Conductance fluctuations near Anderson transition

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Abstract

In this paper 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 ($k_F l \rightarrow 1$) is approached from the metallic side. At room temperatures, the magnitude of the noise shows a shallow maximum around $k_F l \approx 1.5$ and drops sharply as the insulating state is approached.

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Electron localization and Metal-Insulator (MI) transition has been a topic of considerable interest for quite some time and in particular in last two decades after the scaling theory clarified some of the key physics ingredients [1]. One of the most researched mechanism of the 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 done in the past to understand the nature of the transition [2,3]. One very important physical quantity that has not been investigated in doped semiconductors close to the critical composition is the conductance fluctuations or noise. In this paper, we report the results of the measurement of 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 paper we sought an answer to one important question: does the magnitude of 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 Anderson transition is in thin films of In$_2$O$_x$ [5]. The authors reported a sharp rise in the magnitude of the conductance noise (measured close to the 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 it is a universal phenomenon.

Conductance fluctuations with spectral power density $\propto 1/f$ (often known as $1/f$ noise) has been seen in disordered metallic films (like that in Ag and Bi) [6] and also in oxide [7] and C-Cu composites [8] near the composition close to the M-I transition. The main focus of these works, based on disordered films, was to investigate the Universal Conductance Fluctuations (UCF) [4]. The issue of divergence (or its absence) of fluctuations as a function of disorder has been investigated. However, no work has been reported so far on experimental determination of conductance fluctuation in doped crystalline semiconductor (like Si doped with P or B) with concentration close to the critical composition. Our choice of doped single crystal Si was mainly guided by the fact that the Anderson transition has been most well studied in this system and 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 wafers of (111) orientation (grown by the Czochralski method) and thickness \( \approx 300 \mu m \) were sized down to a length of 2 mm, width 0.1-0.2 mm and were thinned down by etching to a thickness of 15-25 \( \mu m \). (The samples used in this experiment were kindly supplied by Prof. D.H. Holcomb of Cornell University.) These wafers were used previously extensively in conductivity studies [9]. Details of growth and conductivity data can be found elsewhere. Table I contains the necessary numbers. In all, we investigated five different samples with \( k_F l \) varying between 2.8 to 0.78. Calculation of \( l \), the mean free path, is based on room temperature resistivity). This contains both uncompensated (Si(P)) and compensated (Si(P,B)) samples.

The noise was measured by a five probe ac technique [10] on samples of bridge type configuration with active volume for noise detection \( (\Omega) \approx 10^{-6} \text{ cm}^3 \) with peak current density \( \approx 10^2 \text{ A/cm}^2 \). The noise was measured at \( T = 300 \text{ K} \) and \( T = 4.2 \text{ K} \) with temperature stability better than \( 10 \text{ mK} \). The background noise primarily consisted of Johnson noise \( 4k_BTR \) from the sample. The spectral power density \( S_v(f) \propto V_{bias}^2 \). Leads of gold wires of diameter \( \approx 25 \mu m \) 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 the relevant numbers about the samples studies are given in table I. 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, \( \sigma_0 \), shown in table I, 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 the samples studied the spectral power density at a given frequency \( (\approx 1 \text{ Hz}) \) was found to depend strongly with sample volume \( \Omega \) 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 predominant contribution to the noise arises from the bulk. A strong surface or contact contribution weakens the dependence of noise on \( \Omega \) 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 had substantial contribution from surfaces 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 5 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 room temperature resistivity \(\rho\) using the free electron expression relation \(l = \hbar k_F/|e^2\rho|\). The noise is expressed through the normalized value \(\gamma\) defined as:

\[
\gamma = f S_v(f)(\Omega n)/V_{bias}^2
\]

In this representation we used \(\gamma\) as a dimensionless number which represents the normalized noise. \(\gamma\) is often referred to as the Hooge’s parameter. Strictly speaking, this normalization to a frequency independent \(\gamma\), is valid only for \(S_v(f) \propto 1/f\). To be consistent we have evaluated \(\gamma\) at \(f = 3\) Hz for all the samples. It can be seen in figure 2 that \(\gamma\), has a distinct dependence on \(k_F l\). At \(T = 300\) K \(\gamma\) shows a shallow hump at \(k_F l \approx 1-1.5\). However as the insulating state is approached \(\gamma\) shows a turn around and actually decreases. At \(T = 4.2\) K (see inset of figure 2) \(\gamma\) has a peak at \(k_F l \approx 2.3\). However, \(\gamma\) stays close to 1 and does not diverge as \(k_F l \to 1\). The mechanism of noise at 4.2 K and 300 K are expected to be different. As a result we do not expect the same dependence of \(\gamma\) at two widely different temperatures. However, our data shows that irrespective of the temperature, \(\gamma\) does not diverge as we enter the insulating state. This is unlike what has been seen in disordered films of \(\text{In}_2\text{O}_x\) where \(\gamma > 10^5\) when \(k_F l \leq 1\). For the sake of comparison this is shown in figure 3 along with our data. In our case \(\gamma\) never becomes as large as \(10^5\) to \(10^7\) as seen in the oxide films and over the whole range \(\gamma\) is substantially smaller. In the same graph we have shown \(\gamma\) of thin metal films. For \(\text{Si}(\text{P,B})\) samples the \(\gamma\) are at least three orders of magnitude higher than that seen in conventional thin metallic films \((\gamma \approx 10^{-3} \text{ to } 10^{-5})\). It is extremely interesting to note that 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. The lightly doped Si
samples in 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 $\gamma$ at room temperature has a level of doping $\approx 4 \times 10^{18}$ /cm$^3$ and for this sample $\gamma$ is already down to 0.25. If this trend continues then $\gamma \to 10^{-3}$ for $n \leq 10^{16}$ /cm$^3$. We believe that for $n$ less than this level of doping, the surface states will dominate the noise mechanism.

We next investigate the spectral dependence of the noise power $S_v(f)$. At both $T = 4.2$ K and 300 K the predominant spectral dependence is almost $1/f$ type with $S_v \propto 1/f^\alpha$ with $\alpha \approx 0.9\text{--}1.25$. 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 $k_Fl = 2.8$ (PS24), 1.68 (D150) and 0.78 (E90). At $T = 4.2$ K the spectral dependence of noise tend to deviate from pure $1/f$ form. This can be seen in figure 4, where we have plotted the data as $f \times S_v(f)$ vs. $f$. For all the samples the $f \times S_v(f)$ is featureless at room temperature and the slope corresponds to $\alpha \approx 1.05\text{--}1.2$. 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. This is quite prominent in the most disordered sample E90 which is rather close to the insulating side ($\sigma_0 = 0$). Given the scope of the paper we do not elaborate on this point. However, we note the important observation that as the critical region is approached ($k_Fl \to 1$), the spectral dependence of the noise power undergoes a change.

As pointed out earlier, the dependence of $\gamma$ on $k_Fl$ at both $T = 4.2$ K and 300 K is drastically different from that carried out on thin disordered films of In$_2$O$_x$ near the Anderson transition [5]. Study of conductance fluctuations noise near Anderson transition has also been done in C-Cu films [8]. Interestingly, in this case the $\gamma \approx 1\text{--}5$ at room temperature for all the samples which are close to the critical region. The noise at $T = 4.2$ K in the same systems show some what larger $\gamma \approx 10$ but it is not as large as that seen in the In$_2$O$_x$ films. Also, noise measurements near the Anderson transition in La$_{1-x}$Sr$_x$VO$_3$ 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, $\gamma$ undergoes a change by 3-4 orders of magnitude when the percolation threshold is crossed. We can then conclude that the behavior of $\gamma$ close to the critical region of Anderson transition may not be universal. In all likelihood, it depends on the mechanism that produces the noise. For the Si(P.B) we are carrying out an extensive investigation of the noise to find the temperature and field dependence which can identify the mechanism which is causing the noise. This will be elaborated in a future publication.
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## TABLES

### TABLE I.

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

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

**Fig.2.** Variation of the normalized noise parameter $\gamma$ as a function of disorder as measured by the parameter $k_F l$ at $T = 300$ K. Inset shows that data at $T = 4.2$ K. The solid line is guide to the eye.

**Fig.3.** Comparison of $\gamma$ for different solids with varying $k_F l$. The data points show our data. The shaded and hatched regions have been taken form other published data, principally ref.5.

**Fig.4.** Variation of spectral density of 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.
$fS_v/V^2 \times 10^{-15}$ vs. $\Omega \times 10^{-12} \text{ m}^3$ for $T = 300 \text{ K}$.

- D150 (filled circles)
- PS41 (open squares)
- PS24 (filled squares)
