Thermodynamic Signature of 2D Metal-Insulator Transition

M.V. Cheremisin

A.F.Ioffe Physical-Technical Institute, St.Petersburg, Russia

A great deal of interest has been focussed on the anomalous behavior of 2D electron(hole) systems,[1] whose resistivity unexpectedly decreases as the temperature is lowered, exhibiting a behavior generally associated with metals, rather than insulators. Recently, low-T transport of dilute 2D systems has been considered in Ref.[2] taking into account both the carrier degeneracy and thermal correction[3] owing Peltier and Seebeck effects combined. The current causes heating(cooling) at the first(second) sample contact due to the Peltier effect. Under adiabatic conditions the temperature gradient is linear in current, the contact temperatures are different. The measured voltage includes Peltier effect-induced thermoemf which is *linear* in current. The total resistivity yields[2]

$$\rho^{tot} = \rho \left(1 + \alpha^2/L\right), \tag{1}$$

where ρ is the ohmic resistivity, α the 2D thermopower, L the Lorentz number. We report on a study of α and compressibility, $K = \frac{dN}{d\mu}$, for dilute 2D system within MIT regime. Both quantities exhibit density and temperature dependencies which give the strong evidence of thermodynamic nature of 2D MIT. Simultaneous measurements data[4−6] for ρ, α and K confirm our predictions.

Let us consider, for clarity, Si-MOSFET 2DEG within strong inversion regime. At fixed gate voltage the quasi-Fermi level, μ, in the semiconductor bulk is shifted with respect to that of the metal gate. The number of occupied states below quasi-Fermi level denotes the density of electrons assumed to occupy the first quantum-well subband with isotropic energy spectrum. Using Gibbs statistics, thermopower yields $\alpha = -\frac{k}{e}\left[\frac{2F_1(1/\xi)}{F_0(1/\xi)} - \frac{1}{\xi}\right]$, where F_n is the Fermi integral, $\xi = kT/\mu$ the dimensionless temperature. Here, we assumed that the electron scattering is characterized by energy-independent momentum relaxation time. Within Boltzman limit ($\mu < 0, |\xi| \ll 1$) the thermopower yields $\alpha = -\frac{k}{e}(2 - 1/\xi)$. For strongly degenerated 2DEG ($\xi \ll 1$), we obtain $\alpha = -\frac{k}{e}\frac{\pi^2\xi}{3}$. Then, at elevated temperatures ($\xi > 1$) the thermopower approaches the universal value $\alpha_s = -\frac{k}{e}\frac{\pi^2}{6\ln 2}$. Our support of the above behavior(see Fig.1a, insert) is confirmed by diffusion thermopower data,[4] found to diverge at certain value $\sim 0.6k/e$ being of the order of α_s.

We now discuss 2DEG compressibility, known to be a fundamental quantity generally more amenable to theoretical and experimental analysis. Within our simple approach the 2D density yields $N = -\frac{d\Omega}{d\mu} = N_0\xi F_0(1/\xi)$, where where Ω is the thermodynamic potential, $D = \frac{2m}{\pi\hbar^2}$ the density of states, $N_0 = D\mu$ the density of strongly degenerate 2DEG. Therefore, $K = DF_0'(1/\xi)$, where $F_n'(z)$ is the derivative of the Fermi function. Fig.1b represents the dependence of inverse compressibility parameter $d(\mu) = \epsilon/Ke^2$. For strongly degenerated electrons($\xi \ll 1$) one obtains a constant value $d_0 = \epsilon/De^2$ in consistent with experiments.[5] However, at $\mu \to 0$ the inverse compressibility data[5,6] known to diminish and, furthermore, become negative. Usually, this behavior is explained[5] in terms of Hartree-Fock exchange omitted within our simple model. However, further diminishing of 2D density results in an abrupt upturn of inverse compressibility which cannot be explained within Hartree-Fock scenario. We argue that the above feature has the natural explanation within our model(see dashed line in Fig.1b) since $d = d_0\exp(-1/|\xi|)$ at $\mu < 0, |\xi| \ll 1$ and, hence, exhibits T-activated behavior.

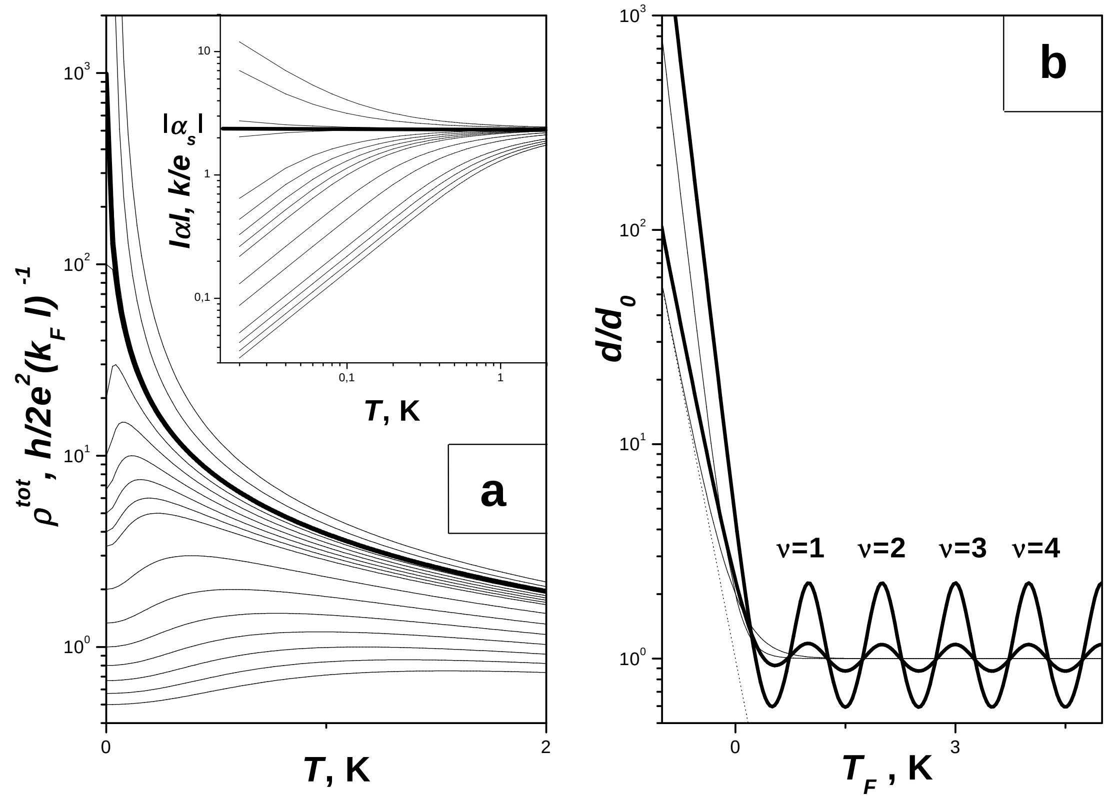

Figure 1: a) T-dependence of resistivity(see [2] and Eq.(1)) and thermopower(inset) for $\mu/k = T_F[K]$=2-0.25(step 0.25), 0.2-0.05(step 0.05), 0.01, 0(bold line),-0.1,-0.2. b) Dimensionless inverse compressibility vs Fermi temperature at zero magnetic field(thin lines) and $\hbar\omega_c = 1$K(bold lines) at fixed temperatures T=0.15,0.25K. Dashed line depict zero-field asymptote at $\mu < 0, |\xi| \ll 1$

In general, for 2DEG placed in perpendicular magnetic field the compressibility yields

$$K = \frac{D}{4\xi\nu}\sum_n \frac{1}{\cosh\left(\frac{\varepsilon_n-\mu}{2kT}\right)^2} \simeq D\left[F_0'(1/\xi) + 4\pi^2\xi\nu\sum_k \frac{(-1)^k k\cos(2\pi\nu k)}{\sinh(2\pi^2 k\nu\xi)}\right], \qquad (2)$$

where we use the thermodynamic potential modified with respect to spin-unresolved zero-width Landau level(LL) energy spectrum $\varepsilon_n = \hbar\omega_c(n+1/2)$, where $n = 0, 1..$ in the LL number, $\omega_c = \frac{eB_\perp}{mc}$ the cyclotron frequency. Then, $\nu = \frac{\mu}{\hbar\omega_c}$ is the filing factor. According to Eq.(2), at fixed magnetic field and temperature the dependence $d(\mu)$ can be viewed(see Fig.1b) as a superposition of zero-field dependence and LLs related oscillations. These findings are consistent with experimental observations.[5,6]

This work was supported by LSF(HPRI-CT-2001-00114, Weizmann Institute).

References

[1] E.Abrahams, S.V. Kravchenko and M.P.Sarachik, Rev.Mod.Phys.**73** (2001) 251

[2] M.V.Cheremisin, Sov. Phys. JETP **92** (2001) 357; cond-mat/0211535

[3] C.G.M.Kirby, M.J.Laubitz, Metrologia **9**, 103, 1973

[4] R. Fletcher R. et al, cond-mat/0103283

[5] J.P. Eisenstein et al, Phys.Rev.Lett., **68**, 674 1992, Phys.Rev.B, **50**, 1760, 1994

[6] S.C. Dultz, H.W. Jiang, Phys.Rev.Lett, **84**, 4689, 2000