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OPTICAL ALIGNMENT OF TWO-DIMENSIONAL ELECTRON MOMENTA AND POLAR SCATTERING IN MULTIPLE QUANTUM WELL STRUCTURES

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During his study of surface polaritons in the seventies the author of this paper had the pleasure to discuss repeatedly his experimental results with Prof. V.M. Agranovich. These stimulating discussions contributed to the success of the work, reflected, in particular, in the author's review (ch. 1 in ref. [1]). That is why the author was very grateful to Prof. D.L. Mills for his suggestion to contribute to this issue of Physics Reports.

The work presented here is concerned with the study of photoluminescence of hot electrons in two-dimensional (2D) systems such as quantum wells, and with the determination of the interaction of 2D electrons with polar optical phonons*). In such structures the phonon spectrum is considerably modified as compared with the bulk spectrum. In particular, the comparatively small thickness of the layers must increase the interaction of 2D electrons with interface phonons [1].

The available theoretical calculations (see, for instance, ref. [2]) are based on some special models. The experimental results are also uncertain (see below). Thus it was not clear a priori how much the rate of polar interaction will differ from the volume case. As we shall see, this difference appeared not to be very great, at least in not very thin quantum wells, which have been studied by us.

The results presented here have been obtained by the author in collaboration with Drs. D.G. Poljakov, I.I. Reshina, V.F. Sapega and A.A. Sirenko. The quantum well structures used in this work have been grown by Dr. P.S. Kopjev's group in the Physical–Technical Institute of the Academy of Sciences of the USSR.

The methods of hot photoluminescence (HPL) spectroscopy under continuous pumping have been successfully used in recent years to solve a wide range of problems in semiconductor physics [3–6]. In this work these methods are used in the study of quantum well structures.

Hot electron relaxation in two-dimensional systems has been studied by a great number of authors, but as a rule with the aid of the technique of pico- and subpicosecond pulses (see the reviews [5, 7]). Comparison of the results of these authors shows that the measured values of the time of polar optical scattering vary widely. This is due to some factors which are difficult to take into account, such as phonon heating and screening, which take place at high pumping power. The influence of these factors is different in different experiments, leading to the indicated variation in the results. In our work, the study has been performed under moderate pumping power when the influence of the above-mentioned complicating factors could be neglected.

*) Preliminary results of this study were published previously [3].

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1. Experimental

The structures under study were p-GaAs/$Al_{0.28}Ga_{0.72}As$ quantum wells. They were grown by the Molecular Beam Epitaxy Method onto (100) oriented GaAs substrates. A schematic of the structures is shown in fig. 1. The widths of the wells in different structures was in the range 70–100 Å, and the AlGaAs barriers had a width of 100 Å. Thus the wavefunctions of separate wells did not overlap to very good approximation. The concentration of the acceptor levels (carbon) in the region of quantum wells was of the order of 10^{16} cm^{-3} and the barrier height for electrons was $\Delta E_c = 255$ meV. The luminescence was excited by Kr and He–Ne laser lines at 1.65, 1.83, 1.92 and 1.96 eV. The exciting laser beam was directed perpendicular to the surface of the structure. The luminescence was registered in the backscattering configuration. The pumping power did not exceed 3×10^2 W/cm^2. This corresponded to a concentration of the photoexcited carriers smaller than 2×10^{10} cm^{-2}. The magnetic field was applied perpendicular to the plane of the structure, i.e. along the light beam (Faraday geometry).

2. Results and discussion

The photoluminescence spectrum under $E_{exc} = 1.65$ eV excitation is shown in fig. 2. For such an excitation energy the electrons are excited only into the first electron subband (see the scheme of the

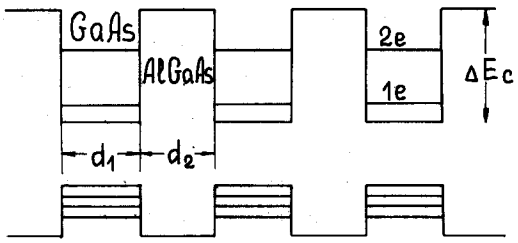

Fig. 1. Schematic of the multi-quantum-well structure. d_1 is the well thickness, d_2 is the barrier thickness, ΔE_c denotes the barrier height for electrons in the quantum well.

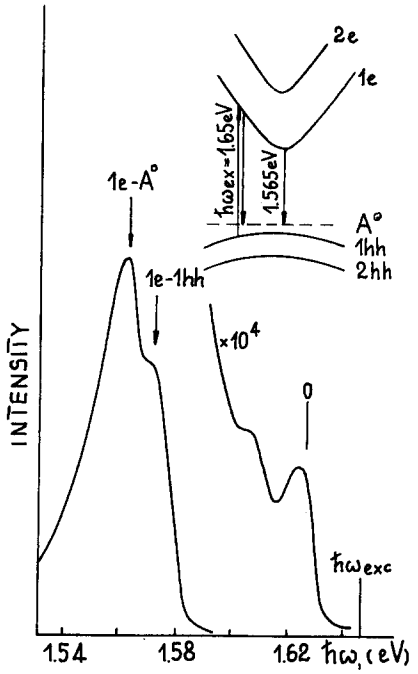

Fig. 2. The photoluminescence spectrum of the quantum well structure GaAs/$Al_{0.28}Ga_{0.72}As$ ($d_1 = 70$ Å, $d_2 = 100$ Å). The right part of the curve is the spectrum of hot luminescence. "0" designates the zero-phonon peak recombination. The scheme of the transitions is shown in the upper right-hand corner.

transitions in fig. 2). In the luminescence spectrum the 1e–1hh excitonic transition (i.e. exciton formed by the electron from the 1e subband and the hole from the 1 heavy holes subband) and the 1e–A^0 excitonic transition (from the first electron subband to the acceptor levels) are shown. The high-frequency tail of this latter component of the spectrum is just due to the recombination of hot electrons on the acceptor levels. The peak designated as "0" on the high-frequency edge of the spectrum corresponds to recombination of the electrons from the point of their photocreation, i.e. prior to any energy relaxation.

The hot luminescence under linearly polarized excitation turned out to be linearly polarized. The kinetic energy of the electrons in point "0" in fig. 2 is $E_0 = 60$ meV. The degree of linear polarization of the radiation from the point "0" measured under linearly polarized excitation was $\rho = 0.06$. When the excitation energy and accordingly the initial energy of photoexcited electrons are increased the degree of polarization increases too (fig. 3). For example, for an initial energy of the electrons in the 1e subbands $E_0 = 215$ meV we obtained $\rho = 0.28$.

As in the three-dimensional case the linear polarization of HPL in quantum wells has been explained by the optical alignment of electron momenta under linearly polarized excitation [3, 4]. The recombination of such anisotropically distributed electrons results in a linear polarization of the recombination luminescence. In the two-dimensional case, contrary to the three-dimensional one, the degree of polarization for the recombination radiation from the creation point increases with increasing initial energy of the photocreated electron*). Such a behaviour of the initial polarization is due to a peculiarity of the electron's 2D motion. At small kinetic energy (smaller than the confinement energy E_1) the electrons are moving nearly perpendicular to the plane of the structure (along the Z axis). Consequently, for observation along the Z direction their radiation is almost unpolarized.

For $E_0 \gg E_1$ the electrons are moving mostly in the plane of the wells, and recombination radiation observed along the Z axis becomes polarized mainly perpendicular to the direction of the electron momenta.

Polarization of the HPL is due to the anisotropic distribution of the in-plane electron momenta: the momentum distribution function is proportional to $\sin^2\varphi$, where φ is the angle between the electron

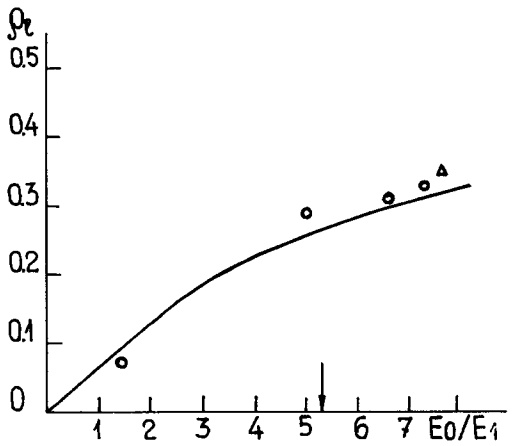

Fig. 3. The degree of polarization as a function of the initial electron energy E_0 in the 1e subband. The value of E_0 is normalized to the confinement energy E_1. The solid curve was calculated according to eq. (1).

*) In the 3D case, the initial polarization of HPL is independent of the electron energy.

momentum and the polarization plane. In a very simplified model [3], which takes into account the quantization of electrons (but not of holes) and neglects the valence band warping, the degree of polarization is given by

$$\rho = \frac{(E_0/E_1)^2}{8(1 + E_0/E_1) + 2(E_0/E_1)^2} . \tag{1}$$

The dependence given by eq. (1) is shown in fig. 3.

One could expect that eq. (1) gives the correct limiting values of the polarization (0 at $E_0 = 0$ and 0.5 at $E_0 \gg E_1$). Apparently the too perfect agreement between the experimental results and eq. (1) is accidental. Let us note that the increase in ρ with energy was also observed when the electron energy exceeded the barrier height, shown in fig. 3 by the arrow on the energy axis. From the polarization characteristics, the two-dimensional spectrum can be followed in the above barrier region up to electron energies exceeding the barrier height by 100 meV.

3. Depolarization in a magnetic field and determination of the polar scattering rate

The study of the depolarization of hot luminescence in a magnetic field makes it possible to determine the characteristic relaxation times of hot electrons [4]. The polarization of recombination luminescence in a magnetic field B directed along the light beam (Faraday geometry) is

$$\rho(B)/\rho(0) = (1 + 4\omega_c^2\tau_0^2)^{-1} , \tag{2}$$

where ω_c is the cyclotron frequency and τ_0 is the "life time" at the point of photocreation E_0. At the moderate doping and pump power used in this work τ_0 has the meaning of the LO phonon emission time τ_{p0}. Indeed, the distinct peak "0" observed in the spectrum (fig. 2) confirms that energy relaxation occurs by LO phonon emission. It follows from $\rho(B)$ measurements at excitation energy equal to 1.65 eV (fig. 4) that $\tau_{p0} = 160 \pm 10$ fs. The initial energy of the electrons in this case ($E_0 = 60$ meV) is lower than the bottom of the second electron subband 2e. Therefore, the measured scattering time corresponds only to intrasubband scattering in 1e subbands. The measured value of τ_{p0} is close to the calculated one for polar scattering of such electrons by bulk phonons (see fig. 5).

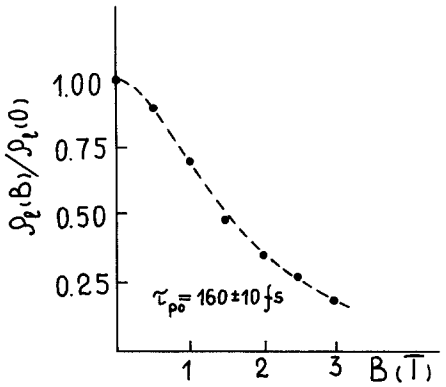

Fig. 4. Magnetic depolarization of hot luminescence is described by the Lorentz contour eq. (2) with $\tau_{p0} = 160$ fs. The $\rho(B)$ dependence was obtained for the zero-phonon peak shown in the spectrum of fig. 2.

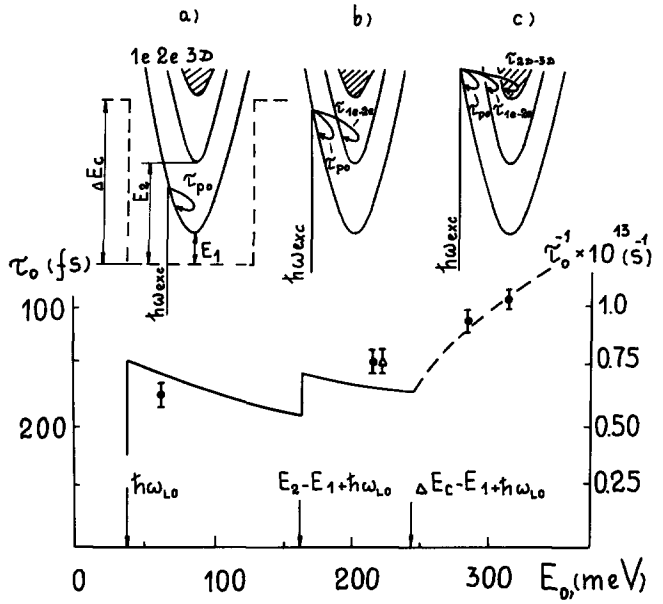

Fig. 5. Scattering rate (τ_0^{-1}) and lifetime (τ_0) of photoexcited 2D electrons as a function of initial energy. The solid line is the calculated dependence for polar scattering of 2D electrons by bulk LO phonons. The dashed line corresponds to the above-barrier region. The scheme of the possible transitions is shown in the upper part of the figure.

The difference between measured and calculated bulk scattering rates is of the order of 20%, in agreement with results of ref. [2] for the case $E_1 = \hbar\omega_{LO}$. It is believed that in still thinner wells the scattering rates in quantum wells will be considerably less than in the bulk.

The applied technique can be used in a wide range of electron energies to study the kinetics of intra- and interband transitions in quantum wells. The results of such measurements for several electron energies are shown in fig. 5. In this figure is also shown the scheme of the different scattering processes. From a comparison of the scattering times at electron energies of 60 meV and 215 meV one can estimate the intersubband scattering time $\tau_{1e-2e} = [\tau^{-1}(215\,\text{meV}) - \tau^{-1}(60\,\text{meV})]^{-1}$. Such an estimate is possible because at 215 meV the scattering of 2D electrons is due to interband as well as to intraband transitions. By such means we obtained $\tau_{1e-2e} = 0.7$ ps. This value is slightly below the calculated bulk phonon scattering time (1.1 ps).

The decrease of the measured outscattering times in the above the barrier region (i.e., when the energy of the confined electrons exceeds the barrier height) is due to the addition of the scattering of confined electrons to the 3D continuum. The time of the 2D–3D transition at an above the barrier electron energy of 100 meV was estimated as 350 fs. If the above the barrier electron energy is of the order of $\hbar\omega_{LO}$ the majority of hot electrons slide down the two-dimensional branch without scattering into the continuum.

4. Summary

In summary the photoluminescence of hot 2D electrons in quantum well structures has been studied. The polarization of hot luminescence due to the optical alignment of 2D electrons has been detected. The peculiarity of the 2D motion manifests itself in the observed increase of the linear polarization of

HPL with the increase of the kinetic energy of the 2D motion. The rates of intrasubband and intersubband transitions of 2D electrons in quantum wells as well as the rate of the 2D–3D (continuum) transition has been estimated. The obtained time of LO phonon emission by 2D electrons (160 fs) is close to the calculated one for interaction of confined electrons with bulk phonons. The polarization measurements reveal a 2D branch in the above the barrier region up to an energy of the order of 100 meV above the barrier.

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