Interface charged impurity scattering in semiconductor MOSFETs and MODFETs: temperature dependent resistivity and 2D "metallic" behavior

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Abstract

We present the results on the anomalous 2D transport behavior by employing Drude-Boltzmann transport theory and taking into account the realistic charge impurity scattering effects. Our results show quantitative agreement with the existing experimental data in several different systems and address the origin of the strong and non-monotonic temperature dependent resistivity.

I. INTRODUCTION

A large number of recent experimental publications on low temperature transport measurements in low-density high mobility two dimensional (2D) electron systems in Si MOSFETs [1], GaAs MODFETs [2], and SiGe hetrostructures [3] report an anomalously strong temperature dependent resistivity in the narrow regime of 0.1-5K. In contrast to the usual Bloch-Grüneisen theory of essentially a temperature-independent low-temperature resistivity, the measured resistivity changes by as much as a factor of ten for a 1-2K increase in temperature. This observed anomaly has led to a great deal of theoretical activity [4,5] involving claims of an exotic metal or even a superconducting system at the interface producing the strong temperature dependent resistivity, which has no known analog in ordinary three dimensional metallic behavior. Much more interest has focused around the possibility of a 2D metal-insulator quantum phase transition being responsible for the observed strong temperature dependent resistivity since theoretically a 2D electron system at T=0 has so far been thought to be (at least in the absence of electron interaction effects) an insulator [6].

In this paper we provide a theoretical explanation for the temperature dependent resistivity of the 2D systems in the "metallic" phase $(n_s \geq n_c)$, where n_s is the 2D density and n_c the critical density which separates "metallic" and "insulating" behavior) in the absence of magnetic field [7] by using the Drude-Boltzmann transport theory with RPA screening and the Dingle temperature approximation to incorporate collisional broadening effects on screening [8]. In our approach we leave out quantum corrections, including localization effects, and neglect the inelastic electron-electron interaction, which may well be significant in the low density 2D systems of experimental relevance. Our calculated resistivity agrees quantitatively with the existing experimental data [1–3] on the temperature dependent low-density resistivity of 2D electron systems. We find that the strong temperature dependence arises from a combination of two effects: the strong temperature dependence of finite wave vector screening in 2D systems and a sharp quantum-classical crossover due to the low Fermi temperature in the relevant 2D systems.

II. THEORY

We use the finite temperature Drude-Boltzmann theory to calculate the ohmic resistivity of the inversion layer electrons, taking into account only long range scattering by the static charged impurity centers with the screened electron-impurity Coulomb interaction. The screening effect is included within the random phase approximation (RPA) with the finite temperature static RPA dielectric (screening) function $\kappa(q, T)$ given by

$$\kappa(q,T) = 1 + \frac{2\pi e^2}{\bar{\kappa}q} F(q) \Pi(q,T), \tag{1}$$

where F(q) is the form factor for electron-electron interactions and $\Pi(q,T)$ is the static polarization. We assume that the charged impurity centers are randomly distributed in the plane parallel to the semiconductor-insulator surface. Within the Born approximation the scattering time $\tau(\varepsilon,T)$ for our model is given by

$$\frac{1}{\tau(\varepsilon, T)} = \frac{2\pi}{\hbar} \int \frac{d^2k'}{(2\pi)^2} \int_{-\infty}^{\infty} N_i(z) dz \left| \frac{v_q(z)}{\kappa(q, T)} \right|^2 (1 - \cos\theta) \delta\left(\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{k}'}\right), \tag{2}$$

where $q = |\mathbf{k} - \mathbf{k}'|$, $N_i(z)$ is the impurity density of the charged center, $\theta \equiv \theta_{\mathbf{k}\mathbf{k}'}$ is the scattering angle between \mathbf{k} and \mathbf{k}' , $\varepsilon = \epsilon_{\mathbf{k}} = \hbar^2 k^2 / 2m$, $\epsilon_{\mathbf{k}'} = \hbar^2 k'^2 / 2m$, $v_q(z)$ is the 2D

electron-impurity Coulomb interaction. In calculating the Coulomb interaction and the RPA dielectric function in Eq. (1) we take into account subband quantization effects in the inversion layer through the lowest subband variational wavefunction. The resistivity is given by $\rho = m/(ne^2\langle\tau\rangle)$, where m is the carrier effective mass, n the effective free carrier density [5], and $\langle\tau\rangle$ the energy averaged scattering time. The average is given by $\langle\tau\rangle = \int d\varepsilon \tau(\varepsilon)\varepsilon \left(-\frac{\partial f}{\partial\varepsilon}\right)/\int d\varepsilon \left(-\frac{\partial f}{\partial\varepsilon}\right)\varepsilon$, where $f(\varepsilon)$ is the Fermi distribution function, $f(\varepsilon) = \{1 + \exp[(\varepsilon - \mu)]/k_BT\}^{-1}$ with finite temperature chemical potential, $\mu = \mu(T, n)$, which is determined self-consistently.

III. RESULTS AND CONCLUSION

It is physically instructive to first consider the asymptotic behavior of the temperature dependent part of resistivity, $\rho(T)$. In the quantum regime at low temperature, $T \ll T_F$ with $T_F \equiv \mu(T=0)/k_B$, the dominant behavior of $\rho(T)$ is linearly increasing with T, i.e., $\rho(T) \propto T/T_F$ arising from the temperature dependent screening, $\kappa(q,T)$ [8]. In the high temperature limit $(T \gg T_F)$ corresponding to the classical regime, the resistivity is decreasing with temperature, i.e., $\rho(T) \propto T_F/T$ due to the energy averaging of τ . For intermediate temperatures $(T \sim T_F)$ the system crosses over from a non-degenerate classical to a strongly screened degenerate quantum regime [5].

In Fig. 1 we give our numerically calculated resistivity $\rho(T,n)$ for the Si-12 sample of Ref. [1] using the effective carrier density $n=n_s-n_c$ [5] at several values of $n_s>n_c$ and different Dingle temperatures. The impurity density, N_i , sets the overall scale of resistivity $(\rho \propto N_i)$, and does not affect the calculated T and n dependence of $\rho(T,n)$. We obtain, at low densities, both the observed non-monotonicity and the strong drop in $\rho(T)$ in the $0.1 \sim 2K$ temperature range [1–3,9]. Our high density results show weak monotonically increasing $\rho(T)$ with increasing T similar to experimental observations [1–3]. In the inset we show the analytic zero temperature conductivity as a function of density n_s , following the approach of Ref. [10]. An approximately linear dependence is in a good agreement with the $T \to 0$ extrapolation of the experimental [1] resistivity. Obtained results suggest that the reduced effective density and not the total value contributes to conductivity and supports our basic freeze-out or binding model [11]. These analytic results coincide with the full numerical calculation, further justifying validity of our methods.

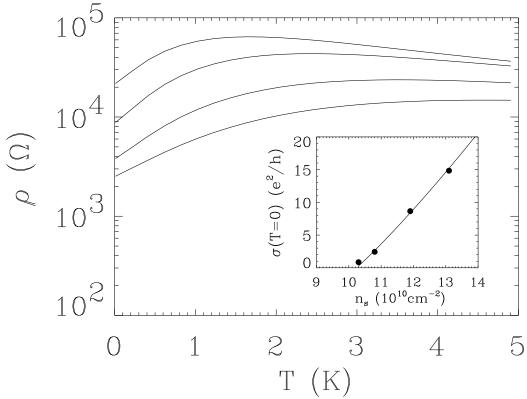


FIG. 1. The calculated resistivities for various electron densities, $n_s = 1.03$, 1.08, 1.19, $1.31 \times 10^{11} cm^{-2}$ (top to bottom) as a function of T for the Si-12 sample of Ref. [1], using the critical density $n_c = 10^{11} cm^{-2}$. In the inset we show the analytic zero temperature conductivity as a function of density n_s . Points represent extrapolated $\sigma(T \to 0)$ from Si-12 sample of Ref. [1].

In conclusion we obtain good agreement with the experimental results. The strong temperature dependence of resistivity at low and intermediate densities $(n_s \geq n_c)$ arises from the temperature dependent screening and a low Fermi temperature by virtue of the low effective carrier density. Thus, charged impurity scattering, carrier binding and freeze-out, temperature and density dependence of 2D screening, and classical to quantum crossover are playing significant roles in the experiments and can not be neglected in theoretical analysis of the "2D M-I-T" phenomenon.

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