Magnetophotoconductivity Studies of D^0 and D^- Centers in GaAs Quantum Wells in Metallic and Insulating States

Y. H. Chang, T. C. Chen, C. J. Chen, and Y. F. Chen
Department of Physics, National Taiwan University, Taipei, Taiwan, Republic of China
(Received 6 July 1992)

D^0 and D^- states in GaAs quantum wells are studied simultaneously by far-infrared magnetophotoconductivity. In high magnetic fields, the observed sharp transitions are attributed to transitions between ground and excited states of D^0 and D^- centers, respectively. In low magnetic fields, the spectra are dominated by free-electron response. The changes in spectral responses are explained in terms of a magnetic-field-induced metal-insulator transition of the D^0-D^- band.

PACS numbers: 73.20.Dx, 71.30.+h, 78.50.Ge

There has been much interest in the properties of D^- centers in GaAs quantum wells recently [1-3]. A D^- center is a shallow impurity which binds two electrons, and is negatively charged. To form D^- centers, extra supplies of electrons are required. For the bulk material, this is accomplished by illuminating the sample with band-gap radiation or by applying an electric bias to the sample [4]. D^- centers can be found more readily in quasi-two-dimensional systems since the structure can be tailored. With impurities placed at both the quantum wells and the potential barriers, an impurity atom in the well can capture an extra electron released from an impurity atom in the barrier to form a D^- center. In this Letter we report magnetophotoconductivity measurements on D^- and D^0 (neutral impurity) centers in GaAs quantum wells. The measurements are performed using a far-infrared Fourier-transform spectrometer in conjunction with a 9-T superconducting magnet. This system has the advantage that the spectral responses of the sample are taken while the magnetic field is fixed. *Sharp* transitions from the D^- ground state to excited states as well as $1S$-$2P_\pm$ transitions of D^0 centers are observed at magnetic fields higher than 6 T. At intermediate magnetic fields (3-5 T), broadened $1S$-$2P_\pm$ transitions of D^0 centers are observed. At low magnetic fields, free-electron response dominates the spectra. The change in spectral response is shown to be caused by the magnetic-field-induced metal-insulator transition of D^- and D^0 centers.

Two samples were investigated. LM505 has 20 210-Å GaAs quantum wells separated by 21 150-Å $Al_{0.3}Ga_{0.7}As$ barriers. Each well is doped at the center 70 Å with an n-type (Si) impurity concentration of 2×10^{16} cm^{-3}; the barriers are undoped. LM506 has the same structure, doping concentration, and doping position in the quantum well as LM505, but each barrier is doped at the center 100 Å with an n-type impurity concentration of 1×10^{16} cm^{-3}. These two samples were grown consecutively in the same run in a molecular-beam epitaxy system. Ohmic contacts to the sample were made by alloying In dots into the sample in H_2 atmosphere at 420°C for 30 min. The data reported here are photoconductivity responses of the samples at 5 K. In the experiments, magnetic field is applied parallel to the crystal growth (z) direction and data are taken in the Faraday geometry.

Photoconductivity responses of LM505 from 0 to 7 T are shown in Fig. 1(a). Two peaks corresponding to $1S$-$2P_\pm$ transitions can be observed. The peak positions correspond to the intra-D^0 transitions of impurities exactly at the center of the quantum well, which has the largest transition probability because of the large effective density of states [5]. The low-energy tails are intra-D^0 transitions of impurities on both sides of the well center. The transition energies and probability for these impurities are smaller than those for the well-center impurities. The observed transition energies versus magnetic field agree very well with transmission and capacitively coupled photoconductivity measurements performed on similar systems [6], and are also in good agreement with theoretical calculation [7]. Spectral responses from LM506 are depicted in Figs. 1(b) and 1(c). Before we discuss the spectral responses, it is important to note that in LM506, electrons associated with impurities in $Al_{0.3}Ga_{0.7}As$ will find it energetically more favorable to be ionized and stay in the GaAs quantum well. An impurity atom in the quantum well thus has a probability to capture one of these electrons and become a D^- center. Because there are at most 10^{10} cm^{-2} excess electrons (doping concentration × doping width in the barrier) in each quantum well and there are 1.4×10^{10} cm^{-2} impurity atoms in each well, D^0 and D^- centers coexist in each quantum well. D^0- and D^--related transitions are expected to show up simultaneously.

At magnetic fields above 6 T, four peaks can be observed. These fours peaks can be divided into two groups. One group is the $1S$-$2P_\pm$ transitions of D^0 centers. The transition energies as a function of magnetic field of these transitions are the same as is observed in LM505. This indicates that the quantum well widths of these two samples are the same. The other group is D^- related transitions. Because the transition energies for this group are close to those of the intra-D^0 transitions in bulk GaAs, it is important to show that the observed transitions are really D^- related. Tilted-magnetic-field experiments

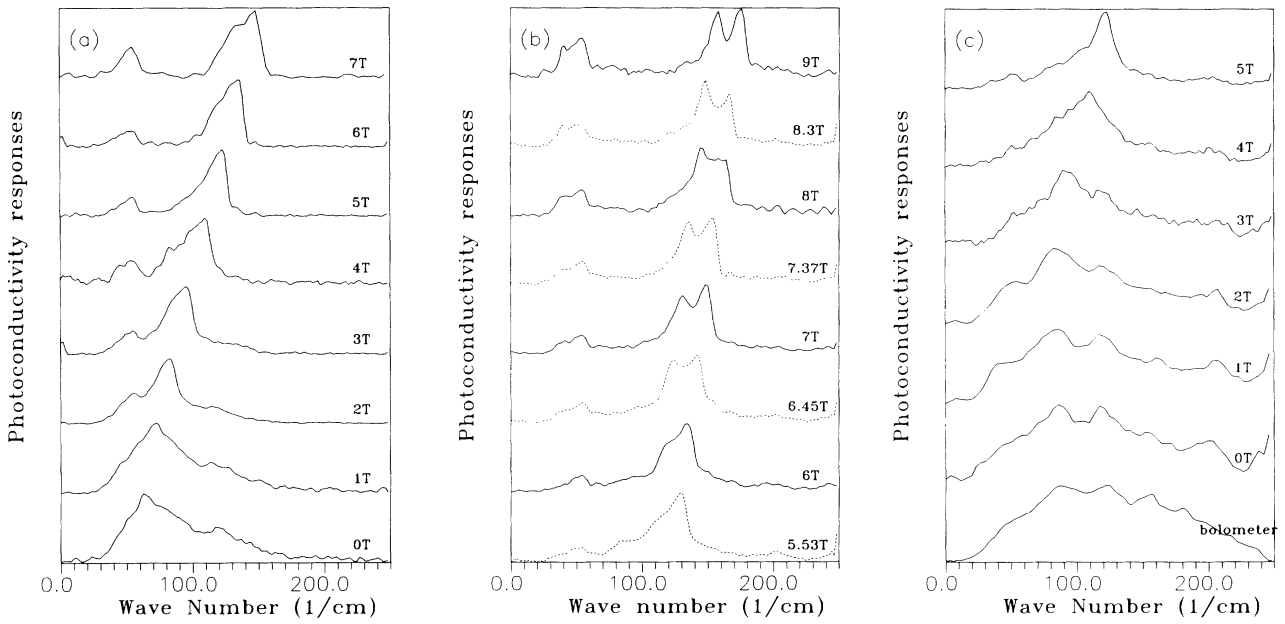

FIG. 1. (a) Spectral response of LM505 from 0 to 7 T at 4.2 K. The high-energy peaks are $1S$-$2P_+$ transitions and low-energy peaks are $1S$-$2P_-$ transitions. (b) Spectral response of LM506 from 5.5 to 9 T. The four peaks, from low-energy to high-energy, are $E^+(0)$-$E^+(-1)$, $1S$-$2P_-$, $E^+(0)$-$E^+(+1)$, and $1S$-$2P_+$ transitions, respectively. Dashed lines are spectra taken at tilted magnetic fields. (c) Spectral response of LM506 from 0 to 5 T, and the response of a Ga-doped Si bolometer. The spectra at 0–3 T are dominated by free-electron response, and from 4 to 6 T, broadened $1S$-$2P_+$ transitions dominate.

were performed with the sample tilted an angle of 23° with respect to the direction of the magnetic field. The dashed spectra in Fig. 1(b) are the results of these experiments. The magnetic-field strength shown in the figure is the magnetic field ($B\cos\theta$) perpendicular to the two-dimensional system. The $B\cos\theta$ rule is obeyed and the observed transitions are all quasi-two-dimensional related.

The two D^--related transitions are assigned, following the notation of Ref. [3], as $E^+(0)$-$E^+(1)$ and $E^+(0)$-$E^+(-1)$, where the former corresponds to the high-energy transition and the latter corresponds to the low-energy transition. Here "+" means that the spatial wave function of the two-electron D^- center is symmetrical and $0, \pm 1$ is the total z-component angular momentum of the electrons. The transition energies of $E^+(0)$-$E^+(\pm 1)$ of the D^- center and $1S$-$2P_\pm$ of the D^0 center as a function of magnetic field are depicted in Fig. 2. Optical selection rules in the Faraday geometry require that the allowed transitions are $\Delta m = \pm 1$, where Δm is the change in total z-component angular momentum. The observed sharp D^--related transitions as well as the consideration of optical selection rules support the assignment of the observed transitions to intra-D^- transitions, i.e., transitions between discrete D^- ground and excited states.

The observed difference in transition energies between $E^+(0)$-$E^+(+1)$ and $E^+(0)$-$E^+(-1)$ is smaller than $\hbar\omega_c$, where $\omega_c = eB/m^*$ is the free-electron cyclotron frequency and m^* is the band-edge effective mass. It has been shown that, for a parabolic conduction band, $1S$-$2P_+$ and $1S$-$2P_-$ as well as $E^+(0)$-$E^+(-1)$ and $E^+(0)$-$E^+(+1)$ both have an energy difference of $\hbar\omega_c$[3,7]. For a conduction band which is slightly nonpara-

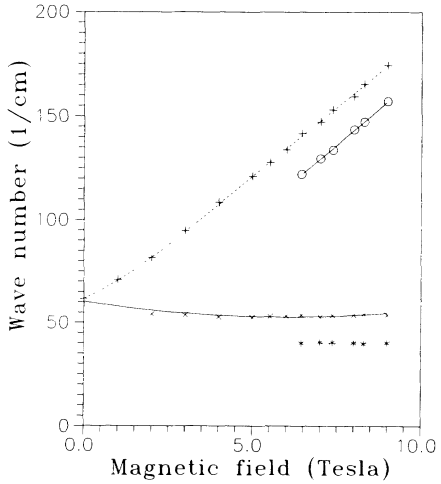

FIG. 2. Transition energies of $1S$-P_+ (+), $1S$-$2P_-$ (×), $E^+(0)$-$E^+(+1)$ (○), and $E^+(0)$-$E^+(-1)$ (*) for samples LM505 and LM506 from 0 to 9 T. The energy difference between $E^+(0)$-$E^+(-1)$ and $E^+(0)$-$E^+(+1)$ transitions is always about 5 cm^{-1} smaller than the energy difference between $1S$-$2P_-$ and $1S$-$2P_+$ transitions.

bolic such as the GaAs conduction band, the difference is slightly smaller than $\hbar\omega_c$. This is observed experimentally for D^0-related transitions. The observed $E^+(0)$-$E^+(+1)$ and $E^+(0)$-$E^+(-1)$ transitions, however, have an energy difference about 5 cm^{-1} smaller than the difference in transition energy between $1S$-$2P_+$ and $1S$-$2P_-$ from 6 to 9 T. This is not due to the nonparabolicity of the GaAs conduction band because in doing the comparison the effect of nonparabolicity has been already included in the energy difference between $1S$-$2P_+$ and $1S$-$2P_-$ transitions. The origin of this systematic deviation is not understood, but the electron-electron interaction is probably responsible for this deviation.

The spectral responses of the system change dramatically from low fields to high fields. This result is attributed to a magnetic-field-induced metal-insulator transition (MIT). It is known that in doped semiconductors, it occurs when $N^{1/3}a_H \sim 0.2$ [8]. Here N is the impurity concentration and a_H is the Bohr radius of an impurity electron. In bulk GaAs, the MIT occurs at an impurity concentration of around 8×10^{15} cm^{-3}. If the criterion is correct for a two-dimensional GaAs impurity system, and the Bohr radius of the electron is assumed to be the same as in the three-dimensional system, then the MIT should occur at a two-dimensional impurity concentration of 4×10^{10} cm^{-2}. This estimation should be regarded as an upper bound of the MIT for the doped two-dimensional GaAs system. In the real system, the Bohr radius in lateral directions is larger than the 3D Bohr radius due to the confinement in the z direction, and the MIT can be expected to occur at a smaller impurity concentration. It is shown that for the D^- center, one electron stays in the $1S$ orbit and the other electron is in the $2S$ orbit [2], and we know that the $2S$ orbit has a radius of $2a_H$. Following the argument presented above, the MIT for D^- centers should occur when the concentration is 1×10^{10} cm^{-2}. Again, this should only be regarded as an upper bound. In our system the concentration of D^- centers is 1×10^{10} cm^{-2}. In addition, there are also 0.4×10^{10} cm^{-2} D^0 centers distributed randomly among D^- centers. In this case there can be substantial overlap between wave functions of D^- electrons as well as overlap between wave functions of D^- electrons and D^0 electrons to form an impurity band at zero field. In this case the spectrum at zero magnetic field is dominated by free-electron response. The low field data shown in Fig. 2(c) are similar to the spectral response of a Ga-doped Si bolometer placed in a similar arrangement. The line shapes reflect the combined effect of beam splitter, filters, and light-pipe optics. The spectral response of a bolometer is nearly flat. The spectral response of the low field data is thus attributed to free-electron response similar to an InSb free-electron detector [9].

As the magnetic-field strength increases, at 3–5 T, broadened D^0-related $1S$-$2P_+$ transitions are observed. The linewidth becomes narrower as the strength of the magnetic field increases. At higher magnetic fields both D^0-related and D^--related transitions can be observed. It is known that magnetic field can shrink the wave function of an electron in the plane perpendicular to the magnetic field. The shrinking of the electron wave function reduces the overlap between electron wave functions of adjacent atoms. As the Mott criterion $N^{1/3}a_H = 0.2$, where a_H is now the Bohr radius of the electron in the presence of magnetic field, is satisfied, the system changes from the metallic state (impurity band) to the insulating state (isolated donors). This is known as a magnetic-field-induced MIT. Our system is more complicated than the usual doped semiconductor system since there are both D^0 and D^- centers in the quantum wells. The change in spectral response can be understood as follows: As the strength of the magnetic field increases, the Bohr radii of both D^0 and D^- centers become smaller in the x-y plane. Since D^0 has a smaller Bohr radius, and is distributed randomly among D^-, the overlap between wave functions of D^0 and D^- disappears first and the D^0 become isolated impurities. So the spectra are dominated by the D^0-related intraimpurity transitions. As the magnetic-field strength increases further, the overlap between electron wave functions of D^- centers decreases even more and at around 6 T, a clear indication of D^--related transitions originating from isolated D^- centers can be observed. The spectral response is thus clear evidence of a metal-insulator transition of the D^0-D^- band.

Further evidence of a magnetic-field-induced MIT is shown in Fig. 3, where the sample resistance measured at 4.2 K is plotted as a function of magnetic field. The sample resistance varies slightly below 5 T but increases significantly above 5 T. This behavior is typical of a magnetic-field-induced MIT in a doped semiconductor system [10]. As discussed before, at low magnetic fields there are substantial interactions between D^- centers to form an impurity band. In this case, the sample resis-

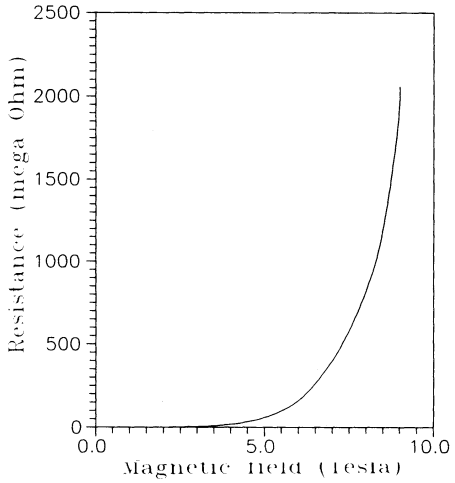

FIG. 3. The resistance of sample LM506 as a function of magnetic field. From 0 to 5 T the resistance does not increase much; above 5 T the resistance increases very rapidly.

tance only has a weak dependence on magnetic field. In the high magnetic-field regime, the interactions between impurities become weak enough that all D^- and D^0 centers can be regarded as isolated centers. In this situation the sample resistance depends strongly on the magnetic field. This is because the number of conduction electrons is proportional to $\exp(-E_B/kT)$, where E_B is the magnetic-field-dependent binding energy, and T is the sample temperature. A small change in E_B can decrease the number of conduction electrons dramatically and therefore lead to a large increase of the sample resistance. The observed MIT transition at around 4–5 T is consistent with the conclusion drawn from the change of the spectral response.

In conclusion, the D^- center in GaAs quantum wells has been studied by far-infrared magnetophotoconductivity measurements. Sharp intra-D^- transitions can be observed in high magnetic fields and they are assigned as $E^+(0)$-$E^+(+1)$ and $E^+(0)$-$E^+(-1)$ transitions. The energy difference of these two transitions is systematically 5 cm^{-1} lower than $\hbar\omega_c$ even after the effect of the nonparabolic conduction band is taken into consideration. From the change in spectral response from low to high magnetic fields, a clear indication of a metal-insulator transition of the D^0-D^- band is observed. The observed transition occurs at around 5 T for a D^- concentration of 1×10^{10} cm^{-2} and D^0 concentration of 0.4×10^{10} cm^{-2} in a 210-Å quantum well.

This work is supported in part by the National Science Council of the Republic of China. The authors would like to thank Dr. C. P. Lee and Dr. K. S. Chang for providing us with the samples. Fruitful discussions with Dr. C. D. Hu are also gratefully acknowledged.

[1] S. Huant and S. P. Najda, Phys. Rev. Lett. **65**, 1486 (1990).
[2] T. Pang and S. G. Louie, Phys. Rev. Lett. **65**, 1635 (1990).
[3] D. M. Larsen and S. Y. McCann, Phys. Rev. B **45**, 3485 (1992).
[4] C. J. Armistead, S. P. Najda, R. A. Stradling, and J. C. Mann, Solid State Commun. **53**, 1109 (1985).
[5] R. L. Greene and K. K. Bajaj, Phys. Rev. B **34**, 951 (1986).
[6] B. D. McCombe, N. C. Jarosik, and J. M. Mercy, in *High Magnetic Fields in Semiconductor Physics,* edited by G. Landwehr (Springer, New York, 1987), p. 238.
[7] R. L. Greene and K. K. Bajaj, Phys. Rev. B **34**, 951 (1986).
[8] N. F. Mott, *Metal-Insulator Transitions* (Taylor & Francis, London, 1974).
[9] L. C. Robinson, *Physical Principles of Far-Infrared Radiation* (Academic, New York, 1973).
[10] Y. J. Wang, B. D. McCombe, and W. Schaff, Surf. Sci. **263**, 547 (1992).