Photoluminescence study of silicon donors in *n*-type modulation-doped GaAs/AlAs quantum wells

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We have studied the photoluminescence spectra from GaAs/AlAs quantum wells doped with silicon donors in the AlAs barriers. The GaAs well width in these structures was chosen so that the lowest conduction subband e_1 lies above the donor states. An impurity-related feature is identified as the donor-to-valence-band transition. A comparison of the energy of this feature with that of the AlAs *X*-valley-to-valence-band transition yields the donor binding energy.

INTRODUCTION

Donors in GaAs/$Al_{0.3}Ga_{0.7}As$ quantum-well structures have been investigated extensively using photoluminescence,[1-3] Raman,[4,5] and far-infrared absorption[6,7] spectroscopies. Issues such as the dependence of the donor binding energy on well and barrier dimensions or the position of the impurity atoms in the structures have been explored. These donors are associated with the Γ-symmetry point of the conduction band in GaAs and are shallow (binding energy $=5.83$ meV for bulk GaAs) with a large Bohr radius (100 Å). Donor impurities in AlAs, on the other hand, are not so well studied. This material has an indirect gap with the *X*-valley minimum lying lower than the Γ point at the Brillouin-zone center. Optically detected magnetic resonance studies of *n*-type AlAs epilayers have shown that the donors in this semiconductor are associated with the *X*-band minima.[8] Silicon donors in *n*-type modulation-doped GaAs/AlAs structures in which the lowest conduction subband e_1 lies below the donor states release their electrons into the GaAs wells. A schematic diagram of the conduction band for such structures is shown in Fig. 1(a). The presence of a quasi-two-dimensional electron gas in this type of quantum wells has been verified using magnetoluminescence and Raman spectroscopies.[9] These studies have shown that the properties of the electrons which are confined in the GaAs wells are qualitatively similar to those of the widely studied GaAs/$Al_{0.3}Ga_{0.7}As$ system, but have not produced any information on the parent donor states from which the electrons originate. In order to do that one has to investigate narrower structures in which the e_1 subband lies above the donors as is shown in Fig. 1(b). At low temperatures the electrons remain attached to the silicon donors from where they can recombine with photogenerated holes confined in the GaAs wells.

In this work we present a photoluminescence (PL) study of an *n*-type modulation-doped GaAs/AlAs quantum-well structure in which the well width has been selected so that the energy of the e_1 subband lies above the donor state. An impurity-related feature present only in doped structures is identified as the donor $\rightarrow h_1$ ($D \rightarrow h_1$) transition, where h_1 is the ground-state hole subband. The presence of LO phonon replicas of this donor-related transition strongly indicates that it is indirect in k space. A comparison of the energy of the $D \rightarrow h_1$ PL feature with that of the AlAs *X*-valley $\rightarrow h_1$ transition yields the binding energy of the donor.

EXPERIMENT

The samples used in this study along with some relevant parameters are listed in Table I. The structures were grown in a Varian 360 molecular-beam epitaxy system. A (100) GaAs substrate was used and the growth rate for the GaAs and AlAs was 0.65 and 0.22 μm/h, respectively. Following oxide desorption, the GaAs buffer and subsequent quantum-well layers were grown at 600 °C. A 15-sec growth interruption was used after the AlAs layer to smooth the interface and to decrease intralayer thickness fluctuations. Sample 1 was doped with silicon donors over the central 1/3 of the AlAs barriers (donor concentration $=4\times10^{18}$ cm^{-3}). Sample 2 was not intentionally doped and is used as a reference. The photoluminescence spectra were excited either with the 4880-Å line of an argon-ion laser or with the 6328-Å line of a helium-neon laser. The samples were placed in a closed-cycle refrigerator which permits optical work in the 10–300-K temperature range. The emitted luminescence was focused onto the entrance slit of a double

TABLE I. Sample parameters.

Sample	Well width (Å)	Barrier width (Å)	Doping
1	62	131	Si, 4×10^{18} cm^{-3}
2	73	73	Undoped

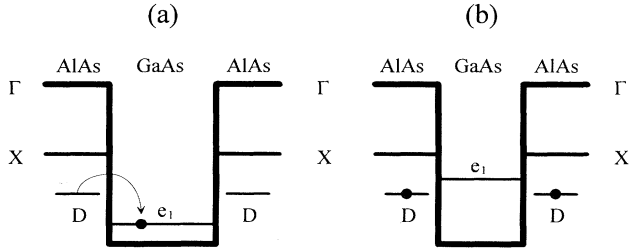

FIG. 1. Schematic diagram of the band structure for n-type modulation-doped GaAs/AlAs quantum wells. (a) e_1 lies below the AlAs donor state. (b) e_1 lies above the AlAs donor state.

monochromator equipped with a cooled photomultiplier tube and standard photon counting electronics. Reflectivity spectra were also recorded in order to identify the position of the free excitons in these structures.

DISCUSSION

The PL spectrum at $T=10$ K from sample 1 is shown in Fig. 2(a). It contains three features marked (i), (ii), and (iii) at 1626.7, 1593.2, and 1555.0 meV, respectively. Peak (i) is identified as the ground-state e_1h_1 exciton because it coincides with the lowest-energy feature in the reflectance spectrum. Feature (ii) is related with the presence of donors in the barriers, since it is absent from the undoped sample 2. It is attributed to the recombination of an electron on the donor with a photogenerated hole in the highest valence subband ($D\rightarrow h_1$). The interpretation of feature (ii) as a donor(AlAs)$\rightarrow$ acceptor(GaAs) was excluded because no carbon-related PL lines were observed in the undoped sample 2. Feature (iii) is interpreted as an LO-phonon replica of (ii), because it follows the intensity variations of feature (ii). The vertical arrows indicate the calculated positions for GaAs and AlAs LO-phonon replicas at 36.3 and 50 meV below feature (ii), respectively. While the GaAs LO replica is clearly visible, this is not the case for the AlAs LO replica. If the AlAs LO replica is present, it is much weaker than the GaAs LO replica and thus appears as an unresolved shoulder on the low-energy side. The presence of phonon replicas in the PL spectra clearly indicates that the $D\rightarrow h_1$ transition is indirect in k space,[10] with the X-symmetry electron in the AlAs barrier and the Γ-symmetry hole in the GaAs well. The lifetime of the $D\rightarrow h_1$ transition is increased (compared to that of the spatially direct e_1h_1 exciton) thus allowing the electron and the hole to interact with the AlAs and GaAs LO phonons, respectively. In type-II short-period GaAs/AlAs superlattices the intensities of the two LO-phonon replicas of the Xh_1 exciton are comparable.[10] In our system, the intensity of the AlAs LO replica is much smaller than that of the GaAs LO replica. The origin of this difference is not understood. The luminescence from sample 2 [see Fig. 2(b)], which was not intentionally doped, contains only feature (i), i.e., the ground-state e_1h_1 exciton. No impurity feature is present in the spectrum of Fig. 2(b). This is a clear indication that features (ii) and (iii) present in the PL spectra of sample 1 are associated with the silicon donors in the AlAs barriers.

The temperature dependence of the PL spectra from sample 1 is shown in Fig. 3. The intensity I (ii) of the $D\rightarrow h_1$ transition increases monotonically in the temperature range $10<T<40$ K. The intensity exhibits a maximum at $T=37$ K and at higher temperatures it decreases monotonically with T. At $T=90$ K, features (ii) and (iii) disappear. A plot of $\ln[I(\text{ii})]$ for sample 1 versus $1/T$ is shown in Fig. 4 using circles. The temperature

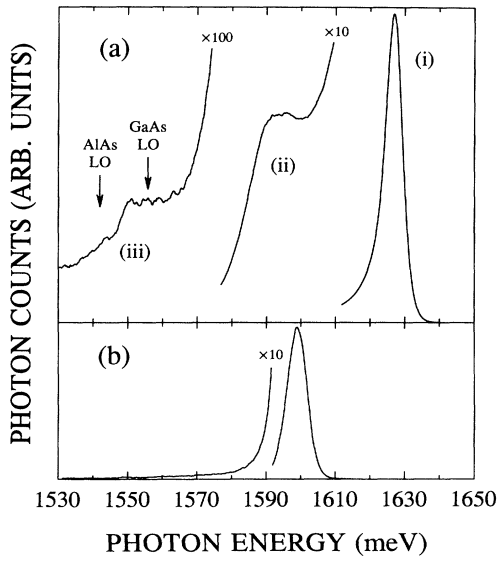

FIG. 2. Photoluminescence spectra at $T=10$ K. (a) Sample 1. The vertical arrows indicate the expected positions of the GaAs LO and AlAs LO phonon replicas of feature (ii). (b) Sample 2.

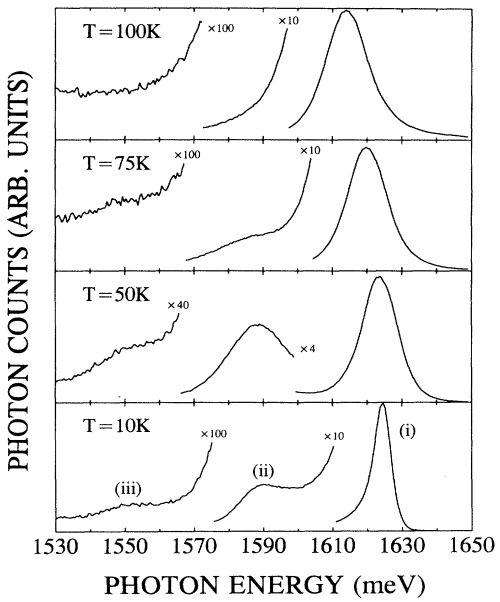

FIG. 3. Temperature evolution of the PL spectra from sample 1.

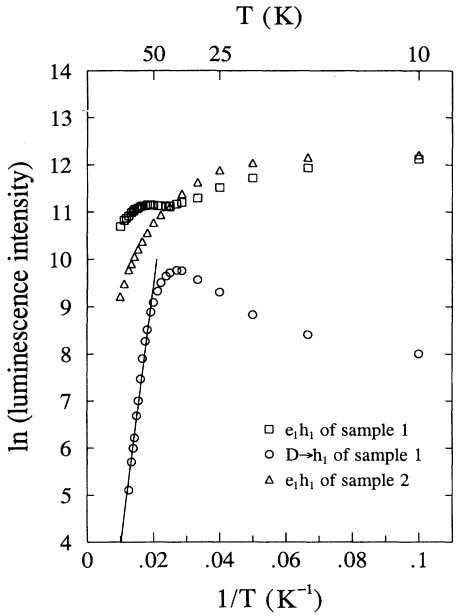

FIG. 4. Logarithm of the intensities, in arbitrary units, of the PL features in samples 1 and 2 plotted as function of $1/T$. Squares, e_1h_1 exciton, sample 1; circles, $D\rightarrow h_1$ transition, sample 1; triangles, e_1h_1 exciton, sample 2. The straight line is fit to the $D\rightarrow h_1$ transition in sample 1.

dependence of I(ii) in this structure is understood as follows: At low temperatures the energy, and thus the wave vector, distribution of the lowest hole subband h_1 is narrow. A donor impurity with a compact wave function will favor recombination processes which involve large hole k vectors ($k\sim 1/a_B$, where a_B is the impurity Bohr radius). At low temperatures the occupation of h_1 holes with high k vector is small. As the temperature increases, more holes with large k vectors become available and this results in an enhancement of the $D\rightarrow h_1$ transition intensity. Above 37 K the intensity I(ii) declines because the silicon donors are ionized by transferring their electrons to the e_1 subband of the GaAs wells, which lies approximately 45 meV above the donor state. A least-squares fit of the slope of the ln[I(ii)] versus $1/T$ curve in Fig. 4 (solid line) for $T>37$ K corresponds to an energy difference $\Delta E=47$ meV. The shoulder on the high-energy side of the e_1h_1 exciton at $T=100$ K in Fig. 3 could be due to band-to-band recombinations of thermally excited electrons occupying the e_1 subband with photoinjected h_1 holes. In Fig. 4 we also plot the natural logarithm ln[I(ii)] of the e_1h_1 exciton intensity as function of $1/T$ for samples 1 (squares) and 2 (triangles). The exciton intensity dependence on $1/T$ is different in the two structures. In the undoped sample 2 the intensity of e_1h_1 drops monotonically with increasing temperature. In the case of sample 1, which is n-type, the exciton intensity drops with temperature in the 10–30-K range. It then remains approximately constant between 30 and 65-K and then drops again for $T>65$ K. The difference between samples 1 and 2 can be understood as follows: In the 10–30-K range the e_1h_1 and $D\rightarrow h_1$ transitions in sample 1 are competing processes because they share the final state (the photogenerated h_1 holes). The intensity e_1h_1 in sample 1 drops faster with temperature than in sample 2 because in the latter the $D\rightarrow h_1$ transition is not present. In the 30–65-K range the trend reverses because the donors in sample 1 start to thermally ionize and thus cannot contribute to the $D\rightarrow h_1$ recombination channel which competes with e_1h_1. Instead the thermally excited electrons that populate the e_1 subband enhance the e_1h_1 transition whose intensity remains approximately constant. Finally for $T>65$ K all the donors in sample 1 have transferred their electrons to the e_1 subband and the temperature dependence of the e_1h_1 exciton approximately follows that of sample 2.

The binding energy of the silicon donor with respect to the X-valley minimum can be determined from the energy difference between the $D\rightarrow h_1$ and $X\rightarrow h_1$ transitions. The latter transition is not observed in samples 1 and 2. We have observed the $X\rightarrow h_1$ transition in a type-II 40 Å/150 Å GaAs/AlAs quantum-well structure at 1711 meV. When the h_1 hole confinement energy difference between this sample and sample 1 is taken into account a binding energy of $E_b(D)=104$ meV for the silicon donors in the AlAs barriers is determined. Here we used a binding energy of 10 meV for the Xh_1 type-II exciton[11] and a heavy-hole mass of $0.34m_e$ for the calculation of the heavy-hole confinement energies.[12] The experimental value of the donor binding energy is in good agreement with previous work on AlAs epilayers.[13,14] The large binding energy of donors in AlAs is associated with heavy effective masses of the AlAs X band.[15,16] From simple hydrogenic impurity arguments one expects a correspondingly small donor Bohr radius in this system. For this reason, the donor binding energy is not expected to be sensitive to confinement except for structures with very narrow barriers. The following difficulty arises if one accepts a compact wave function for the donor: The overlap integral between the wave function of a donor at the center of AlAs barrier and the h_1 hole, and thus the intensity of the $D\rightarrow h_1$ transition should be very small. We can resolve this difficulty if we assume that during growth the distribution of donors has shifted away from the barrier center towards the AlAs/GaAs interface in the growth direction. Such a drift of donors along the growth direction has been observed in edge doped GaAs/Al_xGa_{1-x}As quantum wells.[2] Another apparent difficulty is the absence of distinct donor bound excitons in the PL spectra of sample 1. In GaAs/$Al_{0.3}Ga_{0.7}$As quantum wells doped with silicon donors in the GaAs wells these transitions are pronounced.[2,3] The e_1h_1 exciton and the donor wave functions in these structures extend over the width of the GaAs wells. In the GaAs/AlAs system, on the other hand, the e_1h_1 excitons are confined in the GaAs wells while the donors, even though close to the AlAs/GaAs interface, have a small Bohr radius which would make the binding of the excitons difficult. Thus it is not surprising that no donor bound exciton features are present in the PL spectra from sample 1.

CONCLUSIONS

We have presented a PL study of a GaAs/AlAs quantum-well structure doped with silicon donors in the AlAs barriers. The well width has been chosen so that the lowest conduction subband e_1 lies above the donor levels. An impurity-related feature present only in the doped sample has been attributed to donor $\rightarrow h_1$ transitions. A binding energy of 104 meV has been determined for these donors which are associated with the AlAs X-valley minima. In wider wells in which the e_1 subband lies below the donor states, these impurities ionize and transfer their electrons to the GaAs wells.[9] We plan to extend these studies for structure in which the AlAs X-valley minima are degenerate with the Γ-symmetry e_1 subband in the GaAs wells.

ACKNOWLEDGMENT

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