Radiative recombination at a heterojunction

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A new mechanism for radiative recombination at a heterojunction has been found. This mechanism results from transitions from donors in the narrow-gap material to acceptor-like surface states. The basic characteristics of the photoluminescence band associated with this process, such as the large (15-meV) energy shift with an increase in the excitation intensity, the exponential dependence of the radiative lifetime on the spectral position, and the anomalous behavior in a magnetic field, are determined by tunneling recombination of donor-acceptor pairs at the heterojunction.

The low-temperature (1.6-K) photoluminescence of *p-p* (same-type) GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunctions has been studied. The heterojunctions were grown by molecular-beam epitaxy with a residual impurity concentration of 1×10^{15} cm^{-3} in the GaAs and 2×10^{16} cm^{-3} in the $Al_{0.3}Ga_{0.7}As$ (Ref. 1). As the excitation intensity is raised, we observe a short-wave shift of the new photoluminescence band which belongs to the heterojunction[1,2] (the *M* band). This band lies in a spectral region between the emission lines of bound excitons and donor-acceptor pairs from the interior of the GaAs (see the inset in Fig. 1). Yuan *et al.*[2] have attributed this shift to a change in the position of the Fermi quasilevel of the free carriers which collect in a potential well near the heterojunction.

Measurements of the kinetics of the photoluminescence in the *M* band revealed two regions of a decay of the emission: an exponential region ($\tau\sim1$ μs) and a power-law region ($\tau\sim100$ μs). A kinetics of this sort is characteristic of tunneling recombination of carriers which are localized at spatially separate impurity centers. Analysis of the initial parts of the photoluminescence decay showed that there is a characteristic

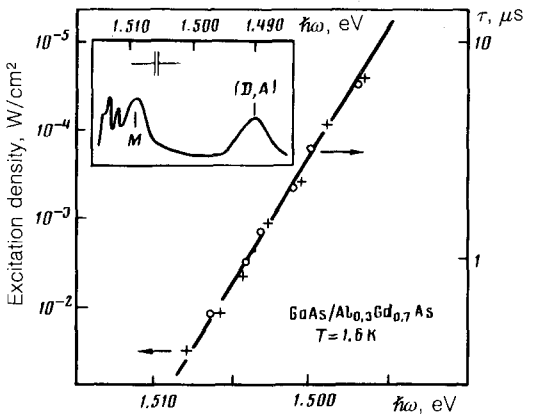

FIG. 1. +—Spectral position of the *M* band versus the excitation density; O—radiative lifetime versus the energy of the emitted photon. Inset: Photoluminescence spectrum of a *p-p* (same-type) GaAs-$Al_{0.3}Ga_{0.7}As$ heterojunction.

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emission time corresponding to each energy in the interval in which the band is seen. This characteristic time falls off exponentially with increasing energy of the emitted photon (Fig. 1). This dependence corresponds to an increase in the probability for radiative recombination of donor-acceptor pairs with decreasing distance between impurity centers. The maximum of the volume emission band of the donor-acceptor pairs shifts a few millielectron volts because of an increase in the Coulomb interaction between centers. The primary reason for the large spectral shift (15 MeV) of the M band is the energy spectrum of the acceptor-like surface states at the heterojunction. We suggest that the spectrum is formed by charged centers in the wide-gap material near the heterojunction. Such centers attract carriers from the narrow-gap material to the heterojunction and form a broad spectrum of bound states, whose energy is determined by the distance from the centers to the interface. This assumption regarding the nature of the localized states is supported by the fact that the energy interval in which the M band is seen is essentially independent of the band gap and the nature of the heterojunction (in slightly doped structures). This band has been observed for p-p, n-n, and p-n heterojunctions over a broad range of the composition of the solid solution.[2] Extrapolation of the plot of the spectral position of the band peak, M, to an extremely low excitation intensity yields an energy $\hbar\omega = 1.492$ eV, which corresponds to photoluminescence of volume donor-acceptor pairs involving a residual carbon impurity. The same impurity, but at the heterojunctions, is manifested in the photoluminescence of structures with quantum wells[3] grown under the same conditions as for the heterojunctions studied here.

The probability for tunneling recombination of donor-acceptor pairs at the heterojunction is proportional to the overlap integral of the wave functions of the electron and hole:

$$W = |\int d^3r \varphi_e(r)\varphi_h(r)|^2 . \qquad (1)$$

This integral is determined to an exponential accuracy by the donor wave function at the position of the acceptor: $W \sim \exp(-2r/a_0)$, where $r = |r_A - r_D|$, and r_D and r_A are the coordinates of the donor and the acceptor, and a_0 is the Bohr radius of the donor. The tunneling length is $r = \sqrt{\rho^2 + l^2}$, where l is the distance from the donor to the heterojunction, and $\rho = \rho_A - \rho_D$ is the projection of the donor-acceptor separation onto the plane of the heterojunction. As the states are filled, there is a decrease in $\bar{\rho}(E) \sim N_s^{-1/2}(E)$, where N_s is the density of filled surface states, and E is the energy up to which these states are filled. The decrease in the tunneling length with increasing excitation level determines the exponential decay of the radiative lifetime and the energy shift of the M band (Fig. 1). The slowing of the energy shift observed at $\hbar\omega > 1.510$ eV corresponds to a delocalization of hole states determined by the condition $N_s(E)a_h^2(E) \sim 1$, where $a_h(E)$ is the radius of a surface state.

To test this model for tunneling recombination at a heterojunction, we studied the behavior of the M band in a magnetic field directed perpendicular to the heterojunction. The first point we notice (Fig. 2a) is that the rate at which the band shifts decreases with increasing magnetic field. This behavior cannot be described by means of diamagnetic shifts of donor and acceptor-like states, which increase with increasing magnetic field. Furthermore, the magnitude of the shift decreases with increasing excitation energy. This behavior of the M band can be linked with a rearrangement

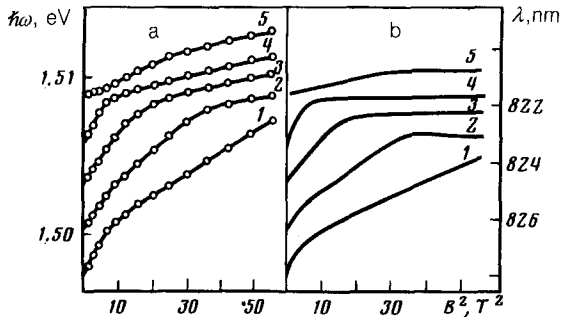

FIG. 2. Energy position of the M band versus the square magnetic field B^2 at various excitation levels (W/cm^2): 1—6×10^{-5}; 2—2×10^{-4}; 3—2×10^{-3}; 4—10^{-2}; 5—8×10^{-2}. a: Total band shift. b: The shift of the volume donor in the magnetic field has been subtracted. The magnetic field is directed along the normal to the heterojunction: $B\|z$.

(filling) of acceptor-like surfaces states in the magnetic field. By reducing the probability for tunneling in the plane of the heterojunction during steady-state excitation, a magnetic field causes a further filling of states, in such a way that the radiative lifetime is preserved through a decrease in $\bar{\rho}(E)$.

In strong fields, where the shifts of the band peak of the various excitation levels become similar, these shifts can be described highly accurately in terms of a change in the energy of a donor—the center with the lower binding energy—in a magnetic field. Figure 2(b) shows this behavior as a function of the square magnetic field B^2 after subtraction of the shift of the donor energy. We see three characteristic regions with different slopes along the B^2 scale. In the maximum fields, for all the excitation levels, the shift of the M band is determined by the change in the energy of a volume donor in GaAs. For a quantitative analysis of the first two regions, we consider how the overlap integral changes because of a change in the donor wave function in a magnetic field:

$$W_B \sim \exp\left(-\frac{2r}{a_0} - \frac{\rho^2 r a_0}{12L^4}\right), \tag{2}$$

where the magnetic length is $L = (\cosh/Eb)^{1/2}$. At low excitation levels, where the filling of acceptor-like surface states is slight ($\bar{\rho} \gg l$), the second term in the exponential function can be written $\rho^3 a_0/12L^4$. In this case, the tunneling occurs primarily in the plane of the heterojunction, determining the large energy shift $\sim\rho^3$ in the initial region. With increasing excitation density, or with increasing magnetic field, $\bar{\rho}(E)$ decreases, causing a decrease in the slope of the first region, and it reaches values $\bar{\rho} \lesssim l$ (for $B = 0$, curve 3 in Fig. 2b). This is the condition for a transition to the central region, where the tunneling in the plane of the heterojunction, regulated by the magnetic field, is now an increment with respect to hopping along the normal to the heterojunction. The energy shift due to the change in terms of localized states ceases, as in the case $B = 0$, when the condition $N_s(E)a_h^2(E) \sim 1$. is satisfied. At high excitation levels, the shift of the M band is again of a diamagnetic nature (curve 5, Fig. 2, a and b), since a magnetic field $B\|z$ does not affect the probability for impurity-channel tunneling. A conductivity along the heterojunction is observed at these excitation densities.

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