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Magneto-capacitance measurement of a selectively doped n-AlGaAs/GaAs heterojunction with InGaAs quantum dots

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Two dimensional electron systems with quantum dots (QDs) are promising for the device applications such as charge-storage memories [1,2] or interband and intersubband photodetectors [3-5]. In these devices, QDs are placed near a two dimensional electron gas (2DEG) channel and the interaction of the channel electrons by the QDs plays a key role in determining their performances. Several studies have been made on transport phenomena of a 2DEG flowing in the vicinity of QDs and clarified scattering processes of 2D electrons by QDs [6-9].

In this work, we investigate the effect of QDs on a 2DEG in the quantum Hall regimes by magneto-capacitance measurements. The magneto-capacitance between a 2DEG and a gate electrode shows minima in the quantum Hall regimes where the Fermi energy lies between successive Landau levels. These minima were explained by a resistive plate model, in which the total complex capacitance C is given by [10-14]

$$C = C_e + (C_0 - C_e)\frac{\tanh a}{a} \quad , \qquad (1)$$

$$a = \left(\frac{i2pf(C_0 - C_e)K}{s_{xx}}\right)^{\frac{1}{2}} \quad , \qquad (2)$$

where C_0 is the capacitance at zero frequency, C_e is the capacitance due to the edge channel, and s_{xx} is the bulk conductance of the 2DEG. f and K are the frequency of the superimposed ac modulating voltage and a constant which is determined from the sample shape. Here, we compare the resistive plate model with the magneto-capacitance in a selectively doped n-AlGaAs/GaAs heterojunction with InGaAs dots and show that the s_{xx} is frequency f dependent, which is resulted from the presence of the QDs.

For our study, we prepared selectively doped n-AlGaAs/GaAs heterojunctions with embedded InGaAs dots on CrO-doped semi-insulating GaAs (100) substrates by molecular beam epitaxy (MBE). We first grew a 300 nm-thick GaAs buffer layer and a short-period superlattice buffer (20×10 nm-AlGaAs/3 nm-GaAs) and 3 nm GaAs at the substrate temperature T_{sub} = 580 °C. After a 800 nm-thick GaAs layer was grown, we reduced T_{sub} to 510 °C and deposited 6.5 monolayer (ML) of $In_{0.5}Ga_{0.5}As$ to form InGaAs dots which were covered with a 3 nm-thick GaAs. Then a 27 nm-thick GaAs layer was grown while T_{sub} was raised up to the previous value rapidly. We then deposited an undoped 10 nm-thick AlGaAs spacer, a 80 nm thick Si-doped AlGaAs layer with N_{Si} ~ 5.0×10^{17} cm^{-3} and a 10 nm GaAs cap layer. InGaAs dots were again formed on the sample surface under the same growth condition for the analysis of the density and shape of dots by the atomic force microscopy (AFM). It is found that the uncovered $In_{0.5}Ga_{0.5}As$ dots on the sample surface are 4 nm in average height and 20 nm in average diameter and their concentration N_{dot} is 1.3×10^{11} cm^{-2}. The wafer was processed into a Hall bar geometry with a 100 nm-thick Al gate on top where the gated area is 50×500 µm.

We measured the differential capacitance C between the gate and channel by a capacitance bridge (Andeen Hagerling 2700 A) at the modulation frequency f = 120Hz ~ 12kHz. The magnetic field B was applied perpendicularly to the sample by a super-conductive magnet. By using a He^3 cryostat, the temperature of the sample was reduced to 0.4 K. The modulation amplitude of the gate voltage was less than 3 mV so that the measurement signal was not in-

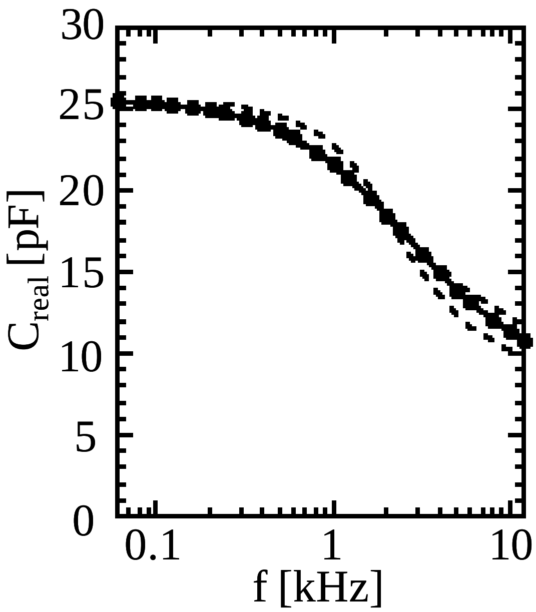

Fig.3 Frequency f dependence of the capacitance C_{real} at the filling factor $n = 2$. The solid and dotted lines are calculated with and without considering the f dependence of the bulk conductance s_{xx}.

fluenced. The f dependence of the differential capacitance C was examined at the capacitance minimum corresponding to the filling factor of the Landau Levels $n = 2$ ($B \sim 3.4$ T). The real part C_{real} of the capacitance C are plotted by solid circles in Fig.3. Experimental data are fitted to Eq. (1) and (2). As shown by the dotted line in Fig. 1, the agreement between theory and experiment is not satisfactory. We also compared the experimental data (solid circles in Fig. 2) and the theoretical values (dotted line in Fig. 2) of the imaginary part C_{imag} of the capacitance C, which results in the disagreement between them. For the sake of comparison, we fabricated a reference sample without InGaAs dots and performed the similar measurement and analysis. In that case, the theoretical values agree well with the experimental data (not shown), which is consistent with earlier works [11,12].

To explain the discrepancy between theory and experiment in our sample, we suppose that s_{xx} in Eq. (2) is dependent on the frequency f. In our sample, the QDs produce potential valleys whose density may be comparable with the QDs. In such dense potential valleys, electrons can transfer from one potential valley to another by tunneling or hopping through a barrier. This transition leads to a frequency dependent (ac) conductivity whose dependency is determined by the relaxation time. In many amorphous semiconductors or some of impurity conductions, the ac conductivity s is explained by the similar mechanism. When the relaxation times extend over a very wide range, s is given by [15-19]

$$s(f) = s_{dc} + Af^{S} \quad (S \le 1) . \qquad (3)$$

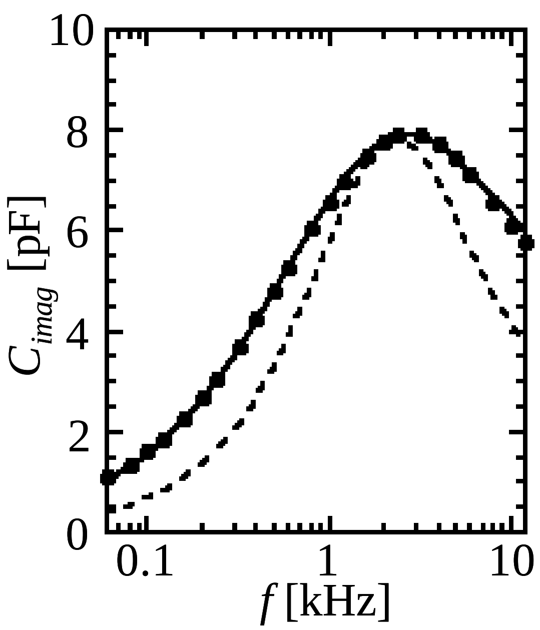

Fig.4 Frequency f dependence of the imaginary component C_{imag} of the capacitance at the filling factor $n = 2$. The dotted line is calculated with a constant bulk conductance s_{xx}.

By comparing Eq. (1) ~ (3) with the experimental data, we found that the good agreement is achieved at s_{dc} ~1.8 nS, $S = 0.51$ and A~0.04 nS sec^{S} as shown by the solid line in Fig. 1 and 2.

In summary, we have investigated the magneto-capacitance of a n-AlGaAs/GaAs selectively doped heterojunction with InGaAs quantum dots (QDs) as a function of the frequency f. By comparing the experimental data with a resistive plate model, we found that s_{xx} behaves like $s(f) = s_{dc} + Af^{S}$, indicating that the electron transitions occur between the potential valleys caused by the QDs.

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