that is highly nonparabolic) this increase of the cyclotron mass corresponds to the hole heating up to 30 meV, i.e. $T_w > 300$ K. On the other hand from Fig. 2 one can estimate the "barrier" hole temperatute in the sample with "shallow" QWs as low as $T_b \leq 50$ K since up to this figure the saturation current is insensitive to the increase of the lattice temperature. Moreover from these curves it is possible to estimate the ratio of the hole concentrations in "barrier wells" and in the QWs N_b/N_w. It is quite natural to assume from the data in Fig. 2 the hole mobility in the QWs to be independent on electric field and that in the "barrier wells" to be equal to zero. Under this assumption one should continue the linear parts of I-V curves at $T = 40 \div 100$ K as the straight line with the same slope up to $E = 2.5$ kV/cm (if the hole number in QWs would be constant). Then it is possible to estimate N_b/N_w as the ratio of lengths of the vertical segments (i.e. at $E = $ const.) between the above straight line and certain I-V curve and between the I-V curve and the absciss axis. This procedure gives $N_b/N_w \approx 0.5$ for $T = 4.2 \div 40$ K at $E = 2.5$ kV/cm. On this base one

can reformulate the relation (1) in more simple and "transparent" manner:

$$p = \frac{n_b}{n_w} = \frac{N_b}{N_w} \frac{T_w}{T_b} \frac{m_w}{m_b}. \tag{2}$$

Substituting in (2) the experimentally obtained figures $N_b/N_w \approx 0.5$, $T_w \approx 300$ K, $T_b \approx 50$ K, $m_w \approx 0.19 m_0$ and the well known hole effective mass in GaAs $m_b \approx 0.5 m_0$ one readily gets $p \approx 1.1$. Since in the expression (2) the hole concentration in the barriers was surely underestimated by neglecting their mobility it is possible to assert the realization of the population inversion ($p > 1$) in the real MQW heterostructure.

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