Suppression of universal conductance fluctuations by an electric field in doped Si(P,B) near the meal-insulator transition

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Abstract

We present results of 1/f noise measurements at low frequency ($10^{-3} < f < 10Hz$) at low temperatures ($1K < T < 20K$) in single crystals of Si doped with P and B. The doping concentration n is close to the critical composition n_c of the metal-insulator transition (MIT). We observed that the noise which originates from the Universal Conductance fluctuation (UCF), can be suppressed effectively by an electric field of moderate magnitude at $T < 20K$. Near the critical region of MIT ($n \approx n_c$) the suppression is extremely large. We show that this effect can originate by dephasing arising from an electric field in presence of electron-electron interaction.

Key words: Universal Conductance Fluctuations; decoherence; electron-electron interactions

1. Introduction

At low temperatures the electrical conductance G of a disordered metallic system is a sensitive function of the defect configuration. This random, but reproducible variation in conductance with change in defect configuration, magnetic field or chemical potential is called the universal conductance fluctuations (UCF) [1].UCF is observable as random time dependent conductance fluctuations with approximately $1/f$ power spectra [2,3].

UCF can occur even in bulk 3D systems like single crystals of Si heavily doped with dopant P and B at the region of MIT ($n \approx n_c$) [4,5]. In this paper we report a new phenomenon where application of a small electric field leads to suppression of the UCF in these heavily doped Si single crystals.

Experiments were done in P and B doped single crystals of silicon ($\langle 111 \rangle$- Czochralski grown) . Noise measurements done with a 5-probe ac technique [6]aided by digital signal processing can measure a noise power ($S_v(f) \leq 10^{-20}$ V ^{2}/Hz).The temperature stability was $|\Delta T/T| < 0.01\%$.

Experiments were done on a number of samples containing various concentration of P and B. We report our findings on two of the samples both of which have P doping and B compensation. At $T \leq 10$ K, the conductivity $\sigma(T) \approx \sigma_o + AT^{1/2}$. For more metallic D150 $n/n_c \approx 2$ and it has $\sigma_o \approx 120S/cm$ while for E90 with $n/n_c \approx 1$, $\sigma_o \approx 0$.

Figure 1 shows the scaled spectral power $\gamma = n\Omega \frac{fS_V(f)}{V^2}$, Ω being the sample volume. The data were taken with a low measuring field ($E < 10$V/m)a .γ increases at low temperatures due to dominant contribution from UCF which has been confirmed by its suppression in a magnetic field [4].The relative fluctuation ,$\langle \delta G^2 \rangle / G^2$, is obtained from the spectral power by integrating over the bandwidth. For $\Omega \gg L_\phi^3$,where L_ϕ is the phase coherent length, noise from different coherent regions of volume L_ϕ^3 are superposed classically and the net relative conductance fluctuation can be expressed as [2,3],

$$\frac{\langle (\delta G)^2 \rangle}{G^2} = \frac{L_\phi^3}{\Omega} \frac{\langle (\delta G_\phi)^2 \rangle}{G_\phi^2} \quad (1)$$

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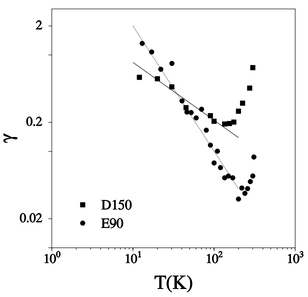

Fig. 1. The temperature dependence of the scaled noise γ for the two samples. The rise at low T is due to UCF.

where $G_\phi(=\sigma L_\phi)$ is the conductance of a single phase coherent box of volume L_ϕ^3 , which can be obtained from the MR data. We found from the conductance fluctuations and L_ϕ that, the noise is actually saturated and has a value $\langle(\delta G_\phi)^2\rangle^{1/2} \approx (1-1.5)\times(e^2/h)$ [4]. In this case of saturated UCF , eqn. 1 can be simplified to $\frac{\langle(\delta G)^2\rangle}{G^2} \propto \sqrt{\tau_\phi}$, where τ_ϕ^{-1} is the dephasing rate.

In figure 2 we show that the spectral power is severely suppressed by even a moderate electric field which becomes more severe as the MIT is approached. A moderate field ($\approx 10^2 V/m$) can suppress the noise even by a factor of 10. In comparison, the maximum suppression by a magnetic field is a factor of 4. We find that for $E >(E^*(T))$, the noise is T independent and is a function of the applied field E . $E^*(T)$ decreases as T is decreased.

The suppression of the noise in the electric field can be due to decrease of τ_ϕ in an applied electric field . In systems with strong electron-electron interaction it has been shown that such a low frequency electric field may in fact cause dephasing in the particle-hole channel [7]. This effect occurs when two interacting electrons moving in the same closed Feynman path releases an excitation of energy ϵ at some instant and traverse rest of the path with unequal momentum under an ambient time dependent vector potential. Quantitatively, the phase difference acquired in such a process depends on the energy scale $\Sigma(E) = (\hbar e^2 D E^2)^{1/3}$. We observe that at a large enough E ($E \gg E^*$) the value of τ_ϕ becomes independent of T and depends essentially only on E. In this regime, as can be seen from fig 2, the dephasing rate $\tau_\phi^{-1} \propto E^q$, where $q \approx 1.3 \pm 0.05$ for D150 and $\approx 2.0 \pm 0.1$ for E90 . The τ_ϕ^{-1} is expected to be directly related to $\Sigma(E)$, the energy scale that characterizes the extra phase the electron gains from the field E. For such a process, we expect $\tau_\phi^{-1} \propto \tau_{ee}^{-1}$, the quasiparticle scattering rate , which is $\propto \epsilon^\zeta \propto \Sigma(E)^\zeta$. We will then have $\tau_{ee}^{-1} \propto E^{2\zeta/3}$. From the observed data we find $\zeta = (3/2)q \approx 2$ for D150 and 3 for E90. ζ has been evaluated from the Fermi liquid theory [8]and

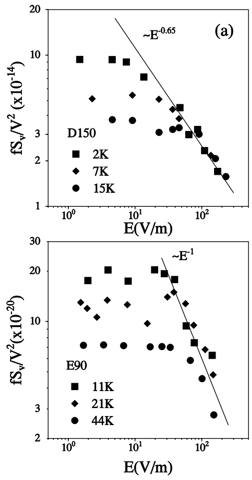

Fig. 2. Electric field dependence of the spectral power $S_v(f)$ noise at three different temperatures for D150 (a) and E90 (b).The spectral power shows 1/f frequency dependence. At high field the S_v/v^2 shows a power law dependence on the measuring field E (see text).

typical value is between 1-2. The value of ζ estimated from the experiment is thus quite close to what is expected from this simple theoretical approach.

This effect is not due to heating of the sample because: (1) even at the highest bias the power dissipation is $\leq 20\mu W$ and σ is not significantly power dependent, (2) if the complete dephasing was due to electron heating, τ_ϕ obtained at the highest bias corresponds to that at $T \approx 200$ K which is rather unlikely . Using UCF as a sensitive probe of dephasing, we establish that the measuring field can induce dephasing (without electron heating) in disordered electronic systems with interaction.

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