Magnetic Field Tuned Energy of a Single Two-Level System in a Mesoscopic Metal

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We study the effect of an external magnetic field H on an individual tunneling system by measuring the time-dependent bistable conductance of a submicron Bi sample near 1 K. The amplitude of the dynamic conductance fluctuations is a random function of H. The transition rates are significantly modified by the field, from which we infer an H-dependent energy splitting. This splitting is symmetric near $H=0$, but exhibits nonmonotonic features at higher fields, possibly arising from the coupling of local electron-density fluctuations to the defect.

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In metals it is well known that impurities and structural defects act as scattering centers for conduction electrons, leading to a reduction of electrical conductivity. If the defects are mobile they can also modulate the conductance in time. One such manifestation of this is $1/f$ conductance noise which arises from defects whose dynamics are broadly distributed [1]. The dynamics of the defects are described by activated, over-the-barrier hopping at high temperatures [2], while at low temperatures the appropriate description invokes tunneling in a double-well energy potential. A connection between the latter process and electron quantum interference in mesoscopic systems, as probed through $1/f$ noise, has recently been established [3-5]. Conversely, the conduction electrons are expected to influence the defect dynamics; for light impurities, transport energies are significantly renormalized [6,7].

With the advent of submicron technology, it is possible to prepare sufficiently small metallic wires that conductance fluctuations due to *individual* defects are resolvable [8,9]. In particular, for weakly disordered metals in the diffusive electron regime, the universal conductance fluctuation (UCF) mechanism [3] leads to an enhancement of the conductance response due to the change of state of a single defect. We report here on the influence of an applied magnetic field H (up to 9 T) on the energetics of individual two-level systems in small Bi wires below 10 K. Our principal findings are (1) the amplitude of the dynamic conductance fluctuations is a random function of H, and (2) the fluctuation frequencies are significantly modified by the field. We infer that the field *renormalizes the energy splitting* of the tunneling two-level system (TLS). The splitting is not a simple function of H but rather exhibits a symmetric component, upon which is superposed smaller nonmonotonic features, with a field scale of a few T. We compare these results to a recent theoretical prediction based on a linear coupling of the defect energy to the local electron density [10].

The samples were 30-nm evaporated Bi films deposited at room temperature on oxidized Si substrates through a stencil produced using electron-beam lithography [11] which is subsequently lifted off. The deposition rates of the two films (total of three lithographic samples measured) were about 1 nm/sec. The films were patterned into five-probe (standard four-probe plus a center contact) conductance samples with typical linewidth between 60 and 80 nm, and lengths varying between 0.15 and 0.6 μm. Bi was chosen to provide high resistivity (about 700 $\mu\Omega$ cm), and because its mesoscopic properties have previously been established [5,9,12].

The electrical measurement was a five-probe ac conductance measurement [13]; we digitized the voltage as a function of time and simultaneously measured the power spectral density $S(f)$ using a signal analyzer. Typical parameters were the measurement current $I \lesssim 10^{-7}$ A, current density $J \lesssim 10^4$ A/cm^2, and measurement time 100-2000 sec. The bandwidth was 10^{-3} Hz $\le f \le 20$ Hz, determined by maximum digitization time of 2000 sec, and by a low-pass filter used to reject Johnson noise, line-frequency harmonics, and higher-frequency conductance noise sources in the sample. To be considered as valid data, we insisted that the conductance $G(t)$ be a "clean" bistable signal: G had to have only two discrete values, with the total noise from all other sources (mentioned above) being smaller in size than the dominant switcher. In other words, we required a signal in which it was always unambiguously possible to assign G to being in one of the two states. Signals were most often rejected because there were multiple TLS present, with no single one dominant. For good statistics, we tried to observe 100-200 switches for each data point. The time dynamics of a single TLS were stable for times lasting up to several weeks, after which the signal would be completely changed, with either no TLS or a different TLS (as characterized by the time dynamics) observed. In this paper, we have displayed data from the same single TLS (with one exception noted later) which exhibited behavior characteristic of all defects studied [14]. Thus the data shown in the figures may be examined in the context of a single set of physical parameters.

The basic measurement is illustrated in the inset to Fig. 1, measured in a magnetic field $H=4.4$ T applied perpendicular to the substrate. The conductance fluctuation δG_1 was derived from the difference of the average up and down values. To determine switching rates, we calculated duration times spent in up and down states. These duration times were exponentially distributed, and fits by an exponential decay yielded the characteristic rates for the shorter-lived ($\tau_{\rm fast}^{-1}$) and longer-lived ($\tau_{\rm slow}^{-1}$)

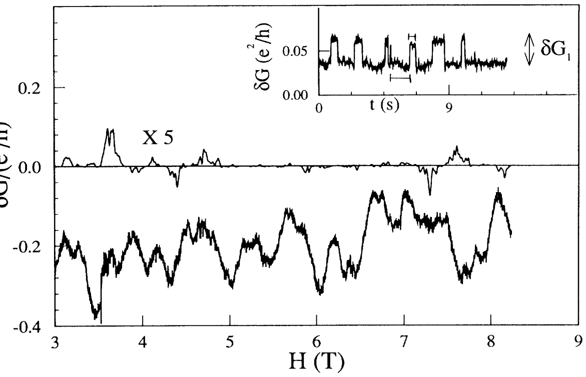

FIG. 1. Inset: Conductance change δG [13], in units of e^2/h, as a function of time, at $H=4.4$ T and $T=0.5$ K, measured in the sample with length 0.3 μm. G switches between two bistable values, corresponding to two defect configurations. The amplitude δG_1 is indicated by the vertical arrow. Switching rates are derived from the duration times indicated by the horizontal bars. Main body: Lower curve, random $\delta G(H)$ (magnetofingerprint) at $T=0.5$ K in units of e^2/h. Superposed on the reproducible structure are time-dependent fluctuations [maximum amplitude about $\frac{1}{5}$ of the structure in $\delta G(H)$] of the type illustrated in the inset. Upper curve, amplitude $\delta G_1(H)$ of the time-dependent fluctuations, multiplied by a factor of 5. $\delta G_1(H)$ fluctuates randomly positive and negative, and is background-noise limited (i.e., no TLS visible in time record) over substantial ranges of H, such as the region from 5 to 7 T.

states individually. We also fitted $S(f)$ by a Lorentzian spectrum, which is the expected spectral shape for exponential decay; the amplitude and knee frequency provided consistency checks for δG_1 and the rates. As in previous work, we assign the two conductance states to two different structural configurations of a single microscopic defect [8,9,15]. Although we do not know the microscopic constitution of this defect, likely candidates include sites at internal surfaces (i.e., grain boundaries and dislocations) and external surfaces.

We first examine the dependence of δG_1 on H. To do this, we first consider the aperiodic $G(H)$, the lower curve in Fig. 1. The structure of $G(H)$ exhibited in Fig. 1 is static; this aperiodic "magnetofingerprint" is a well-known result [16] with an amplitude of order e^2/h and a magnetic-field scale set by sample size and temperature [17]. Superposed on this static structure is time-dependent noise like that in the inset which is, at maximum, about 5 times smaller in amplitude than the reproducible structure in $G(H)$. While the individual time-dependent switches from slow to fast state and back are random, the amplitude of the envelope is a static function of H, just as is $G(H)$. We derive the amplitude of the time-dependent noise by defining $\delta G_1(H)$ as $\delta G_1(H)=\langle(G_{\rm slow}-G_{\rm fast})\rangle_T$, where, e.g., $G_{\rm fast}$ is the value of G in the higher-conductance state in the inset. Here, the average is over a time T less than the time over which a substantial range of H is traversed, but greater than $\tau_{\rm fast}$ and $\tau_{\rm slow}$, so that the average is over many switches. $\delta G_1(H)$ is shown as the upper curve in Fig. 1. Note that the definition yields a sign for δG_1 [18] [e.g., δG_1 is negative for $G(t)$ in the inset]. We have not shown the range below $H=3$ T, because there $\tau_{\rm fast}^{-1}$ and $\tau_{\rm slow}^{-1}$ are too close to make this assignment. $\delta G_1(H)$ fluctuates randomly, *both positive and negative*, and is zero (δG_1 smaller than background noise) over substantial regions of H. The substantial deviations of δG_1 from zero (clustered in about five regions below 5 T and two regions above 7 T) correspond to regions where the TLS is clearly visible in the time traces.

To examine the field scale of the fluctuations, we have calculated autocorrelation functions $C(\Delta H)\equiv\langle X(H)X(H+\Delta H)\rangle$, where $X(H)$ is either $G(H)$ or $\delta G_1(H)$. We then define correlation fields H_c by $C(H_c)=\frac{1}{2}C(0)$. For the data in Fig. 1, $H_c[G]\simeq 0.15\pm 0.02$ T and $H_c[\delta G_1]\simeq 0.07\pm 0.02$ T, at $T=0.5$ K; uncertainties reflect bounds of several measurements. We note that for all measurements, there are no obvious statistical cross correlations between $G(H)$ and $\delta G_1(H)$.

The general features of $G(H)$ and $\delta G_1(H)$ are nonetheless similar: Both are random and possess correlation fields of about the same magnitude. These similarities suggest that $\delta G_1(H)$ has an origin very similar to that of the magnetofingerprint, which is explained by the UCF theory [17]. In a diffusive regime, where the electron wave function is coherent over a length L_ϕ, the conductance depends upon the specific configuration of elastic scatterers, due to random constructive and destructive interference. Application of a magnetic field then introduces phase shifts in the Feynman paths of the electrons which result in aperiodic fluctuations of order e^2/h in $G(H)$. The correlation field is then [17] $H_c[G]\sim\Phi_0/\min(L_\phi,L_z)\min(L_\phi,L_y)$, where Φ_0 is the flux quantum, and L_y and L_z are the sample width and length. From H_c, we estimate $L_\phi(T=0.5\text{ K})\simeq 0.3$ μm and $L_\phi(T=9\text{ K})\simeq 0.06$ μm, in good agreement with previous measurements on similar Bi films [5]. δG_1 arises because the interference pattern can be affected by the motion of one strong scatterer [3]. Thus the magnitude and sign of $\delta G_1(H)$ depend on the electron probability amplitude near the TLS defect: Changing H changes the electron "speckle pattern," and thus causes the randomness in $\delta G_1(H)$. Our results show that $H_c[G]$ is greater than $H_c[\delta G_1]$ by about a factor of 2, suggesting that a different numerical prefactor should emerge in a quantitative theory of these phenomena. The fact that $\delta G_1(H)$ changed over a period of days while the dynamics often remained the same over longer periods is consistent with the defect configuration (other than the measured TLS) changing, and thus rescrambling the random pattern.

We now consider the effect of H on the time dynamics of the TLS. Figure 2 shows the transition rates for the same TLS as in Fig. 1. The rates show very different behaviors: $\tau_{\rm fast}^{-1}$ changes by less than a factor of 2 over the field range, while $\tau_{\rm slow}^{-1}$ decreases symmetrically from $H=0$ by about an order of magnitude. In addition, there

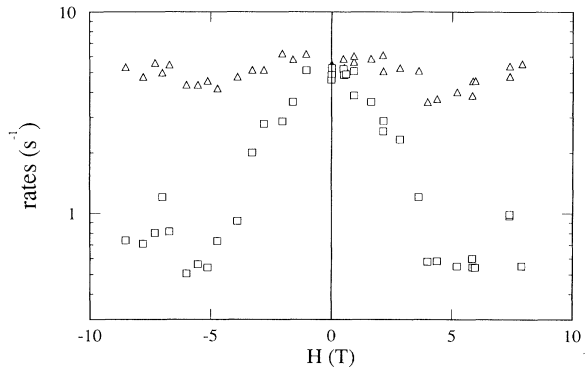

FIG. 2. Transition rates $\tau_{\rm fast}^{-1}$ ($\triangle$) and $\tau_{\rm slow}^{-1}$ ($\square$) as a function of magnetic field H applied perpendicular to the film, for the same TLS as in Fig. 1, measured at $T=0.5$ K. These data were measured over the course of about three weeks. The uncertainty is reflected by the reproducibility. For instance, the three data sets at $H=0$ were measured on three different days, with a spread of about $\pm 10\%$.

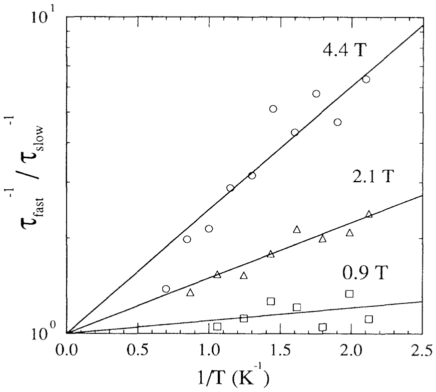

FIG. 3. Arrhenius-type plot of ratio of average switching times, deduced from curves including those in Fig. 1, for three different magnetic fields as noted. From $\ln(\tau_{\rm fast}^{-1}/\tau_{\rm slow}^{-1})=E/k_BT$, best-fit straight line slopes yield TLS energy splittings $E/k_B \simeq 0.9$ K ($\circ$), 0.4 K ($\triangle$), 0.1 K ($\square$).

are smaller sharp nonmonotonic features in $\tau_{\rm slow}^{-1}$. To illustrate the reproducibility, we note that there are three data sets at $H=0$, with a spread of about $\pm 10\%$ for both $\tau_{\rm slow}^{-1}$ and $\tau_{\rm fast}^{-1}$. This reproducibility and the fact that $\tau_{\rm fast}^{-1}$ evolves smoothly and changes by less than a factor of 2 allows us to identify these data as corresponding to a single physical TLS [19].

The two rates are related by the energy splitting E of the defect. To demonstrate this, we examine the temperature dependence of the rates at fixed magnetic field. For a thermodynamic ensemble of identical TLS with energy splitting E, the relative population $N_{\rm low}/N_{\rm high}=e^{E/k_BT}$, where $N_{\rm low}$ ($N_{\rm high}$) is the number of TLS in the lower- (higher-) energy state. For a single TLS, we replace N by the average time spent in each state, averaged over many transitions: $\tau_{\rm fast}^{-1}/\tau_{\rm slow}^{-1}=e^{E/k_BT}$. Figure 3 shows a plot of this ratio versus $1/T$. The good fits confirm the above relation. In particular, they show that E is independent of temperature within the uncertainty. It is clear that E is strongly modified by the application of a magnetic field, increasing by about 1 K from low to high fields.

Figure 4 is a compilation of the energy splitting at many values of H. The lower curve is the same TLS shown in previous figures, while the upper curve is a different defect. In this figure, the noise was measured at a single temperature ($T_0=0.5$ K), and E is obtained from $E=k_BT_0\ln(\tau_{\rm fast}^{-1}/\tau_{\rm slow}^{-1})$. The uncertainty in $E(H)$, estimated as ± 0.07 K, arises from the statistical uncertainties in $\tau_{\rm fast}^{-1}$ and $\tau_{\rm slow}^{-1}$. $E(H)$ has a symmetric systematic increase of about 1 K over the field range. There is a smaller nonmonotonic structure superposed, with a smaller vertical scale of about 0.1–0.2 K, separated by several T. Thus, we have demonstrated the energy splitting of a defect is *tunable* by an applied magnetic field.

There are two possibilities for how H can affect the energy splitting of a TLS. First, if the two configurations have a difference in magnetic moment Δm (which seems unlikely for structural rearrangements in Bi), then $E(H)=\Delta m H$, a linear dependence in obvious disagreement with the data. Second, there could be an indirect effect on the TLS via interaction with the conduction electrons, whose energy is changed by H.

Such a mechanism was proposed by Al'tshuler and Spivak [10], in which there are two essential components. First, the quantum interference which leads to the random $G(H)$ also leads to a random local electron density [20] (electron speckle pattern) which is a random function of H, $n(H)$. Then, a charge coupling to the TLS would yield an interaction energy $E_{\rm int}=Un(H)$, where U is the interaction strength. They predicted that $E(H)$ would be a random function, with autocorrelation func-

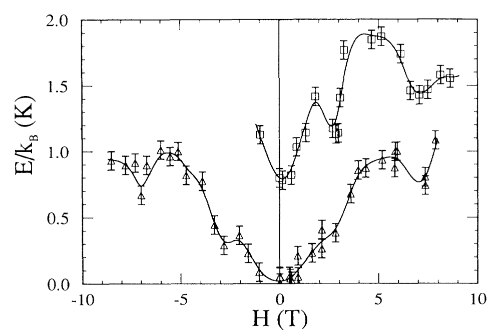

FIG. 4. TLS energy splitting E as a function of applied perpendicular magnetic field H, derived as described in the text. The two curves correspond to two different TLS in the same sample, measured over different periods in time. The lower curve ($\triangle$) represents the same TLS as in the previous figures. Lines are guides to the eye. Measurements in a second sample show very similar results: E/k_B has a symmetric increase of about 1 K over the range of H, and has smaller, reproducible nonmonotonic features separated by several T.

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$$\langle E(H)E(0)\rangle \simeq \frac{(\hbar\omega_c)^2 l}{L_z} \Rightarrow \frac{\{\langle [E(H)]^2\rangle\}^{1/2}}{k_B} \simeq 0.1H\ \mathrm{K}$$

(H in tesla), where l is the elastic mean free path. This prediction may account for the smaller nonmonotonic structure observed in Fig. 4. The systematic increase in $E(H)$ is not predicted, but could be explained as follows. The barrier height in the double-well potential is of order 100 K [21], while the asymmetry in the well depths (which contributes to E) is less than or of order 1 K. A delicate balance in the potential energy is necessary to achieve this presumably relatively rare configuration. A systematic increase in E would result if this balance is suppressed by the $E(H)$ prediction above. However, we would expect that, starting from nonzero asymmetry at $H=0$, E should have equal probability to increase or decrease. In the three cases we measured with $E(H=0)$ nonzero (upper curve in Fig. 4 and two data sets not shown), $E(H)$ always increased.

In summary, we have observed the effect of an applied magnetic field on the conductance fluctuation and time dynamics of a tunneling TLS. The fluctuation amplitude $\delta G_1(H)$ is a random positive and negative function, with a field scale indicating that it arises from the same basic mechanism that causes the aperiodic magnetofingerprint $G(H)$. The TLS energy splitting E can be strongly affected by H, with a large symmetric systematic increase in E/k_B of about 1 K over the field range, and smaller reproducible nonmonotonic features. These may be related to a recent theoretical prediction based on the interaction of the TLS with the quantum-coherent electron gas [10]. Even though we have compared our results to a theory invoking electron phase coherence, we have no direct evidence that this is a necessary requirement for a field-tuned defect energy.

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[14] We note that all of our results for the magnetic-field dependence of both amplitude and time dynamics come from detailed measurements of five and four TLS, respectively, obtained from two lithographic samples (lengths 0.3 and 0.6 μm) on one substrate. If we assume that this Bi film has TLS with a density typical of bulk amorphous metals (10^{32} erg^{-1}cm^{-3}), then only one or two defects should be active in the 0.3-μm sample below 1 K in a four-decade bandwidth. This estimate agrees with our observations.
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[18] Note that, because $G(H)$ is measured using the five-probe noise measurement circuit, the sign of δG_1 cannot be absolutely defined, but is correctly relatively defined for all measurements on the same physical TLS.
[19] We note that, like $G(H)$, $\delta G_1(H)$ changed its pattern completely over the course of several days, while the TLS dynamics remained stable over longer periods. This fortuitous fact allowed us to compile the data in Fig. 2, measured over the course of three weeks.
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