Photoluminescence of δ-*p*-doped gallium arsenide

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The mechanisms for radiative recombination in δ-p-doped GaAs have been studied by the method of low-temperature photoluminescence. Intense luminescence lines which have been observed are evidence of a recombination of photoelectrons with holes in quantum-well levels.

The transport and recombination characteristics of semiconductor structures containing δ-doped layers have recently been attracting much interest. Perry *et al.*[1] have studied the recombination of charge carriers in gallium arsenide samples containing single δ-doped layers with an n-type conductivity. They did not observe luminescence lines associated with a radiative recombination of electrons in the two-dimensional potential well of the δ-layer. The effect of the δ doping was manifested in a deformation of the lines of bulk exciton recombination upon the application of a strong magnetic field. In contrast with those previous results, the results which we are reporting in the present letter reveal some new and intense lines in the luminescence spectra of δ-p-doped gallium arsenide. These new lines are apparently associated with a radiative recombination involving holes in levels of the quantum-well potential of the δ-layer.

The test samples were grown by molecular-beam epitaxy on semi-insulating GaAs (110) substrates at a rate of 1 μm/h at 480 °C. The samples were of epitaxial gallium arsenide, not deliberately doped [the carrier density was $p_{77\mathrm{K}} \approx (N_A - N_D) \lesssim 1\times10^{13}$ cm^{-3}]. In this gallium arsenide, a beryllium-doped layer was formed by the interrupted-growth method. The hole density per unit surface area was $p_{77\mathrm{K}} \approx 1.3\times10^{13}$ cm^{-2}. The photoluminescence was excited by a helium-neon laser. The luminescence spectra were measured at a temperature of 2.2 K by a photomultiplier with an S-1 photocathode operating in the photon-counting mode.

Figure 1a shows photoluminescence spectra measured at various excitation intensities for a sample containing a single δ-doped layer. In the spectra we see a line (A) whose energy position is the same as that of the lines of exciton recombination in the bulk material. There are also some intense lines B and C and an extended long-wavelength tail. An increase in the excitation intensity results in an increase in the relative intensity of line A and a change in the relation between the intensities of lines B and C. The shape and relative intensity of the long-wavelength tail are essentially independent of the degree of excitation. Lines B and C (1.440–1.485 eV) dominate the spectra. These lines are not observed in the photoluminescence spectra of samples which do not contain δ-p layers. The spectra in the energy interval 1.40–1.50 eV in Fig. 1b are shown in normalized form. With increasing excitation intensity, lines B and C shift in the short-wavelength direction (the shift is approximately logarithmic in the intensi-

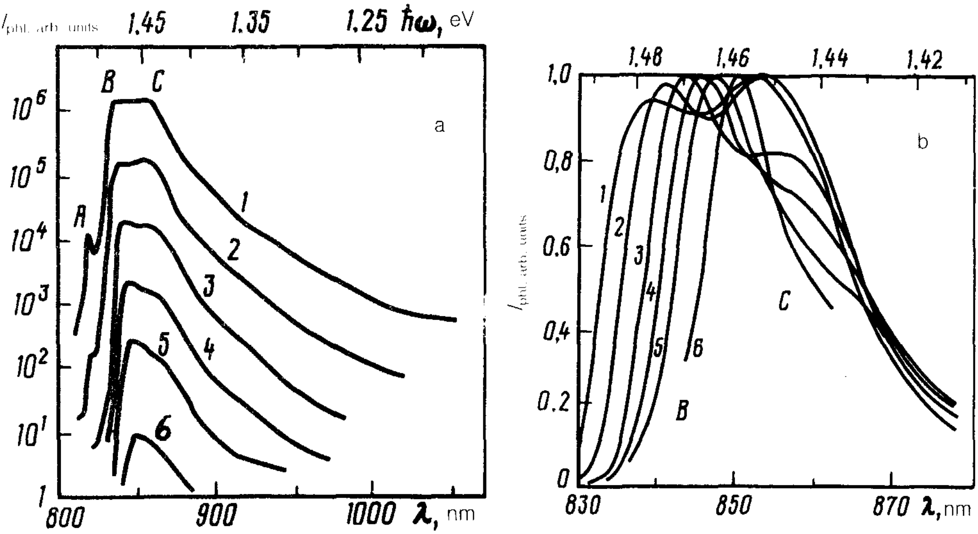

FIG. 1. a,b: Luminescence spectra of a sample with a single δ-p-doped layer at different photoexcitation intensities I/I_0: Curve 1–1.0; 2–10^{-1}; 3–10^{-2}; 4–10^{-3}; 5–10^{-4}; 6–10^{-5} ($I_0 \approx 20$ W/cm^2).

ty), and there is a simultaneous intensification of the luminescence in long-wavelength line *C*.

We will interpret these experimental results in a qualitative model based on the assumption that a tunneling mechanism is predominant for the radiative recombination of geometrically separated photoelectrons and holes in this structure. The energy diagram in Fig. 2 explains our model. Here the electric field of the hole potential well created by the heavily doped δ layer leads to a spatial separation of the holes which are occupying two quantum-well levels in the potential well from the thermalized photoelectrons. As a result, the carriers must tunnel through a potential barrier if recombination is to occur. Since the probability for recombination is low (in comparison with the bulk material), the steady-state electron density is comparatively high, and there is

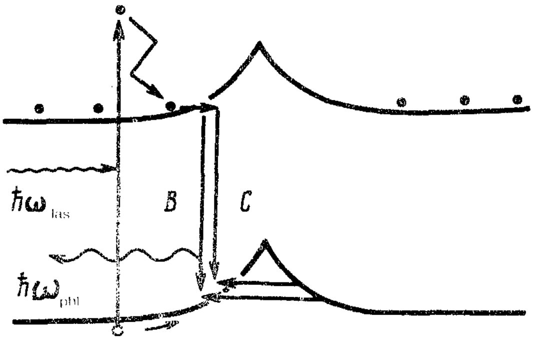

FIG. 2. Model energy diagram of the structure in the excited state, used in explaining the mechanisms for carrier recombination. The straight arrows represent generation and recombination transitions and also the thermalization of carriers; the wavy lines represent excitation and luminescence photons.

little band curvature in the interior of the structure. An increase in the level of photoexcitation leads to a narrowing of the well and an expulsion of the hole levels from it, by increasing the degree to which free carriers screen the well potential. At the same time, the decrease in the distance between the electrons and the holes leads to an increase in the relative probability for the recombination of electrons with holes in the low-energy level. This effect causes a short-wavelength shift of lines *B* and *C* and an increase in the relative intensity of line *C* with increasing degree of excitation. In this model, the high efficiency for radiative recombination of spatially separated carriers in the case of δ-*p* doping is explained on the basis that the potential well for holes is narrow in comparison with the well for the electrons in δ-*n* doped samples. Likely mechanisms for the large width (about 15 meV) of lines *B* and *C* are fluctuations in the dimensions of the potential well and in the positions of the hole levels in the well over the area of the sample, because of statistical fluctuations in the density of holes or fluctuations of the diffusive displacement of impurity atoms away from the δ-doped plane. Another possibility is the occurrence of recombination transitions in which quasimomentum is not conserved.

Another important distinction between the photoluminescence spectra in Fig. 1 and those of spatially homogeneous samples is the long-wavelength tail. The reason for the appearance of the tail is not clear at this point, but in our opinion the most likely mechanisms for the appearance of wide long-wavelength tails in the spectra are the recombination of electrons with holes in the state-density tails of the δ-layer and radiative recombination of carriers through deep levels of beryllium complexes—point lattice defects.[2]

In summary, we have reported the observation of some new lines in the luminescence spectra of δ-*p*-doped gallium arsenide. These new lines are evidence of a radiative recombination of photoelectrons with holes in quantum-well levels of the potential of the doped layer.

[1] C. H. Perry *et al.*, Surf. Sci. **196**, 677 (1988).
[2] K. S. Zhuravlev *et al.*, in: *Proceedings of the Seventh All-Union Conference on Crystal Growth*, Vol. 4, 1988, p. 45.

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