Photoluminescence of $(\mathrm{InAs})_n(\mathrm{GaAs})_m$ superlattices under stress

A. V. Braslavets, K. S. Zhuravlev, N. T. Moshegov, A. I. Toropov, and S. I. Stenin
Institute of Semiconductor Physics, Academy of Sciences of the USSR, Siberian Branch, 630090, Novosibirsk

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A study of the photoluminescence of $(\mathrm{InAs})_n(\mathrm{GaAs})_m$ superlattices reveals that its intensity may be substantially higher than that of GaAs in the barriers. A mechanism of carrier trapping in quantum wells is proposed. The transition from the case of noninteracting quantum wells to superlattices as the barrier thickness is varied is analyzed. A polarized photoluminescence of $(\mathrm{InAs})_n(\mathrm{GaAs})_m$ superlattices under stress has been observed.

Superlattices under stress are of research interest and hold promise for practical applications.

We have studied the low-temperature photoluminescence (at $T=4$ K) of $(\mathrm{InAs})_n(\mathrm{GaAs})_m$ superlattices with $n=2$ and $m=8$, 10, 20, and 40 on GaAs (001) substrates. The total number of pairs of layers ranged from 25 to 40. The structures were grown by molecular beam epitaxy.[1]

Figure 1a shows photoluminescence spectra of structures with various barrier thicknesses. The positions of a line which we link with optical transitions between quantum levels in the superlattice are marked. A similar line has been observed in a single quantum well.[2] As the barrier thickness is reduced, this line shifts to lower energies. The position of this line (at $T=77$ K) is shown in Fig. 1b as a function of the In concentration in the solid solution, on the average over the superlattice; also shown is E_g versus x for $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ (Ref. 3). In contrast with the results of Ref. 4, where a study was made of the photoluminescence of $(\mathrm{InAs})_n(\mathrm{GaAs})_m$ superlattices on InP substrates, this line cannot be attributed to an $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{As}$ solid solution.

The high intensity of the photoluminescence, even in single narrow quantum wells, and the behavior of the ratio of the photoluminescence intensity of the quantum wells and the edge photoluminescence intensity of GaAs as a function of the barrier thickness are rather unusual. We believe that the explanation lies in the following features of the energy and momentum relaxation of the photoproduced carriers. For simplicity we will conduct the discussion for the case of electrons, but the discussion also applies to holes, with appropriate changes for the masses and level positions. At low temperatures, the photoproduced electrons in GaAs, after emitting a finite number of LO phonons (the emission time is 10^{-13} s), enter a passive region, where their energy is lower than the energy of an LO phonon (Ω). The electrons then undergo a slow relaxation, emitting acoustic phonons (the emission time is 10^{-8} s). They may

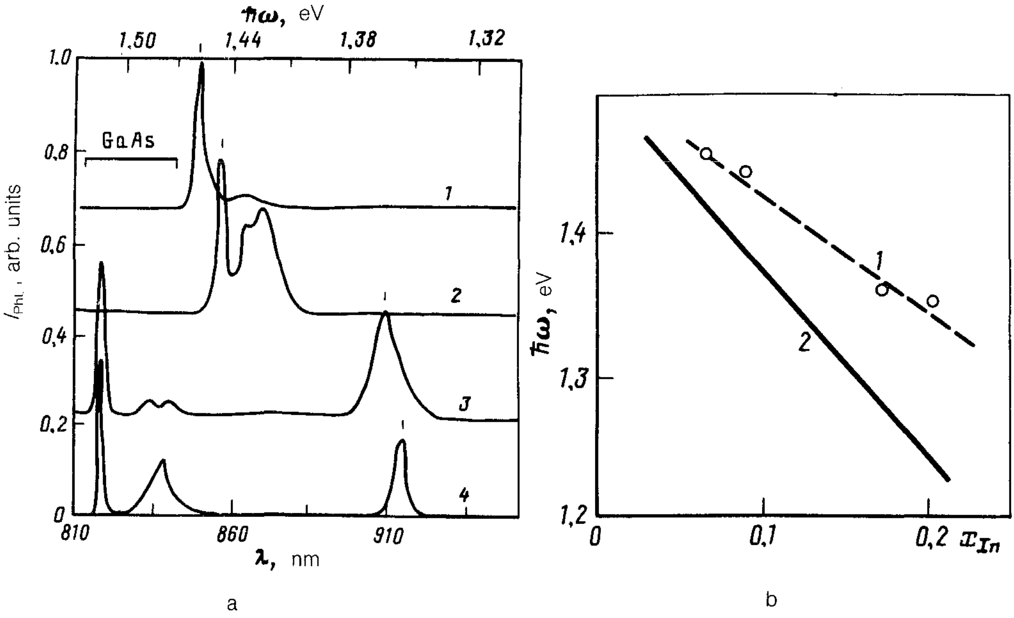


FIG. 1. a: Photoluminescence spectra at $T = 4.2$ K of $(InAs)_n(GaAs)_m$ structures with (1) $m = 40$, (2) 20, (3) 10, and (4) 8. b: 1—Energy position of the line corresponding to the $C1$–$LH1$ transition at $T = 77$ K versus the In concentration x, found as an average over the superlattice; 2—$E_g(x)$ for $In_xGa_{1-x}As$.

recombine in a radiative process (for which the time scale is 10^{-7}–10^{-8} s). An important point is that in the emission of *LO* phonons the electron momentum distribution becomes partially isotropic, so the electrons—even those produced with a momentum directed along the growth axis—acquire a momentum component along the layers of the superlattice after emitting a few *LO* phonons. The depth of the level (of an electron in this case!) in an InAs well varies from 60 meV to 120 meV as the barrier thickness is varied from 40 to 8 monolayers. Since the effective mass of an electron in InAs is small (in comparison with that in GaAs) in the case of thick barriers ($m = 20$ or 40), the dispersion curves for electrons in the GaAs passive region and in a level in an InAs well cross in terms of the momentum components along the layers, and a trapping occurs in a process accompanied by the emission of *LO* phonons with small q. Since the matrix element of the electron–phonon interaction is proportional to q^{-1}, this trapping is more likely than a trapping accompanied by the emission of *LO* phonons with large q in the absence of a crossing of the dispersion curves. An effective mechanism for a flow of carriers into the quantum well thus arises in the GaAs passive region, in which the carriers relax slowly. This trapping model agrees with the observed behavior of the ratio of the photoluminescence intensities of the GaAs and the quantum well. With decreasing barrier thickness, the level in the well becomes lower, and the necessary condition for an effective trapping (a crossing of the dispersion curves in the passive region) is violated. The photoluminescence of the bulk GaAs intensifies.

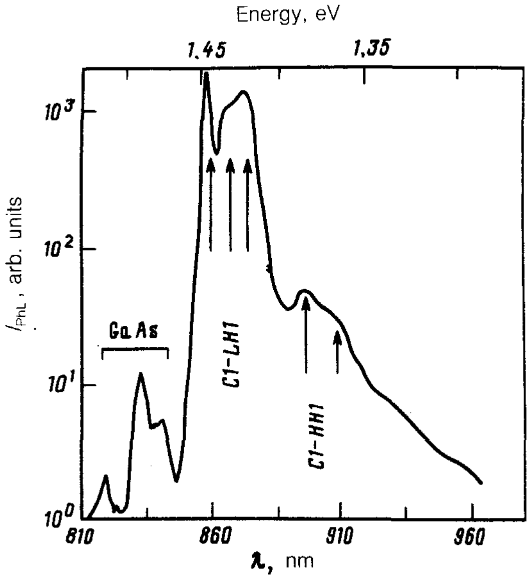


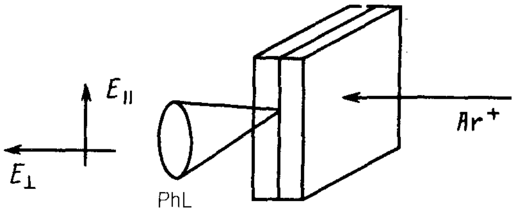
FIG. 2. Photoluminescence of an $(InAs)_2(GaAs)_{20}$ structure ($T = 4.2$ K; the power density of the Ar$^+$ laser was $P = 70$ W/cm^2).

Figure 2 shows a photoluminescence spectrum in semilogarithimic scale for one of the structures studied ($m = 20$). We see photoluminescence lines of the bulk GaAs [(A^0,X) at 1.5129 eV and (θ,A) at 1.489 eV] and intense lines which are probably associated with $C1$-$LH1$ (1.431 eV) and $C1$-$HH1$ (1.382 eV) optical transitions, since their energy positions correspond to those calculated by the envelope-function method. These calculations allowed for the circumstance that the epitaxial InAs layers on the GaAs (001) substrate are compressed in the plane because of the lattice mismatch of InAs and GaAs. This compression may be thought of as a combination of a hydrostatic compression (which leads to an increase in E_g) and a uniaxial extension along the (001) direction. The uniaxial deformation lifts the degeneracy of the Γ_8 zone at $\vec{k} = 0$ and mixes states of heavy and light holes. According to Raman scattering data, the GaAs layers can be assumed unstressed.[1] For a 7% relative deformation of the InAs, we find the distance between the bottom of the conduction band and the top of the band of heavy (or light) holes in the deformed InAs to be 493 meV (or 740 meV). In the calculation of the level energies in the superlattice, the ratio of the discontinuities in the conduction and valence bands was assumed to be 85:15.

The low intensity of the low-energy line can be explained on the basis of this trapping model. As holes with an energy $\epsilon \gg \Omega$ relax, they convert almost completely into heavy holes, but since m_h in InAs is greater than m_h in GaAs, they are trapped in a well only with difficulty (since the trapping involves LO phonons with large q). In contrast, the trapping in states of light holes as a result of a crossing of the dispersion curves of light holes in the well and of heavy and light holes in the GaAs passive layer can occur in a process accompanied by the emission of small-q phonons.

In our case, it is not really valid to use the envelope-function method and a continuum description of the InAs layers, as in the usual calculations on the band structure of superlattices, because the thickness of the wells is only 2 monolayers. On the other hand, the period of the superlattices is too large to permit the use of quantum-chemistry methods for band-structure calculations, since the unit cell which emerges from the calculation contains 20 atoms, even at a barrier thickness $m = 8$.

The small width of the resolved photoluminescence line, of about 2 meV (6 meV in Ref. 5), confirms the high structural quality of the superlattices, which had been established previously by transmission electron microscopy and Raman scattering.[1] We might note in this connection that the three lines at 1.446, 1.431, and 1.423 eV apparently correspond to the photoluminescence of structural regions with thicknesses of 1, 2, and 3 monolayers, respectively. The difference between the line positions is close to the calculated change in the energy of an optical transition upon a change of one monolayer in the well thickness: about 20 meV. These regions are fairly large, since small-scale fluctuations in the thickness of a well would lead to a broad band with an unresolved internal structure, which is observed in certain samples.



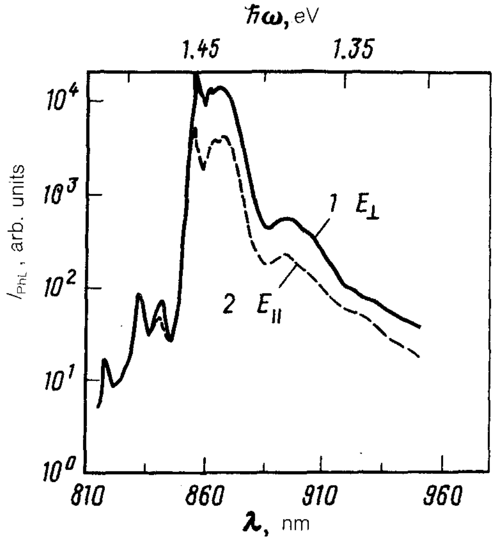


FIG. 3. Spectrum of the polarized photoluminescence at $T = 4.2$ K of an $(InAs)_n(GaAs)_m$ structure.

For an additional identification of the structural features in the photoluminescence spectrum, we studied the polarization of the luminescence. The exciting light was incident along the normal to the surface of the sample; the photoluminescence was detected from the end. In the unstressed composite superlattices based on III–V materials, the photoluminescence from the end of the superlattice during electron–(heavy hole) recombination is polarized in the plane of the layers of the superlattice. During electron–(light hole) recombination, the photoluminescence is polarized predominantly along the growth axis.[6] The polarized photoluminescence spectra of a sample ($m = 20$) are shown in Fig. 3; curves 1 and 2 correspond to the polarizations respectively perpendicular and parallel to the layers of the superlattice. The polarization of the photoluminescence corresponds to that expected for the $C1$–$LH1$ transition. The nature of the line which we attribute to the $C1$–$HH1$ transition requires further study, since its polarization is quite different from that predicted, even when we allow for a mixing of hole states. There is the possibility that this line is associated with a band–acceptor recombination in a well: Its polarization should be similar to that of the $C1$–$LH1$ line.

In summary, we have observed a dependence of the intensity ratio of the edge photoluminescence of GaAs and the photoluminescence of quantum wells on the barrier thickness. We have proposed a mechanism involving a trapping of carriers in a well to explain this dependence. We have identified the lines in the photoluminescence spectra which are associated with a recombination of carriers in quantum wells.

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