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Far-infrared magnetoabsorption study of weakly bound electrons in GaAs/$Al_xGa_{1-x}As$ multiple quantum wells

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Far-infrared magnetoabsorption experiments have been performed at 4.2 K on GaAs/$Al_xGa_{1-x}As$ multiple-quantum-well (MQW) heterostructures that were selectively doped with Si donors in the centers of the quantum wells and barrier layers. Data were obtained for several values of dopant concentration in the barriers. The results provide strong evidence for the binding of electrons in the wells to positively charged ions in the barriers.

Recently, the nature of isolated hydrogenic impurities in systems of reduced dimensionality has received much theoretical[1] and experimental[2] attention. Shallow donors in GaAs/$Al_xGa_{1-x}As$ multiple quantum wells have proven to be a model system for experimental investigations. Previous experimental studies[2-4] have reported absorption features associated with confined neutral donors in the GaAs wells. The transition energies of these lines as functions of the well width, the position of the impurity centers within the wells, and the strength of an applied magnetic field are in very good agreement with recent calculations.[1]

In the present work, we report the results of far-infrared magnetoabsorption experiments performed at 4.2 K on molecular-beam-epitaxy (MBE)-grown GaAs/$Al_{0.3}Ga_{0.7}As$ multiple-quantum-well (MQW) heterostructures that were selectively doped with Si donors over the central third of the quantum well *and* barrier layers. The electron concentration (n) in the quantum wells was adjusted by varying the dopant concentration in the barriers (N_b). Motivations for this investigation include (a) the need for detailed information on the binding of electrons in the wells to positively charged impurities in the barriers, (b) the possibility of studying the screening of the Coulomb interaction by free carriers in this quasi-two-dimensional system, and (c) the identification of previously observed and unidentified absorption features reported in recent studies[2-4] of shallow donors in MQW structures.

The present measurements reveal an absorption line that is characteristic of weakly bound electrons in the GaAs layers. Because this absorption feature exhibits a strength that is proportional to the dopant concentration in the barrier, it appears to arise from an intracenter transition of an electron bound to a positively charged Coulomb center in the $Al_xGa_{1-x}As$ barrier layers. This assignment is consistent with results of recent theoretical investigations.[5]

The samples investigated consisted of GaAs/$Al_{0.3}Ga_{0.7}As$ multiple quantum wells (~50 layers) grown on semi-insulating GaAs substrates. The well and barrier widths were approximately 200 Å. While the central third of the QW's was doped with Si at a density of 1×10^{16} cm^{-3} (N_w), the dopant density in the central third of the barrier layers (N_b) varied between 1 and 8×10^{16} Si atoms/cm^3. A control sample was also grown with the same set of structure parameters and dopant density in the wells but with undoped $Al_{0.3}Ga_{0.7}As$ barrier layers.

The far-infrared measurements were made in a light pipe system at 4.2 K with a Bomem Fourier-transform spectrometer in conjunction with a Ga:Ge photoconductive detector and a 13-T superconducting magnet. Data were obtained with the QW growth axis parallel to the applied magnetic field and incident radiation. The ground state ($m=0$) to first excited state ($m=+1$) transitions are the dominant features observed under these experimental conditions. The transitions are labeled by the usual low-magnetic-field hydrogenic spectroscopic notation, where + refers to the magnetic quantum number +1.

Transmission spectra obtained at 4.2 K for several values of dopant concentration in the $Al_xGa_{1-x}As$ barrier layers are shown in Fig. 1. The peaks observed in these spectra, labeled by 1, 2, and 3, occur at energies higher than that of electron cyclotron resonance (CR). The observation of absorption features 1 and 2 have been reported preliminarily in recent works.[6,7] As the samples are heated to higher temperatures, we observe a decrease in the absorption strength of these features and a simultaneous increase in the intensity of cyclotron resonance. Therefore, these features arise from defects that weakly bind electrons. Furthermore, because the transition energies of the features in Fig. 1 scale with the component of the magnetic field parallel to the growth axis, they cannot be attributed to shallow donors in the substrate or buffer layers of the sample.[4,7] The origin of peak 3, which occurs at ~178 cm^{-1} when $B=9$ T, is well understood and arises from $1s$-$2p^+$ transitions associated with the neutral-donor impurities located in the center of the GaAs wells.[2-4]

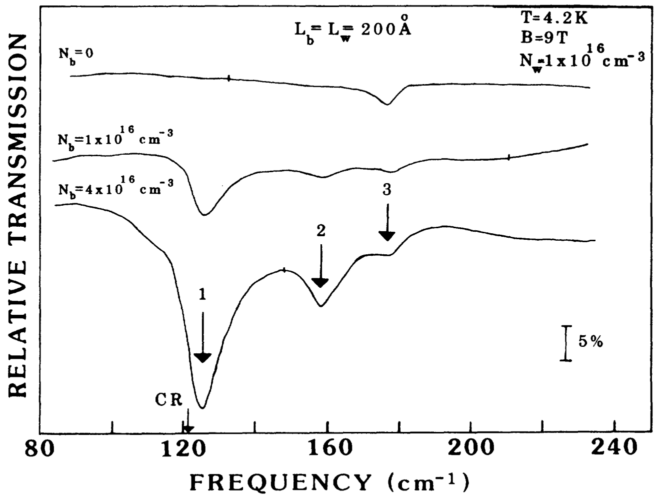

FIG. 1. Representative transmission spectra obtained for several values of dopant concentration (N_b) in the barrier layers. Peaks 1 and 3 are assigned to intra-impurity transitions of electrons bound to donors in the centers of the barriers and wells, respectively. Bars indicate typical noise levels (CR denotes cyclotron resonance).

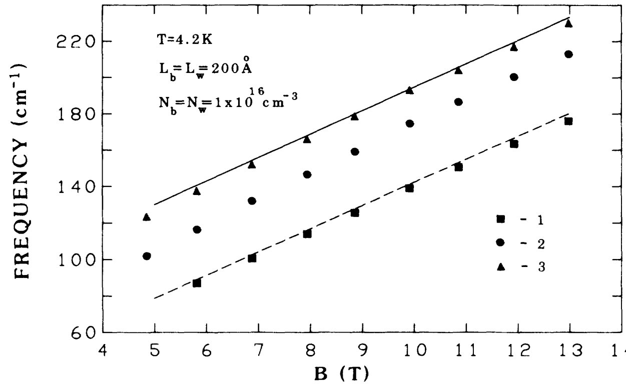

FIG. 2. Compilation of the transition energies of the three peaks at 4.2 K. The ground-state ($m=0$) to first-excited-state ($m=+1$) transition energies calculated for donors located at the centers of the wells ($L_w=200$ Å) and barriers ($L_b=200$ Å) are shown by the solid and dashed lines, respectively. The errors associated with the determination of the peak positions are $\sim$1–2 cm^{-1}.

As indicated in Fig. 1, the strength of the absorption features labeled 1 and 2 increases significantly with increasing N_b. In addition, these low-energy absorption features exhibit a rapid decrease in intensity relative to that of peak 3 as the temperature is increased to 20 K. This observation suggests that absorption features labeled 1 and 2 arise from impurities whose ground state is shallower than that of donors located at the center of the quantum well. A comparison of two samples with two different barrier widths and nominally the same well widths indicates that peak 1 shifts to higher energy as the barrier width is reduced. The peak positions of features 2 and 3 are unchanged to within our experimental error. This observation combined with those previously mentioned suggests that peak 1 arises from an intra-impurity transition of an electron in the quantum well bound to a positively charged ion in the barrier. Peak 1 occurs at a higher energy for samples with smaller barrier widths because the mean separation between the positively charged ion in the barrier and the weakly bound electron in the quantum well becomes smaller.

A compilation of the transition energies as a function of magnetic field for the samples with barrier widths of 200 Å is shown in Fig. 2. Recent calculations[5] have been performed for the binding energies of the ground and first few excited states for electrons in the wells in the presence of a uniform distribution of donors and a magnetic field applied perpendicular to the layers. The results for the ground-state ($m=0$) to first-excited-state ($m=+1$) transition energies for donors located at the centers of the wells ($L_w=200$ Å) and barriers ($L_w=200$ Å) are shown in Fig. 2 by the solid and dashed lines, respectively. In addition, at zero magnetic field, the dipole matrix element for electronic transitions associated with donors located at the center of the barrier layers is predicted[5] to be significantly greater than that for donors located at the center of the quantum wells.

The present observations of the substantial difference in line intensities between the low- and high-energy peaks, the dramatic increase of the integrated intensity of peak 1 with dopant density in the barrier, and the agreement between theory and experiment for the intracenter transition energies verify our assignment of peak 1. The absorption "tail" observed at frequencies above the resonance energy of line 1 is attributed to a distribution of donor atoms *away* from the center of the barriers and, thus, closer to the electrons in the wells. This leads to a distribution of bound states with larger binding and transition energies associated with those positive ions in the barrier located closer to the GaAs/$Al_xGa_{1-x}As$ interface.

The origin of peak 2 is not understood. Several possibilities have been considered; transitions arising from (a) higher-lying excited-state transitions of the barrier impurities,[5] (b) interfacial impurities,[8] and (c) D^- centers.[9] Possibility (a) appears unlikely because the energy of peak 2 does not change as the barrier width is reduced. Possibility (b) appears not to be viable because calculations[5] predict that electronic transitions involving interfacial impurities should occur at a *substantially* lower energy than peak 2. Possibility (c) requires[9] that other transitions occur at integer multiples of the cyclotron resonance energy from peak 2. Evidence for these transitions has not been observed.

Additional measurements were performed after illumination with a red light-emitting diode of the sample nominally undoped in the barrier layers. After this procedure (top trace in Fig. 3), features were observed at the resonance energies of peaks 1 and 2. However, the line strengths were much weaker than those for the corresponding peaks found in the spectra of the samples intentionally doped with Si atoms in the barriers. Apparently, these absorption features were not observed initially because of compensation.[3,4] However, after exposure to light, these absorption features are observed due to trap-

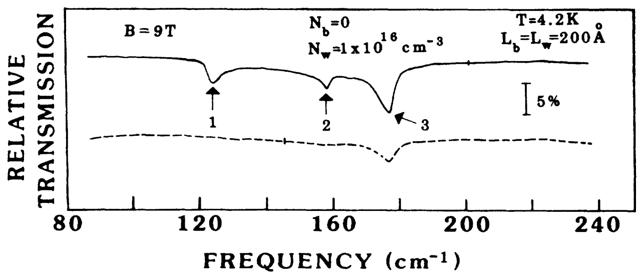

FIG. 3. Representative transmission spectra obtained before (bottom trace) and after (top trace) illumination with a red LED of the sample nominally undoped in the barrier layers. Bars indicate typical noise levels.

ping of optically created electrons in the quantum wells. These electrons could arise from ionization of deep levels in the $Al_xGa_{1-x}As$ and from persistent photoconductivity effects.[10] These observations indicate that infrared studies provide a valuable probe for estimating the concentration of *residual* positively charged defects in undoped barrier layers. From a comparison of the integrated intensity of peak 1 observed after illumination with similar measurements on samples with known dopant concentrations in the barrier, a lower limit for the residual impurity concentration in the barrier layers is estimated to be 10^{15} cm^{-3}. Previous infrared measurements[2-4] on MQW's doped with donors in the center of the wells have observed features similar to that of peak 1. The current investigations suggest that these features arise from residual positively charged defects in the $Al_xGa_{1-x}As$ barriers.

Preliminary measurements[6] have been performed on samples with larger dopant concentrations in the barriers ($N_b = 8\times10^{16}$ cm^{-3}). These spectra reveal a large cyclotron resonance peak ($n \sim 1.5\times10^{11}$ cm^{-2}) and a reduction (8–12 cm^{-1}) of the $1s$-$2p^+$ transition energy (peak 3) as a function of the applied magnetic field at 4.2 K. This shift is suggested to arise as a consequence of screening of the Coulomb interaction[11] and phase-space filling effects.[12] However, the magnitude of the observed shift is less than that inferred from results of recent theory.[11] Similar shifts in line positions have not been observed in samples with the smaller doping concentrations in the barriers because of the absence of *free* carriers (i.e., the electrons are weakly bound) at low temperatures. These results suggest that samples with similar dopant concentrations and profiles but with larger barrier widths should be investigated. For such samples, the binding energy of the electrons bound to positively charged ions in the barriers will be smaller, and therefore it is anticipated that free carriers will exist for lower doping concentrations in the barriers. The smaller concentration of free carriers should allow the low-density limit of screening and phase-space filling effects to be explored.

In summary, far-infrared magnetoabsorption experiments have been carried out on $GaAs/Al_xGa_{1-x}As$ MQW heterostructures that were intentionally doped with Si donors in the centers of the quantum wells and barrier layers. The measurements reveal an absorption feature that is confinement related with an intensity that is proportional to the dopant concentration in the barrier. These observations and the good agreement between the observed and calculated transition energies provide strong evidence for the assignment of this feature to intracenter transitions of electrons in the GaAs wells that are weakly bound to positively charged ions in the $Al_xGa_{1-x}As$ barrier layers. Information regarding the binding of electrons to spatially separated ions is valuable in several respects. First, these measurements suggest that a new type of photoconductive detector can be based upon these ideas. In such detectors, the separation between the ions in the $Al_xGa_{1-x}As$ barrier and the weakly bound electrons in the GaAs quantum well, a design parameter, determines the low energy threshold for detection of radiation. Second, it is well documented that the mobility of modulation doped heterojunctions is reduced if the spacer layer between the dopant atoms in the $Al_xGa_{1-x}As$ and the $GaAs/Al_xGa_{1-x}As$ interface is reduced. The current measurements provide insight into scattering mechanisms that are responsible for this observation.

Note added. Recent angle-dependent measurements performed on the sample nominally undoped in the barrier layers indicate that only a small fraction of the integrated intensities at peaks 1 and 2 (see Fig. 3) are confinement related. Thus, the estimate for the lower limit of the residual impurity concentration in the AlGaAs barrier layers is too large. These results will be discussed in a future work.

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[1]R. L. Greene and K. K. Bajaj, Phys. Rev. B **31**, 913 (1985), and references therein.

[2]B. V. Shanabrook, Surf. Sci. **170**, 449 (1986), and references therein.

[3]N. C. Jarosik, B. D. McCombe, B. V. Shanabrook, J. Comas, J. Ralston, and G. Wicks, Phys. Rev. Lett. **54**, 1283 (1985); N. C. Jarosik, Ph.D. thesis, State University of New York at Buffalo, 1985 (unpublished).

[4]R. J. Wagner, B. V. Shanabrook, J. E. Furneaux, J. Comas, N. C. Jarosik, and B. D. McCombe, in *Proceedings of the Tenth International Conference on Gallium Arsenide and Related Compounds, Biarritz, France, 1984,* edited by B. de Crenoux, Institute of Physics Conference Series 74 (IOP, Bristol and London, 1985).

[5]Pat Lane and R. L. Greene, Phys. Rev. B **33**, 5871 (1986);

R. L. Greene and Pat Lane, *ibid.* **34**, 951 (1986); and (private communication).

[6]E. Glaser, B. V. Shanabrook, R. J. Wagner, R. L. Hawkins, W. J. Moore, and D. Musser, in *Proceedings of the Modulated Semiconductor Structures Conference (MSS-III), Montpellier, France, 1987* (Les Editions de Physique, Paris, in press).

[7]J.-M. Mercy, B. D. McCombe, W. Beard, J. Ralston, and G. Wicks, in *Proceedings of the Seventh International Conference on Electronic Properties of Two-Dimensional Systems, Santa Fe, New Mexico, 1987* [Surf. Sci. (to be published)].

[8]See, e.g., M. H. Meynadier, J. A. Brum, C. Delalande, M. Voos, F. Alexandre, and J. L. Lievin, J. Appl. Phys. **58**, 4307 (1985).

[9]C. J. Armisted, S. P. Naida, P. A. Makado, R. A. Stradling, P. C. Colter, and G. E. Stillman, Solid State Commun. **48**, 51 (1983).

[10]See, e.g., H. L. Stormer, R. Dingle, A. C. Gossard, W. Wiegmann, and M. D. Sturge, Solid State Commun. **29**, 705 (1979).

[11]J. A. Brum, G. Bastard, and C. Guillemot, Phys. Rev. B **30**, 905 (1984).

[12]See, e.g., D. A. Kleinman, Phys. Rev. B **32**, 3766 (1985); S. Schmitt-Rink and C. Ell, J. Lumin. **30**, 585 (1985).