Electric field induced suppression of universal conductance fluctuations and dephasing in disordered systems

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We report a novel phenomenon that the universal conductance fluctuations (UCF) can be suppressed by a small electric field $E$. The experiment has been carried out on single crystals of Si doped heavily with P and B beyond the critical composition of insulator to metal transition. The phenomenon is identified as a consequence of electric field induced dephasing of the electron wavefunction. Over the range of measurements, the observed dephasing rate $(\tau_{\phi}^{-1})$ varied as $\tau_{\phi}^{-1} = aT + bE^q$ with $q \approx 1.3$ and for $E \gg E^*$, a cross-over field, $\tau_{\phi}^{-1} \sim E^q$, independent of $T$. This experiment also establishes that the UCF can be utilized as a sensitive electron “interferometer” to measure dephasing rate.

72.70.+m, 72.10.-d, 71.30.+h

Strong impurity scattering at low temperatures gives rise to a number of interesting phenomena due to quantum interference of the multiply back scattered electrons. At $T = 0$, the electrical conductance $G$ of a disordered metallic system becomes a very sensitive function of the defect configuration and change in the position of even a single scatterer over a sufficient length scale ($\sim k_F^{-1}$, $k_F$ is the Fermi wave vector) can produce a variation in the conductance $\delta G_1 \approx e^2/h$. This random, but reproducible variation in conductance with defect configuration, magnetic field or chemical potential is called the universal conductance fluctuations (UCF) and it arises due to interference of phase coherent electrons over large length scales. At finite $T$, the length scale over which the interference is relevant is the phase coherence length $L_\phi$, which is related to the dephasing rate $\tau_{\phi}^{-1}$ through the relation $\tau_{\phi}^{-1} = D/L_\phi^2$, $D$ being the electron diffusivity. In the past decade and half experimental studies have established the occurrence of UCF in a number of 1D and 2D disordered electronic systems. At low temperatures, UCF can be identified through magneto-fingerprinting where the reproducible conductance variations are studied as a function of applied magnetic field $B$ in samples with one or more lateral dimensions $\lesssim L_\phi$. In larger samples with dimensions $L \gg L_\phi$, UCF is observable as random time dependent conductance fluctuations with approximately $1/f$ power spectra.

In a recent experiment on heavily doped single crystals of Si (dopant P and B), it has been shown by us that UCF can occur even in bulk 3D systems. These single crystals with electronic concentration $n \approx (2 - 2.5) \times n_c$ where $n_c$ is the critical concentration for the insulator-metal transition, are disordered electronic system with $k_F l \approx 2-5$, $l$ being the elastic mean free path. They show such effects as weak localization and electron-electron interaction. The occurrence of the UCF in 3D bulk crystals of Si has also been seen upto the range of Anderson transition ($n \approx n_c$).

In this paper we report a new and novel phenomenon where we were able to suppress the magnitude of UCF in these heavily doped Si single crystals by application of a small electric field. We explain this novel effect as arising from dephasing of the electrons by the applied electric field which in turn suppresses the UCF.

The phenomenon of UCF essentially rests on one crucial aspect, namely the phase coherence of the electron over a finite length scale $L_\phi \gg l$. Any interaction with the environment that introduces the phase decoherence, will also suppress the UCF. A very well known example is the suppression of the UCF by a factor of 2 in a magnetic field which breaks the time reversal symmetry. The extreme sensitivity of the UCF to the phase coherence of the electron thus makes UCF a sensitive “electron interferometer” which can be used to measure dephasing of the electron. Our experiment is based on this basic concept.

We have carried out all our experiments in single crystals of silicon ((111)- Czochralski grown) made metallic by doping with P and B. (These are the same samples on which we did the previous experimental work.) The samples had dimensions of $0.5 \text{ mm} \times 0.10$-$0.15 \text{ mm}$ and a thickness of $\approx 30\mu \text{m}$. Sample volume for noise detection $(\Omega) \approx 1.5 - 2.0 \times 10^{-12} \text{ m}^3$. Noise, electrical conductivity and magnetoresistance (MR) were all measured in the same sample to avoid any ambiguity. For noise measurement we used a five probe ac technique aided by digital signal processing methods to measure extremely low magnitude of noise power $(\lesssim 10^{-20} \text{ V}^2/\text{Hz})$. The temperature stability was $|\Delta T/T| < 0.01\%$. The Hall coefficient was found to be essentially temperature independent down to 2 K with the variation in the whole range being $\lesssim 20\%$.

Experiments were done on a number of samples containing various concentration of P and B. They yield
quanti tatively similar results. For simplicity and concis- 
ness we report our findings on one of the samples. The 
sample (Si:P,B) contained P concentration of 1 × 10^{25} 
m⁻³. Disorder was introduced in the form of boron com-
pen-sation (compensation factor K ≈ 0.4). The net car-
rier concentration as obtained from Hall measurement is 
n ≈ 2 × nᵗ. From the resistivity we find that kᵥl ≈ 3 at 
low temperatures and hence the weak localization (WL) 
theories are applicable. At T ≤ 10 K, the conduc-
tivity σ(T) has a limiting correction Δσ(T) ∝ T^{m/2} aris-
ing from weak localization (m ≈ 1). Magnetoresistance 
(MR) measurements showed additive contributions from 
WL correction and electron-electron interaction. The 
phase breaking length Lᵦ was obtained from the WL con-
tribution to MR. The details of the conductivity and MR 
analysis are given elsewhere [1].

Noise measurements were done as a function of temper-
ature and measuring electric field with E < 300 V/m. In 
figure 1 we show the measured relative fluctuation mag-
itude ⟨δG²⟩/G² as a function of E for T = 2 K. In the 
inset(a) of figure 1 we show the temperature dependence 
of the fluctuation measured with a very low field (E ≈ 7 
V/m). For T ≈ 100 K the dominant contribution to the 
noise originates from the UCF mechanism as has been 
explained elsewhere [4]. Briefly, the rise of the fluctua-
tion at low T and the suppression of the noise by factor 
of 2 in a magnetic field (see inset (b) of figure 1) are the 
two hall marks for UCF. From figure 1 we see the impor-
tant result that the noise is severely suppressed by even 
a moderate electric field. At E ≈ 250 V/m the noise is 
only about one fifth of that measured at E ≈ 10 V/m. It 
can be compared with the suppression of the noise by a 
magnetic field. In this sample, a magnetic field of about 
10⁻² T can suppress the noise by a factor of 2. A fur-
ther suppression by another factor of 2 (due to removal 
of spin degeneracy) takes place at H ≥ 1.5 T. Thus the 
maximum suppression that one would get from the ap-
plication of H is a factor of 4. In contrast, in an electric 
field we have already achieved a suppression of factor of 
5 and there is no approach to saturation detectable at 
the maximum electric field applied.

In figure 2 we show the suppression of noise as a func-
tion of the electric field measured at three temperatures. 
It can be seen that the noise is suppressed by the elec-
tric field at all T. There is, however, a very interesting 
observation. Beyond a certain measuring field (marked 
E*(T)), the measured noise does not depend on T. In-
stead it is a function of the applied field E alone. The 
cross over field E*(T) decreases as T is decreased. We 
emphasize that what we are presenting here is the data 
in one sample. For various P and B concentration the 
data are qualitatively the same as long as the sample 
remains on the metallic side of the metal-insulator tran-
sition. In the following part of the paper we would like to 
provide an explanation of this experimental observation 
and would like to discuss it in the general perspective of 
the issue of decoherence in disordered system.

As stated earlier, at T = 0, the conductance is an 
 extremely sensitive function of the defect configuration. At 
finit e but low temperatures, as long as the phase coher-
ence length Lᵦ ≫ l, this sensitivity is retained within a 
single phase coherent volume of Lᵦ. We had shown 
before from the experimentally observed magnitude of 
conductance fluctuations in these systems that, ⟨⟨δGᵦ⟩²⟩, 
the fluctuations in a single phase coherent volume Lᵦ, 
is actually saturated and has a value ⟨⟨δGᵦ⟩²⟩ ≈ 2 × (e²/h) [7]. 
This is a very important observation and we will use it in our discussion below.

For a sample with volume Ω ≫ Lₙ, noise from different 
coherent regions of volume Lₙ are superposed classically 
and the net relative conductance noise can be expressed 
as,

\[
\frac{⟨⟨δG⟩²⟩}{G²} = \frac{Lₙ}{Ω} \frac{⟨⟨δGᵦ⟩²⟩}{Gᵦ} \tag{1}
\]

where Gᵦ (= σLᵦ) is the conductance of a single phase 
coherent box and σ is the conductivity of the material. 
When the number of mobile/active scatterers in Lₙ is 
sufficiently large, the mean square variance of conductance 
saturates to ⟨⟨δGᵦ⟩²⟩/Lₙ ≈ (e²/h). As discussed before 
in this particular case the noise is indeed saturated and 
⟨⟨δGᵦ⟩²⟩ ≈ 1.5 × (e²/h). In this case eqn. (1) can be 
simplified to

\[
\frac{⟨⟨δG⟩²⟩}{G²} ≈ \frac{2.3Lₙ(T)}{σ²Ω} (e²/h)² = \frac{2.3√D(e²/h)²}{σ²Ω} \tag{2}
\]

Eqn. (2) clearly shows that the temperature dependence 
of saturated UCF noise is dominated by the temperature 
dependence of the phase coherence length Lᵦ = √D/τᵦ, 
or that of the dephasing rate τᵦ⁻¹. In fact one can uti-
lize this information to obtain the value of the dephasing 
rate τᵦ⁻¹ in disordered systems at low temperature [8]. 
Another way one can evaluate the dephasing rate is from 
the MR measurements. Since we have done both the 
measurements we can independently determine the de-
phasing rate τᵦ⁻¹. This has been shown in figure 3a. 
The measurements were done with an excitation electric 
field of 5 V/m. Within the experimental accuracy we 
found, τᵦ⁻¹ ∝ T. One can see that the dephasing rates 
determined from both the measurements agree quite well. 
This particular check of internal consistency establishes 
clearly that it is τᵦ that predominantly determines the 
temperature dependence of the observed noise.

We argue that the suppression of the noise in the elec-
tric field arises due to increase of the dephasing rate 
(hence reduction of τᵦ) 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 [9]. 
This effect occurs when two interacting electrons moving
in the same closed Feynman path releases an excitation of energy \( \epsilon \) at some instant \( t' \) 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 \( \Delta \phi/2\pi = e\Delta x \cdot E \eta \), where \( \Delta x \) is the displacement between the point of interaction and that of observation and \( \eta \) is time taken to traverse the full path. The interference is lost when \( \Delta \phi/2\pi \approx 1 \) within a thermal path length \( L_T = \sqrt{\hbar D/k_BT} \). Since only those paths with \( \eta \leq \hbar/k_BT \) contribute to the phase relaxation, \( \Delta \phi/2\pi \approx 1 \) when \( eEL_T \approx k_BT \). This condition defines an energy scale \( \Sigma(E) \) defined as

\[
\Sigma(E) = (\hbar e^2 DE^2)^{1/3}
\]

We will discuss the implication of the energy scale \( \Sigma(E) \) later on.

If indeed the electric field introduces dephasing (i.e., increases \( \tau_\phi^{-1} \)) and hence suppresses the noise, then the electric field dependence of the measured noise can be converted into a dependence of \( \tau_\phi \) on \( E \) using eqn 2. In the inset of figure 2 we show the value of \( \tau_\phi^{-1} \), as a function of the electric field \( E \). At low electric fields, \( \tau_\phi^{-1} \) is independent of \( E \), as expected of a linear system. As the field is increased, \( \tau_\phi^{-1} \) increases implying an increase in the total dephasing rate. By scanning over 2 orders of magnitude of electric field, the dephasing rate increases by similar order.

We observe that at a large enough \( E \) (\( E \gg E^* \)) the value of \( \tau_\phi \) becomes independent of \( T \) and depends essentially on \( E \). In this regime the dephasing rate \( \tau_\phi^{-1} \propto E^q \), where \( q \approx 1.3 \pm 0.05 \). For small \( E \) (\( E \ll E^* \)), the dephasing rate \( \tau_\phi^{-1} \propto T^p \), where \( p \approx 1.0 \pm 0.05 \). We can interpolate in the intermediate field region using the relation:

\[
\tau_\phi^{-1} = aT^p + bE^q
\]

where \( a \) and \( b \) are constants independent of \( E \) and \( T \). The fit of the dephasing rate data to eqn 4 are shown in the inset of figure 2. This particular way of expressing the dephasing rate assumes that we have two independent dephasing channels. The temperature dependent part arises from the usual inelastic scattering (e.g., the electron-electron interaction, electron-phonon interaction or TLS-electron interaction etc.) [11, 12]. The field dependent part of the dephasing is expected to be directly related to \( \Sigma(E) \), the energy scale that characterizes the extra phase the electron gains from the field \( E \). We believe this dephasing is a many-body effect arising from the electron-electron interaction. For such a process, the quasiparticle scattering rate \( (\tau_{ee}^{-1}) \) depends on the energy transfer in the process \( (\epsilon) \) and one can formally write \( \tau_{ee}^{-1} \propto e^\zeta \). We suggest that in this particular case of field induced dephasing the energy transfer will be determined by \( \Sigma(E) \) (see eqn 2), so that \( \epsilon \propto \Sigma(E) \). We will then have \( \tau_{ee}^{-1} \propto E^{2\zeta/3} \). Experimentally, \( q \approx 1.30 \pm 0.05 \) so that \( \zeta \approx 1.95 \pm 0.07 \). From the Fermi liquid theory for a clean system with long mean free path \( \zeta = 2 \) and for a dirty systems with short mean free path \( \zeta \approx 1.5 \) [13].

The value of \( \zeta \) estimated from the experiment is thus quite close to what is expected from this simple theoretical approach.

We can define a temperature dependent cross-over field \( E^*(T) \) from our experiment using eqn 4 so that when \( E = E^* \) the dephasing rate obtained from both channels are equal. We obtain \( E^* \propto T^{p/q} \approx T^{1/2} \). In figure 3b we show the variation of observed \( E^* \) as a function of \( T \). The solid curve is the line \( T^{1/q} \) where \( q \approx 1.3 \) as obtained from the experiment. The agreement is very good.

We have the following strong reasons to believe that this effect is not due to heating of the sample in the usual sense: (1) even at the highest bias the power dissipation is \( \lesssim 20 \mu W \), (2) the value of \( \tau_\phi \) obtained at the highest bias corresponds to that at \( T \approx 200 \) K if the complete dephasing was due to electron heating, which is rather unlikely when the sample is held at 2 K and (3) if there would have been electron heating, the conductivity \( \sigma \) would have been strongly affected and would have become a strong function of the field. The observed field dependence of the conductivity then can be used as a “thermometer” for the electron temperature. We find a small dependence of \( \sigma \) on the electric field. At the highest field and the lowest \( T_0 \), \( \delta \sigma/\sigma \lesssim 0.1\% \). Taking \( \sigma \) as the temperature scale and assuming that the entire field dependence of \( \sigma \) arises from heating we obtain an upper limit of the electron temperature rise of \( \approx 0.05 \) K.

We hence conclude that the dephasing seen with applied electric field is not a heating effect.

Our experiment thus revealed for the first time that at low temperature dephasing can be induced by an \( E \) field. In none of the earlier studies, made in low dimensional systems like wires, films etc. [13], such a field induced dephasing was reported. We make use of the UCF as a direct probe to find the dephasing, unlike the previous experiments where \( \tau_\phi \) was extracted as a fit parameter from MR experiments. Given the sensitivity of the UCF to the phase of electron wave functions, it may actually be a better tool for detecting dephasing.

In recent years there is an interesting debate on the issue of electron dephasing at low temperatures [13]. In this context our experiment can be seen as a useful and new contribution. Using UCF as a sensitive probe of dephasing, we establish that the measuring field can induce dephasing (without electron heating) in disordered systems with interacting electrons. At lower temperatures, such phase relaxation is brought about by relatively smaller fields and beyond a characteristic field scale \( E^*(T) \), the dephasing rate becomes independent of temperature and is determined only by the electric field.

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Figure caption:

**figure 1:** Electric field dependence of total noise magnitude at 2 K. The solid line is the fit as described in text. Inset (a) shows the temperature dependence of the noise magnitude measured with a field of \( \approx 7 \) V/m. Inset (b) shows the magnetic field dependence of noise. \( \nu(H) = \langle (\delta G)^2_H \rangle / \langle (\delta G)^2_{H=0} \rangle \). Two separate reductions of \( \nu(H) \) by factors of 1/2 clearly establishes the signature of UCF.

**figure 2:** Electric field dependence of noise at three different temperatures. Arrows denote the cross-over field \( E^* \). The inset shows the similar dependence of the dephasing rate \( \tau^{-1}_\phi \) obtained using eqn. [2]. The dotted lines are fits as described in text.

**figure 3:** (a) Temperature dependence of \( \tau_\phi \) from noise (eqn. [2]) and MR measurements. The measuring field \( E \ll E^* \). Both the lines have slope \( \approx 1.0 \pm 0.05 \).
(b) Temperature dependence of the cross-over field \( E^* \). The slope of the line is \( \approx 0.75 \) which is fairly close to the expected value of \( p/q \approx 0.77 \).