Photoluminescence from partially Si-doped AlAs/GaAs single-quantum-well structures

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Photoluminescence spectra of partially Si-doped AlAs/GaAs single-quantum-well (SQW) structures were investigated by varying doping position and configurations. The isolated-donor-related emission was observed on the SQW's Si doped on the center and on the edge of the well layers. On the other hand, for the SQW Si doped in the middle of the well layer with parallel configurations, this isolated-donor-related emission was not observed, and a new sharp emission line appeared. The energy of this emission was modulated by the spacing between the barrier and the doped layer. The confinement of the donor in the well layer is a key to the appearance of this emission.

The electronic behavior of impurities in quantum-well (QW) structures is interesting from both the theoretical and experimental points of view. The binding energies of donors and acceptors in GaAs/$Al_xGa_{1-x}As$ QW structures have been calculated as a function of barrier height, well width, and location of impurity.[1-11] These theoretical studies have suggested attractive physical phenomena relating to confinement effects on the impurity electronic states. Optical spectroscopic techniques such as photoluminescence,[12-15] Raman scattering,[16,17] and far-infrared absorption,[18] sometimes combined with modulation by application of electric or magnetic fields, have been employed in the experimental approaches to the electronic behavior of impurities in QW structures. The Si-donor-associated states have been studied by several groups.[12,14,16,18] Good agreement between theoretical and experimental values in the binding energies has been obtained. In this Brief Report, we discuss some photoluminescence properties of partially-Si-doped QW's, concentrating on relationships between photoluminescence spectra and doping configuration.

We chose all-binary single-quantum-well (SQW) structures consisting of AlAs barrier and GaAs well layers as samples. These SQW structures were fabricated on (100)-oriented GaAs substrates by conventional molecular-beam epitaxy (MBE). The growth rate was controlled to 1 monolayer (ML) per second by monitoring the oscillation of specular beam intensity of reflection high-energy electron diffraction (RHEED) during the growth. The Si impurities were partially incorporated into the well layer by shutter operation of the Si effusion cell during MBE growth. The Si concentration was 3×10^{17} cm^{-3} in the doped region. Photoluminescence measurements were made on the sample immersed in liquid nitrogen or liquid helium by use of excitation from an Ar^+-ion laser operating at 514.5 nm and a conventional lock-in–amplifier detection technique.

Photoluminescence spectra of undoped GaAs(30 ML)/AlAs SQW structures at 77 K are shown in Fig. 1(a). Only excitonic radiative recombinations due to heavy and light holes were observed. In the photoluminescence spectrum of GaAs/AlAs SQW's doped with Si on the center region (10 ML), a broadband emission ascribed to a Si impurity also appeared [Fig. 1(b)]. This emission is attributed to donor-to-acceptor (D-A) transitions. This assignment of transition processes is supported by the well-width dependence of the emission energy and calculated binding energies of the donor[2] and acceptor[3] in the QW structures. The peak energy of the D-A transition is slightly varied among the SQW structures as a function of the location of doped impurities. The binding energy of impurities confined in the well layer was varied by the location. A difference of a few meV in emission peak energy was observed between the SQW structures doped on the center and on the edge. However, this difference is small compared to that expected by

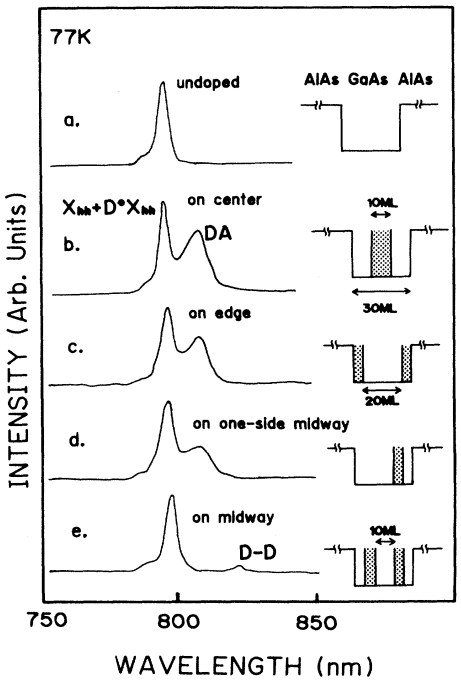

FIG. 1. Photoluminescence spectra from GaAs/AlAs single-quantum-well (SQW) structures (a) undoped and (b)–(e) doped with Si to 3×10^{17} cm^{-3} at 77 K. Doped configurations and positions are also indicated by shading.

calculation of binding energies of the donor and acceptor as a function of position. In the samples used, the acceptor impurities are residual ones, and are considered to be distributed uniformly along the growth axis. Therefore, the spectral shape of the D-A transition is rather broad, and the emission energy is determined by the acceptor binding energy, because the variation of binding energy of the acceptor is larger than that of the donor. The heavy-hole exciton peak consists of free and donor-bound exciton (X_{hh} and D^0X_{hh}) recombinations in the doped QW.[19] A similar spectral profile was observed in the SQW doped on the edge of the well layer [Fig. 1(c)] and on one side in the middle of it [Fig. 1(d)]. However, we found a considerable spectral change in the SQW structure Si doped in the middle of the well layer with a symmetric configuration (hereafter labeled type S) as shown in Fig. 1(e). In the type-S SQW, the D-A emission observed in the other doped SQW structures disappeared. At the same time, a new, weak peak (hereafter labeled D-D) appeared at 1.508 eV. The D-D emission is enhanced at a temperature of 4.2 K, as shown in Fig. 2. A very sharp spectral profile, characteristic of an excitonic transition, was observed.

In order to check the effects of confinement on the D-D emission, we measured the photoluminescence spectra of other type-S SQW's having various barrier-impurity spacings. The energy position of the D-D state, which is measured from X_{hh} as a function of the confinement factor (that is, as a function of spacing between barrier and doped region), is shown in Fig. 3. The energy position is increased as the barrier–doped-layer spacing decreases. This result indicates that the confinement enhances the depth of the energy position from X_{hh}. However, in another type-S SQW having large barrier–doped-region spacing, 55 ML, which is obviously larger than the Bohr radius of the donor, the D-D emission was not observed in the photoluminescence spectra. The spectrum consists of weak band-edge emission and a strong broad extrinsic emission as shown in Fig. 4. Therefore, the confinement by barriers is required to obtain the spectral profile as

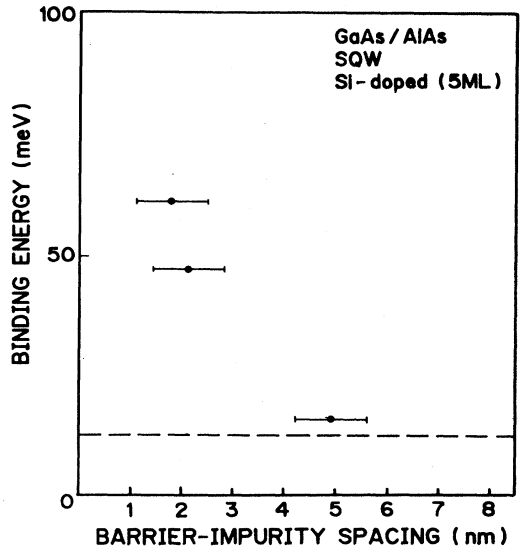

FIG. 3. Activation energies of interacting donors as a function of impurity-barrier spacing. Dots show the center of doping region. Bars indicate the width of the doping region. The dashed line is the isolated donor level for well widths of 30 ML.

shown in Fig. 2. It seems that the barrier-impurity spacing is an effective factor in inducing the spectral change.

The type-S SQW's having a well width of 28 ML and two kinds of barrier conditions—a thin barrier (10 ML) and an asymmetric barrier structure—were also employed to investigate the confinement effects. Figure 5 shows photoluminescence spectra of the type-S SQW's having different barrier conditions—a thin barrier and an asymmetric barrier structure, as also shown in Fig. 5. Their spectral profiles are similar to those shown in Fig. 1(e). The energy positions of these type-S SQW's with a 28-ML well width were 61 meV, while the intrinsic excitonic peak energy is affected by the different barrier structure. The spectral profile does not suffer from the influences of the modulation of electronic structure in-

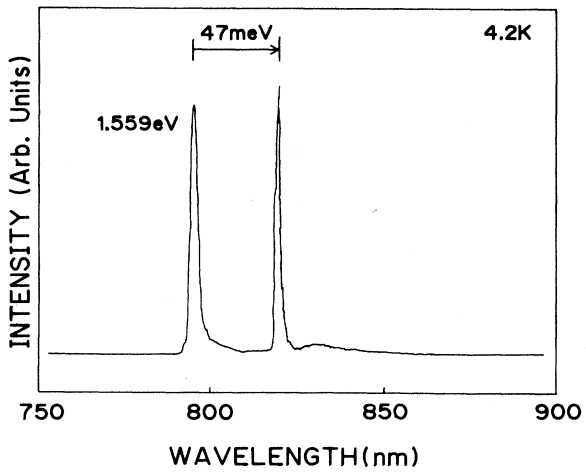

FIG. 2. Photoluminescence spectra from GaAs/AlAs SQW structures Si doped in the middle with a parallel configuration [corresponding to Fig. 1(e) at 4.2 K].

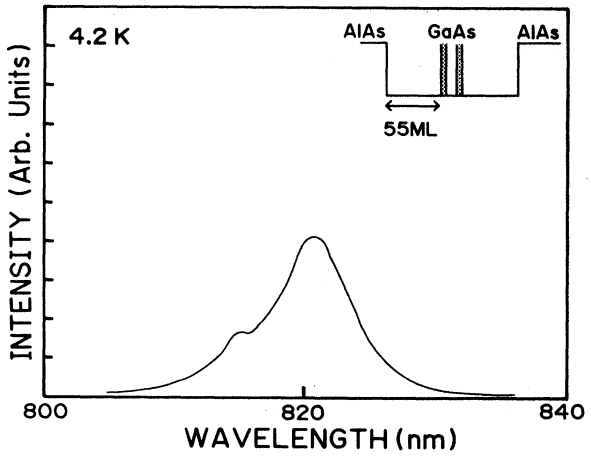

FIG. 4. Photoluminescence spectrum from a type-S SQW structure having an impurity-layer–barrier spacing of 55 ML, which is larger than the Bohr radius of the donor.

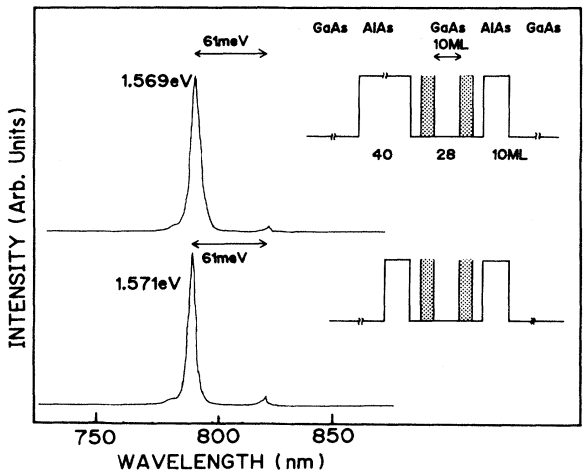

FIG. 5. Photoluminescence spectra from type-*S* GaAs/AlAs SQW structures having (a) an asymmetric barrier and (b) a thin barrier structure.

duced by these barrier conditions. The *D-A* transition could not leak via the modulation induced by the barrier conditions.

From results described above, when the state related to the *D-D* state is formed by the doping in the middle of the QW with a symmetric configuration, the photoexcited carriers recombine as the *D-D* emission rather than the *D-A* emission. This means that the *D-D* emission has a larger oscillator strength than the *D-A* emission. Although the electronic structure of the *D-D* state is not known at the present, some interaction between the impurities induces the *D-D* state. An interesting experimental result which supports the interaction is that the *D-D* emission is also observed at 1.503 eV in the SQW doped on the center with the larger Si concentration of 8×10^{17} cm^{-3}.[20] The interaction is probably Coulombic, because of its confinement character. Moreover, the absence of *D-D* emission in the SQW doped on the edge is due to the penetration of the wave function of the donor into the barrier layers, because the *D-D* emission is also observed in the SQW in which the spacing between impurity layers is 20 ML [the same distance in the structure shown in Fig. 1(c)] and the impurity-barrier spacing is 10 ML.[20] Therefore, the complete confinement of donors within the well layers is an important factor in promoting the *D-D* transition. The interacting donors are probably thought of as comprising a possible center.

In summary, we have measured photoluminescence spectra of partially-Si-doped GaAs QW's. The spectral change due to doping configuration was observed. The *D-A* emission related to the isolated donor was not observed in the type-*S* SQW in which the Si was located in the middle, with a symmetric configuration. The sharp line that we call the *D-D* emission was observed at an energy lower than the isolated donor level. The activation energy measured from the intrinsic excitonic line was modulated by the spacing between the barrier and doped layer. The confinement is a key factor for this spectral change.

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[1]G. Bastard, Phys. Rev. B **24**, 474 (1981).
[2]C. Mailhiot, Y. C. Chang, and T. C. McGill, Phys. Rev. B **26**, 4449 (1982).
[3]W. T. Masselink, Y. C. Chang, and H. Morkoç, Phys. Rev. B **28**, 7373 (1983).
[4]S. Chaudhuri, Phys. Rev. B **28**, 4480 (1983).
[5]J. A. Braun, G. Bastard, and C. Guillemot, Phys. Rev. B **30**, 905 (1984).
[6]C. Priester, G. Bastard, G. Allan, and M. Lannoo, Phys. Rev. B **30**, 6029 (1984).
[7]W-m. Liu and J. J. Quinn, Phys. Rev. B **31**, 2348 (1985).
[8]R. L. Green and K. K. Bajaj, Solid State Commun. **53**, 1103 (1985).
[9]L. E. Oliveira and L. M. Falicov, Phys. Rev. B **34**, 8676 (1986).
[10]E. A. de Andrada e Silva and I. C. da Cunha Lima, Solid State Commun. **64**, 113 (1987).
[11]R. L. Green and K. K. Bajaj, Phys. Rev. B **37**, 4604 (1988).
[12]R. C. Miller and A. C. Gossard, Appl. Phys. Lett. **43**, 954 (1983).
[13]D. C. Reynolds, K. K. Bajaj, C. W. Litton, P. W. Yu, W. T. Masselink, R. Fischer, and H. Morkoç, Phys. Rev. B **29**, 7038 (1984).
[14]X. Liu, A. Petrou, B. D. McCombe, J. Ralston, and G. Wicks, Phys. Rev. B **38**, 8522 (1988).
[15]M. H. Meynadier, J. A. Brum, C. Delalande, M. Voos, F. Alexandre, and J. L. Lievin, J. Appl. Phys. **58**, 4307 (1985).
[16]B. V. Shanabrook, J. Comas, T. A. Perry, and R. Merlin, Phys. Rev. B **29**, 7096 (1986).
[17]D. Gammon, R. Merlin, W. T. Masselink, and H. Morkoç, Phys. Rev. B **33**, 2919 (1986).
[18]N. C. Jarosik, B. D. McCombe, B. V. Shanabrook, J. Comas, J. Ralston, and G. Wicks, Phys. Rev. Lett. **54**, 1283 (1985).
[19]X. Liu, A. Petrou, B. D. McCombe, J. Ralston, and G. Wicks, Phys. Rev. B **38**, 8522 (1988).
[20]T. Kamijoh, N. Sugiyama, and Y. Katayama (unpublished).