Experimental evidence for screening effects from surface states in GaAs/AlGaAs based nanostructures

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Abstract

We performed low-temperature conductance measurements on a lateral quantum dot device which is electrostatically defined by a split-gate and two overlaying finger gates which introduce tunnel barriers. The observed abrupt change in the measured Coulomb oscillations period is ascribed to the presence of the surface states. Using a simple model, we estimate the surface density of states in our system to be $10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$. This value is an order of magnitude lower than that in a GaAs/AlGaAs two-dimensional electron system. Our studies provide the first non-invasive measurements of the surface density of states in a GaAs system.

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In semiconductors, it was found that a two-dimensional (2D) electron system formed at the interface of a GaAs/AlGaAs heterostructure partially screens an external electric field from an electrode. For example, using a capacitive technique, Eisenstein and co-workers [1] studied a double layer 2D electron systems and measured the fraction of the AC electric field applied by the gate that penetrates one electron layer and impinges the second. Such a study provides important information on the density of states of the screening semiconductor layer.

Consider a lateral quantum dot that is weakly coupled to the source and drain contacts. If the energy required for adding an extra electron to the quantum

dot is much higher than the chemical potentials in the source and drain contacts, transport through the quantum dot is prohibited. This is the Coulomb blockade of single electron tunnelling. By changing the applied gate voltage to align the energy state required for adding an extra electron in the dot, with the chemical potential in the leads, transport through the dot can occur via single electron tunnelling. Thus, one observes a series of periodic Coulomb oscillations as a function of applied gate voltage.

Using both screening in semiconductors and Coulomb oscillations observed in a quantum dot in a double 2DEG, Field et al. [2] have studied a quantum dot shaped in the upper 2DEG where Coulomb oscillations in the quantum dot is observed as a function of back-gate voltage. The period of the observed Coulomb oscillations varies as the penetrating electric

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field through the lower 2DEG is changed. In this way, Coulomb oscillations can be served as a non-invasive probe [3] of local density of states in the lower 2DEG.

To date, GaAs/AlGaAs heterostructure based systems have been one of the most commonly used materials for studying low-dimensional electron behaviours. It is also well known that the high density of surface states in GaAs pins the Fermi energy in the mid-gap of an undoped GaAs layer. However, there are few experimental studies on the screening effect from the surface states in GaAs based materials. Moreover, when attempting to model the electrostatics of GaAs samples, the predicted device behaviour is very critical to the nature of the surface states. In this paper, we use Coulomb charging effects observed in a lateral quantum dot device to estimate the density of the surface states in a GaAs/AlGaAs system using a simple model.

The multilayered gated quantum dot device shown in Fig. 1(a) and (b). In contrast to conventional split-gated quantum dot devices [4], in our system a lateral quantum dot is electrostatically defined by a split-gate, and two overlaying finger gates which introduce tunnel barriers. There is a 30 nm-thick polymethylmethacrylate (PMMA) which has been highly dosed by an electron beam to act as a dielectric [5] between the split-gate (SG) and finger gates (F1 and F2) so that all gates can be independently controlled. The Schottky gate pattern shown was lithographically defined, 157 nm above a 2DEG. The carrier concentration of the 2DEG was $1.9 \times 10^{15} \text{ m}^{-2}$ with a mobility of $250 \text{ m}^2/\text{Vs}$ without illumination. Experiments were performed in a dilution refrigerator at $T = 50 \text{ mK}$ and the two-terminal conductance $G = dI/dV$ was measured using an AC excitation voltage of $10 \text{ } \mu\text{V}$ with standard phase-sensitive techniques. In all cases, a zero-split-gate-voltage series resistance due to the bulk 2DEG ($\sim 900 \text{ } \Omega$) is subtracted.

Fig. 2 shows the conductance measurements $G(V_{\text{SG}})$ when V_{F1} and V_{F2} are simultaneously decreased. Let us first consider the uppermost curve. Consider the 4th single electron tunnelling (SET) peak counted from pinch-off. It is evident that with decreasing finger gate voltage, the same SET peak occurs at a less negative split-gate voltage. Decreasing V_{F1} , V_{F2} and V_{SG} all depletes electrons within the quantum dot. Thus, increasing the negative biases on both F1 and F2 reduces the required V_{SG} for observ-

Fig. 1. Schematic diagrams of the (a) cross-sectional and (b) top view of the device that we studied.

ing the same SET peak. As clearly shown in Fig. 2, the general trend is that all SET peaks shift to less negative V_{SG} with decreasing V_{F1} and V_{F2} .

When we further decrease the finger gate voltage, a striking effect is revealed, as shown in Fig. 2. Over two V_{F1} and V_{F2} ranges as labelled A and B, decreasing V_{F2} becomes “ineffective” in shifting the SET peak position to a less negative V_{SG} . To provide further understanding of this effect, Fig. 3(a) shows the 4th SET peak (labelled in Fig. 2) position in V_{SG} , and Fig. 3(b) shows the measured CB period in V_{SG} at various finger gate voltages. It is evident that there are sudden decrease in the measured period when the peak position remains approximately constant, as illustrated by the dotted lines.

Our multilayered gated quantum dot device was fabricated on an ultra-high-quality high electron mobility transistor. When both finger gates are grounded to the 2DEG, clean ballistic conductance steps with no res-

Fig. 2. $G(V_{SG})$ at various V_{F1} (and V_{F2}). From top to bottom: $V_{F1} = V_{F2} = -1.43$ to -1.53 V in 2 mV steps. Curves have been successively offset for clarity.

onant feature superimposed on top are observed. Also periodic conductance oscillations in V_{SG} are only observed when equal negative biases are applied both on F1 and F2. All these demonstrate that our quantum dot is defined by the surface gates and the impurity scattering within the dot is negligible. The fact that we observe “screening” effects at two different cool-downs strongly suggest that defects within the non-conducting regions of the device [6] have little effects on the screening phenomenon.

The most probable reason is that the surface density of states give rise to the abrupt change in the measured CB period. The density of surface states results from surface reconstruction giving a peak at mid gap. The states may be mobile on the time scale of the measurements and this screen over even over screen the top gates when we vary the finger gate voltage. In this case, the surface states act as a second 2DEG which the electric field can penetrate in the same way as a double 2DEG density of states detector [1]. The work of Field et al. [1] can be explained by the “quantum

Fig. 3. Peak position of the forth single electron tunneling peak in V_{SG} as a function of V_F . (b) Measured Coulomb oscillation period as a function of V_F . The dotted lines serve as a guide to the eye.

capacitance” model proposed by Luryi [7]. We shall follow the procedure described in Ref. [1] to estimate the surface density of states in our system. The geometric capacitance of the finger gate is estimated to be 2.506×10^{-4} F/m². The finger gate area A is given by $2 \times 0.05 \times 0.8 \mu\text{m}^2$ since both finger gate voltages are simultaneously varied.

$$1/C_{QS} + 1/C = 1/C_{tot}, \quad (1)$$

C_{QS} is the quantum capacitance due to the surface states, C is the geometric capacitance per unit area due to the finger gates, and C_{tot} is the overall capacitance per unit area between the finger gates and the quantum dot. We can calculate C_{tot} using the averaged CB period in finger gate voltage and thus C_{QS} can be estimated. The surface density of states dN/dE is then given by

$$dN/dE = e^2 C_{QS}. \quad (2)$$

It is evident that if dN/dE approaches infinity as the surface states perfectly screen the finger gate voltage, leading to a fixed SET peak position in V_{SG} , resulting an “infinite” CB period in V_{SG} . Thus the

Fig. 4. Estimated surface density of states dN/dE as a function of finger gate voltage V_F . Note that the sudden increases in region B can only be considered as a guide to the eye.

inverse of dV_{SG}/dV_F can be considered as a measure of the quantum capacitance. Finally Fig. 4 shows the estimated surface density of states as a function of V_F . We first numerically differentiate the data shown in Fig. 3 (a). Then convert the inverse of dV_{SG}/dV_F using the measured CB period in V_F . As mentioned earlier, dN/dE should approach infinity as the surface states perfectly screen the finger gate voltage. Therefore, the value shown in region (C) can only be considered as a general trend. In principle, our model shows that

over regions (A), (B) and (D), the estimated surface density of states dN/dE is order of $10^{12} \text{ cm}^{-2} \text{ eV}^{-1}$. This is an order of magnitude lower than that in a two-dimensional GaAs/AlGaAs system.

In summary, we have performed low-temperature measurements on a lateral quantum dot defined by a split-gate and two overlaying finger gates which introduce tunnel barriers. Using the measured Coulomb oscillation period, we are able to estimate the “quantum capacitance” of the surface states. Using a simple model in which the measured CB period, we are able to estimate the surface density of states in a non-invasive way, for the first time. Our study shows that surface states can screen the electric fields over a certain gate voltage range. And thus urge further experimental and theoretical studies on the surface effects which can provide better understanding the electrostatics of split-gated devices.

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