Hopping in Si-MOSFETs near the 2D metal-insulator transition

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Abstract

We investigated the temperature dependence of resistivity of a high mobility Si MOSFET in the insulating regime near a 2D metal-insulator transition. Coulomb hopping in a wide range of temperature and carrier density was found. Quantitative analysis of the results suggests that electron-electron interaction is screened by the metal-gate as the localization length increases. The hopping is highly correlated, i.e. the observed hopping energy is one order of magnitude smaller than the expected value from a single-particle hopping picture.

Key words: Coulomb hopping, metal-insulator transition, hopping energy

1. Introduction

Recently many experiments showed evidence of the metal-insulator transition in 2D [1]. The experiments cover various materials, orders of magnitude in disorder, and different sample geometry. While all these results are well-understood in a phenomenological level to indicate that this belongs to a certain type of phase transition, a solid understanding of what drives an insulator to a metal has not been accomplished yet. Most studies so far have approached this transition from the metallic side and are more focused on the region near the transition point. We here present the behavior of hopping conductivity in a strongly localized state as the metal-insulator transition is approached from the insulating side.

All of our samples are generic Si-MOSFETs with rectangular gates and moderate peak mobility ($\mu_p \simeq 0.5 m^2/Vs$) at $T = 4K$. The devices have 50nm of oxide deposited onto the lightly p-doped ($\sim 10^{15} cm^{-3}$) substrates. One is 5 μm long (S-5) and has the metal-insulator transition point at an electron density $n_c \simeq 1.7 \times 10^{15}/m^2$ [2]. Another sample (S-50) is 50 μm long (has slightly lower mobility than S-5) and has $n_c \simeq 1.1 \times 10^{15}/m^2$. The sample temperature was controlled in a dilution refrigerator in the range between $4K$ and $0.05K$. Two-probe measurements were performed with small AC signals ($V_{exc} < 2\mu V$) from lock-in amplifiers.

2. Results and Analysis

Hopping resistivity can be described by

$$\rho = \rho_o \exp(r_c/\xi), \tag{1}$$

where r_c is the characteristic hopping length scale. Across the Coulomb gap and screened Mott hopping regimes, the length r_c has the form [3],

$$\begin{aligned} r_c/d &= (\xi/d) ln[(\rho(T)/\rho(\infty)] \\ &= [C_{ES} f(x)/x]^{1/2}, \end{aligned} \tag{2}$$

where $x = T/T_\xi$, and $T_\xi = e^2\xi/\epsilon k_B d^2$, k_B is Boltzmann's constant, e is carrier charge and ϵ encodes the dielectric response of the 2D gas and the oxide. For sample S-5, neither the Efros-Shklovskii nor the Mott exponent appears in the bare $\rho(T)$ data. So fol-

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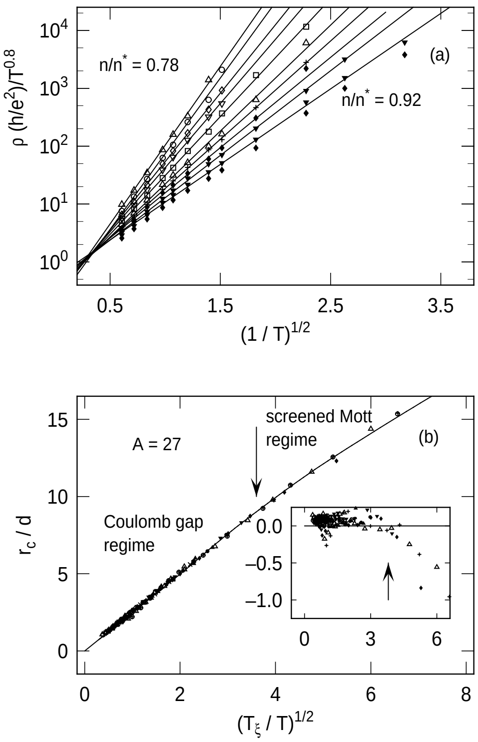

Fig. 1. (a) $\rho(T)$ for sample S-5, with the temperature-dependent prefactor, $T^{0.8}$. We assume that prefactor comes from the conventional phonon-assisted hopping mechanism. (b) Values of r_c inferred from (a) follow the scaling curve (solid line) derived in [3]. The inset is a plot of $r_c/d - \sqrt{C_{ES}T_\xi/T}$ *vs* $\sqrt{T_\xi/T}$ highlighting the crossover (marked by arrows) from Coulomb gap hopping to Mott hopping as temperature decreases.

lowing reference [5], we have observed that the exponent 1/2 is recovered when ρ in Eq. (1) is replaced by $\rho/T^{0.8}$. This extra temperature-dependent factor was attributed there to phonon-assisted hopping. [5–7] The localization lengths are obtained from the high temperature limit as

$$\xi = C_{ES}e^2/\epsilon k_B T_{ES} \tag{3}$$

where T_{ES} is the hopping energies in Coulomb hopping regime, and the single-electron hopping constants C_{ES} is 6.2. However, we found that using the single-particle hopping amplitude (6.2 in 2D) gives unreasonably high localization lengths. Therefore, we believe that the correlated hopping is dominating and the hopping amplitude must be renormalized by a reduction factor A (from the fit, $A \simeq 27$ within 10 % error for both S-5 and S-50).

T_{ES} appears to vanish as density approaches to the metal-insulator transition point. Because the localization length is inversely proportional to the hopping energy, T_{ES}, the localization length diverges at $n = n^*$. It turns out that n^* is the same as n_c in sample S-5. In larger samples, however, S-50, n^* is slightly less than n_c. In all samples (including Ref. [4]) the localization length diverges in the same power-law form, $1/\xi \sim (n - n^*)^{4/3}$.

3. Conclusion

Experimental data show the existence of a crossover due to screening and provide evidence for correlated hopping. In addition there is evidence for the scaling of $1/\xi$ to zero as the carrier concentration n approaches a critical value (*ie* the metal insulator transition).

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