BINDING ENERGIES OF D^- ION IN GaAs QUANTUM WELL

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Abstract—Magnetic field dependent binding energies of the D^- ion in the center of a 210 Å GaAs quantum well are determined by temperature dependent magneto-transport measurements. The binding energies increase from 2.1 meV at 2T to 4 meV at 8T, and are consistently higher than the transition energies obtained from magneto-optical measurements performed on the same sample. We conclude from these data that in the magneto-optical measurement the observed transitions are between ground and excited D^- states.

The properties of D^- ions in GaAs quantum wells have attracted much attention recently[1–9]. A D^- ion is a shallow impurity that binds two electrons. The binding energy of a D^- ion is lower than for the neutral impurity (D^0) because of the Coulomb repulsion energy between the two electrons. This is a simple many electron system and is an analogue of the H^- ion in atomic physics. D^- ions can be generated much easier in a quantum well system than in a 3D system[10]. With shallow impurities placed in both GaAs quantum wells and AlGaAs barriers the impurity atoms in the wells can capture an extra electron released from barrier impurities to form a D^- ion. Because of the effect of quantum confinement, the binding energy of D^- ion in quantum well is enhanced over the corresponding three dimensional value. For example, the binding energy of a D^- ion in bulk GaAs is 0.32 meV, while the binding energy of a D^- ion in the center of a 100 Å GaAs quantum is about 1.7 meV[2]. In the presence of a magnetic field, the energy levels of D^- ion are strongly modified. From optical measurements, transitions between D^- ground state to other states can be observed. But there is still some controversy whether the final states in the observed optical transitions are free electron Landau levels or excited states of D^- ion. In the former case, the binding energy of D^- ion can be easily determined from optical transition energies, while in the latter case, the binding energy of D^- ion can not be deduced from the transition energies directly. Here, we report our study on the activation energies of D^- ion in a 210 Å GaAs quantum well in the presence of magnetic field determined from transport measurements.

The sample used in this study is grown by molecular beam epitaxy with 20 layers of 210 Å quantum wells and 21 layers of 150 Å $Al_{0.3}Ga_{0.7}As$ barriers.

The center 70 Å of the wells are doped with n -type impurities of concentration $2 \times 10^{16} \text{ cm}^{-3}$ and the center 100 Å of the barriers are doped with n -type impurities of concentration $1 \times 10^{16} \text{ cm}^{-3}$. Hall pattern is defined by standard photo-lithography technique and contacts are made by alloying In dots into the sample. The sample, after being cooled down in the dark to 5 K is illuminated with red LED for about 1 min. The purpose of light illumination is to eject all the electrons trapped in AlGaAs into GaAs quantum well[11]. After the sample is illuminated with LED, there are nominally $1.4 \times 10^{10} \text{ cm}^{-2}$ neutral impurities and $1.0 \times 10^{10} \text{ cm}^{-2}$ excess electrons in each quantum well if the sample is uncompensated. Because there are not enough excess electrons, not all the neutral impurities can capture an excess electron to form D^- ion. At low temperature, when thermal equilibrium is reached, $1.0 \times 10^{10} \text{ cm}^{-2}$ D^- ions and $0.4 \times 10^{10} \text{ cm}^{-2}$ D^0 in each quantum well are expected. After LED is turned off, the sample resistance reaches a constant value in a couple of minutes. Data were then taken with constant current flowing through the sample in sweeping magnetic field at fixed temperature. Far infrared photo-conductivity response of this sample has been published elsewhere[6]. Both D^0 and D^- related transitions can be clearly identified.

Typical dependence of longitudinal and transverse resistivities, ρ_{xx} and ρ_{xy} , with magnetic field applied along crystal growth (z —) direction are depicted in Fig. 1. Strong temperature dependence of ρ_{xx} and ρ_{xy} is a clear indication of activated transport. Since electron mobility in low magnetic field and low temperature is found to be around $2 \times 10^4 \text{ cm}^2/\text{V-s}$, the condition $\mu B > 1$ is satisfied and the free electron concentration (n_s) is given approximately[12,13] by:

$$n_s = \frac{1}{e} \frac{\rho_{xy}}{\rho_{xx}^2 + \rho_{xy}^2} B. \quad (1)$$

But we also know that for thermally activated transport, n_s is given by $n_s = A \times \exp(-E_a/kT)$, here A is

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Fig. 1. Magnetic field dependence of ρ_{xx} and ρ_{xy} at (a) 7.5 K and (b) 25 K.

a constant, k is Boltzman constant and E_a is the activation energy. The logarithm of free carrier concentration calculated according to eqn (1) for different temperatures and magnetic fields, is plotted against inverse temperature in Fig. 2. It is clear that $\ln n_s$ depends linearly on $1/T$ from 2 to 8 T, and from the slopes of the curves magnetic field dependent activation energies can be determined. These activation energies are assigned as the magnetic field dependent binding energies of D^- ion in GaAs quantum wells. The justification of this assignment is that the binding energies of D^- ion is much lower than the binding energy of D^0 impurity. Thus, in the temperature range studied, the conducting electrons mostly come from the process $D^- \rightarrow D^0 + e$. The number of free electrons released from the process $D^0 \rightarrow D^+ + e$ is too small and can be ignored.

Fig. 2. Temperature dependence of carrier concentration for different magnetic fields.

Fig. 3. ($\square$) Binding energies obtained from transport measurement and ($\blacklozenge$) transition energies obtained from optical measurement for a D^- ion at the center of a 210 Å GaAs quantum well.

The dependence of binding energies of a D^- ion in the center of a 210 Å GaAs quantum well on magnetic fields is shown in Fig. 3. Also shown in the figure are transition energies between D^- ground state ($|1S^2\rangle$) and first excited state ($|1S^12P^+\rangle$) obtained from magneto-photoconductivity measurements performed with sample cut from the same wafer[14]. Here the notation of Ref.[9] is used. As can be seen from Fig. 3, the binding energy of D^- ion increases monotonically with magnetic field and in the low magnetic field region the D^- binding energy increases faster than for the high field region. These results are qualitatively consistent with theoretical calculation. For a quantitative comparison, we can only compare our results with available calculations for D^- ion in bulk GaAs and D^- ion in the center of a 100 Å GaAs quantum well. At $B = 6.7$ T, the binding energies of D^- ion at the centre of a 100 Å GaAs quantum well is 4.1[9] ~ 4.5[2] meV, and the binding energy of a D^- ion in bulk GaAs is 1.9 meV[2]. At the same magnetic field, the binding energy obtained from our data is 3.8 meV which is close to the binding energy of D^- ion in the center of a 100 Å GaAs quantum well and is apparently quite reasonable.

From Fig. 3 we can see quite clearly that the binding energies determined from transport measurements are different from the transition energies obtained from optical measurements. The optical transition energies are always higher than the transport binding energies. These results clearly indicate that in the optical measurements, the observed transitions are from ground to excited D^- states, i.e. $|1S^2\rangle$ to $|1S^12P^+\rangle$ transition, and not from ground D^- state to free electron Landau level. For the latter to be true, the binding energies obtained from optical and transport measurements would be the same. From these data, we can also conclude that the energy level of the first excited state of a D^- ion in a 210 Å quantum well is higher than the lowest

free electron Landau level for magnetic field below 8T.

In conclusion, we have obtained the binding energies of a D^- ion in the center of a GaAs quantum well for magnetic fields from 2 to 8T. The results are quite consistent with theoretical calculations. Comparing the transport and optical data, we conclude that the transitions observed in optical measurements are between D^- ground and excited states. We also show that the first excited state of a D^- ion in the center of a 210 Å GaAs quantum well has an energy higher than the energy of ground state Landau level when the magnetic field is smaller than 8T, as predicted by Ref.[4] and concluded also in Ref.[7].

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