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Peculiar Nonlinear Depletion in Double-Layered Gated Si-δ-Doped GaAs

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Abstract: The low-temperature measurement of Hall effect of the two-dimensional electron system in a double-layered gated Si-δ-doped GaAs is presented. A complex peculiar nonlinear dependence of the depletion on gate voltage is observed. The nonlinearity is also explained on the basis of the assumption that the double-capacity model consists of two δ-doped two-dimensional electron layers and a metallic gate, and the experimental result that the electron mobility is linear with the electron density on a log-log scale.

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1 Introduction

For a gated two-dimensional electron system (2DES), it is necessary to investigate the dependence of depletion on the gate voltage when we study the electron transport in the system. It is well known that the depletion of the gated AlGaAs/GaAs two-dimensional electron gas (2DEG) system is similar to the capacity discharge. That is to say, the electron density n linearly decreases with the increase of the negative gate voltage[1,2]. But few articles have presented the studies on the depletion in other 2DES. In this paper, the depletion of 2DES in a double-layered gated Si-δ-doped GaAs is reported in details for the purpose of our studying the singular "metallic-like" behavior of low-temperature electron transport of 2DES in this sample[3]. Some unexpected peculiarities of the depletion are observed. The depletion is characterized as the complex nonlinear dependence of electron density n on the gate voltage V_g. A physical model is suggested to explain the singular effect.

2 Experiment

The sample investigated in this work is taken from the same wafer that has been described in Ref. [4], which consists of an MBE-grown GaAs with delta-doped donor layers at the depths of 270 and 470nm (seen in Fig. 1(a)). The donor atoms are Si with a sheet concentration N_d of 7×10^{11} cm^{-2}. Due to the background compensation by native bulk acceptors, the effective electron density is

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estimated to be 0.5N_d, which corresponds with the initial 2D electron density n_0 of $3.5\times10^{11}\,cm^{-2}$ in each layer. These two layers are connected electrically in parallel in several points of the Hall-bar probes. Measurement of the Hall effect was carried out at 80mK in the Oxford Klevinox dilution refrigerator, with current I not exceeding 0.1nA.

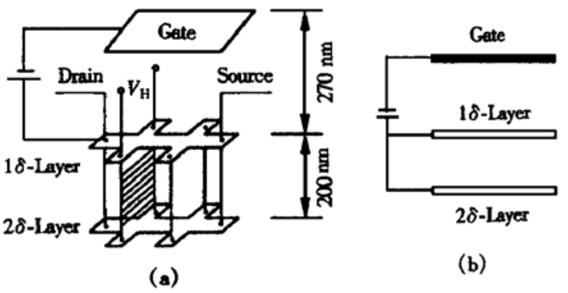

FIG. 1 Schematic Diagram of Sample Structure (a) and Double Capacities Model (b)

3 Discussion and Result

The "depletion curve", plotted with solid diamond symbol, is presented in Fig. 2. The 2D electron density n_H of IB/eV_H is obtained from the Hall effect measurement at 80mK, where B is a perpendicular magnetic field; e is the electron charge; V_H is the Hall voltage that is the average of four experimental values $V_H^{(i=1,2,3,4)}$ of the current and magnetic field in two opposite directions. In our sample, single value of $V_H^{(i)}$ can be measured properly only when $V_g = -3.0V$. At a higher negative V_g, $V_H^{(i)}$ as a function of V_g, undergoes strong changes, though the average V_H can give reasonable values for n_H. Variations in $V_H^{(i)}$ could be contributed to the transition to inhomogeneous conductance of the sample. The inhomogeneity is developed with $|V_g|$ increasing and depletion becoming stronger.

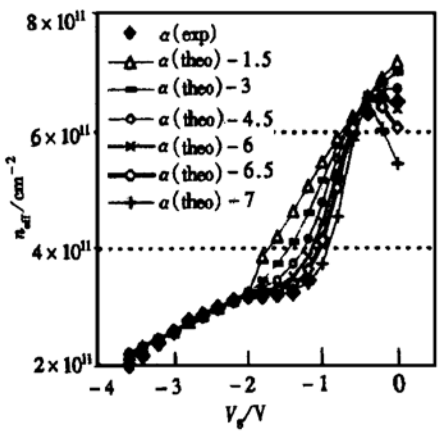

FIG. 2 Experimental and Theoretical Results of Effective Electron Density n_{eff} vs Gate Voltage V_g at 80mK α(exp) represents the experimental curve, and α(theo)-1.5, 3, 4.5, 6, 6.5, 7 represent the fitting result as a_{theo} = 1.5, 3, 4.5, 6, 6.5, 7, respectively.

Our analysis is on the assumption that the depletion starts in the upper (first) δ-layer nearest to the gate electrode when the lower (second) layer is screened by the upper one; while the lower layer starts to deplete only when the negative gate voltage exceeds some value. i.e. $|V_g| > |V_0|$. and the upper layer has depleted completely. This assumption is called double capacities model, as is shown in Fig. 1(b).

Because both conducting δ-layers are responsible for the dependence observed at the relatively small gate voltages, the electron density determined in the Hall measurement is the effective value of n_{eff}. According to the sample's structure, the schematic diagram of the circuit induced by Hall effect is shown in Fig. 3. Where, E_1 and E_2 are the electromotive force induced by Hall effect in the upper and lower δ-layers, respectively; r_1 and r_2 are the transverse resistance in upper and lower layers, respectively; I_1 and I_2 are the current from source to drain in upper and lower layers, respectively. i_0 is the current through the circuit. V_H is the

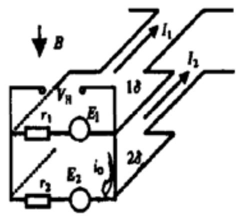

FIG. 3 Schematic Diagram of the Circuit Induced by Hall Effect (See Fig. 1(a) Shadow Face from Left to Right)

Hall voltage. The connection resistance between upper and lower δ-layers can be neglected because of the high density Ge diffusion. Thus, one can obtain the following equation group

$$I = I_1 + I_2$$

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} = \frac{e\mu_1 n_1}{e\mu_2 n_2} = \frac{\mu_1 n_1}{\mu_2 n_2}$$

$$E_1 = I_1 \frac{B}{en_1},\ E_2 = I_2 \frac{B}{en_2}$$

$$i_0 = \frac{E_1 - E_2}{r_1 + r_2}$$

$$r_1 = \frac{\lambda}{e\mu_1 n_1},\ r_2 = \frac{\lambda}{e\mu_2 n_2}$$

$$V_H = \frac{E_1 r_2 + E_2 r_1}{r_1 + r_2}$$

where I is the total current from source to drain in the sample. λ is the structural factor. R_1 and R_2 are the longitudinal resistance of upper and lower δ-layers, respectively. n_1, μ_1, n_2 and μ_2 are the actual (non-effective) electron density and mobility in the upper and lower δ-layers, respectively. It is easy to obtain the following relation from above equation group.

$$V_H = \frac{BI}{e} \times \frac{n_1\mu_1^2 + n_2\mu_2^2}{(n_1\mu_1 + n_2\mu_2)^2} = \frac{BI}{e} \times \frac{1}{n_{eff}}$$

Thus

$$n_{eff} = \frac{(n_1\mu_1 + n_2\mu_2)^2}{n_1\mu_1^2 + n_2\mu_2^2} \quad (1)$$

In case $|V_g| < |V_0|$, only the upper δ-layer is depleted. In the interval of $|V_g|$, both n_1 and μ_1 depend on V_g, while n_2 and μ_2 are constant. Due to the initial compensation, negatively charged acceptors are situated in the bulk GaAs while positively charged donors of the equal number are in the δ-layers even when $V_g = 0$. As a result, a built-in voltage V_1^{bi} appears between the gate and the first δ-layer, and a voltage V_2^{bi} appears between the first and the second layers. Considering the similarity of the two layers and the homogeneity of acceptor distribution, one can suppose that V_2^{bi} is close to zero. Nevertheless, it redistributes a small amount of carries between two δ-layers. Based on the analysis above, one can use the relation

$$n_1(V_g) = C_{g1}(V_g - V_1^{bi})e + N_d/2 - C_{12}V_2^{bi}/e \quad (2)$$

where C_{g1} is the capacitance of the structure "gate electrode-first d-layer", which is equal to the geometric capacitance of two plates placed in a dielectric with the permit of GaAs ($e = 13.2$) at the distance of 270 nm (in our sample, $C_{g1} = 43\mathrm{nF/cm^2}$). C_{12} is a geometric interlayer capacitance. Correspondingly, at a low $|V_g|$,

$$n_2 = N_d/2 + C_{12}V_2^{bi}/e \approx \mathrm{const} \quad (3)$$

Figure 4 shows the curve of effective mobility μ_{eff} versus the effective electron density n_{eff} on a log-log scale. When the upper δ-layer has been depleted completely, $\lg\mu_{eff}$ is linear with $\lg n_{eff}$ for the lower δ-layer, where $\mu_{eff} = \mu_2$ and $n_{eff} = n_2$. So, for the second δ-layer

$$\lg\mu_2 \propto \lg n_2$$

It can also be written as

$$\mu_2 = A n_2^{\alpha}$$

where α is the corresponding slope of the line shown in Fig. 4, and A is a constant. For the first δ-layer, there is a similar relation to second δ-layer.

$$\mu_1 = A n_1^{\alpha}$$

Thus, the relation between the mobilities is assumed to be

$$\mu_1/\mu_2 = (n_1/n_2)^{\alpha} \quad (4)$$

Substituting both (4) and (2) into (1), one can obtain

$$n_{eff} = \frac{[1 + (n_2/n_1)^{1+\alpha}]^2}{1 + (n_2/n_1)^{1+2\alpha}} \times [C_{g1}(V_g - V_1^{bi})/e + N_d/2 - C_{12}V_2^{bi}/e] \quad (5)$$

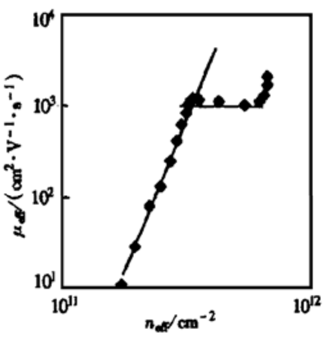

FIG. 4 Experimental Result of Effective Mobility μ_{eff} vs Effective Electron Density n_{eff}

If $n_2(V_g) = n_2(0) =$ const, carrying out the fit with V_1^{bi}, V_2^{bi} and a as adjustable parameters, one can recover $n_1(V_g)$ and n_2 at small gate voltages. The best fit is observed when $\alpha_{theo} = 6.5$, $V_1^{bi} = -0.46$V and $V_2^{bi} = 0.02$V. The results of the fit are shown in Fig. 2. According to Fig. 4, it can be found that the slope $\alpha_{exp} \approx 6.9$, and the fitting α_{theo} in good agreement with the experimental α_{exp}.

According to our initial insight, the second part of the experimental dependence shown in Fig. 1 corresponds to the change in electron density in the lower δ-layer only, because the first delta-layer is empty at a certain gate voltage V_0. Consequently, defining the capacitance between the gate and the second delta-layer as C_{g2} (in our sample $C_{g2} = 25$nF/cm^2), one can write the following relation when $|V_g| > |V_0|$:

$$n_2(V_g) = N_d/2 + C_{g2}[V_g - V_0 + V_1^{bi}]/e + C_{12}V_2^{bi}/e \quad (6)$$

where V_0 is an adjustable parameter. Then V_0 obtained is -2.07V. The experimental data can be fitted by using Eq. (6) unless $|V_g| > 3.4$V. Quick depletion under a higher V_g may be due to the inhomogeneous electron distribution in δ-doped 2DES[5,6]. Further experiments are needed to clarify the influence of sample inhomogeneity on the depletion in 2D system.

4 Conclusions

In this paper, a complex nonlinear depletion is reported as a function of gate voltage in a double-layered gated Si-δ-doped GaAs. Moreover, it is observed that lgμ is linear with lg$n$, lg$\mu \propto$ lg$n$, and the slope a of this linear relation is about 6.9. This depletion phenomenon is also explained based on the above experimental result and the assumption of double capacities model, which consists of two δ-doped 2D electron layers and a metallic gate. At a result, the theoretical α_{theo} agrees well with the experimental α_{exp}.

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带门极双层 Si-δ-掺杂 GaAs 中的奇特非线性耗尽

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摘要: 报道了带门极双层 Si-δ-掺杂 GaAs 样品中的二维电子系统 Hall 效应的低温测量实验, 观察到了电子耗尽过程中电子浓度与门电压的奇特、复杂的非线性关系. 根据双电容器 (由两个 δ-掺杂二维电子层和一个金属门电极构成) 模型的假设和在双对数坐标中电子迁移率与电子浓度呈线性关系的实验结果, 解释了这一非线性耗尽现象.

关键词: 非线性耗尽; 带门极双层 Si-δ-掺杂 GaAs

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