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Kinetics of Indirect Electron–Hole Recombination in a Wide Single Quantum Well in a Strong Electric Field

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The kinetics of the indirect recombination of electrons and holes in wide single quantum wells in a strong electric field has been analyzed. It has been shown that the recombination time increases exponentially up to 20 μs due to the spatial separation of oppositely charged particles. The results of a theoretical model predicting the behavior of the recombination time as a function of the applied field are in good agreement with experimental data.

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1. There are very interesting theoretical predictions for phenomena occurring in systems of closely spaced 2D layers of electrons and holes, in particular, the BCS instability of such an object with respect to the transition to the superfluid state [1]. Dissipationless electron and hole currents appearing in neighboring layers are manifestations of superfluidity but with an unusual pairing mechanism based on the Coulomb attraction between oppositely charged particles. To observe such phenomena as superfluidity and superconductivity [1–3], as well as Bose condensation and macroscopic quantum coherence [4, 5], the effective cooling of the objects under investigation to temperatures as low as possible, as well as the creation of high concentrations of electrons and holes, is required. However, sufficient densities of opposite-sign charge carriers in closely spaced layers can be reached only under nonequilibrium conditions in laser photoexcitation; in this case, questions naturally arise concerning the real temperature in the layers and concerning possible overheating of the system, particularly in experiments at very low temperatures of about tens of millikelvin. The problem of the creation and examination of dense electron–hole layers cooled to 50–100 mK can possibly be solved by a method with pulsed photoexcitation, when the study of the system is performed with a time delay after a heating laser pulse. In this case, the nonequilibrium concentrations of electrons and holes are determined by the pumping level, and their thermalization is ensured because the lifetime is much longer than the energy relaxation time. For photoexcited carriers to reach a temperature of about 100 mK, their lifetimes must be 1 μs or longer [6]. The overwhelming majority of investigations of double electron–hole layers were performed for double quantum wells in which the existence of a barrier between the wells in the presence of an electric field makes it possible to reach radiative recombination times up to hundreds of nanoseconds [7, 8]. However, even this increase by two orders of magnitude as compared to the lifetime of the electron and hole in the same layer does not guarantee the necessary cooling. In this work, we show that the creation of electron–hole layers [9] with radiative recombination times of about several tens of microseconds is possible in a wide single quantum well in a strong electric field, which opens prospects for the investigation of such objects at ultralow temperatures.

2. We examined three samples grown by molecular beam epitaxy that contain single undoped quantum wells with widths of 500, 400, and 250 Å. Similar to a structure used in [9], a semitransparent metal deposited on the sample surface is one of the gates and a strongly doped quantum well with a width of 300 or 150 Å is the other gate for the structure with the narrowest undoped well (250 Å) or two other structures, respectively. Pumping is produced by a 780-nm short-pulse Hamamatsu PLP-10 laser with a pulse duration of 1 ns and a repetition rate from 100 kHz to 2 MHz in dependence on the characteristic time of the recombination under investigation. A quartz optical fiber 0.4 mm in diameter is used for the photoexcitation, and another such optical fiber is used to collect the luminescence signal and transfer it to the input of the spectrometer. To analyze the kinetics of the optical signal, a Quantum Leap image intensifier is used; it is placed at the output of the spectrometer in front of a CCD camera and ensures a time resolution of 1 ns. All the experiments are carried out in liquid helium at a temperature of 4.2 K.

3. It is known that the electron–hole recombination time in double layers increases due to a decrease in the overlap of the wavefunctions of recombining particles.

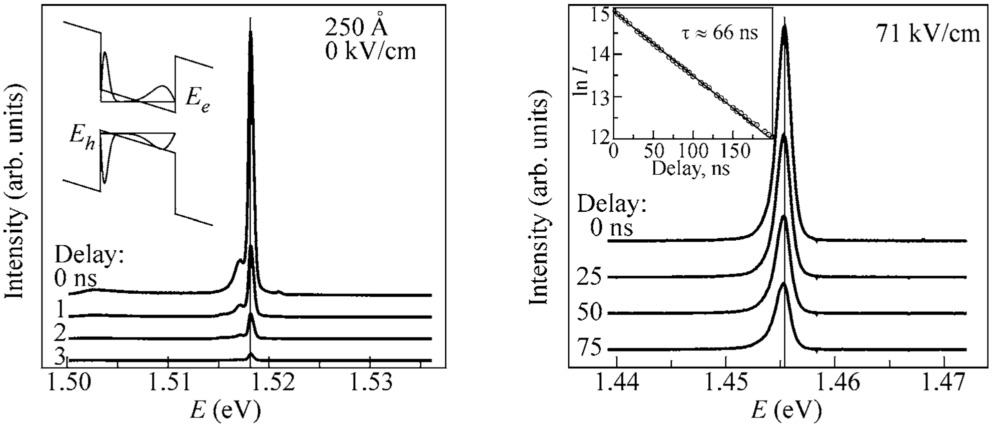

Fig. 1. Luminescence spectra measured in a quantum well 250 Å in width for two strengths of the applied electric field and for various delays after the laser pulse. The scheme illustrates the localization of the wavefunctions of oppositely charged particles near the opposite walls of the quantum well in the external electric field. The inset shows the delay dependence of the integral intensity I of the indirect recombination line.

In the system of double quantum wells, this decrease is primarily ensured by a barrier between the neighboring wells. The spatial separation of the electron and hole in a single quantum well can be ensured by applying the electric field in the direction perpendicular to the well plane (see Fig. 1) [9]. Beginning with a certain field strength E, the electric length $L = \lambda(\hbar^2/2meE)^{1/3}$ corresponding to the distance between the turning points of the trajectory of a classical particle in the triangle potential becomes smaller than the well width (for the hole, this relation is realized for a weaker field than for the electron, because the hole is heavier than the electron). Here, m and e are the mass and charge of the particle, respectively, and $\lambda = 2.338$ is the first zero of the Airy function. With a further increase in the electric field, the localization of the particle near one wall of the well is also enhanced and the wavefunction of the electron or hole is less sensitive to the existence of the other wall. For this reason, the recombining particles in sufficiently strong electric fields can be considered as confined in the z direction in the effectively triangular potential with the infinitely high barrier on one side. The solutions of the Schrödinger equation for this model are well known: the wavefunctions of the particles are Airy functions [10], which decreases exponentially when passing behind the turning point on the "wall" formed by the electric field. Therefore, it should be expected that the overlap of the wavefunctions of the electron and hole in strong fields is exponentially small, which results in an exponential increase in the recombination time. The matrix element of the corresponding radiative transition is expressed in terms of the overlap of the wavefunctions as [11]

$$\Gamma = \Gamma_0(E)\left|\int dz \Psi_e(z)\Psi_h(z)\right|^2.$$

Here, $\Psi_e(z)$ and $\Psi_h(z)$ are the z components of the electron and hole wavefunctions, respectively, and $\Gamma_0(E)$ is the quantity of the appropriate dimension that varies slightly (compared to the leading dependence given by the overlap integral) with the electric field. Therefore, the radiative recombination time is given by the expression

$$\tau = \frac{\tau_0}{\left|\int dz \Psi_e(z)\Psi_h(z)\right|^2}. \quad (1)$$

Taking $m_e = 0.067m$ and $m_h = 0.45m$, where m is the free-electron mass, for the electron and hole masses in the z direction, respectively, we retain only one free parameter τ_0 in this formula; the choice of this parameter does not affect the form of the total dependence. The radiative recombination time τ_0 in the quantum well in the absence of the external electric field was measured in many experiments and discussed in many theoretical works. Experiments yield values from hundreds of picoseconds to one nanosecond [12], whereas theoretical models give values from tens to hundreds of picoseconds [13]. The electron–hole recombination time in the ideal quantum well was predicted to be of about 30 ps [14]. However, the effect of the localization of the particles on various defects caused by fluctuations in the well width or by remote charged impurities increases the calculated lifetime to 100–200 ps in dependence on the localization length, well width, and other input parameters [13]. We emphasize that the above consideration is applicable for describing not only the neutral system of rarefied electron and hole layers but also weakly charged systems.

4. While increasing the strength of the electric field, the luminescence lines from the quantum wells are strongly shifted towards lower energies. The slopes of the electric-field dependences of the recombination energies allow estimation of the dipole moment between the electron and hole and correspond to distances 330 and 240 Å between recombining particles in

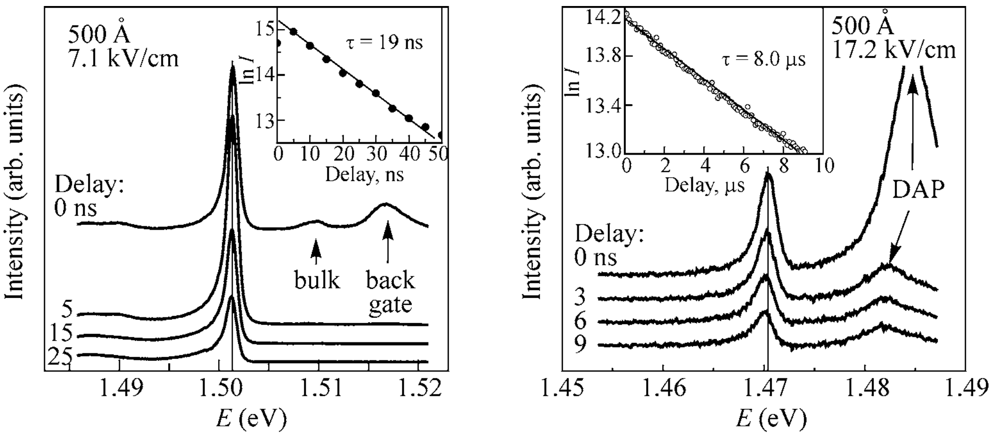

Fig. 2. Luminescence spectra from a quantum well 500 Å in width for two electric field strengths and for various delays after the pump pulse. The luminescence lines from the back gate, as well as bulk and (DAP) donor–acceptor recombination lines, are marked.

the wells 500 and 400 Å in width, respectively, in the fields stronger than 20 kV/cm, and to a distance of about 120 Å for a well width of 250 Å for field strengths higher than 50 kV/cm (see also [9]).

Figures 1 and 2 show experimental spectra from quantum wells 250- and 500-Å wide for several electric field strengths. These spectra are recorded for various time delays from the laser pulse. The indirect electron–hole recombination line is placed in the center of all the figures. The 1.510- and 1.512-eV lines in Fig. 2 refer to the fast (with times of about 1 ns) recombination processes in the bulk of the GaAs sample substrate and recombination in the doped back gate, respectively. The wide 1.485-eV line corresponds to the bulk donor–acceptor recombination (DAP). It is worth noting that, when bands are strongly tilted by the electric field, the energy of the emitted photons decreases slightly by 0.2–0.4 meV in the process of recombination. This shift can be attributed to a change (decrease) in the current flowing through the sample with time owing to which the effective electric field inside the quantum well increases.

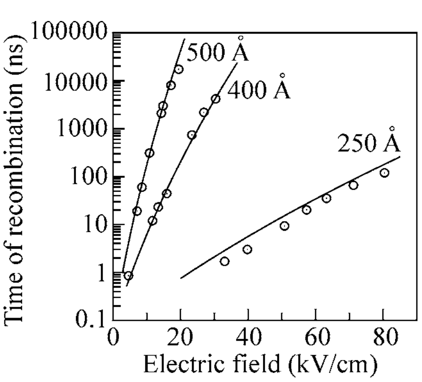

Fig. 3. Recombination time vs. the applied electric field for three samples under investigation. The lines are the predictions of the simplest theoretical model discussed in the paper.

It is worth discussing the monotonic increase (in the process of the increase in the electric field) in the width of the luminescence lines from the narrowest well from the minimum value of 0.4 meV to a value of about 1.5 meV in a field of 70 kV/cm, which is seen in the spectra in Fig. 1. Such a behavior can be attributed either to the nonuniformity of the created electric field along the sample surface, which is responsible for different Stark shifts of the electron and hole energy levels at different points of the structure, or to a change in the dark charge density in the well under variation in the electric field with the transition to the case of charged electron–hole layers [9]. In the latter case, the line width is determined by the Fermi energy of the particles prevailing in the system.

Using the integral intensity of the observed line as a function of the delay from the light pumping instant, one can determine the recombination time as shown in the insets in Figs. 1 and 2. The results of measuring the kinetics of the luminescence in various electric fields for all three samples are shown by points in Fig. 3, where dependences obtained from Eq. (1) with $\tau_0 =$ 150 ps are also presented. We point to the good agreement between the experimental points and the results obtained in the proposed model. As seen, the well 500 Å in width makes it possible to reach recombination times on the order of tens of microseconds even in moderate electric fields of about 20 kV/cm. Owing to such slow kinetics, high concentrations of charge carriers, 10^9–10^{10} cm^{-2}, can be reached for low pumping power densities, and the effective postpulse cooling of the produced electrons and holes to very low lattice temperatures of about tens of millikelvin is ensured.

In addition to the channel of the radiative recombination of electrons and holes, the nonradiative recombination channel can make a certain contribution, whose existence can be a serious obstacle for reaching high concentrations in the electron–hole layers. The contribution of the dark recombination is manifested at long radiation times as a decrease in the integral intensity of the luminescence, when the radiative recombination time becomes longer than the nonradiative loss. In experiments, the integral intensity of the luminescence line for the widest well (under the continuous pumping) begins to noticeably decrease when the electric field strength increases beginning with a value of 14 kV/cm. Since the radiative recombination time in the 500-Å well at 14 kV/cm is equal to 2 μs (see Fig. 3), the estimate of the nonradiative recombination time in the structures under consideration is equal to several microseconds. It is worth noting that this parameter can be controlled and improved: for purer and higher quality structures, the concentration of impurity centers is lower and, thereby, the characteristic time of this process is longer.

In summary, we analyze the dependence of the indirect recombination time in single quantum wells on the applied electric field. The simplest model proposed for this dependence provides good agreement with experimental data. The contribution of the nonradiative recombination channel under consideration has been found, and the characteristic time of this processes in the samples under investigation has been estimated. The possibility of reaching record slow kinetics of radiative processes with times on the order of tens of microseconds has been experimentally shown.

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