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LETTER TO THE EDITOR

Conductance fluctuations near the Anderson transition

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Abstract. In this letter we report measurements of conductance fluctuations in single-crystal samples of Si doped with P and B close to the critical composition of the metal–insulator transition ($n_c \approx 4 \times 10^{18}$ cm^{-3}). The measurements show that the noise, which arises from bulk sources, does not diverge as the Ioffe–Regal limit ($k_F l \to 1$) is approached from the metallic side. At room temperature, the magnitude of the noise shows a shallow maximum at around $k_F l \approx 1.5$ and drops sharply as the insulating state is approached.

Electron localization and the metal–insulator (MI) transition have been topics of considerable interest for quite some time and in particular in the last two decades, since the scaling theory clarified some of the key physics ingredients [1]. One of the most researched mechanisms of MI transition is the Anderson–Mott transition that occurs in semiconductors doped to a critical concentration (n_c). A number of thermodynamic and transport studies have been carried out in the past in an effort to understand the nature of the transition [2, 3]. One very important physical quantity that has not been investigated for doped semiconductors close to the critical composition is the conductance fluctuation or noise. In this letter, we report the results of measurements of the conductance noise in single crystals of Si, doped with P and B so that we can approach the critical region from the metallic side ($n/n_c \to 1$).

In this letter we seek an answer to one important question: does the magnitude of the conductance fluctuations diverge as we approach the Anderson transition in the heavily doped Si system? We think that this issue has not been rigorously looked into. The only reported experiment that has systematically studied the fluctuations as a function of disorder close to the Anderson transition was on thin films of In_2O_x [5]. The authors reported a sharp rise in the magnitude of the conductance noise (measured close to room temperature) as the disorder is increased and the Ioffe–Regal limit ($k_F l \approx 1$) is approached. It is thus of interest to investigate whether this is a universal phenomenon.

Conductance fluctuations with spectral power density $\propto 1/f$ (often known as $1/f$ noise) have been seen in disordered metallic films (like those of Ag and Bi) [6] and also in oxide [7] and C–Cu composites [8] near the composition close to the MI transition. The main focus of these earlier studies, based on disordered films, was investigating electronic phase-coherence effects manifested in the universal conductance fluctuations (UCF) [4]. The issue of divergence (or its absence) of fluctuations as a function of disorder has not been investigated in the cited papers. However, no work has been reported so far on the experimental determination of conductance fluctuation in doped crystalline semiconductors (like Si doped with P or B) with

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concentrations close to the critical composition. Our choice of doped single-crystal Si was mainly guided by the facts that the Anderson transition has been most thoroughly studied for this system and that most theoretical work has taken this as a model substance. This is also a well defined system in which it is possible to get well characterized samples.

Polished ⟨111⟩-oriented doped silicon wafers (grown by the Czochralski method) with thickness ≈300 μm were reduced to a length of 2 mm and width of 0.1–0.2 mm, and were thinned down by etching to a thickness of 15–25 μm. (The samples used in this experiment were kindly supplied by Professor D H Holcomb of Cornell University.) These wafers were used previously extensively in conductivity studies [9]. Details of the growth and conductivity data can be found elsewhere. Table 1 contains the relevant parameters. In all, we investigated five different samples with $k_F l$ varying between 2.8 and 0.78. The calculation of l, the mean free path, is based on the room temperature resistivity. Our study included investigations of both uncompensated (Si(P)) and compensated (Si(P, B)) samples.

Table 1. Dopant concentration and relevant transport parameters of the samples studied.

Sample (dopant)	n (cm^{-3})	K	n/n_c	σ_{RT} (S m^{-1})	$k_F l$
PS24 (P)	1.0×10^{19}	—	2.5	1.5×10^4	2.80
PS41 (P)	6.5×10^{18}	—	1.5	1.1×10^4	2.30
D150 (P, B)	1.0×10^{19}	0.4	2.0	0.9×10^4	1.68
C286 (P, B)	5.5×10^{18}	0.5	1.1	3.7×10^3	0.84
E90 (P, B)	4.5×10^{18}	0.6	1.0	3.3×10^3	0.78

The noise was measured by a five-probe ac technique [10] on samples in a bridge-type configuration with an active volume for noise detection (Ω) $\approx 10^{-6}$ cm^3 with peak current density $\sim 10^2$ A cm^{-2}. In this method the measurement of the noise was carried out by exciting a balanced Wheatstone bridge with an alternating current ($f_0 = 370$ Hz) and detecting the error signal with a lock-in amplifier. The two halves of the sample (contained within the five leads) form two arms of the bridge. The spectral power measured in phase with the carrier frequency gave the noise from the sample and the background. Simultaneous measurement of the quadrature component gave the background, which was then subtracted from the total to obtain the noise from the sample. The noise was measured at $T = 300$ K and $T = 4.2$ K. The temperature stability at 300 K was better than that at 10 mK, and at $T = 4.2$ K the thermal stability of the bath was $\sim \pm 1$ mK. The background noise primarily consisted of the Johnson noise $4k_B T R$ from the sample. The spectral power density $S_v(f) \propto V_{bias}^2$. Leads made of gold wire of diameter ≈25 μm were bonded to the sample by a specially fabricated wire bonder. The contacts were ohmic and have temperature-independent contact resistance $\ll 1\ \Omega$. All of the relevant values for the samples studied are given in table 1. In this table the mean free path l in the parameter $k_F l$ has been obtained from the room temperature resistivity data. The zero-temperature conductivity, σ_0, shown in table 1, has been obtained from the conductivity ($\sigma(T)$) below 4.2 K by using the power law $\sigma(T) = \sigma_0 + mT^\nu$.

For all of the samples studied, the spectral power density at a given frequency (≈1 Hz) was found to depend strongly on the sample volume Ω when it was varied by more than a factor of 20. We show three examples in figure 1. Typically, $S_v(f) \propto \Omega^{-\nu}$ with $\nu \approx 1.1$–1.3. This is seen at both 300 K and 4.2 K. This implies that the predominant contribution to the noise arises from the bulk. A strong surface or contact contribution weakens the dependence of the noise on Ω and makes $\nu < 1$. This is an important observation, because in previous studies on semiconductors (done on films or devices with interfaces) the doping concentration was much smaller ($n \ll n_c$) and the noise contained a substantial contribution from surfaces

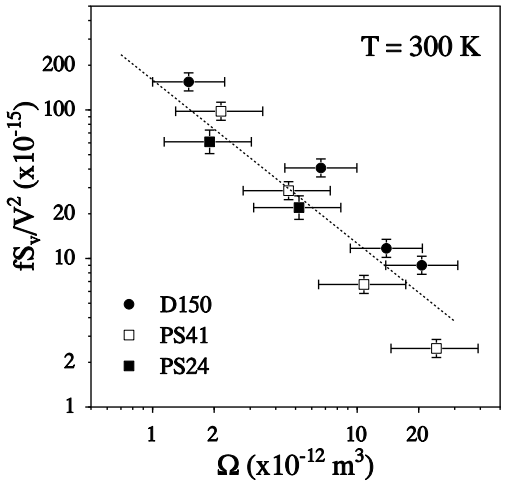

Figure 1. The dependence on the volume (Ω) of the noise in Si(P, B) samples at room temperature. A similar dependence has been observed at $T = 4.2$ K as well. The relatively large error in the volume determination results from the rounding-off of the edges of the samples during chemical etching. The dotted line has a slope of $\approx$1.1.

or interfaces [11]. Our experiments clearly show that the noise in heavily doped single crystals arises from the bulk.

In figure 2 we show the noise (measured at $f = 3$ Hz) as a function of the parameter $k_F l$ for the five samples studied by us. The data at 4.2 K are shown in the inset. Here k_F is determined from the carrier density n using $k_F = (3\pi^2 n)^{1/3}$ and l was determined from the

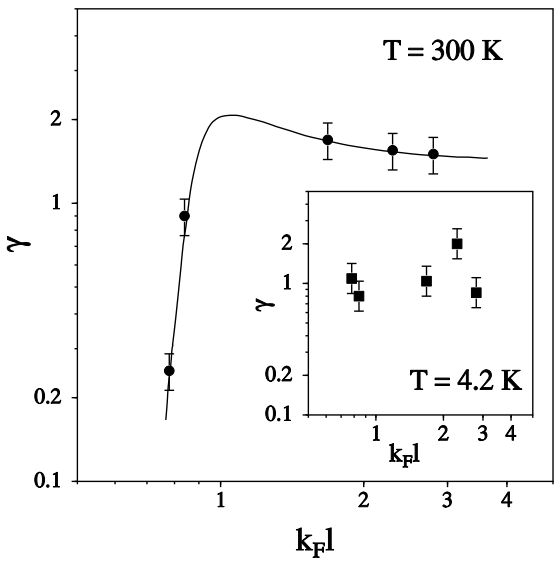

Figure 2. The variation of the normalized noise parameter γ as a function of disorder as measured by the parameter $k_F l$ at $T = 300$ K. The inset shows the data at $T = 4.2$ K. The solid line is a guide to the eye.

room temperature resistivity ρ using the free-electron expression $l = \hbar k_F/ne^2\rho$. The noise is expressed through the normalized value $\gamma(f)$ defined as

$$\gamma(f) = fS_v(f)(\Omega n)/V_{bias}^2. \tag{1}$$

In this representation we used $\gamma(f)$ as a dimensionless number which represents the normalized noise. γ is often referred to as Hooge's parameter. We do not assign any fundamental significance to $\gamma(f)$, as it has been found that it varies to a large extent in different solids. We use it here only as a convenient way to normalize the measured spectral power using equation (1) so that data for different samples can be compared. To be consistent, we have evaluated γ at $f = 3$ Hz for all of the samples. It can be seen in figure 2 that γ has a distinct dependence on $k_F l$. At $T = 300$ K, γ shows a shallow hump at $k_F l \approx 1$–1.5. However, as the insulating state is approached, γ shows a reversal and actually decreases. At $T = 4.2$ K (see the inset of figure 2), γ has a peak at $k_F l \approx 2.3$. However, γ stays close to 1 and does not diverge as $k_F l \to 1$. The mechanisms of the noise at 4.2 K and 300 K are expected to be different. As a result, we do not expect the same dependence of γ at two widely different temperatures. However, our data show that, irrespective of the temperature, γ does not diverge as we enter the insulating state. This is unlike what has been seen for disordered films of In_2O_x, where $\gamma > 10^5$ when $k_F l \leqslant 1$. For the sake of comparison, this is shown in figure 3 along with our data. In our case, γ never becomes as large as 10^5–10^7 as seen for the oxide films and, over the whole range, γ is substantially smaller. On the same graph we have shown γ for thin metal films. For Si(P, B) samples the γ-values are at least three orders of magnitude higher than those seen for conventional thin metallic films ($\gamma \approx 10^{-3}$ to 10^{-5}). It is extremely interesting to note that for lightly doped Si films on sapphire samples $\gamma \approx 10^{-3}$, although in this case it is likely that the noise arises from the surfaces/interfaces. For the lightly doped Si samples for which $\gamma \approx 10^{-3}$ has been observed, the doping level $\approx 10^{13}$–10^{14} cm^{-3}. In our case, the sample which has the least value of γ at room temperature has a level of doping $\approx 4 \times 10^{18}$ cm^{-3} and for this sample γ has already reduced to 0.25. If this trend continues, then $\gamma \to 10^{-3}$ for $n \leqslant 10^{16}$ cm^{-3}. We believe that for n less than this level of doping, the surface states will dominate the noise mechanism.

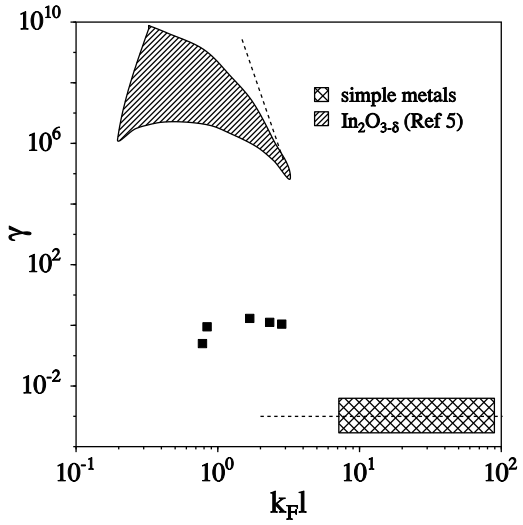

Figure 3. Comparison of γ for different solids with varying $k_F l$. The data points show our data. The shaded and hatched regions have been taken from other published data, principally reference [5].

We next investigate the spectral dependence of the noise power $S_v(f)$. At both $T = 4.2$ K and $T = 300$ K, the predominant spectral dependence is almost of $1/f$ type, with $S_v(f) \propto 1/f^{\alpha}$ with $\alpha \approx 0.9$–1.25. This $1/f$ dependence has been seen over six orders of magnitude in frequency in the range $f \sim 10^{-4}$ Hz to 10^2 Hz for three samples with $k_F l = 2.8$ (PS24), 1.68 (D150) and 0.78 (E90). In the lower-frequency region the long-term drifts and temperature stability are of concern. From the degree of our temperature control, $\mathrm{d}\rho/\mathrm{d}T$ for these materials and the detection bandwidth, we find that the contribution to the spectral power due to temperature effects will be as low as $S_v \sim 5 \times 10^{-23}$ V^2 Hz^{-1} which is much less than the spectral power observed by us. Also, in the bridge method of measurement where two parts of the same samples form two arms of a bridge, the drift of the off-balance signal due to thermal drifts cancels out significantly. At $T = 4.2$ K, the spectral dependence of the noise tends to deviate from the pure $1/f$ form. This can be seen in figure 4, where we have plotted the data as $fS_v(f)$ versus f. For all of the samples, $fS_v(f)$ is featureless at room temperature and the slope corresponds to $\alpha \approx 1.05$–1.2. At $T = 4.2$ K, the uncompensated (and more metallic) samples retain their $1/f$ form. However, as the disorder increases on compensation by B doping, additional features show up, as can be seen in figure 4. These are quite prominent for the most disordered sample E90, which is rather close to the insulating side ($\sigma_0 = 0$). Given the scope of this letter, we do not elaborate on this point. However, we note the important observation that as the critical region is approached ($k_F l \to 1$), the spectral dependence of the noise power undergoes a change.

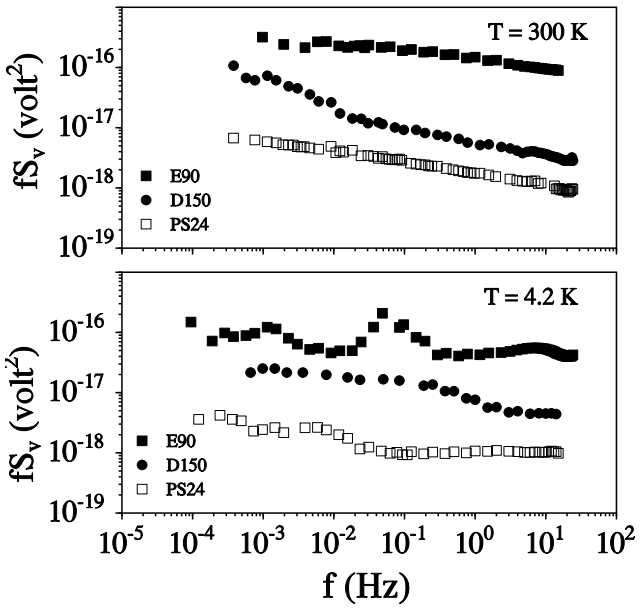

Figure 4. The variation of the spectral density of the noise with frequency at $T = 300$ K and $T = 4.2$ K in three representative samples. Data for different samples have been shifted for clarity.

As pointed out earlier, the dependence of γ on $k_F l$ at both $T = 4.2$ K and $T = 300$ K is drastically different from that shown by thin disordered films of In_2O_x near the Anderson transition [5]. A study of the conductance fluctuation noise near the Anderson transition has also been carried out for C–Cu films [8]. Interestingly, in this case $\gamma \approx 1$–5 at room temperature for all of the samples which are close to the critical region. The noise at $T = 4.2$ K

in the same systems shows a somewhat larger $\gamma \approx 10$ but this is not as large as that seen for the In_2O_x films. Also, noise measurements near the Anderson transition for $La_{1-x}Sr_xVO_3$ thin films did not show any indication of divergence [12]. Another study of noise, where the metal–insulator boundary has been crossed, is the investigation on a percolating-system Pt/SiO_2 composite done at 300 K [13]. In this case, however, γ undergoes a change by 3–4 orders of magnitude when the percolation threshold is crossed. We can thus conclude that the behaviour of γ close to the critical region of the Anderson transition may not be universal. In all likelihood, it depends on the mechanism that produces the noise. For the Si(P, B) we have carried out an extensive investigation of the noise to find the temperature and field dependence, which can identify the mechanism which is causing the noise. Given the limited scope of this communication, we do not go into the details, which are given elsewhere [14]. Briefly, we found that at $T < 100$ K, the noise predominantly arises from UCF. In this case, in all likelihood, the noise will have an upper bound. This is because the noise in a phase-coherent volume of size L_ϕ^3 typically saturates at $\langle(\delta G_\phi)^2\rangle \approx e^2/h$, where $\langle(\delta G_\phi)^2\rangle$ is the variance of the conductance within a single phase-coherent volume. The noise in a bulk volume Ω can be built up by adding the fluctuations classically, so $\langle(\delta G)^2\rangle/G^2 \approx (L_\phi^3/\Omega)\langle(\delta G_\phi)^2\rangle/G_\phi^2$. If, on approach to the Anderson transition, L_ϕ does not diverge (being mostly determined by electron–electron and electron–phonon interactions), then since $\langle(\delta G_\phi)^2\rangle$ is bounded, $\langle(\delta G)^2\rangle$ is expected not to diverge either.

For $T > 150$ K, we found that the noise predominantly arises from local interference [15]. In this mechanism, $\langle(\delta G)^2\rangle$ is related to quantities like the mean free path, scattering cross-section and defect concentration, which are essentially single-scattering-site parameters having no divergence associated with them when $n \to n_c$. For both of the mechanisms, we find no direct parameter which can diverge near the critical composition—which is consistent with our observation. It must however be admitted that the theories for these mechanisms were all developed in the weakly localized regime where the correlation length ξ does not enter into the consideration. It will be an interesting exercise to see what happens when ξ becomes the dominant length scale in the problem.

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