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8th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 19–23, 2000
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Experimental determination of the energy distribution function of hot holes in InGaAs/GaAs quantum well heterostructure

V. Ya. Aleshkin†, A. A. Andronov†, A. V. Antonov†, V. I. Gavrilenko†, D. M. Gaponova†, Z. F. Krasil'nik†, D. G. Revin†, B. N. Zvonkov‡ and E. A. Uskova‡

† Institute for Physics of Microstructures RAS, Nizhny Novgorod, Russia
‡ Physical-Technical Institute of Nizhny Novgorod State University, Russia

Abstract. The symmetrical part of the hot hole distribution function in MQW $In_{0.21}Ga_{0.79}As/GaAs$ heterostructure is obtained from the spectra of the modulation of the fundamental absorption by application of high electric field pulses.

Introduction

To now there are two experimental methods to determine the distribution function of hot carriers in bulk semiconductors. The first method is based on measurements of the modulation of free-hole intervalence-band absorption of infrared radiation by high electric field. This method was successfully used to obtain both symmetrical part of the distribution function and the degree of its anisotropy for hot holes in *p*-Ge [1, 2]. The second method is based on measurements of the modulation of fundamental absorption edge by high electric field in degenerate semiconductors. The last method was used to study high electric field effect on the electron distribution function under Fermi level in degenerate *n*-GaAs [3, 4].

The possibility to determine the distribution function of hot carriers in quantum wells by the second method was experimentally demonstrated in our previous work [5]. In contrast to the case of bulk semiconductors in a quantum well the distribution function of hot carriers can be obtained for energy which exceeds Fermi level as well. However, only estimations for hole effective temperatures were made in [5] and the distribution function was not obtained. In the present work the changes of the symmetrical part of the distribution function of hot holes in high electric field have been determined in $In_{0.21}Ga_{0.79}As/GaAs$ heterostructure. To make it we measured destruction of Burstein-Moss effect (modulation of the interband optical absorption) by application of high electric field pulses and used the corresponding mathematical data processing.

1. Experiment

The investigated structure was grown by MOCVD technique on semi-insulating GaAs and contains 20 QWs $In_{0.21}Ga_{0.79}As$ ($d_{QW} = 10.5$ nm) separated by 60 nm GaAs barrier layers. Two delta-layers of Zn were introduced 5 nm apart both sides of each QW. The measured by Hall technique ($T = 300$ K) hole concentration and mobility in QW were $p_s \approx 1.7 \cdot 10^{11}$ cm^{-2} and 315 cm^2/V s, respectively.

Photoluminescence (PL) and modulation of the light transmittance were measured at $T = 4.2$ K. The lateral pulsed electric field (E) up to 1.9 kV/cm 3 to 10 μs in duration was applied to the structure via strip electric contacts. PL was excited by cw Ar^+ laser. In transmittance experiments the light from halogen lamp was dispersed by monochromator, guided to the sample by optical fibre and detected by Ge-diode placed behind the sample.

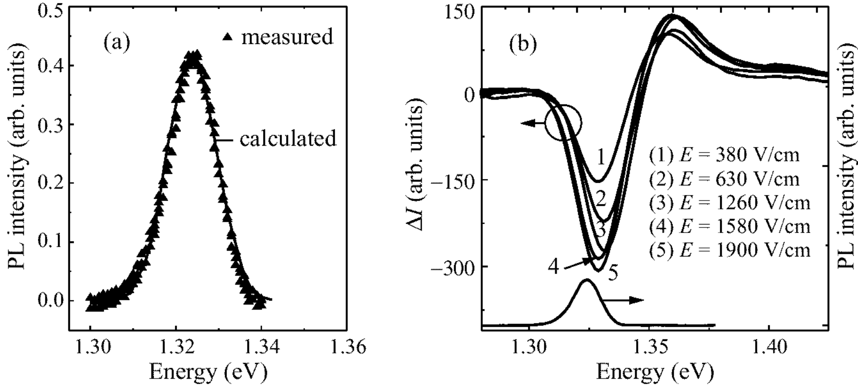

Fig. 1. PL (a) and modulation of transmitted light (b) spectra.

The measured transmittance signal was proportional to the difference between the intensities of light passed through the sample without and under applied electric field.

In PL spectrum there is only one peak at $E = 0$ due to the optical transitions between the ground electron and heavy hole subbands. We suppose that the width of PL peak measured at 4.2 K ($\approx$18 meV) is determined by fluctuations of quantum well parameters. The measured and calculated PL spectra are shown in Fig. 1(a). To calculate PL spectrum we took into account the content fluctuations in QWs. We described the fluctuations of the In fraction by the Gaussian distribution function with average value $\bar{x}$ and dispersion σ_x. Values for $\bar{x}$ and σ_x were obtained by fitting the measured and the calculated PL spectra. It is clealy seen from Fig. 1(a) that these spectra practically coincide for $\bar{x} = 0.21$ and $\sigma_x = 0.006$.

At zero electric field the hole concentration in quantum wells is high enough to shift the edge of the fundamental absorption due to the Burstein–Moss effect. Hole heating results in the changes of the hole distribution and the light absorption around edge. The measured modulation of light transmittance by electric field is presented in Fig. 1(b). PL spectrum at $E = 0$ is also given in Fig. 1(b) for comparison. It is clearly seen from Fig. 1(b) that the electric field increases transmittance in the short wavelength region and decreases it in the long wavelength one. The transmittance modulation is observed starting from low enough electric field of 40 V/cm. Both positive and negative transmittance modulations rise with the electric field, being approximately the same up to 200 V/cm. In high enough electric fields the negative modulation of the transmittance dominates. Variation of the electric field practically does not change the maximum and the minimum positions in the transmittance modulation spectra.

2. Discussion

Taking into account content fluctuation in QWs we can write the transmitted light intensity modulation $\Delta I(\hbar\omega)$ in the following form

$$\Delta I(\hbar\omega) = \frac{(1-R)I}{\sqrt{2\pi}\sigma_x} \int_{-\infty}^{\infty} \exp\left(-\frac{(x-\bar{x})^2}{2\sigma_x}\right) \Delta f_h \left(\frac{m}{m_h}\{\hbar\omega - \varepsilon(\bar{x}) - B(x-\bar{x})\}\right) dx \tag{1}$$

where R is the reflection coefficient, I the intensity of incident light, Δf_h the modulation of the symmetrical part of the hole distribution function, $m = m_e m_h/(m_e + m_h)$, $m_{e,h}$

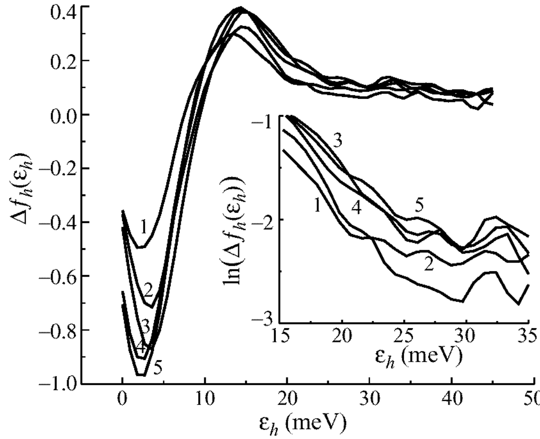

Fig. 2. Calculated modulations of the hole distribution function. Notations are the same as in Fig. 1

the electron and hole masses, $\varepsilon(x)$ the energy of optical transition in QW $In_xGa_{1-x}As$, $B = d\varepsilon(x)/dx$ for $x = \bar{x}$. Eq. (1) is valid if σ_x is small and sizes of regions where x is nearly constant are greater then sizes of the space charge regions in QW. The last condition means that the effect of x fluctuation on the hole concentration in QW is negligible. We suppose that both these conditions are satisfied and neglect influence of the Zn concentration fluctuation on light transmission.

To find the dependence $\Delta f(\varepsilon_h)$ on the hole energy ε_h from measured dependence $\Delta I(\hbar\omega)$ it is necessary to solve integral Eq. (1). But it is impossible to find the correct general solution of this equation if $\sigma_x \neq 0$. However, one can find approximate solution of (1). Indeed, Green's function of integral operator (1) can be written in the form

$$G(y - y') = \lim_{a \to 0}[G_a(y - y')],$$

$$G_a(y) = \frac{1}{2\pi(1 - R)I} \int_{-\infty}^{\infty} \frac{\exp(iky)}{\exp\left(-\frac{(k\sigma_x Bm)^2}{2m_h^2}\right) + ak^2} dk. \qquad (2)$$

Now we can find approximate solution of (1) using G_a for nonzero a as approximate Green's function:

$$\Delta f_h(\varepsilon_h) = \int_{-\infty}^{\infty} G_a(y - \varepsilon_h)\Delta I\left(\frac{ym_h}{m} + \varepsilon(\bar{x})\right) dy. \qquad (3)$$

Dependencies $\Delta f_h(\varepsilon_h)$ determined from experimental data by the use of expression (3) ($a = 0.03$) are shown in Fig. 2. Since the absolute values of ΔI were not measured the obtained dependencies $\Delta f_h(\varepsilon_h)$ are not normalized. We can find the corresponding coefficient from the requirement that the minimal value of Δf_h is of the order of -1 at the highest electric field ($E = 1900$ V/cm).

From Fig. 2 one can see that integral of $\Delta f_h(\varepsilon_h)$ over hole energy approximately equals zero at low fields. This reflects the conservation of the hole number in the first subband. This integral is negative at high fields (>380 V/cm) due to the decrease of the hole number in the first subband. Note that holes in excited subbands make a weak contribution

to the light modulation due to selection rules for optical transitions. The minimal value of Δf_h (negative modulation) tends to the saturation at high electric fields. It is clear that limit for this minimum is -1 that corresponds to a full hole escape from low-energy states. Dependencies $\Delta f_h(\varepsilon_h)$ in logarithmic scale for energies exceeding maximum are presented in the insert to Fig. 2. It is clearly seen that for relatively low energies (up to 20–30 meV) these dependencies are approximately linear, and further change irregularly. Linear region corresponds to Maxwell's type of the hole distribution function. The temperatures determined from these linear dependencies are: $T(E = 380\,\text{V/cm}) = 110 \pm 30$ K, $T(630\ \text{V/cm}) = 90 \pm 25$ K, $T(1260\,\text{V/cm}) = 110 \pm 15$ V/cm, $T(1580\ \text{V/cm}) = 125 \pm 15$ K, $T(1900\ \text{V/cm}) = 127 \pm 15$ K. In high energy region ($\varepsilon_h > 30$ meV) there are significant errors in determination of $\Delta f_h(\varepsilon_h)$ due to low experimental accuracy in measurements of weak signals.

Acknowledgements

This work was supported by the grants of RFBR, INTAS and Russian Scientific Programs "Physics of Solid State Nanostructures" and "Fundamental Spectroscopy".

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