Intrinsic Decoherence in Mesoscopic Systems

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We present measurements of the phase coherence time τ_ϕ in six quasi-1D Au wires and clearly show that τ_ϕ is temperature independent at low temperatures. We suggest that zero-point fluctuations of the phase coherent electrons are responsible for the observed saturation of τ_ϕ. We introduce a new functional form for the temperature dependence and present the results of a calculation for the saturation value of τ_ϕ. This explains the observed temperature dependence of our samples as well as many 1D and 2D systems reported to date. [S0031-9007(97)03022-6]

PACS numbers: 73.23.–b, 03.65.Bz, 72.70.+m, 73.20.Fz

Perhaps the most fundamental property of a particle in any quantum system is the time over which the phase coherence is maintained in its wave function. It is well understood that coupling the quantum system to an environment [1] can cause a reduction in the constructive interferences of all possible Feynman paths due to changes induced in the environment by the particle and/or by phase randomization in the particle's wave function caused by the environment. In condensed matter electron systems, the components of the environment which can cause decoherence are the electron-phonon (EP), the electron-electron (EE), and magnetic impurity interactions [2]. In addition, under certain conditions dephasing can occur in the absence of any inelastic process [3]. Elastic scatterings from nonmagnetic impurities are known not to cause phase randomization [4]. The standard approach for determining the phase coherence time τ_ϕ in diffusive 1D and 2D systems is to fit weak localization theory to the measured change in resistance as a function of magnetic field near zero field [2,5]. Theoretically, this measured $\tau_\phi(T)$ should increase with decreasing temperature becoming infinite in very large systems at $T = 0$ because both the EP and EE interactions produce a $\tau_\phi \sim 1/T^p$ where p varies between 0.5 and 3 [2,3,5,6]. Yet in every published experiment performed down to very low temperatures, the phase coherence time is universally found to approach a temperature independent and finite value [7–10]. The temperature at which this saturation occurs varies by orders of magnitude ranging from 10 K in some GaAs devices to as low as 20 mK in a 2D Au film.

There have been many different theoretical approaches aimed at understanding the temperature dependence of τ_ϕ [2,3,6]. At temperatures below which the phonons are important, Altshuler *et al.* [6] have shown that the EE process with large energy transfer should dominate with $\tau_\phi = \tau_{ee} \propto L_T$, where $L_T = \sqrt{\hbar D/k_B T}$, and D is the classical diffusion coefficient in d dimensions. Subsequently, it was suggested that at low temperatures an EE process with small energy transfer will dominate the temperature dependence of the scattering rate with $\tau_\phi = \tau_N \propto 1/T^{2/3}$ [6]. This latter form has been veri-

fied by several papers where the Aharonov-Bohm phase of the electron wave function is used to compute the mean square value of τ_ϕ, which is then related to the resistance of the phase coherent volume of the system using the fluctuation-dissipation theorem [2,3]. Also many experiments have claimed to find agreement with this form over some temperature range [7,8], but at lower temperatures they observe a much weaker temperature dependence or an approach to a complete saturation in τ_ϕ.

In this Letter we report an extensive set of experiments designed to understand what sample parameters control the magnitude and functional form of the temperature dependence of τ_ϕ. We also observe the saturation in τ_ϕ at low temperatures, and show that it is not due to heating or magnetic impurities as frequently suggested. We propose that zero-point fluctuations of phase coherent electrons are responsible for the observed saturation. This is fundamentally different from previous attempts to include intrinsic fluctuations in mesoscopic systems where only the zero-point motion of impurity ions was considered [11]. We show that all our data can be surprisingly fit by one universal form that includes the zero-point decoherence time. This form fits most 1D and 2D data reported over the last 15 years. We present the results of the first calculation of this decoherence time.

All our samples were fabricated from pure gold containing less than 1 ppm of magnetic impurities and patterned into wires whose width, thickness, length, and disorder varied considerably as shown in Table I. A typical weak localization measurement for a 1D Au wire at 11 mK is shown in the inset of Fig. 1. We fit this data to the standard 1D form including both the singlet and triplet terms to obtain the phase coherence length L_ϕ [2]. The phase coherence time is obtained by $\tau_\phi = L_\phi^2/D$. Our samples are 1D with respect to L_ϕ and L_T, but most are 3D with respect to the elastic mean free path l_e. Figure 1 displays $\tau_\phi(T)$ from 11 mK to 7 K for one of our samples. Below 200 mK the temperature dependence of τ_ϕ is slower than expected from any theory [5], and clearly saturates below 40 mK. At temperatures above 2 K, the EP interaction begins to dominate the temperature dependence

TABLE I. Parameters of the samples shown in Figs. 1–4.

Sample	w (nm)	t (nm)	L (μm)	R/L (Ω/μm)	d	$D \times 10^3$ (m^2/s)	τ_0^{exp} (ns)	τ_0^{calc} (ns)	α	A_{ep} (ns K^3)
Au-1	60	25	57.9	29.14	3	9.0	3.41	0.72	0.61	6.8
Au-2	110	60	207	1.46	2	61.2	4.19	4.58	0.89	4.9
Au-3	100	35	155	9.31	3	12.0	2.24	2.91	0.85	6.1
Au-4	60	25	57.9	31.29	3	8.37	1.56	0.77	0.77	12.0
Au-5[a]	190	40	18.9	191.7	3	0.27	0.45	-	0.74	10.7
Au-6	180	40	155	2.91	3	18.8	3.39	7.9	0.80	10.5
1D-Si[b]	440	2DEG	100	1219	2	7.2	0.11	0.11	0.138	NA
1D-Si[b]	200	2DEG	100	2777	2	6.9	0.039	0.025	0.087	NA
1D-nGaAs[c]	53	2DEG	2.5	1.25×10^4	2	4.8	0.0035	0.0084	0.094	NA
1D-GaAs[c]	70	2DEG	1.9	5.85×10^3	2	55.0	0.014	0.012	0.074	NA
2D-Au[d]	-	7.6	-	$R_\square = 24\ \Omega$	3	2.2	4.8	2D	0.37	NA
2D-AuPd[e]	-	12	-	$R_\square = 38\ \Omega$	3	2.3	6.55×10^{-4}	2D	0.48	5.7
2D-AuPd[e]	-	16	-	$R_\square = 153\ \Omega$	3	0.4	0.012	2D	0.29	12.0

[a]Reference [18].   [b]Pooke *et al.* [8].   [c]Hiramoto *et al.* [9].   [d]Mueller *et al.* [10].   [e]Lin *et al.* [7].

of τ_ϕ. In this paper we will assume that the scattering time due to phonons is given by $\tau_{ep} = A_{ep}/T^p$ with $p = 3$ which is the most easily justified form [6]. We have measured over twelve different 1D Au wires with varying width from 35–210 nm, thickness from 20–135 nm, and length from 19−4120 μm. D varied by more than a factor of 250, ranging from 0.000 27 to 0.07 m^2/s. Our low temperature L_ϕ varied by more than a factor of 40, from 0.43−18 μm, increasing with increasing D. Figure 2 displays the temperature dependence of $\tau_\phi(T)$ for four of our samples representing a broad range of disorder. For our samples, $\tau_\phi(T) > \hbar/k_B T$, the thermal time, over the entire data range. At low temperatures, all our $\tau_\phi(T)$ data show saturation or a much weaker temperature dependence

than predicted from any theory. The temperatures at which these samples begin to deviate from the theoretically expected form differ from one another, but they all show the same qualitative behavior.

We believe that heating is not responsible for the observed saturation for three reasons. Our experiments were done in the regime where τ_ϕ is independent of current. In addition, we have measured the temperature dependence of the change in resistivity $\Delta\rho_{ee}$ due to the EE interaction in a finite magnetic field sufficient to destroy weak localization. As shown in the inset of Fig. 2 we find that the correction $\Delta\rho$ still remains temperature dependent down to our lowest temperatures, even though τ_ϕ clearly saturates. The straight line is the theoretically expected behavior, $\Delta\rho_{ee} = (2e^2 R^2 wt/hL^2)\sqrt{\hbar D/k_B T}$ [5], demonstrating

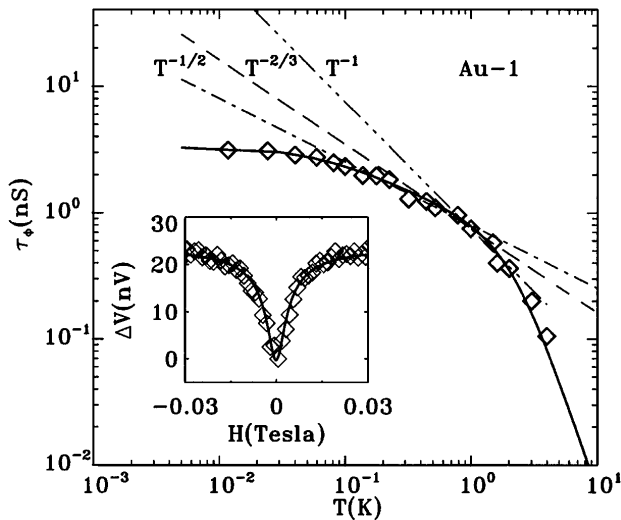FIG. 1. Temperature dependence of τ_ϕ for sample Au-1. The broken lines are the functional forms expected from previous theories. The solid line is a fit to Eq. (1) with phonons. The inset shows the typical weak localization data taken with 2 nA at 11 mK with a fit to the standard 1D theory.
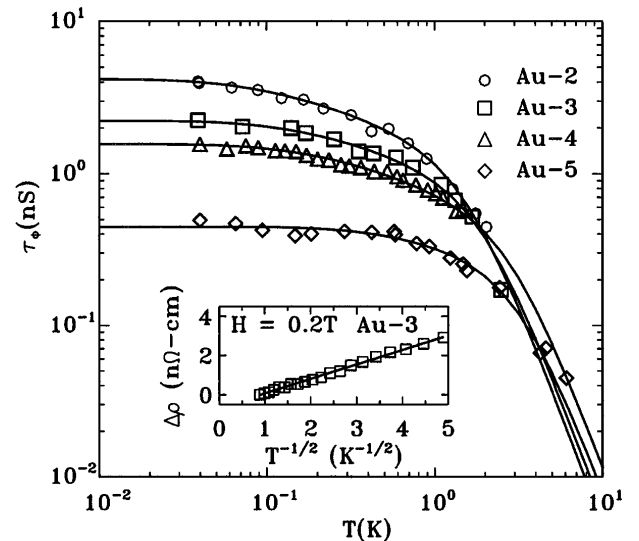

FIG. 2. Temperature dependence of τ_ϕ for four Au wires. Solid lines are fits to Eq. (1) with phonons. The inset is the EE contribution to $\Delta\rho$ with the theoretical prediction.

that the electrons are still in good contact with the thermal bath. Finally, we have placed some of our samples in a second dilution refrigerator with higher levels of shielding of the external electromagnetic environment at the sample site and find exactly the same $\tau_\phi(T)$.

We have also studied the effects of magnetic impurities on $\tau_\phi(T)$ by ion implanting Fe, the dominant magnetic impurity in Au, after measuring the full $\tau_\phi(T)$ in the clean sample. In Fig. 3, we compare the temperature dependence of τ_ϕ for one sample before and after implantation of ~2.8 ppm of Fe. The effect of adding magnetic impurities is to lower the magnitude of the phase coherence time, but *not* to cause saturation in $\tau_\phi(T)$. The low temperature data is clearly temperature dependent in agreement with previous experiments [12,13]. In addition, the saturation of τ_ϕ found in experiments on semiconductor wires [8,9] cannot be due to magnetic impurities since these structures are thought not to contain any of these impurities. The inset of Fig. 3 shows the low temperature behavior of $\Delta\rho(T)$ for the implanted sample after subtracting the EE contribution $\Delta\rho_{ee}$ determined from the clean sample before implantation. The straight line is the expected behavior $\Delta\rho \sim \log T$ for an AuFe Kondo system [14], containing 4.8 ppm of Fe [15].

For the reasons given above, we are confident that the saturation in τ_ϕ observed for all our clean Au samples represents a fundamental quantum mechanical effect. We believe that the origin of the observed saturation in τ_ϕ is that the zero-point fluctuations of the phase coherent electrons are playing an important role in the dephasing process. It is predicted that at low temperatures the mean square voltage in an electrical resistor will be finite at $T = 0$ due to the zero-point fluctuations of the electrons [1]. We propose that zero-point fluctuations of

the intrinsic electromagnetic environment [16] seen by the phase coherent electrons should cause intrinsic dephasing and lead to a finite temperature saturation of τ_ϕ. We have discovered that, at low temperatures, one very simple form fits the temperature dependence of $\tau_\phi(T)$ for all our Au samples,

$$\tau_\phi = \tau_0 \tanh\left[\frac{\hbar \alpha \pi^2 D}{k_B T L_T L_\phi^0}\right] = \tau_0 \tanh\left[\alpha \pi^2 \sqrt{\frac{\hbar}{\tau_0 k_B T}}\right],$$

(1)

where $D = v_F l_e / d$, τ_0 is the measured saturation value, and $L_\phi^0 = \sqrt{D\tau_0}$. Equation (1) could have been anticipated once the connection to the fluctuation-dissipation theorem [16] has been made because the inverse of the average Einstein energy of the phase coherent electrons is $\langle E \rangle^{-1} = \tau_\phi/h = (\tau_0/h) \tanh(h/2k_B T \tau_\phi)$ and according to electron-electron theories involving large energy transfer, $\tau_\phi = \tau_{ee} \propto L_T$ [5]. α is a constant which only varies from 0.6 to 1.1 for all our samples. At higher temperatures where phonons become important for dephasing, the total phase coherence time is the inverse of $\tau_\phi^{-1} + \tau_{ep}^{-1}$. The solid lines drawn through *all* our Au $\tau_\phi(T)$ data displayed in Figs. 1–3 are excellent fits to Eq. (1) including phonons.

If Eq. (1) truly describes the temperature dependence of the phase coherence time for our samples, it should apply to all 1D and 2D mesoscopic systems fabricated from metals and semiconductors. Figure 4 displays some representative examples of the previously observed saturation behavior of τ_ϕ in a variety of 1D and 2D systems where the saturation temperature varies from 20 mK to 10 K. For 2D Au [10] and AuPd [7] experiments, Eq. (1) fits the reported phase coherence time extremely well with the constant α reduced only by a factor of π due to the
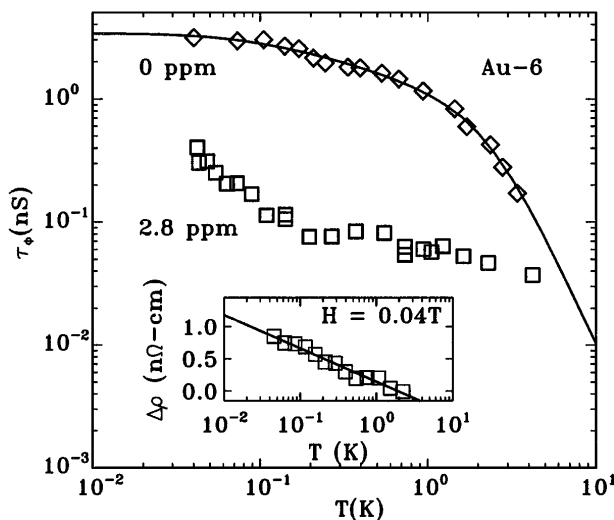
FIG. 3. Temperature dependence of τ_ϕ before (diamonds) and after (boxes) Fe implantation. The solid line is a fit to Eq. (1) with phonons. The inset shows the $\log(T)$ dependence of $\Delta\rho$ due to magnetic impurities with a theoretical fit.
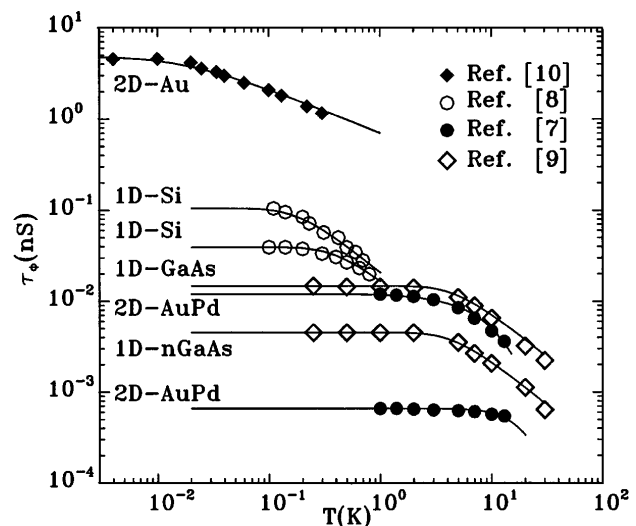
FIG. 4. Temperature dependence of τ_ϕ in a 2D-Au, 1D-Si, 1D-GaAs, and 2D-AuPd experiments. The solid lines are our fits using Eq. (1).

change in dimensionality [5,6]. Similarly, for low mobility 1D Si MOSFETs [8] and for high mobility 1D GaAs heterostructures [9] we find that Eq. (1) must be modified by replacing L_T with the actual width w of the sample and reducing α by π^2. The substitution of w for L_T is generally made because the thermal diffusion length is much larger than the sample width. Amazingly, as shown in Table I, the fits to Eq. (1) describe all the published data extremely well including the high temperature part of the data and give us further confidence that this zero-point dephasing mechanism correctly describes the essential physics of the phase coherence time for all mesoscopic samples.

It is now possible to calculate the value of τ_0 contained in Eq. (1) using a combination of previous approaches. Starting from the fluctuation-dissipation theorem and integrating the fluctuations in the low temperature limit of Einstein energy over frequency we can obtain a single effective, sample dependent, average energy. This energy can then be related to the dephasing time [2,3]. In a separate publication we will describe in detail our approach to solving this problem [17], but a preliminary result (valid only for diffusive 1D systems) which describes many of the 1D experiments published to date, including ours, is

$$\tau_0 = \left(\frac{4\pi \hbar^2 L}{e^2 d^2 R m^* D^{3/2}} \right)^2, \qquad (2)$$

where R/L is the resistance per length, and m^* is the effective mass of the electron. The calculated values τ_0^{calc} for all 1D experiments are listed in Table I, and are within a factor of 2 or 3 from the measured value τ_0^{exp}. For 1D systems fabricated from a two-dimensional electron gas (2DEG) with $L \sim L_\phi$, it is interesting to note that Eq. (2) reduces to $(4h/m^*D)(\hbar/\Delta)$ where Δ is the separation between energy levels in the phase coherent volume of the system. We find the agreement of Eq. (2) with the measured values quite remarkable considering the extreme sensitivity of τ_0 on D and R/L. An error of only 25% in the width and thickness of a sample can easily propagate to give an error of a factor of 2 in τ_0.

In conclusion, we report a comprehensive set of experiments in 1D gold wires, which clearly shows that the phase coherence time saturates at a finite temperature. This saturation is not due to heating, magnetic impurities, or external environmental effects. We suggest that zero-point fluctuations are responsible for this observed saturation and introduce both a functional form for the temperature dependence and a calculation for the saturation value for the phase coherence time. We find that all our data as well as the data from many other groups on a wide variety of systems including 1D wires (both semiconductors and metals), and 2D films can be fit quite well to the form given in Eq. (1) essentially with only one adjustable parameter, τ_0, the zero temperature phase coherence time. Our approach allows us, for the first time, to theoretically calculate τ_0 for any 1D mesoscopic system from only R/L and D, and the agreement between the calculated value and measured value of τ_0 is extremely good in our as well as others' experiments.

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