Electron localization at a heterojunction of the second kind

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A localization of photoelectrons has been observed in a 2D potential well at a heterojunction of the second kind in the *p*-GaInAsSb–*p*-GaSb system. The localization energy of the electrons in the well is shown to be determined by the level of doping of the narrow-gap layer; specifically, the localization energy increases with decreasing doping level. The filling of the well depends in a nonmonotonic way on the temperature, going through a maximum at 20–50 K. An external magnetic field directed parallel to the heterojunction strongly affects the filling of the wells.

In semiconductor structures which have a heterojunction of the second kind, the discontinuities in the conduction and valence bands have the same sign. The result is an unusual situation, in which self-consistent potential wells which localize carriers of different signs arise on the two sides of the heterojunction. In other words, the heterojunction separates the electrons and the holes. Figure 1 shows an energy diagram of a heterojunction of this sort, specifically, for an isotypical *p-p* heterojunction. The depth of the wells which arise is determined by the discontinuities in the energy bands (in this case, the valence band) and may exceed kT by a large factor. In structures with a fairly sharp heterojunction, such wells should be effective channels for the collection and recombination of nonequilibrium carriers.

In the present letter we report the first observation of a localization and a recombination of electrons in a 2D potential well at a heterojunction of the second kind, specifically, in a p-$Ga_{0.8}In_{0.2}As_{0.18}Sb_{0.82}$–$p$-GaSb structure. The structures are fabricated by liquid-phase epitaxy of layers of *p*-GaInAsSb, doped to different levels with an acceptor dopant (germanium), on an undoped *p*-GaSb(111)*B* substrate. The concentration of intrinsic acceptors in the *p*-GaSb is 2×10^{17} cm^{-3}, and the doping level of the GaInAsSb layer varies over the range $p = 10^{17}$–10^{18} cm^{-3}. The structures are excited on the side of the GaInAsSb layer, which has a thickness of 1.5 μm, by the line from a He-Ne laser with a photon energy of 0.815 eV.

Figure 2, a and b, shows luminescence spectra of structures with different doping levels of the GaInAsSb layer. At the doping levels selected, the shallow-acceptor states of germanium are degenerate and merge with the valence band. In the spectra we should accordingly expect to find only a single band, corresponding to interband transitions in the narrow-gap GaInAsSb layer. Actually, the spectrum reveals another band, at a lower energy, in addition to interband spectral band A. With increasing excitation density, the shift of the new band with respect to band A decreases. These circumstances allow us to link the origin of the new band with a localization of photoelectrons in a potential well at the heterojunction. The 2D nature which we find in this

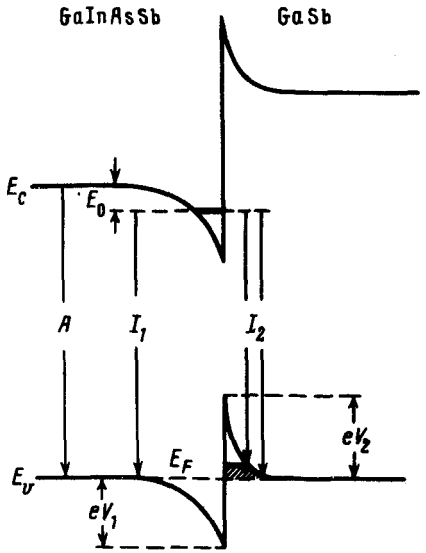

FIG. 1. Diagram of the energy bands and of the recombination transitions at a heterojunction of the second kind in an isotypical *p-p* heterostructure.

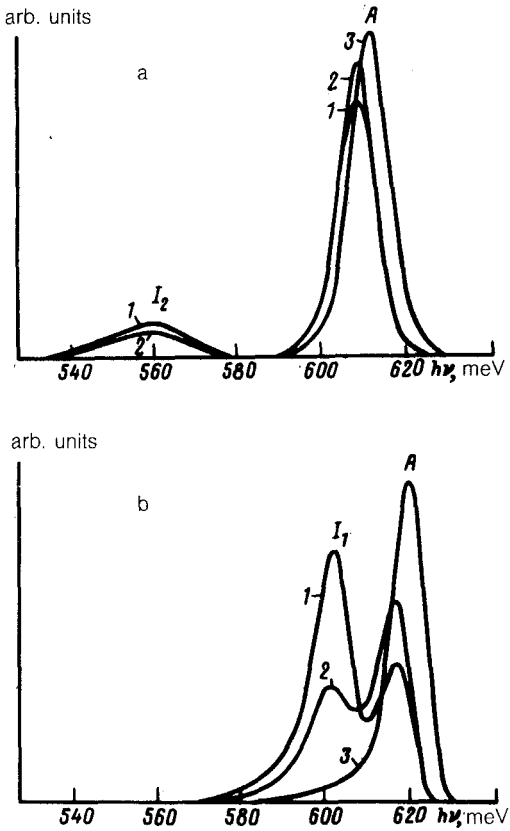

FIG. 2. Luminescence spectra at 4.2 K of *p*-$Ga_{0.8}In_{0.2}As_{0.18}Sb_{0.82}$–*p*-GaSb structures with two doping levels of the GaInAsSb layer. a: $p = 1\times10^{17}$ cm^{-3}. b: 8×10^{17} cm^{-3}. 1—In the absence of a magnetic field; 2—$B = 0.3$ T; 3—$B = 3$ T. The excitation density is 10 mW/cm^2.

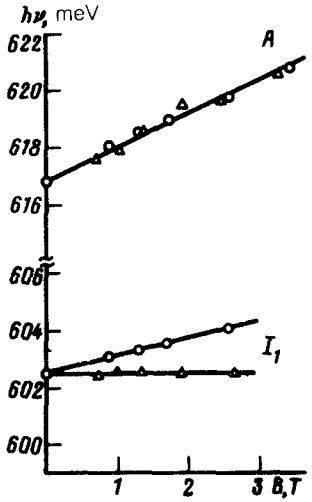

FIG. 3. Shift of the luminescence bands in the spectrum in Fig. 2b when a magnetic field is imposed. ○—The field is directed perpendicular to the heterojunction; △—parallel to the heterojunction.

case for the electron states was confirmed directly by experiments in an external magnetic field. It was found that the shift of the maximum of the new band in a field depends strongly on the orientation of the field with respect to the heterojunction (Fig. 3). In the case of a perpendicular orientation, the maximum of the band shifts up the energy scale in a manner linear in the field; in the case of a parallel orientation, on the other hand, we observe no significant shift. The maximum of band A, on the other hand, undergoes an identical and large shift for the two orientations of the field.

Further evidence for a localization of electrons in a well at the heterojunction comes from the observed suppression of the new band by a magnetic field directed parallel to the heterojunction (Fig. 2, a and b). The disappearance of the new band is accompanied by a corresponding buildup of bulk band A. We attribute the observed effect to a slowing of the diffusion of electrons toward the heterojunction in a magnetic field; this slowing reduces the filling of the well near the junction and correspondingly increases the density of electrons in the interior of the GaInAsSb layer. The importance of the diffusive influx of electrons for increasing the filling of the well is seen directly in the temperature dependence of the intensity of the new band. As the temperature is raised from 2 K to 20–50 K, the new band intensifies by a factor of several units, while the intensity of band A falls off. The intensification of the new band can be explained in a natural way in terms of an increase in the mobility and thus the diffusion length of the electrons with the temperature. At high temperatures, the intensity of the new band also begins to fall off.

We have estimated the localization energy of the electrons in the potential well near the junction. A charged double layer forms at the boundary of the isotypical p-p structure which we studied. This double layer consists of a quasi-2D layer of holes, on the GaSb side, and a region of an acceptor space charge in the GaInAsSb layer. Working from the constancy of the Fermi level, and assuming that the distance from the Fermi level to the edge of the valence band is much smaller than the discontinuity

in the valence band, Δ (we assumed $\Delta = 0.15$ eV in accordance with Ref. 1), we find

$$eV_1 + eV_2 = \Delta,$$

$$eV_2 = 2.36 \left(\frac{\hbar^2}{2m_h}\right)^{1/3} \left(\frac{4\pi e^2}{\epsilon_1} \sqrt{\frac{\epsilon_1 V_1}{2\pi e}}\, p\right)^{2/3}. \quad (1)$$

Here eV_2 is the part of the surface band curvature which occurs in the GaSb. It was calculated by a variation method in the Hartree approximation.[2] The quantity eV_1 is the part of the surface band curvature which corresponds to the space-charge region in the GaInAsSb layer. Solving Eqs. (1), taking the required parameter values from Ref. 3, we find eV_1, which is the depth of the potential well for electrons in the GaInAsSb layer. The position of the quantum level for electrons in the well, E_0, is found through a numerical solution of the Schrödinger equation. In this manner we find the energy shift of the new band with respect to interband transitions in the interior of the GaInAsSb layer. In particular, with $p = 1\times10^{17}$ cm^{-3} and 8×10^{17} cm^{-3} we find estimates of 50 and 10 meV, respectively, for E_0, in close agreement with the shifts seen experimentally (Fig. 2, a and b). Our calculation leads to the important qualitative conclusion that the potential well for the electrons becomes broader and deeper as the doping level of the narrow-gap layer is reduced and as the localization of electrons in well correspondingly becomes more pronounced.

The electrons which are localized at a heterojunction of the second kind are capable of recombining with holes on both sides of the junction (Fig. 1). A recombination with holes in the interior of the narrow-gap layer (transitions I_1) is more probable when the layer is heavily doped, since in this case (first) there is an increase in the number of holes, and (second) there is a decrease in the depth of the electron level in the well. Correspondingly, the electron wave function penetrates further into the layer. The lowering of the doping layer should lead to a predominance of the recombination of electrons with holes localized in the self-consistent well on the other side of the heterojunction (transitions I_2). We believe that the spectra in Fig. 2, a and b, correspond to these two different cases. In Fig. 2b the new band and band A have the same half-width and the same shape, as they should in the case of transitions I_1. In Fig. 2a, the new band is twice as wide as band A, possibly because of a wider energy distribution of the localized holes, which is manifested in the case of transitions I_2.

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