Electron localization by reflection from a heterojunction

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The above-barrier reflection of electrons near heterojunctions gives rise to quasilocal states with a typical lifetime of 10^{-11}–10^{-9} s. An interfacial photoluminescence line due to these quasilocal states has been observed in InAs–InAsPSb heterostructures.

Progress in advanced semiconductor technology, which has now made it possible to grow layers of atomic scale, has stimulated the development of the physics of two-dimensional structures. The electronic properties of these structures are determined to a large extent by the spatial quantization of the charge carriers. We would like to call attention to the possibility that quasilocal states could arise (and could be observed) in semiconductor heterostructures as a result of a reflection of electrons from the heterojunction.

As a quantum-mechanical particle moves above a potential barrier, it undergoes reflection from the boundary of the barrier. The reflection coefficient may be large $(1-\epsilon/\Delta)$ if the energy of the particle above the barrier, ϵ, is small in comparison with the barrier height Δ. Under certain conditions, this reflection results in a localization of the current carriers near the heterojunction.

Let us consider the electron states in the potential well shown in Fig. 1a. A narrow step of thickness L and height Δ (layer 1) is bounded on the left by an infinitely high potential barrier. A potential well of this sort is easily arranged in quantum heterostructures.

The energy spectrum of the electrons in layer 1 can be found by solving the Schrödinger equation for the free electron with the boundary conditions

$$\Psi\Big|_{x=-L}=0, \qquad \frac{\Psi'(x)}{\Psi(x)}\Big|_{x=0}=i\chi\ . \tag{1}$$

The condition at $x=0$ corresponds to a constant flux across the boundary. The coefficient χ (which generally depends on the energy of the electrons) is directly related to the reflection coefficient of the boundary. If the electrons have a simple parabolic dispersion law, and if the kinetic energy ϵ of a carrier in layer 1 is small in comparison with the barrier height Δ, we have $\chi\simeq\sqrt{2m\Delta}/\hbar$.

A solution of the Schrödinger equation shows that quasilocal states with a complex energy $\epsilon_n=E_n-i\Gamma_n$ arise in this case. In the lowest approximation in the parameter E/Δ, the positions of the corresponding levels are precisely the same as the positions of the energy levels in a potential well of width L with infinitely high walls:

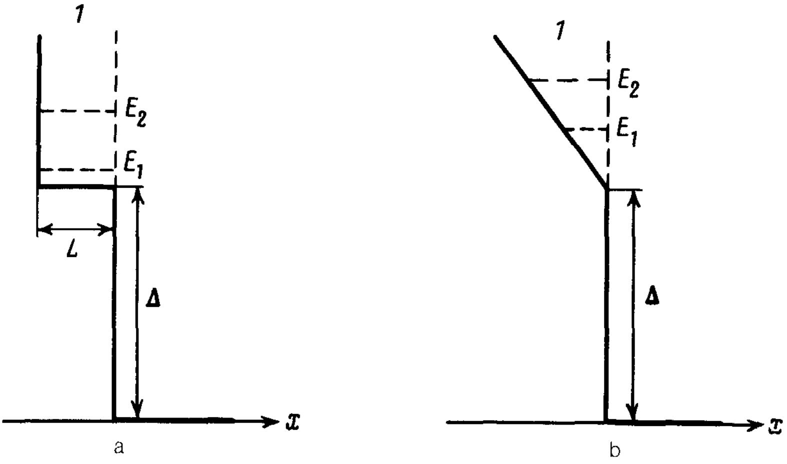

FIG. 1. Potentials of (a) square and (b) triangular barriers at a heterojunction.

$$E_n = \frac{\hbar^2\pi^2}{2mL^2}n^2, \quad \text{where } n = 1,2,3\ldots. \tag{2}$$

The decay of level n is determined by

$$\Gamma_n \simeq E_n\frac{2}{\pi n}\left(\frac{E_n}{\Delta}\right)^{1/2} = E_n\frac{2}{L\chi}. \tag{3}$$

Here we have $\Gamma_n \ll E_n$ as long as the level energy is small in comparison with the barrier height Δ.

Corresponding states arise in the case of a triangular potential $U(x) = \Delta - e\mathscr{E}x$ (Fig. 1b). A potential of this sort can serve as a model of the case which actually arises in varigap structures, at a boundary in heterojunctions, and in quantum-well systems upon the imposition of an electric field. In this case, with strong reflection, the energy of the quasilocal states is described by

$$\epsilon_n = \left(\frac{\hbar^2e^2\mathcal{E}^2}{2m}\right)^{1/3}\alpha_n - i\left(\frac{\hbar^2e^2\mathcal{E}^2}{2m\Delta}\right)^{1/2}, \tag{4}$$

where α_n are the roots of the Airy function. These roots are given quite accurately by the asymptotic expression

$$\alpha_n \simeq \left(\frac{3\pi}{2}(n + \frac{3}{4})\right)^{2/3}, \quad \text{where } n = 0,1,2\ldots. \tag{5}$$

The decay does not depend on the index of the level.

The situation that arises is completely analogous to one in the realm of optics: a Fabry–Perot interferometer with a quality factor $Q \sim E_n/\Gamma_n$. In this case the quality factor determines the accumulation of particles in the "quasiwell," i.e., the average number of particle-reflection events which occur before the particle crosses the boundary. If the reflection of a particle from the boundary is sufficiently strong, the electron lifetime in the quasilevel, $\tau \simeq \hbar/\Gamma$, may become comparable to the time scales of the radiative and radiationless transitions in semiconductor structures. One might therefore expect that corresponding quasilocal states should be manifested in single heterojunctions and also in multilayer semiconductor laser structures with an accumulation of current carriers.

In III–V semiconductors, the electron wave function in the conduction band is a hybrid of S and P wave functions, and the dispersion is not parabolic. These circumstances simply increase the reflection coefficient at the heterojunction.

A convenient device for observing these quasilocal states would be a *P–p* heterostructure of the first type, with the energy diagram shown in Fig. 2. The photoluminescence spectrum of such a heterostructure should exhibit an interface line between the luminescence lines of the narrow-gap and wide-gap regions.

Indeed, we have observed a corresponding line (Fig. 3) in the photoluminescence spectrum of a *P*-InAsPSb/*p*-InAs heterostructure during pumping by a neodymium laser from the side of the wide-gap region. With increasing excitation intensity, this new line shifts to a higher energy.

To explain the experimental results, we note that the curvature of the conduction band of the *P*-InAsPSb layer near the heterostructure gives rise to quasisteady energy levels (Fig. 1). As the nonequilibrium electrons diffuse toward the heterojunction, they accumulate in the lower quasisteady level, and the interface line that arises is a consequence of a recombination of these electrons with holes which have accumulated near the heterojunction on the side of the narrow-gap region (Fig. 2).

In the approximation of a triangular potential, the energy of the zeroth level of

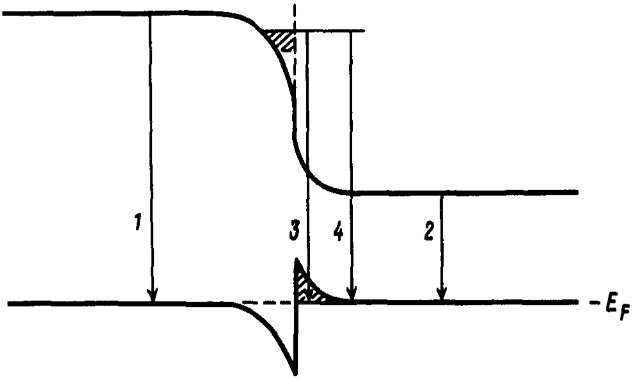

FIG. 2. Energy diagram of a *P–p* heterostructure of the first type. Here E_F is the Fermi level of the holes at equilibrium. *1–4*—Radiative transitions in the volume and at the heterojunction. Holes in the quantum level in the enrichment region and electrons in the depletion region near the heterojunction are shown schematically.

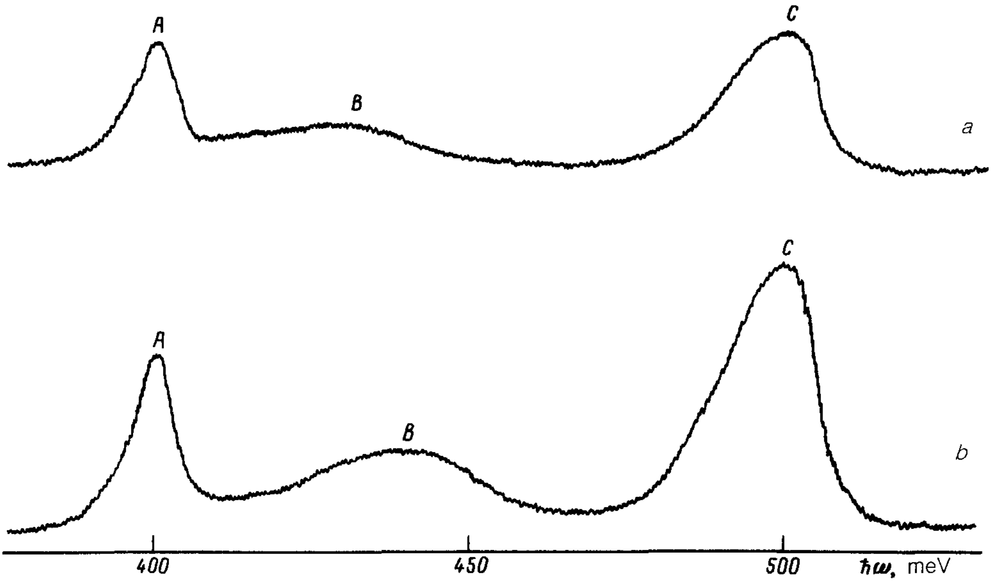

FIG. 3. Photoluminescence spectra of an $InAs_{0.63}P_{0.25}Sb_{0.12}$/InAs *P–p* heterostructure at two excitation levels. The pump intensity for spectrum *a* is half that for spectrum *b*.

the electron is $E_0 \sim (N_A eV_0)^{1/3}$, where eV_0 is the energy corresponding to the curvature of the conduction band (i.e., the depth of the well), and N_A is the concentration of acceptors in the *P*-InAsPSb layer. For our structure we have $eV_0 \sim 50$–35 meV (this value is calculated from the known formulas from the theory of heterojunctions) and $E_0 \sim 25$–40 meV (with N_A between 10^{16} and 10^{17} cm^{-3}).

The accumulation of electrons in a quasiwell affects the shape of the potential, as

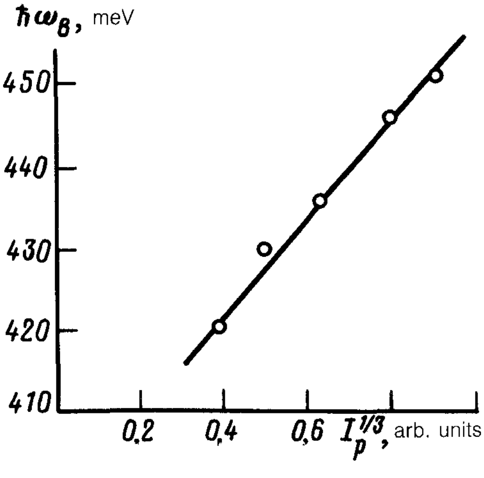

FIG. 4. Shift of the interface luminescence line versus the excitation level. The points are experimental data.

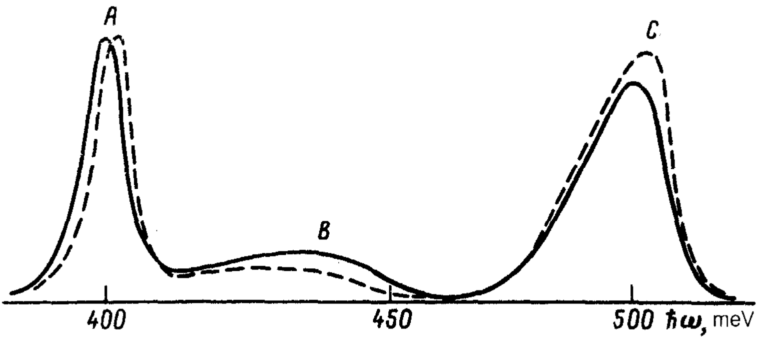

FIG. 5. Luminescence spectra of a P-InAsPSb/p-InAs heterostructure (dashed line) in a magnetic field $H \approx 3.5$ kOe parallel to the heterojunction and (solid line) without a magnetic field.

does an increase in the acceptor concentration N_A. The shift of the quasilocal level E_0 and thus of the position of the luminescence line with increasing pump intensity I_p should thus obey an $I_p^{1/3}$ law. Figure 4 shows experimental data on the position of the interface luminescence line; the independent variable here is $I_p^{1/3}$. We see that the position of the line does indeed shift in accordance with the expectations.

We know that the imposition of a magnetic field parallel to a heterojunction reduces the diffusion coefficient for nonequilibrium electrons, i.e., reduces the buildup of electrons in the well at the heterojunction. In a magnetic field one should thus observe (1) an increase in the intensity of the bulk line of the wide-gap material and (2) a decrease in the intensity of the interface line and a shift of this line toward lower energies. Indeed, the luminescence spectrum recorded in a magnetic field $H \approx 3.5$ kOe (Fig. 5) reveals all these features.

In summary, these experimental results confirm that quasisteady states exist at a p-InAs/P-InAsPSb heterojunction as a result of above-barrier reflection.

These quasilocal states may hold promise for the development of new types of fast optoelectronic devices.

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