Radiative recombination of photoholes localized in potential of δ-doped nini superlattices

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New bands due to interband and exciton recombination of electrons from δ layers and of photoholes localized in the superlattice potential have been observed in the low-temperature luminescence spectra of δ-doped GaAs.

An exciton bound to a 2D electron gas near the surface of silicon was predicted by Averkiev and Pikus[1] and experimentally observed by Altukhov *et al.*[2] Is there an exciton bound to a 2D gas of δ-doped layers in the interior of a semiconductor? Perry *et al.*[3] have shown experimentally that the photoluminescence spectra of structures with a single n-type δ layer, in contrast with a p-type layer,[4] do not contain lines associated with the presence of a δ layer. The apparent reason is that several quantum subbands are filled in an n-δ layer.[5] As a consequence, there is an effective spatial separation of photoholes and electrons in the extended potential of an n-δ layer, whose size exceeds the first Bohr radius of an exciton.

In the present experiments we studied the photoluminescence spectra of δ-nini superlattices consisting of equidistant n-δ layers. By virtue of the localization of photoholes in the potential of the superlattice, we have observed a photoluminescence band due to a recombination of photoholes with electrons from δ layers. The spectra also reveal a new line, which is tentatively linked with a radiative recombination of an exciton consisting of a photohole localized in a superlattice and an electron.

Structures[6] with single n-δ layers and also δ-nini superlattices consisting of five

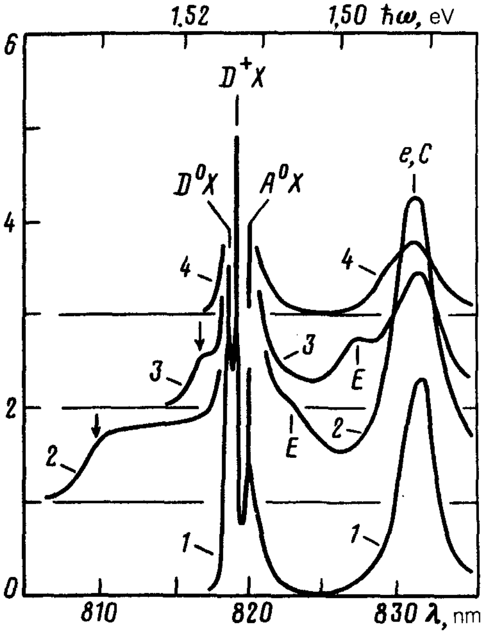

FIG. 1.

periodically positioned n-δ layers separated by undoped GaAs regions ranging in thickness d from 2 to 90 nm, with a donor (Si) concentration $N^{2D} = (0.5 - 1.0) \times 10^{13}$ cm^{-2} in each δ layer, were grown by molecular beam epitaxy. The photoluminescence spectra were measured at $T = 2$K.

Figure 1 shows photoluminescence spectra in δ-nini superlattices with $N^{2D} = 10^{13}$ cm^{-2} and with various periods: $d = 7.5$ (curve 1), $d = 30$ (curve 2), $d = 45$ (curve 3), and $d = 60$ nm (curve 4). Each successive curve has been shifted one scale division vertically. It was found that in superlattices with small periods ($d \leqslant 8$ nm) and large periods ($d \leqslant 60$ nm) the photoluminescence spectra are essentially the same as that of an individual n-δ layer, having no lines which are not also found in the spectra of undoped GaAs. In a superlattice with an intermediate period (curves 2 and 3) we observe, in addition to the known bulk lines of exciton-impurity complexes (D^0X), D^+X) and (A^0X) and the band-acceptor recombination[3] (e,C), a new photoluminescence band, in the form of a plateau with a short-wavelength threshold $\hbar\omega_t$, which depends on the period d. The positions of the threshold on curves 2 and 3 are shown by the vertical arrows. The short-wavelength wing of the band is noticeable on the same curves in the region between the acceptor and exciton lines. We believe that this band is a consequence of a recombination of photoholes localized within the superlattice with the degenerate electron gas formed by the partially overlapping n-δ layers. Figure 2 shows the band diagram of the δ-nini superlattice. It can be seen from Fig. 2 that the position of the threshold $\hbar\omega_t$ is determined by the difference between the Fermi level ϵ_F and the ground quantum-well level of holes in the potential well between the δ layers, ϵ_0^h. With a decrease in the period d, the threshold energy $\hbar\omega_t$ increases, for two reasons. First, a decrease in d is accompanied by an increase in ϵ_0^h,

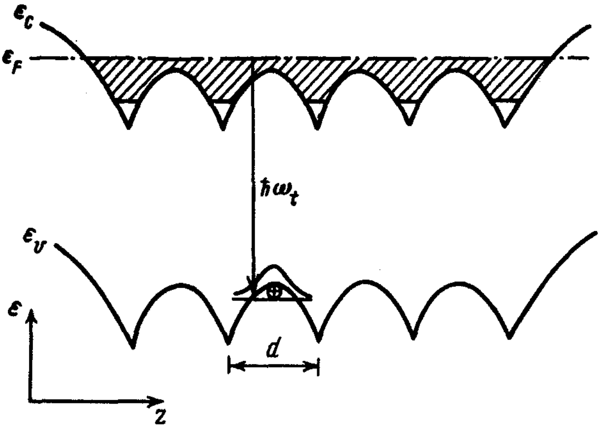

FIG. 2.

second, because of the large overlap of the n-δ layers, the Fermi energy ϵ_F increases with respect to the position of the bottom of the conduction band, ϵ_c, halfway between the δ layers. It can be seen from Fig. 1 that as the period is decreased from $d = 45$ to 30 nm, the threshold increases from $\hbar\omega_t = 1.518$ to 1.530 eV. A comparison of $\hbar\omega_t$ with the gap width $\epsilon_g = 1.519$ eV shows that at $d = 45$ nm the energy ϵ_F lies below ϵ_c between the δ layers. At $d = 30$ nm, the energy ϵ_F apparently lies above ϵ_c, and the individual δ layers overlap, as shown in Fig. 2. With a decrease in the period, ϵ_0^h increases, and the amplitude of the superlattice potential decreases; accordingly, at sufficiently small values of d ($d \lesssim 10$ nm, according to an estimate) there are no hole states localized within wells in the superlattice. As a result, there is no plateau in the spectrum for superlattices with $d < 10$ nm, in agreement with the experiments.

It is clear from Fig. 2 that for a given period d an increase in the concentration N^{2D} should lead to an increase in $\hbar\omega_t$. This conclusion is confirmed experimentally. For superlattices with an identical period $d = 30$ nm an increase in N^{2D} from 5×10^{12} to 1×10^{13} cm^{-2} leads to an increase in $\hbar\omega_t$ from 1.518 to 1.530 eV.

In addition to the plateau, the photoluminescence spectra of the superlattices with the intermediate periods exhibit a new line, E, which is shifted about 20 meV down the energy scale from the threshold $\hbar\omega_t$. The nature of this E line is not clear. It is possible that it is a consequence of an emission of excitons formed as a result of a Coulomb attraction of electrons from δ layers and photoholes in a superlattice. The large shift of the E line with respect to $\hbar\omega_t$ (large in comparison with the binding energy of an exciton in the interior of GaAs) may be due in part to the quasi-2D nature of the exciton and also the circumstance that the given exciton may be bound to an impurity center. In this case, as for excitons bound to a surface-charge layer,[1,2] the screening of the Coulomb interaction by free electrons is apparently weakened (in comparison with that in a uniformly doped semiconductor), because of the effective spatial separation of the electrons and the holes. The stability of such an exciton remains an open question, whose resolution will require a quantitative theory.

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