Solid State Communications, Vol. 69, No. 3, pp.203-206, 1989.
Printed in Great Britain.

0038-1098/89 $3.00 + .00
Pergamon Press plc

OPTICAL ALIGNMENT OF 2D-ELECTRON MOMENTA IN MULTIPLE QUANTUM WELL STRUCTURES

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(Received 10 October 1988 by A.L.Efros)

A linear polarization of the recombination luminescence of photoexcited hot electrons in a multiple quantum well structure has been observed. The peculiarity of electron 2D-motion manifests itself in an observed increase of the polarization with 2D-motion energy. The time of optical-phonon emission by a 2D electron is determined by measuring a magnetic depolarization of the luminescence.

1. Experimental

Spectra and polarization of hot photoluminescence in a quantum-well structure have been first studied in this work. The results are presented for a p-GaAs/$Al_{0.3}Ga_{0.7}As$ structure grown by molecular-beam epitaxy and composed of 100 periods of 70 Å GaAs quantum wells and 100 Å GaAlAs barriers. The acceptor (carbon) concentration in the region of quantum wells was of the order of $10^{16} cm^{-3}$.

The photoluminescence spectrum under Kr-laser E_{ex} = 1.65 eV excitation and directions of the exciting light and observation normal to the plane of the structure, is shown in Fig.1. For such a value of E_{ex}, the electrons are excited only into the first electron subband (see the scheme of the transitions in Fig.1). In the luminescence spectrum the 1e - 1hh excitonic transition as well as that from the first electron subband onto the acceptor level (1e - Å) are revealed. 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 photocreation, i.e. prior to any energy relaxation. The kinetic energy of electrons in this point is E_0= 60 meV. The degree of linear polarization of the radiation from the point "0" measured under linearly polarized excitation has the value P_1=0.06

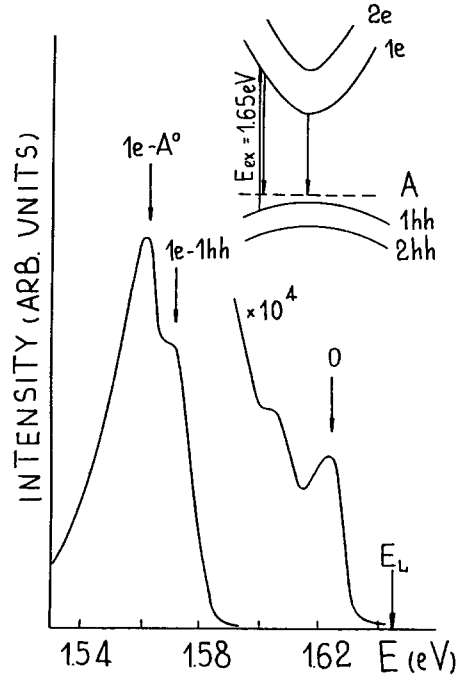

Fig.1. The photoluminescence spectrum of the quantum well structure (the parameters of the structure are given in the text, E_{ex}= 1.65 eV). The right part of the curve is the spectrum of hot luminescence. "0" designates the zero-phonon peak recombination from the point of photocreation. The scheme of the transitions is in the right upper corner.

When E_{ex} is increased, P_1 increases too amounting to 0.28 at E_{ex}=1.83 eV (which corresponds to E_o = 215 meV). As seen in Fig.2, the degree of linear polarization decreases in the course of energy relaxation.

2. Discussion

The obtained results are explained by an optical alignment of electron momenta under linearly polarized excitation from the valence band of the GaAs-type semiconductors. The electrons created in the conduction band have anisotropic distribution of momenta. Let us first remind the result for the 3D-case [1,2]. For the sake of simplicity, we will use a spherical approximation for the valence band. We will also consider the acceptor wave function as formed mainly from the states of the heavy-hole subband [2]. The calculation of matrix elements of the dipole momentum shows that when excited from the heavy-hole subband, the electrons are created with the momenta $\vec{p}$ directed preferentially perpendicular to the electric vector $\vec{e}$ of the exciting light. The distribution function of these electrons is

$$F(p) = f(p)(p_y^2 + p_z^2), \qquad (1)$$

where f(p) is a spherically symmetric function, the exciting light is directed along Z axis and $\vec{e}$ along X axis.

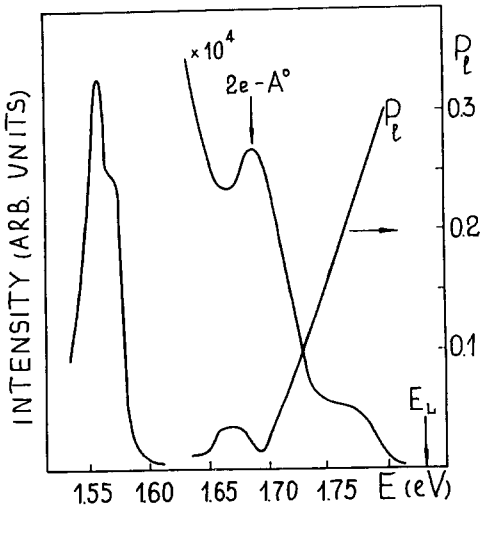

Fig.2. The spectra of photoluminescence intensity and linear polarization for the same structure as in Fig.1. E_{ex} = 1.83 eV. The minimum on P_1 curve is due to contribution of weakly polarized transitions.

A transition probability for recombination has the same matrix elements as for excitation. Consequently the intensity of the radiation polarized along the X and Y axes is respectively

$$I_x \sim \int F(p)(p_y^2 + p_z^2)d\vec{p}, \qquad I_y \sim \int F(p)(p_x^2 + p_z^2)d\vec{p}. \qquad (2)$$

The integration in the 3D-case must be performed in p-space over the angles ϑ and φ (p_x=pSinϑ Cosφ, p_y=pSinϑ Sinφ, p_z=pCosϑ), because to the fixed energy of the recombination quantum corresponds a fixed value of p^2.

Thus, for the recombination from the conduction band into the band of heavy holes or on the acceptor levels it is easy to get the degree of polarization $P_1=(I_x - I_y)/(I_x + I_y) = 1/7$. Note that P_1 does not depend on the energy of the recombining electrons.

In the 2D-case one must take into account a dimensional quantization of electron and hole energies. In a very simplified model, in which the p_z component of the momentum is considered as fixed and is determined by energy E_1 of the bottom of the 1e subband ($p_z^2=2m_cE_1$), the integration in Eq. (2) must be performed only over φ. Then we have for the degree of polarization under the excitation from the subband of heavy holes

$$P_1 = \frac{(E_o/E_1)^2}{8(1+E_o/E_1) + 2(E_o/E_1)^2}, \qquad (3)$$

where the energy of the in-plane motion of the electrons in the point of photocreation is $E_o=(p_x^2 + p_y^2)/2m_c$.

Equation (3) shows that in the 2D-case, contrary to the 3D-one, there exists an essential dependence of P_1 on E_o. P_1 increases from 0 to 0.5 with an increase of E_o. (For electrons excited from the subband of light holes and recombining on the acceptor levels, P_1 changes in the range from 0 to -0.3). Such a dependence of P_1 on E_o results from the fact that at small E_o the electrons are moving nearly normal to the plane of the structure and consequently for the direction of observation along Z their radiation is almost unpolarized. For $E_o \gg E_1$, the movement of the electrons proceeds mainly in-plane and recombination radiation is strongly polarized.

The increase of P_1 with the increasing electron energy E_o, observed in the experiment, is consistent with the presented ideas. For a studied structure,

the value E_o= 60 meV corresponds to E_o/E_1= 1.2 and in accordance with Eq. (3) to P_1= 0.075 (the measured value was P_1= 0.06). The value E_o= 215 meV corresponds to E_o/E_1= 4.3 and the calculated and measured values of P_1 were 0.23 and 0.28 respectively. The minimum on the spectral dependence of P_1 in Fig. 2 is due to the contribution of a weakly polarized transitions from the bottom of the second electron subband (2e - Å).

3. Depolarization in a magnetic field and determination of τ_{po}

The study of the depolarization of hot luminescence in a magnetic field makes it possible to determine characteristic relaxation times of hot electrons [2]. The polarization of recombination luminescence in a magnetic field $\vec{B}$ directed along the light beam (Faraday configuration) is

$$P_1(B)/P_1(0)=(1+4\,\omega_c^2\,\tau_o^2)^{-1}, \qquad (4)$$

where ω_c is the cyclotron frequency, and τ_o is the "life time" of electrons in the point of photocreation E_o. At moderate doping level and pumping density τ_o has the meaning of the LO-phonon emission time τ_{po}. Indeed, the distinct peak "0" observed in the spectrum (Fig.1) confirms that energy relaxation occurs by LO-phonon emission. It follows from $P_1(B)$ measurements at E_o=60 meV (Fig.3) that τ_{po}=150 ± 10 fs. This value agrees with the probability of intraband transitions which was calculated in this work. The applied technique can be used in a wide range of electron energies to study kinetics of intra- and interband transitions in quantum wells. This technique is not influenced by the essentially complicating factors (such as, for instance, phonon heating), which were a reason of large spread in τ_{po} values determined in earlier works on 2D-structures (see, for instance, reviews [3,4]).

4. Luminescence under circularly polarized excitation

We would like to draw attention to some peculiarities of the 2D-case under excitation with circularly polarized light. Let us remind that in the 3D-case in GaAs-type semiconductors the momenta and spins of the electrons created via interband transitions are correlated [1]. The component of the density matrix responsible for the correlation is proportional to $(\vec{\sigma}\vec{p})(\vec{n}\vec{p})$, where $\vec{\sigma}$ are Pauli matrices and $\vec{n}$ is the

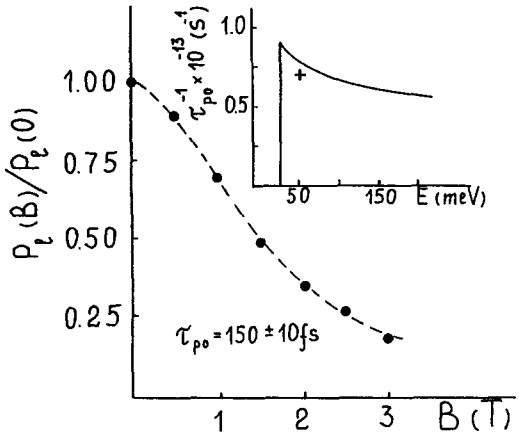

Fig.3. The depolarization of hot photoluminescence in a magnetic field is described by the Lorenz contour (4) with τ_{po}= 150 fs. The calculated energy dependence $\tau_{po}^{-1}(E_o)$ for the studied structure is shown in the right upper corner, the experimental value corresponding to E_o= 60 meV is shown by a cross.

unit vector in the direction of the light beam. Such a correlation does not exist in the 2D-case. This is due to the fact that after averaging over the motion along Z the nondiagonal elements of the matrix $(\vec{\sigma}\vec{p})(\vec{n}\vec{p})$ become zero. A very convincing magnetooptical manifestation of the correlation in the 3d-case is the decrease of circular polarization of the luminescence in a longitudinal magnetic field due to the destroying of the aforementioned correlation [5]. In the 2d-case we did not observe any decrease of circular polarization for magnetic fields as high as 7T, which is a direct evidence of the absence of the correlation.

Let us also attract attention to the dependence of the degree of circular polarization, P_c, on the energy of recombinating electrons. Within the framework of approximation used in p.2 the mean spin of the electrons photoexcited from the subband of heavy holes is

$$S = -\vec{n}(2+E_o/E_1)^{-1}.$$

And the degree of polarization for recombination on the acceptor levels is

$$P_c = -\vec{S}\vec{n} = (2+E_o/E_1)^{-1}.$$

Thus, under excitation close to the bottom of the first electron band the photocreated electrons have com-

pletely oriented spins and P_c=0.5. As E_o increases, the degree of polarization decreases from 0.5 to 0. We have observed the decrease of P_1 from 0.3 at E_o= 60 meV to 0.22 at E_o= 200 meV.

Acknowledgements

The authors would like to thank V.I.Perel for fruitful discussions in the course of this work.

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