Study of the critical density of the metal-insulator transition in two dimensional systems

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The aim of this paper is to study the critical density n_c of the metal-insulator transition in two dimensional electron systems for sample Si-15 MOSFETs. Many methods are used in this investigation that had used previously for other samples. The motivation of this study is the observation of many values of the critical density n_c that are slightly different. We used here four methods in the goal to infer which one is more appropriate to determine n_c.

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1. Introduction

The study of the metal-insulator transition (MIT) in two dimensional (2D) electron systems has been a subject that attracts intense interest and has been controversially debated for three decades [1] since the pioneering discovery of the MIT in 2D systems by Kravchenko et al [2]. Abrahams et al [3] developed the of one parameter scaling theory (OPST) who assumes that all states in 2D electron systems are localized, therefore it denied the existence of Metal insulator transition in 2D. It is interesting to signal here that the OPST neglects electron-electron (e-e) interaction, and after discovering the MIT in 2D electron systems, most of work was focused on the e-e interaction and there effect on metallic behaviour of 2D electron systems[4-8]. In general, the nature of the basic physics of MIT in 2D still up to now not understood [9, 10].

One important character of the MIT is the critical density n_c, where the transition occurs. Many methods are used to identify this critical density: the temperature derivative of the resistivity, the logarithmic derivative, the percolation approach and the study of low-temperature magneto transport in a parallel magnetic field. These methods give different values of n_c [11].

In this paper, we report values of the critical density obtained from each method and comparing each other.

2. Experimental details

We present DC-transport measurements on five Si-MOS structures Si-15A with peak mobility $\mu = 4.1 m2/Vs$, Si-2Ni ($\mu = 3.8$), Si-22 ($\mu = 2.6$), Si-43 ($\mu = 1.7$), and Si-43 ($\mu = 0.5$). The experiments are carried out at low temperature up to 3.25 K in Si-15 sample with different carrier densities ns in the range $0.449 - 4.98\ 10^{11}\ cm^{-2}$ [12]. The resistivity and Hall measurements were performed in a 3He cryostat at temperature down to 325 mK. The samples consist of 5 mm long and 0.8 mm wide Hall bars, covered with 190 nm thick Si-Oxide layer serving as an insulator and a 1000 nm thick Al-gate on top.

3. Results and discussion

3.1 The temperature derivative of the resistivity

In this method, the critical density n_c is located when the derivative $\frac{d\rho}{dT}$ change the sign. This criterion is often used to identify the MIT. A positive (negative) sign of the derivative at the lowest achievable temperatures is empirically associated with a metallic (insulating) phase, this can be described by eq (1):

$$\begin{cases} d\rho/dT < 0 & for\ \ n_s < n_c \\ d\rho/dT = 0 & for\ \ n_s = n_c \\ d\rho/dT > 0 & for\ \ n_s > n_c \end{cases} \quad (1)$$

This method is used Pudalov et al [12], and it turns out that $n_c = 0.719 x 10^{11} cm^{-2}$ for sample Si-15 MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistor).

3.2 The percolation approach

In previous work [13], we demonstrated the existence of percolation type of transition in Si-MOSFETs sample

using the same method used by Lai et al in ref [14]. This method consist to plot of $\sigma_0(n)$, the T = 0 conductivity obtained by linear extrapolation of the curves of $\sigma(T)$ for different values of electron density n_s. Fig. 1 shows the bent obtained by plotting σ_0 versus different values of density n_s, and this bend is just located at the critical density $n_c = 0.72\,x10^{11}cm^{-2}$ where the transition between the insulating and the metallic behaviour occurs.

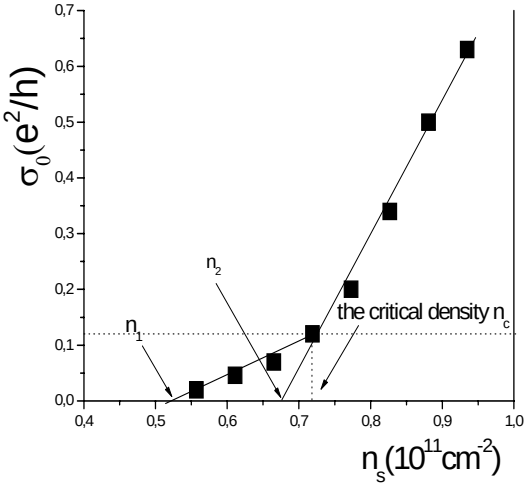

Fig 1. The T = 0 K conductivity σ_0, extrapolated from the T linear fit is plotted as a function of the carrier densities n_s. The solid lines are linear fits on both low-n_s and high-n_s regimes and they extrapolate to σ_0 = 0 at $n_1 = 0.52\times10^{11}cm^{-2}$ and $n_2 = 0.68\times10^{11}cm^{-2}$, (respectively. For more details see ref [13]).

3.3 The logarithmic derivative approach

The third approach is used by Möbius in ref [15] and by Mack et al [16] to studying ultrathin metal films. In this method consist, we calculates the derivative $d\log\sigma/dn_s$, where σ is the conductivity of sample Si-MOSFETs, and then plotted as a function of electron density n_s. For this procedure, we fix temperature and tuning the carrier density n_s for each value of temperature, Fig. 2 shows a sharp pick independent of temperature. For each temperature the pick is located just at $n_c = 0.98x10^{11}cm^{-2}$, and it is marked by arrow in Fig. 2.

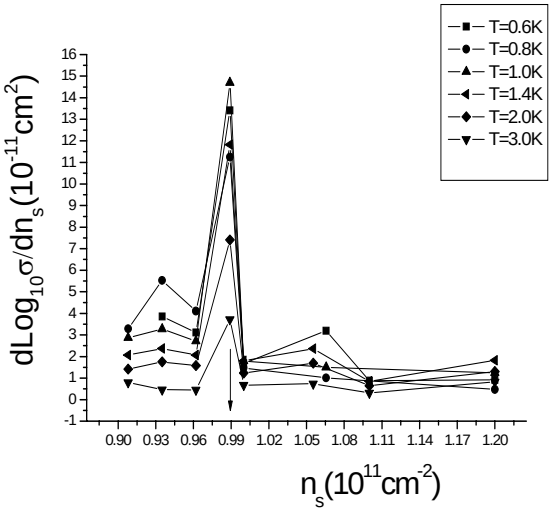

Fig. 2. $d\log\sigma/dn_s$ plotted against n_s for sample Si-15 for different values of temperature as indicated in legend.

3.4 Low-temperature magneto transport in a parallel magnetic

In the last method, we have studied low-temperature magneto transport in a parallel magnetic field. It turns out that the magnetic field, B_c; required to fully polarize electron spins, is a strictly linear function of the electron density n_s [17, 18], and $B_c(n_s)$ vanishes exactly at $n_s = n_c = 0.95\,x10^{11}cm^{-2}$ [19]. Fig. 3 shows B_c versus electron density n_s, and the critical density n_c is marked by arrow.

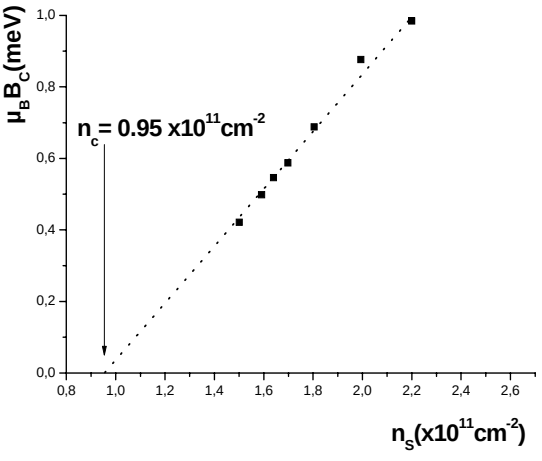

Fig. 3. Polarization field B_c plotted as a function of the electron density n_s.

The first observation by comparing these results is that, in one hand, the value obtained from first method and that obtained from the percolation approach are the same: , and on the other hand, the values obtained from the third and the fourth method are almost equal. This difference between the values of n_c obtained from each method can be explained as follows: either the first and the second methods are wrong, either the third and the firth methods are wrong, more precisely, they are not made with high accuracy. The more appropriate methods are the first and the second one, because using a magnetic field induces many other phenomenons, which are not considered during measurement, and who came disturbs the exact value of n_c.

Generally, those results are not surprising, because the nature of 2D MIT is not understood yet up to now, and it stills an ambiguous subject.

4. Conclusion

In summary, we studied the critical density of the MIT for sample Si-15 MOSFETs, trying to determine the exact value of the critical density n_c. We used four methods: The temperature derivative of the resistivity $\frac{d\rho}{dT}$, the percolation approach, the logarithmic derivative $d\log\sigma / dn_s$ and, low-temperature magneto transport in a parallel magnetic. The first two methods gives the same value of n_c, while the last two gives also the same value of n_c slightly greater, but the more appropriate is the first and the second methods.

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