Effect of charged-impurity potential on exciton formation in quantum wells

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Auxiliary illumination which causes a charge exchange of an impurity in the material of the barriers of quantum wells has been observed to cause an increase in the efficiency of radiative recombination in these wells. The effect is shown to result from an increase in the exciton formation probability in the well as the potential relief set up by deep impurities of the barriers is smoothed over.

In this letter we report a study of the exciton photoluminescence of undoped quantum-well structures grown by molecular-beam epitaxy. The structures consist of 200 alternating layers of GaAs and $Al_{0.4}Ga_{0.6}As$, 100 Å thick.

The exciton photoluminescence is observed in high-quality quantum-well structures over the temperature range 1.6–300 K. The efficiency of this luminescence depends on the energy of the exciting light at low temperatures.[1] In the present experiments we observed that the intensity of the exciton photoluminescence excited in the quantum wells, i.e., excited by light with an energy $\hbar\omega_0 < E_g^b$, where the right side is the band gap of the wide-gap material, depends on a weak auxiliary illumination with $\hbar\omega_{\text{aux}} > E_g^b$ above the barrier. The direct contribution of this auxiliary illumination to the emission from the quantum well does not exceed 1%. The solid line in Fig. 1 is the photoluminescence line of an exciton formed by an electron and a heavy hole from the first quantum-size subbands, during continuous excitation by light with $\hbar\omega_0 = 1.647$ eV at $T = 77$ K. Weak pulsed auxiliary illumination with $\hbar\omega_{\text{aux}} = 2.41$ eV, above the barrier, and with an excitation density $W_{\text{aux}} \approx 10^{-3}$ W/cm^2 intensifies the exciton photoluminescence line by a factor of 2.5–3 (the dashed line). The experimental procedure is illustrated by Fig. 2a. A study of the spectrum of the illumination revealed that the effect has a characteristic of a threshold nature: When the photon energy $\hbar\omega_{\text{aux}}$ falls below E_g^b, the effect of the auxiliary illumination on the exciton photoluminescence in the quantum well disappears.

Figure 2b shows the absolute value of the effect, $\Delta I = I - I_0$, where I_0 and I are the intensities of the exciton photoluminescence before and after the illumination, respectively, versus the observation time t_{ob}. It is interesting to note the long aftereffect of the auxiliary illumination: $\tau_{\text{after}} \approx 1$ ms at $T = 77$ K and $\tau_{\text{after}} \approx 10$ ms at $T = 1.6$ K. The rise time of the effect is no greater than 0.1 μs. A study of ΔI as a function of the intensity of the auxiliary illumination, W_{aux}, at a constant level of the intrawell excitation, W_0, showed that the effect reaches saturation at $W_{\text{aux}} \sim 1.0$ W/cm^2 and $t_p = 20$ μs. The behavior of ΔI as a function of the length of the pulse of auxiliary illumination, t_p, also implies that the magnitude of the effect is determined by the average power of the auxiliary illumination. As W_0 is increased, the relative

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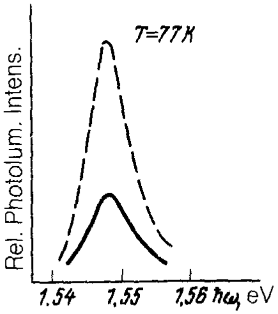

FIG. 1. Emission spectrum of a quantum-well structure with $L_z = 100$ Å at $T = 77$ K. Solid line—during excitation by light with $\hbar\omega_0 = 1.647$ eV; dashed line—with a brief auxiliary illumination with $\hbar\omega_{\rm aux} = 2.41$ eV and $t_0 = 10$ μs at $t_{\rm ob} = 0$.

magnitude of the effect begins to decrease at a certain excitation density, and at $W_0 \sim 100$ W/cm^2 we find $\Delta I / I_0 \approx 2\%$.

The threshold nature of the spectral characteristic, the long aftereffect times, and the characteristic behavior of the saturation of the effect suggest that the illumination above the barrier causes a charge exchange of deep impurities in the material of the barriers. The first Bohr radius of these impurities, a_0, can be estimated by comparing the aftereffect time of the auxiliary illumination, $\tau_{\rm after}$, with the time scale $[\tau(R)]$ for the tunneling from an impurity center at the center of the barrier, $R = 50$ Å, into the quantum well: $\tau(R) \sim \tau_0 \exp[2R/a_0]$, where τ_0, the time scale of multiphonon processes in GaAs, is in the interval 10^{-12}–10^{-11} s. With $\tau(R) \approx 10^{-3}$ s we then find $a_0 \sim 4.5$–5 Å. Such a center might be a residual impurity of oxygen, which forms deep levels at an energy of 0.76 eV in $\rm Al_{0.4}Ga_{0.6}As$ (Ref. 2).

A study of the temperature dependence of the auxiliary-illumination aftereffect time $\tau_{\rm after}$ (Fig. 3) and of the magnitude of the effect, ΔI, shows that by $T \sim 200$ K the time $\tau_{\rm after}$ has decreased to ~ 200 μs, while ΔI has decreased markedly and has become difficult to measure. In this temperature interval the recombination of free carriers begins to contribute significantly to the emission spectrum of the quantum-well structures. These results suggest that the thermal quenching of the effect of the auxiliary illumination is not determined by a change in the potential relief set up by deep

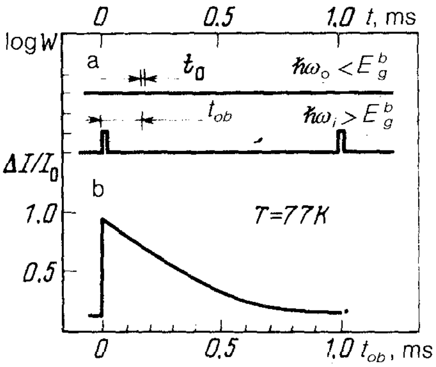

FIG. 2. a: Experimental procedure. The photoluminescence is measured in the temporal window $t_0 = 1$–$50\,\mu$s at a delay $t_{\rm ob} = 10^{-1}$–$10^4\,\mu$s after the pulse of auxiliary illumination, of duration $t_p = 1$–50 μs. b: Magnitude of the effect of the auxiliary illumination versus the observation time for $t_0 = 20$ μs, $t_p = 20$ μs, and $T = 77$ K.

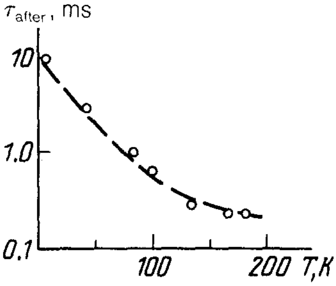

FIG. 3. Temperature dependence of the duration of the aftereffect of the auxiliary lumination, τ_i, i.e., the time over which the magnitude of the effect decreases by a factor of 10 ($t_0 = 10\ \mu s$ and $t_p = 10\ \mu s$).

barrier impurities in the quantum well. It is instead due to a decrease in the cross section for exciton recombination with increasing temperature.[3]

To determine how the deep impurities of the barrier material affect the exciton recombination in the quantum well, we studied the effect of the auxiliary illumination on the electron lifetime by a method of optical orientation. The absorption of circularly polarized light with an energy $\hbar\omega_0 = 1.647$ eV gives rise to the production of electrons and light and heavy holes in the first quantum-size subbands. The spin orientation of the electrons gives rise to a circular polarization in the exciton photoluminescence spectrum.[4] Analysis of the degree of circular polarization and of the polarization decay curve in a transverse magnetic field due to the precession of the electron spins around the field (the Hanle effect) makes it possible to measure the total electron lifetime and the spin relaxation time of the electrons during continuous excitation.[5] Measurements of the half-width of the Lorentzian Hanle line, ΔH, and of the degree of circular polarization, P, at the exciton photoluminescence line showed that illumination above the barrier causes ΔH to increase from 0.38 to 0.80 T, while P increases from 0.36 to 0.46. It can thus be concluded that the total electron lifetime τ_e is shortened by a factor greater than 2.5; this conclusion correlates with the intensification of the photoluminescence during illumination, while the spin relaxation time remains essentially constant.

The total lifetime of an electron in a two-dimensional quantum-size subband is determined by the radiative and radiationless recombination of the electron and also by its binding into an exciton. The orientation of the electron spins is manifested during the annihilation of the exciton. The observed decrease in τ_e during illumination is attributed to an increase in the exciton formation probability. An elimination of other electron recombination mechanisms, which might explain the intensification of the exciton photoluminescence during illumination, would have the opposite effect on τ_e. Since no evidence of any sort for a change in the exciton energy spectrum was observed during illumination, it would be difficult to attribute the effect to a decrease in the radiative lifetime of an exciton. There is the implication that a charge exchange of deep centers in the barrier material smoothes the potential relief set up by these impurities in the quantum well. As a consequence, that spatial separation of electrons and holes which is caused by fluctuations of the electric fields is eliminated, and the time scale for binding into an exciton decreases. An increase in the exciton recombination rate during the auxiliary illumination leads to the observed intensification of the photoluminescence and a decrease in τ_e. It has been predicted theoretically[3,6] that even a weak electric field would greatly reduce the exciton formation cross section, while having essentially no effect on the exciton binding energy.

The effect observed here is the first observation in optical spectra of an effect of the potential of charged centers in a wide-gap material on carrier migration in the plane of a quantum well.

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