Single-defect thermometer as a probe of electron heating in Bi

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We have studied the effect of Joule heating on the dynamics of a single bistable defect in a submicron Bi wire below 1 K. We interpret the ratio of the two defect transition rates as a local thermometer, via the detailed balance relation. As the drive current increases, the defect temperature approaches a power-law dependence with drive, independent of the nominal lattice temperature. The data are consistent with a simple model of electron heating, and strong thermal coupling between the defect and the electron bath below 1 K. A second thermometer, based on the amplitude of the defect-induced resistance fluctuations, does not follow the simple heating model.

It is now possible to study the dynamics of individual defects in metals, due to the development of submicrometer sample fabrication techniques. Several groups have observed discrete jumps in the electrical resistance of small samples due to the motions of individual defects, at temperatures ranging from below 0.1 K to room temperature.[1-5] Our own efforts have been directed toward the low-temperature regime, which has several unique features. First, the sensitivity of the electrical resistance to the motion of a single defect is enhanced[6] at low temperature due to long-range quantum interference, or "universal conductance fluctuations" (UCF).[7] Below 1 K, one can observe discrete resistance jumps in samples with dimensions of order tenths of micrometers, a regime easily accessible by electron-beam lithography. Second, the defects observed below 1 K move by quantum-mechanical tunneling through the barrier of a double-well potential.[4,5] The tunneling dynamics are strongly influenced by interactions with conduction electrons in the metal, causing the tunneling rates to *increase* as the temperature is lowered in some circumstances. Third, due to weak electron-phonon coupling at very low temperatures, it is quite easy to heat the electrons and hence the defects well above the lattice temperature. This effect, always a concern for those performing low-temperature transport measurements, can nonetheless serve as a tool for probing the electron-phonon interaction.[8-11]

We report here the effect of Joule heating on the dynamics of a single bistable defect in Bi. This study was motivated by the observation that defects with small duty cycles are quite sensitive to the amplitude of the measurement current. The ratio of the fast and slow transition rates of a defect depends on temperature through the detailed balance relation $\gamma_f/\gamma_s = e^{\varepsilon/kT}$, where ε is the energy asymmetry of the defect. When $\varepsilon/kT > 1$, this ratio is sensitive to small changes in the temperature T seen by the defect. Since these defects are strongly coupled to the conduction electrons in the sample below 1 K,[4,5] we interpret their sensitivity to drive current as an indication of electron heating. Using the "defect thermometer" to study heating is attractive because it is based purely on statistical mechanics—a feature it shares with the Johnson noise thermometer used by Roukes *et al.*[8] in a previous electron heating study.

An electron heating study based only on the defect thermometer relies on the assumptions that the defect is more strongly coupled to electrons than to phonons, and that the temperature deduced from the defect tunneling rates via the detailed balance relation is the "effective" temperature of the nonequilibrium electron distribution.[12] We will show that the first assumption breaks down for temperatures above about 1 K, based on fits of our data to dissipative quantum tunneling theory.[13,14] The data presented here were taken well below 1 K, where we expect both assumptions to hold.[12] We would have liked to measure the electron temperature directly, and thereby deduce the relative thermal coupling between the defect and the electrons and phonons as a function of temperature. We did not achieve this more ambitious goal, for two reasons. We tried to measure the electron temperature from the amplitude of the resistance fluctuations induced by the moving defect, but this thermometer did not obey a simple heating model. Also, we could not extend our heating measurements above 1 K due to interference from other defects in the sample.

The sample for this study is the same Bi wire used in our previous work.[5] The wire has dimensions 0.1 μm $\times$ 1.0 μm $\times$ 20 nm, a low-temperature resistance of 2.2 kΩ, and has five leads for measurement in a bridge circuit. At several different values of the applied magnetic field, the resistance of the sample shows clear transitions between two distinct values, corresponding to the two states of a bistable defect in one of the sample arms. All of the data presented here were taken with a magnetic field of 7 T, where the energy asymmetry of the defect was largest; hence the ratio of transition rates was most sensitive to temperature. At each value of temperature and drive, several hundred transitions were recorded and analyzed. The individual transitions were found using a comparator, and the histograms of dwell times in each state were fit to exponentials to find the average dwell time in the state. The fast and slow transition rates γ_f and γ_s are the reciprocals of the average dwell times.

Figure 1 shows $\ln(\gamma_f/\gamma_s)$ vs $1/T$, taken with a low enough drive current that no significant heating of the sample occurs. The data can be fit by a straight line through the origin, with a slope equal to the energy asymmetry of the defect, $\varepsilon/k_B = 0.42 \pm 0.02$ K. We performed the heating experiment by increasing the ampli-

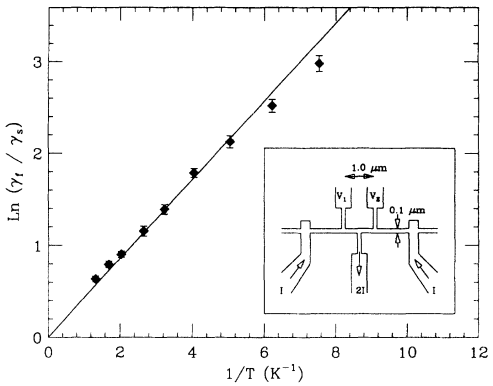

FIG. 1. $\ln(\gamma_f/\gamma_s)$ vs $1/T$ for a single defect in Bi. The transition rates obey the detailed-balance relation with a slope of 0.42±0.02 K. Inset: Schematic diagram of the sample, showing current and voltage leads.

tude of the ac drive current used to measure the resistance. (We checked that using a large dc current for heating plus a small ac measurement current produced consistent results.) Figure 2 shows the results of heating the sample with large drive currents, for lattice temperatures of 0.132, 0.247, and 0.490 K. Rather than plot γ_f/γ_s, we plot the defect temperature, defined as $T_{\text{defect}}=(\varepsilon/k_B)/\ln(\gamma_f/\gamma_s)$. For low drive current, the defect temperature rises slowly above the lattice temperature. As the drive increases, the defect temperature approaches a power-law behavior that depends only on drive, independent of the initial lattice temperature.

Behavior similar to that shown in Fig. 2 has been observed by Roukes *et al.*,[8] who derived an expression for the electron temperature as a function of drive based on an earlier model of Anderson, Abrahams, and Ramakrishnan.[15] The model is based on the observation that the thermal conductance between electrons and phonons in a sample of volume V is $k_{\text{el-ph}}=C_{\text{el}}\tau_{\text{el-ph}}^{-1}$, where $C_{\text{el}}=\gamma_{\text{el}}TV$ is the electronic heat capacity and $\tau_{\text{el-ph}}^{-1}=\alpha T^p$ is the electron-phonon-scattering rate. The exponent p varies between 2 and 3 for typical disordered films.[16] For low drive currents, the temperature offset between the electrons and phonons is proportional to the power dissipated in the sample, $Q=I^2R$. As the current increases, the electron temperature rises, and the electrons become more efficient at cooling themselves by emitting phonons. Eventually the electron temperature approaches the asymptotic dependence on drive $T_{\text{el}}\propto I^{2/(2+p)}$, independent of the initial lattice temperature T_0. Integration of the equation $dQ=k_{\text{el-ph}}(T)dT$ from T_0 to T_{el} yields the expression[8]

$$T_{\text{el}}^{2+p}-T_0^{2+p}=[(2+p)/\alpha\gamma_{\text{el}}](I^2R/V)\ . \tag{1}$$

The solid lines in Fig. 2 represent a single global fit of Eq. (1) to all the data shown in the figure, with the two free parameters p and the product $\alpha\gamma_{\text{el}}$. The values of the parameters obtained from the fit are $p=2.0\pm0.2$, and $\alpha\gamma_{\text{el}}=(4.5\pm1.0)\times10^{10}$ W/K^4 m^3.

Before interpreting these results, we examine the assumptions made regarding heat transfer in the sample. First we consider the thermal coupling of the defect to the electrons and phonons. Figure 3 shows a log-log plot of the fast and slow transition rates of the defect versus temperature. The behavior of these rates below 1 K is described by dissipative quantum tunneling theory,[13] and was the subject of a previous paper.[5] The theory describes tunneling of a defect between the wells of a double-well potential, in the presence of strong interactions with a dissipative environment, or heat bath. In our experiment, the temperature and energy asymmetry are much smaller than the vibrational level spacings in a well, and much larger than the tunneling matrix element. In this regime, the only property of the heat bath that enters into the theory is the low-energy spectral density of excitations $J(\omega)\propto\omega^n$, where n is 1 or 3 for electrons or phonons, respectively. We showed previously[5] that for $T<1.2$ K the data could be fit with a model that considered only electrons in the heat bath. To fit the data above 1.2 K, one must include the phonon contribution. The solid line shown in Fig. 3 is a fit of the data to a function calculated by Grabert[14] that includes the effect of both electrons and phonons. We do not claim that the fit shown in Fig. 3 confirms the formula of Grabert—clearly more high-temperature data points are needed. We are

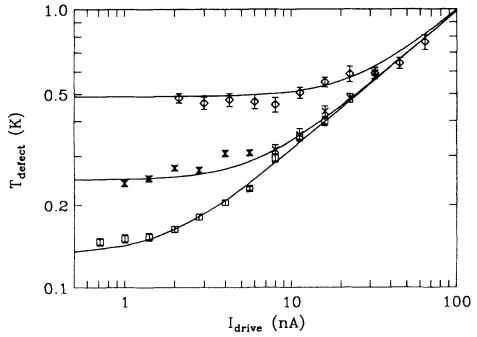

FIG. 2. Log-log plot of defect temperature vs drive current, for three different values of the lattice temperature, $T_0=0.132$, 0.247, and 0.490 K. The defect temperature is determined from the ratio of fast and slow transition rates via the detailed balance relation. The solid lines represent a global least-squares fit of the data to Eq. (1) with two parameters $p=2.0$ and $\alpha\gamma_{\text{el}}=4.5\times10^{10}$ W/K^4 m^3.

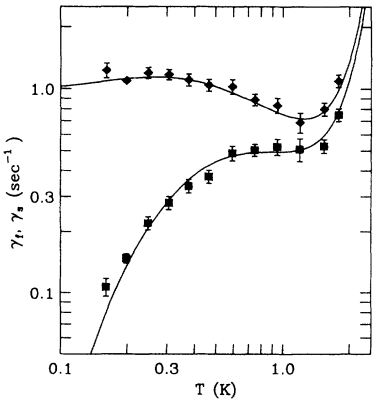

FIG. 3. Log-log plot of fast (♦) and slow (■) transition rates vs temperature. The solid line is a least-squares fit to the theoretical function calculated by Grabert in Ref. 13. The crossover between electron-dominated and phonon-dominated tunneling occurs at $T_{\text{ph}}\approx0.95$ K.

interested in the value of Grabert's parameter T_{ph}, the crossover temperature between electron-dominated and phonon-dominated behaviors. For the data shown in the figure, $T_{ph}=0.95\pm0.03$ K. A fit to data from the same defect measured at a different value of the magnetic field (0.14 T) yields $T_{ph}=0.91\pm0.03$ K. Since the lattice temperatures in our heating study are well below T_{ph}, we are justified in neglecting the thermal coupling between defect and phonons.[14]

Another crucial assumption in the analysis leading to Eq. (1) is that the electrons heat while the phonons remain at the temperature of the cryostat. This assumption is valid if the thermal link between the electrons and phonons is much weaker than that between the phonons and substrate and between the substrate and cryostat.[17] The latter condition is easily fulfilled. The Si substrate has a surface area 10^8 times larger than the sample area, and is immersed in liquid helium in close proximity to the cryostat thermometer. We believe that the former condition is also satisfied, by the following argument. The thermal conductance between film and substrate is about $k_{sub}/T^3A\approx500$ W/m^{2}K^4, where A is the area of the film in contact with the substrate.[18] We estimate $k_{el\text{-}ph}$ in our Bi film as follows: The density of electron and hole states at the Fermi level is generally larger in thin Bi films than in bulk Bi. We take the value $\gamma_{el}=2$ J/K^{2}m^3, which is twice the value for bulk Bi.[19] The electron-phonon scattering rate was measured by Dorozhkin, Lell, and Schoepe,[9] who obtained $\tau_{el\text{-}ph}^{-1}=\alpha T^p$ with $p=3$ and $\alpha=3\times10^9$ s^{-1}K^{-3}. (Our own measurements suggest a smaller value of p, but we will use this as a starting point.) The film thickness is 20 nm, so we have $k_{el\text{-}ph}/T^4A\approx120$ W/K^{5}m^2. The above estimates give $k_{sub}/k_{el\text{-}ph}\approx4$ at 1 K, and 40 at 0.1 K.

A final assumption usually made in heating experiments is that the electron and phonon temperatures are uniform throughout the sample. Unfortunately, this assumption is not valid in our experiment, due to the very small sample size. (This small size is necessary to enable us to detect the motion of a single defect.) In our sample, shown in the inset to Fig. 1, heat dissipated in the sample can flow within the electronic system directly out the leads to the large pads, without first equilibrating with the phonons in the sample. We estimate the thermal conductance out the leads using the Wiedemann-Franz relation: $K/\sigma T=2.5\times10^{-8}$ WΩ/K^2. The longest distance from any part of the sample to the large pads is about 0.5 μm, corresponding to about half the sample resistance, i.e., 1 kΩ. Hence the thermal conductance of the electrons from the hottest part of the sample to the cool pads is about 2.5×10^{-11} TW/K^2. In comparison, the thermal conductance between the electrons and phonons *inside one arm of the sample* ($A=0.05$ μm^2) is only 6×10^{-12} T^{4}W/K^5 according to the estimate made above. These numbers show that the Joule heat generated within the sample diffuses out the leads at least as quickly as it transfers to the phonon system, giving rise to a temperature gradient in the sample.

This last consideration precludes us from obtaining an absolute estimate of the electron-phonon-scattering rate from our data. Equation (1) was derived assuming that all the Joule heat dissipated in the sample transfers to the phonons within the sample volume. If we try to interpret the value of α obtained from Fig. 2 this way, we find $\alpha=2\times10^{10}$ s^{-1}K^{-2}, which is a factor of 7 larger (at 1 K) than the value obtained by Dorozhkin, Lell, and Schoepe.[9] The discrepancy reflects the fact that the heat in the electron system diffuses out the leads, and therefore has a larger volume in which to transfer to the phonon system. If we knew the exact location of the defect in the sample, we might be able to model the heat flow and temperature in the system, but that is not possible in the present experiment. Despite this limitation, our estimate of the temperature dependence of the electron-phonon coupling may still be valid. Our value $p=2.0\pm0.2$ is lower than the value $p=3$ obtained by Dorozhkin, Lell, and Schoepe[9] in a low-temperature heating experiment, but it is consistent with the values between 2 and 2.5 obtained from weak-localization studies carried out at higher temperatures,[20] including those in Ref. 9.

The above analysis presents a consistent, but not unique, explanation of the data in Fig. 2. An alternative explanation for an observed value of $p=2$ has been proposed recently by Kanshar, Wybourne, and Johnson,[21] who point out that the heating model leading to Eq. (1) assumes good thermal coupling between the phonons in the films and substrate. By allowing the coupling to vary, these authors show that data from a heating experiment can obey a power law varying anywhere from $p=2$ to 3, even when the underlying electron-phonon scattering rate depends on temperature with $p=3$. Another concern is our estimate of the electron-phonon scattering rate, $\tau_{el\text{-}ph}^{-1}=\alpha T^p$, based on Ref. 9. The experiments of Ref. 20 give $p=2$, and $\alpha=2\times10^{10}$ s^{-1}K^{-2}. With this larger value of α, we find $k_{sub}\approx0.6k_{el\text{-}ph}$ independent of temperature, so our assumption that the electrons heat while the phonons stay cold may be questionable. We also find with this value of α that the thermal conductance out the leads is less important, and our measured value $\alpha=2.2\times10^{10}$ s^{-1}K^{-2} agrees fortuitously with the values from Ref. 20. We cannot distinguish between these interpretations of our data, but we can assert that our mea-

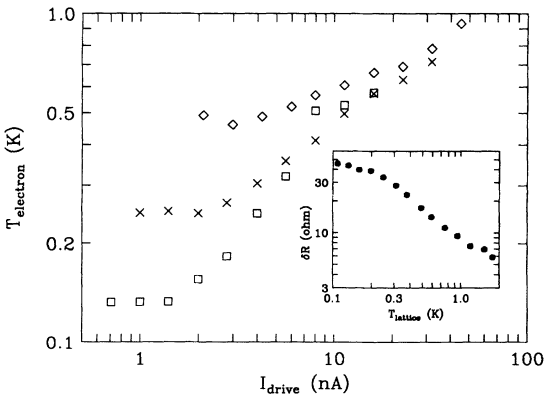

FIG. 4. Log-log plot of electron temperature vs drive current, for the same three lattice temperatures shown in Fig. 2. The electron temperature is deduced from the amplitude of the defect resistance jump, whose equilibrium temperature dependence is shown in the inset. These heating data do not obey Eq. (1).

sured values of α represents an upper bound on the electron-phonon-scattering rate in our sample.

Finally, we discuss our attempt to measure the electron temperature directly, based on the temperature dependence of the amplitude of the resistance fluctuations, δR. We can compare the observed behavior of δR, shown in the inset to Fig. 4, with that predicted by universal conductance fluctuation theory.[6,22] Near 1 K, the phase-breaking length L_ϕ in our sample is between 0.1 and 0.2 μm.[23] Thus the sample is just barely in the one-dimensional (1D) limit, defined by $L_x, L_y < L_\phi < L_z$, where L_x, L_y, and L_z are the sample thickness, width, and length, respectively. In this limit, $\delta R \propto L_{\rm min}^2 L_\phi^{1/2}$, where $L_{\rm min}$ is the smaller of L_ϕ and the thermal length, $L_{\rm th}=(hD/kT)^{1/2}$. At these low temperatures we expect $L_\phi \propto T^{-1/2}$, due to electron-electron scattering, hence $\delta R \propto T^{-5/4}$. The observed dependence is about T^{-1}, which is rather good agreement. As the temperature is lowered, the sample dimensionality will cross over to 0D when L_ϕ becomes comparable to the sample length of 0.5 μm. In this regime the theory predicts $\delta R \propto L_\phi^{-1/2} \propto T^{-1/4}$, which is consistent with the roll-off seen in the inset to Fig. 4 at the lowest temperatures.

Since δR depends only on L_ϕ and $L_{\rm th}$, both of which depend only on the electron temperature, we hoped that δR would serve as a good electron thermometer. Figure 4 shows a plot of the electron temperature, deduced from δR, versus drive. These data were taken simultaneously with those shown in Fig. 2. Unlike the data in Fig. 2, however, the data in Fig. 4 cannot be fit with Eq. (1), because $T_{\rm el}$ does not asymptotically vary as a power law with drive. In addition, $T_{\rm el}$ appears to increase with drive initially much faster than $T_{\rm def}$. This latter observation would be plausible if the defect were only weakly coupled to the electrons, but in the present circumstance we find it disturbing. Given the choice between our two thermometers, we trust more the reliability of the defect thermometer because of its connection to statistical mechanics. We do not know why δR does not serve as a reliable electron thermometer, but we mention incidentally that Bergmann *et al.*[11] found the Coulomb-interaction resistance anomaly to be a poor thermometer in a heating study of Au films, possibly due to violations of Ohm's Law.

In summary, we have shown that the transition rates of a single defect can be used as a local thermometer under nonequilibrium conditions, via the detailed-balance relation. We have used this thermometer to study electron heating in a submicrometer Bi sample, and we find results consistent with a simple heating model, with electron-phonon power law $p=2$. We cannot obtain the absolute electron-phonon-scattering rate from this experiment, due to the nonuniform temperature profile in the submicrometer sample.

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