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Studies of far-infrared magneto-photoconductivity of D^- centers in $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ multiple quantum wells

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Abstract

We present magneto-photoconductivity studies on $\text{GaAs}/\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ multiple quantum wells selectively doped with Si donors in the center of the wells and in the barrier layers. Under extra illumination of an He–Ne laser, dramatic results of the D^- centers were observed as a function of the electron density. A band-bending model associated with a “barrier D^- center” configuration was used to analyze the evolution of the binding energy of the spin-singlet D^- transition and magnetic vaporization. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

A D^- center is a neutral shallow donor that binds an additional electron, analogous to a negative hydrogen ion H^- . The D^- centers provide a simplest “many body” system for studying many-body phenomena such as the electron correlation and screening effect. Recently considerable attention has been paid to the study of D^- centers in multiple-quantum-well heterostructures selectively doped with donors both in the wells and in the barriers [1–14]. Various experimental [1–6] (e.g. the magneto-transmission, magneto-photoconductivity, and resonant tunneling) and theoretical [7–14] (e.g. the diffusion quantum Monte Carlo method, local spin density functional scheme, and variational approach) techniques have been developed to understand the nature and properties of D^- centers in quantum wells. Among these experimental studies, electron-density-dependent techniques have been carried out to investigate the many-electron effects in D^- centers [4]. Surprisingly, it was found that the optical transition related to D^- state shifts to higher energy with increasing excess electron density. This result has been attributed to the effects

of the electron–electron interactions and the dynamical screening in a high magnetic field. Nevertheless, the explanations of how the screening affects the transition energy of the D^- states and the relationship between the transition energy and the absorption intensity of the D^- centers are still ambiguous. The authors also found a shoulder appearing on the lower energy side of the cyclotron resonance (CR) and there is no explanation for this observation. Dzyubenko et al. [12] and Hawrylak [14] discussed these striking features and proposed that one should abandon a picture of D^- states and consider a picture of collective impurity-localized magnetoplasma excitations [12–14]. In Dzyubenko’s calculations, there are two infrared-active impurity-localized magnetoplasma modes existing in the spectrum. One of these two modes can then explain the positive energy shift of the D^- centers using an increase in the contribution of exchange effects with an increasing filling factor (ν) [13].

In this article, we present the magneto-photoconductivity of D^- centers in $\text{GaAs}/\text{AlGaAs}$ multiple quantum wells doped with donors in the wells and in the barriers. With the combination of the illumination of far-infrared and visible lasers, we found several interesting D^- center behaviors, which have not been reported before. Based on a band-bending model, due to the charge transfer associated with a “barrier D^- center” configuration, we explain the peculiar behaviors of the D^- transitions. We also observed the

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Fig. 1. Far-infrared magneto-photoconductivity spectrum obtained on GaAs/ $Al_{0.3}Ga_{0.7}As$ multiple quantum wells in Faraday geometry. The data were taken at 4.3 K with constant current $I = 0.5 \mu A$.

magnetic evaporation of the D^- centers by tuning the illuminated power of the He–Ne laser.

2. Experimental procedure

The sample used was grown using molecular-beam epitaxy with twenty $210 \text{ \AA}$ GaAs quantum wells separated by twenty-one $150 \text{ \AA}$ $Al_{0.3}Ga_{0.7}As$ barriers. The quantum wells were grown on a buffer layer $0.5 \mu m$ thick. At the center of each well $50 \text{ \AA}$ was doped with Si to a concentration of $2 \times 10^{16} \text{ cm}^{-3}$. At the center of each barrier $70 \text{ \AA}$ was also doped with Si to a concentration of $1 \times 10^{16} \text{ cm}^{-3}$. The sample was made in the form of a Hall bar to measure the carrier concentration and to prevent resistance caused by the contacts. The quality of the sample was examined using photoluminescence measurement at 10 K. Its free exciton emission peak with the full width at half-maximum of 2.5 meV revealed the good quality of this sample. The magneto-photoconductivity measurements were performed by scanning the magnetic field at a fixed far-infrared wavelength $118.8 \mu m$ under Faraday geometry. We mounted the sample in an optical Dewar at the center of a split-coil superconducting magnet with a maximum magnetic field of 7 T. The measurements were carried out in a constant current configuration and the photoresponse signal was detected as a change in the voltage drop across the sample using a lock-in amplifier. To change the carrier concentration in the wells, we illuminated the sample using a visible He–Ne laser with power densities changing from $5 \mu W \text{ cm}^{-2}$ to 10 mW cm^{-2} . Carrier concentration variations in the sample were estimated from 4.5×10^{10} to $3.6 \times 10^{11} \text{ cm}^{-2}$.

3. Results and discussion

Fig. 1 shows the magneto-photoconductivity response of the sample under the illumination of FIR radiation with a constant current of $I = 5 \mu A$ at 4.3 K. There are six peaks between 4 and 7 T in the spectrum. These peaks cannot be due to the Shubnikov–deHass oscillation, since we performed the measurement for the conductivity as a function of the magnetic field without FIR radiation as published previously [3]. The spectrum shows a monotonous trend without any structures. To ensure that the observed peaks are due to the two-dimensional carriers, tilted-field experiments were performed and showed that they are all confinement-related. The cyclotron resonance, positioned at 6.124 T, was marked as “CR”. Compared with the figure of the magnetic-field transition energy dependence in prior reports, which have a similar structure to our sample [4,8,15], the peaks at 4.1 and 5.85 T can be identified by the D^- ground state to a singlet excited state associated with the Landau level $N = 1$ [4,8] and the intra-impurity transition of an electron in the well bound to a positively charged ion in the barrier [15], respectively. The intra-impurity transition of $1s-2p^+$ for D^0 in the well occurring at 2.32 T is small in this figure. It is probably merged by a large free electron response. The three peaks at 4.57, 4.97, and 5.39 T are not observed in previous studies of similar multiple quantum wells. These peaks were not caused by the impact ionization from a group of high-lying impurity states, which lead to an increase in the sample conductivity. This is because we did not see them occurring in the high-field region with added higher bias, which will impact and ionize the lower energy group of impurities. Rather, these peaks

Fig. 2. Far-infrared magneto-photoconductivity under the additional illumination of a He-Ne laser with different intensity: (a) 0; (b) 5 μW ; (c) 50 μW ; (d) 100 μW ; (e) 500 μW ; (f), 1 mW; (g) 1.5 mW; and (h) 10 mW. The carrier concentrations corresponding to the illuminated power are shown in the figures. The data was taken at 2.9 K with $I = 5$ nA.

may be due to the interexcited state transition, which also occurs at the energy between the D^- transition and CR in bulk GaAs [16,17]. According to the assignment of Najda et al., peaks at 4.57, 4.97, and 5.39 T should correspond to $2p^0-3d^{+1}$, $2s-3p^+$, and $3d^0-4p^+$ transitions, respectively [16].

When the temperature is decreased to 2.9 K and the bias current is reduced to 5 nA, the photoresponse for the magnetic field between 3 and 7 T are shown in Fig. 2(a). The D^- transition and the electrons bound to impurities in the barriers remain. The CR disappears due to the freeze-out of the conduction electrons. As would be expected, interexcited state transitions also disappear under the lower temperature and lower bias conditions [17]. Now, maintaining the measurement with the same conditions except that the sample is illuminated under an additional He-Ne laser, a striking phenomena occurs as shown in Fig. 2(b)–(h). To confirm that the observed signals are due to resonant effects because of the absorption of the FIR radiation, and not caused by other effects (e.g. Shubnikov–deHass oscillation), a test measurement was performed under the illumination of the He-Ne laser only, as shown in Fig. 3. We can see that the photoresponse shows a monotonic trend where it does not contain any structure. The illumination power of the He-Ne laser was changed from 5 $\mu\text{W cm}^{-2}$ to 10 mW cm^{-2} , which corresponds to the carrier concentration of 4.5×10^{10} to $3.6 \times 10^{11} \text{ cm}^{-2}$. Under dark conditions, the carrier concentration is $4 \times 10^{10} \text{ cm}^{-2}$ and the mobility is 3000 $\text{cm}^2/(\text{V s})$. After adding the illumination of a visible laser with a power density of 5 $\mu\text{W cm}^{-2}$, we can see that (in Fig. 2(b)) the D^- transition is suddenly reduced and shifts to a lower magnetic field, which corresponds to a higher binding energy. Such increasing binding energy behavior had also been observed previously [4]. This is completely opposite to the screening effect prediction. If the number of the free carrier is increased, we expect a reduction in the binding energy of impurity states using the background mobile electrons. By increasing the power of the He-Ne laser, the D^- transition shifts gradually back to a lower energy and the intensity grows, as shown in Fig. 2(c) and (d). Meanwhile, two “valley-like” dips appear at 6.16 and 6.23 T. The former dip dominates gradually and leaves the latter as a shoulder. The dip at 6.16 T, which is also found in the magneto-photoconductivity with $I = 0.5 \mu\text{A}$ at 4.3 K (not shown here), was assigned as the CR. As the illuminated power increased again (Fig. 2(e)–(h)), the D^- transition reduced its intensity, and was merged by a new peak 3.78 T afterwards. Another new peak also appeared at 3.23 T at higher He-Ne laser illumination. On the other sides, the shoulder at 6.23 T disappeared first, then the CR began to decrease and was finally suppressed by the background conductivity. It is noteworthy that the sensitive results were only observed at low bias (5 nA), low temperature (2.9 K), and low He-Ne laser illumination power ($<100 \mu\text{W}$). If the bias is larger (e.g. 50 nA) or the temperature is higher (e.g. 4.2 K), these peculiar features would

Fig. 3. Magneto-photoconductivity spectrum obtained on GaAs/Al_{0.3}Ga_{0.7}As multiple quantum wells in Faraday geometry for the sample under the He–Ne laser with the intensity of 1 mW.

disappear from photoresponse contamination produced either from the large bias, high temperature or stronger illumination.

The D^- transition shift to higher energies was observed in previous electron-density-dependent experiment [4]. The positive energy shifts to D^- transition, however, were opposite to the theoretical prediction of the screening effect. This unresolved issue was interpreted later by Dzyubenko et al.

Fig. 4. The creation of band-bending effect in self-consistent electrostatic potential due to the charge transfer of the photoexcited electrons and holes. It shows that the electrons are confined close to the sides of the quantum wells and the donors are confined in a narrower region after the band-bending effect. The horizontal axis represents the space coordinate in the growth direction.

[12] and Hawrylak [14]. Based on Dzyubenko's analysis, when the spatial extension of the D^- states is comparable to the average distance of the free electrons, the magneto-optical impurity transition has to be described in a picture of collective localized magnetoplasma excitations instead of a simple picture of screened D^- states. There are two active localized collective modes developed from the T^+ and T^- transitions of the D^- states lying in different spectral regions, respectively. One of these modes will cause a higher-energy impurity transition shift due to an increase in the contribution of exchange effects with increasing ν : a negative renormalization of the energies of the filled initial states and an increase in the contribution of binary exchange interactions [12,13]. The calculated value of the increased binding energy agrees qualitatively with the experimental shift in Ref. [4]. However, this picture cannot explain our experimental results completely. First, the increased binding energy calculated from the model is on the order of several tenths cm^{-1} which is not comparable with our measured 3.5 cm^{-1} . In addition, this picture cannot explain the peculiar change (an initial increase then a decrease) of the D^- center binding energy in the experiments. Therefore, other mechanisms, which provide the red shift of the D^- center binding energy, should also be involved.

For the excitation using the He–Ne laser with the photon energy 1.96 eV, photogenerated electron–hole pairs can be created in the AlGaAs layers or the Si donors in the barriers may be ionized. The created electrons will transfer to the closest well region the hole may get trapped by the hetero-interface. Thus, the spatial separation of the electrons and positive charges will change the confining potential from a rectangular to a triangular-like shape [18,19], as shown in

Fig. 4. The band-bending effect will cause the electrons move away from the central region of the quantum wells in the growth direction (z -axis). On the other hand, D^- centers with the separation between the electrons and donor ions along the growth direction is in spirit similar to the “barrier D^- center” [9] or “remote D^- center” [11] models where the positive ion is fixed in the z -axis and the electrons are confined in the x - y plane, whose position relative to the positive ion is defined by ζ . According to the “barrier D^- center” concept, the electron-donor attraction decreases with increasing ζ , whereas, the electron–electron repulsion is independent of the electron-donor distance. Hence, at larger ζ values, the electron–electron Coulomb repulsion will eventually dominate, and the electrons may lower their energy by forming strongly angular corrected states in which they are well separated in position. The D^- centers will thus lose the binding energy with increasing ζ and finally become unbound (magnetic evaporation) when ζ exceeds a critical value [9]. Since the band-bending potential will cause the D^- center electron to accumulate away from the center of the wells along the growth direction, we can use the power of the He–Ne laser as a vehicle for tuning the separation between the D^- center electron and the donor ions. In other words, we can study the configuration change of the barrier D^- centers by changing the illuminated power of the He–Ne laser in our sample. In addition to the above electron–electron correlation effect, the screening effect should be considered as well. As the intrinsic illuminated power is increased, the background mobile electron density also increased. This background electron density adjusts itself in response to the impurity potential, causing a screening potential, which reduces the D^- center binding energy. Therefore, not only the bound electrons but also the free electrons may reduce the binding energy.

Let us now try to qualitatively explain the variation in the transition energy of the D^- centers in the experiments. The evolution of the transition energy can be accounted for by the net effect of the magnetoplasma excitation, which leads to the blue shift of the binding energy, as well as the electron correlation and screening effects, which lead to the red shift of the binding energy. In the low-power He–Ne laser illumination, the density of the electrons from excitation is low and the correlation and screening effects are weak. The exchange effect due to the magnetoplasma excitation is pronounced and the binding energy shifts to high energy. Besides, the electrons will move away from the central region of the quantum wells in the growth direction as the potential bends. Therefore, the formation of the D^- centers located in the central region of the well becomes more difficult even as the density of free excess electrons increases. Thus we can explain the blue shift in the transition energy and the reduction of the intensity of D^- centers in Fig. 2(b) quite well. From Fig. 2(b)–(d), the binding energy of the D^- centers begins to decrease as the power of the He–Ne laser increases from 5 to 50 $\mu\text{W cm}^{-2}$. This can be described by the fact that the band-bending potential increases the

separation of the electrons and donor ions along the z -axis and the electron–electron Coulomb repulsion and angular correlation begins to dominate. In addition, the increase of the electron densities, due to the He–Ne laser illumination enhances the screening effect. Both these effects reduce the binding energy of the D^- centers. The D^- center intensities increase in Fig. 2(c) and (d) indicating that the D^- center electrons are distributed in the region which is closer to the edge of the wells where the electron density is larger (due to the band bending effect). We see that the D^- centers are eventually magnetically evaporated with further increases in the He–Ne laser power from Fig. 2(d)–(f). The evolution of the D^- centers is thus in good agreement with the expectations of Ref. [9]. The magnetic boil-off of the D^- centers has been demonstrated very recently by the magnetic-field tuning of the off-well-center D^- states [5]. To the best of our knowledge, this is the first time this phenomenon was observed by tuning the separation of the electrons and donor ions.

The peak at 6.23 T in Fig. 2(c)–(e) may be attributed to the spin-triplet transition of the D^- centers. According to the theoretical calculation [12], two strong spin-triplet transitions $T^\pm$ are expected in the experimental spectrum. The absence of these transitions is due to the fact that they are not distinguished from the CR and $1s$ – $2p^+$ transition of D^0 in the wells. However, we found the energy difference between the CR and adjacent lower-energy peak in Fig. 2(c)–(e) is 1.0 cm^{-1} , which is rather close to the calculated value (1.2 cm^{-1}) for 196-Å well-width quantum well at $B = 6 \text{ T}$ (see Table 1 in Ref. [12]). Thus we suggest that the peak on the low-energy side of CR may be due to the spin-triplet transition of the D^- centers although this assignment requires further confirmation. There are two new peaks positioned at 3.78 and 3.23 T when the pumping power of the He–Ne laser is greater than 1.5 mW cm^{-2} . The former peak was reported as the $1s$ – $2p^+$ transition of the residual donor impurities in the bulk GaAs substrate under similar conditions [20]. The 3.23 T peak also comes from the donor impurity transition of the bulk substrate but is related to the metastable state [21,22], i.e. a state that arises in a magnetic field out of the donor continuum and does not lead to a donor bound state in the zero field limit. Its transition corresponds to $1s$ –(110) [21,22], where the high-field notation (N, m, μ) represents the principle Landau quantum number (N), the usual magnetic quantum number (m), and the number of nodes of the wavefunction in the direction of magnetic field (μ), respectively.

4. Conclusion

In summary, far-infrared magneto-photoconductivity experiments were implemented in the GaAs/ $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ multiple quantum wells to study the D^- centers. We found several novel features when extra visible laser illumination was added. The binding energy of the D^- centers were

interpreted using the combination of magnetoplasma excitation as well as the electron correlation and screening effects. A band-bending model associated with the “barrier D^- center” configuration was used to explain the variations in the binding energy and the magnetic evaporation of the D^- centers in the experiments.

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