Kondo-Assisted and Resonant Tunneling via a Single Charge Trap: A Realization of the Anderson Model Out of Equilibrium

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We have observed both Kondo-assisted tunneling and simple resonant tunneling via a single charge trap state in the voltage-dependent differential conductance of a point-contact tunnel barrier. From the resonant tunneling signal, we determine parameters of the Anderson model governing the state. This allows comparison of the measured Kondo-assisted signal to results of the Anderson model. The Kondo signal is not adequately described by perturbation theory, but is in qualitative agreement with nonperturbative calculations.

The Anderson model [1] of a electron trap state interacting with the conduction electrons in a metal provides a basis for understanding the properties of magnetic impurities within metals and charge traps in proximity to metals. The case of an Anderson impurity interacting with a thermal-equilibrium distribution of electrons has been solved exactly [2–4]. Recently, the problem of a charge trap interacting with a nonequilibrium electron distribution has received renewed attention, both because this is a tractable problem with which to develop theoretical tools for calculating the transport properties of interacting quantum systems out of equilibrium [5–8], and also because this model describes electron transport through fabricated semiconductor "artificial atoms" [9].

Despite the long history of the Anderson model, previously there has been no physical realization which has illustrated the full range of nonequilibrium transport properties predicted by calculations [5–8]. Measurements performed on tunnel junctions containing charge traps have probed particular facets of the predicted behavior. Simple resonant tunneling of electrons with energy equal to a localized state within a tunnel barrier has been observed in devices of several different geometries [10]. Kondo-assisted tunneling, which enhances the differential conductance $[G(V)=dI/dV]$ for temperatures (T) and voltages (V) less than a characteristic Kondo scale [3,4], has been measured for many defects in large-area planar tunnel junctions [11] and for single defects using crossed-wire tunnel junctions [12]. However, the measurements we report here are the first to observe both Kondo-assisted tunneling and simple resonant tunneling from the same single defect state. This allows direct comparisons with calculations of the Anderson model out of equilibrium.

Figure 1 depicts an energy versus position diagram for electrons in a tunnel barrier which contains a charge trap. The form of the trap-assisted tunneling current is determined by a number of Anderson model parameters: $\bar{\varepsilon}_0$, the energy of the trap relative to the $V=0$ chemical potential in the metal leads [13]; Γ, the energy width of the trap state determined by coupling to the leads; $a_c = (C_l$

$-C_r)/(C_l+C_r)$, the asymmetry in the capacitance of the trap to the left and right leads; U, the on-site Coulomb interaction energy; W, half the conduction bandwidth; and N, the trap degeneracy. For atomic charge traps in insulators, U is generally >100 meV [14], so it is effectively infinite on the scale of the much smaller energies we measure. For Cu, W is of order 5 eV. We will determine the other parameters directly from the measured $G(V)$.

Anderson model calculations [5–8] predict that the tunneling signal $G(V)$ assisted by one charge trap with $\bar{\varepsilon}_0 < 0$ [13] and $|\bar{\varepsilon}_0| > \Gamma$, for magnetic field $B=0$, will consist of three peaks: one at $V=0$ due to Kondo-assisted tunneling, and two satellite peaks due to resonant tunneling via the trap, occurring at V for which the trap energy is degenerate with chemical potential in one of the two leads [Fig. 1(b)]. From the measured positions of the resonant tunneling peaks, V_1 and V_2 ($V_1 < 0$ and $V_2 > 0$) one may determine $\bar{\varepsilon}_0$ and a_c:

$$|\bar{\varepsilon}_0| = \left| \frac{eV_1V_2}{V_2-V_1} \right|, \quad a_c = -\frac{V_1+V_2}{V_2-V_1}. \qquad (1)$$

In the infinite-U limit for an Anderson impurity, the peak in the electron spectral density centered at $\bar{\varepsilon}_0$ has a half width at half maximum (HWHM) of $N\Gamma$ [15]. Consequently, this quantity may be determined from the HWHM, ΔV, of either of the resonant tunneling peaks, if
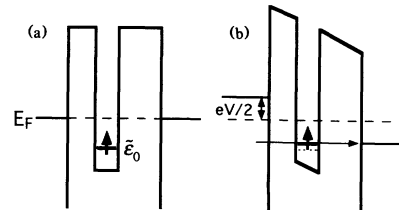

FIG. 1. Schematic diagram of a tunnel barrier containing a charge trap [13] at (a) $V=0$ and (b) V for which the trap energy is equal to the chemical potential in one of the leads $(\bar{\varepsilon}_0+a_ceV/2 = -eV/2)$ so that resonant tunneling enhances $G(V)$.

$k_B T \ll N\Gamma < |\tilde{\varepsilon}_0|$:

$$N\Gamma = \tfrac{1}{2}(1 - a_c)e\Delta V_1 = \tfrac{1}{2}(1 + a_c)e\Delta V_2. \qquad (2)$$

This result is in agreement with numerical calculations of $G(V)$ within the noncrossing approximation [6].

Using the parameters determined from the resonant tunneling peaks, calculations for the nonequilibrium Anderson model provide predictions for the form of the Kondo-assisted signal. Its properties are governed by the Kondo temperature, T_K [15],

$$k_B T_K \sim W\left[\frac{N\Gamma}{\pi W}\right]^{1/N}\exp\left[-\frac{\pi|\varepsilon_0|}{N\Gamma}\right], \qquad (3)$$

where ε_0 is a bare charge trap energy, related to the true energy $\tilde{\varepsilon}_0$ in the presence of interactions with the conduction electrons by

$$|\tilde{\varepsilon}_0| = |\varepsilon_0| - \frac{N\Gamma}{\pi}\ln\left|\frac{W}{\varepsilon_0}\right|. \qquad (4)$$

For $T \ll T_K$, the Kondo-assisted $G(V)$ signal is predicted to have a peak at $V=0$ with amplitude $\leq 2e^2/h$ [3,4] (with the maximum achieved when the couplings of the trap to both leads are equal), with a width of order $k_B T_K/e$ [5,6]. For $T > T_K$, the amplitude is predicted to decrease logarithmically in T, and the width is broadened $\propto T$. In a magnetic field (B), the Zeeman energy leads to a splitting of the Kondo-assisted peak [6,7].

The devices in which we have been able to observe signals from individual Anderson impurities are metal point contacts [16], depicted schematically in Fig. 2(a). These are made using electron beam lithography and reactive ion etching to form a tapered hole with minimum diameter on the order of 3 nm in a silicon nitride membrane. The membrane is then flipped while evaporating metal to form a continuous metal path through the hole. The great majority of electron transport in such devices is by means of the metal filament. In ballistic Cu devices such as we study in this Letter, $G(V)$ from metallic transport has very weak T and V dependence at low T and for $|V| < 10$ mV. In parallel with this signal, on rare occasion tunneling via charge traps in the thin silicon nitride immediately adjacent to the narrowest region of the metallic constriction may also contribute to $G(V)$. As this assisted tunneling has strong T and V dependence, this can dominate the changes in G at low T and V [17].

In Fig. 2(a) we show the measured $G(V)$ of a Cu point contact without significant assisted tunneling through the silicon nitride. As is typical of ballistic metal devices, G shows only weak aperiodic structure at low V, explained by interference of scattered electron waves in the metal [18]. The drop in G beyond $|V| = 10$ mV is due to phonon scattering in the Cu filament [19]. This device was then biased at 350 mV for 1 min to form charge traps in the silicon nitride by means of electrical breakdown. Following this procedure, a very sharp conductance peak was formed at $V=0$, together with a pair of broader peaks at
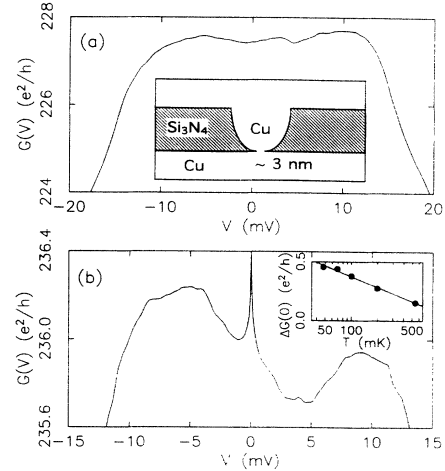

FIG. 2. (a) Differential conductance of a point contact without trap-assisted conductance enhancement, at $T=50$ mK, $B=0$. (Inset) Device cross-sectional schematic. (b) Same device at $T=50$ mK, $B=0$ after a trap has been produced at high bias. (Inset) T dependence of $V=0$ conductance.

higher bias [Fig. 2(b)]. After measurements were performed on this sample, it was biased again at 350 mV, and all three peaks were eliminated simultaneously.

These signals can be identified as due to assisted tunneling via a charge trap. The $V=0$ peak exhibits Zeeman splitting (Fig. 3), unambiguous evidence that it is due to a magnetic defect or defects [6]. The fact that the
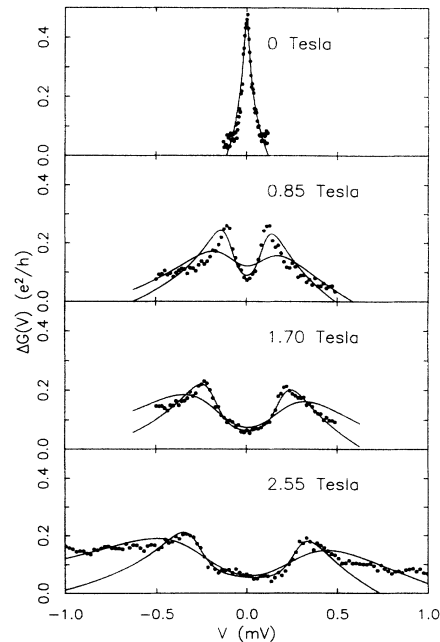

FIG. 3. Points: Kondo-assisted tunneling signal at 50 mK for different B, for the same trap as in Fig. 2(b). The background has some weak magnetoconductance, so relative offsets on the $G(V)$ axis are uncertain. Lines: Alternative fits to perturbation theory, as discussed in the text.

signal is a peak in G identifies it as Kondo-assisted tunneling through the silicon nitride rather than scattering from a magnetic impurity within the Cu, which would produce a $V=0$ dip in G [20]. The T dependence of the amplitude of the $B=0$ signal is approximately logarithmic from 50 to 500 mK [inset, Fig. 2(b)]. This provides an upper bound on T_K of roughly 50 mK. An independent measurement of a similar limit on T_K is provided by the fact that the width of the $V=0$, $B=0$ peak remains strongly T dependent down to 50 mK (HWHM $=35$ μV at 50 mK).

The amplitude of the $V=0$ peak at 50 mK is $0.5e^2/h$ above the background, consistent with the maximum possible due to Kondo-assisted tunneling from one trap, $2e^2/h$ [3,4]. This is an initial indication that the signal may be due to tunneling via a *single* charge trap. The narrow width is also evidence for a lone trap. We have measured >10 samples which exhibited Kondo-assisted tunneling signals larger than $2e^2/h$, indicating that two or more traps were contributing to $G(V)$. In all these cases, the HWHM of the $V=0$ peak exceeded 1 mV at low T, more than 30 times the width in Fig. 2(b). We suggest that interactions between traps greatly increase the width of the Kondo signal when two or more traps are present in the small region about the point contact [4].

We identify the two broader peaks in Fig. 2(b), which appeared together with the $V=0$ signal, as due to resonant tunneling through the same charge trap which produces the $V=0$ signal. The amplitude of these peaks,

$\leq 0.6e^2/h$, is consistent with an upper bound for the resonant tunneling signal through a single trap, $2e^2/h$ [21], and the widths are appropriate for lifetime-broadened states in an insulator a few nm thick [22]. In contrast to the Kondo-assisted signal, these features show little dependence on $T \leq 4.2$ K and little dependence on $B \leq 3$ T, as expected for resonant-tunneling peaks when $k_B T$, $\mu_B B \ll N\Gamma$ [5,6]. The asymmetry visible in the amplitudes of the resonant tunneling peaks is expected due to capacitance asymmetry when $a_c \neq 0$ and due to the effects of electron correlations in tunneling [23].

Compelling evidence that all three peaks in Fig. 2(b) are due to assisted tunneling from one charge trap is provided by a quantitative comparison to results of the Anderson model. Some care is required in making this comparison, because phonon scattering in the metal filament of the constriction leads to a sharp decrease in $G(V)$ beyond 10 mV [see Fig. 2(a)], unrelated to assisted tunneling from the trap. In Fig. 2(b), the positive-V resonant peak is cut off by this effect, making accurate determination of its position and width impossible [24]. We estimate that the true peak position may be anywhere in the range $8.8 \leq V_2 \leq 15$ mV. However, the center of the negative-V peak is at low enough $|V|$ that it is in the regime where phonon scattering is negligible. This allows a measurement of both its position $V_1 = 5.2$ mV and HWHM $\Delta V_1 = 4.4$ mV.

This is all the information that is required in order to predict T_K within the Anderson model. Combining Eqs. (1)-(4), the expression for T_K may be written

$$k_B T_K \sim \left| \frac{V_2 \Delta V_1}{\pi W (V_2 - V_1)} \right|^{1/N} \left(\left| \frac{V_1 V_2}{V_2 - V_1} \right| + \frac{V_2 \Delta V_1}{\pi (V_2 - V_1)} \right) \left| \ln \left| \frac{W}{\varepsilon_0} \right| \right| \exp \left(\frac{-\pi |V_1|}{\Delta V_1} \right). \tag{5}$$

Only parameters of the negative-V peak occur in the exponential. Assuming for the moment that $N=2$ (expected from spin degeneracy, for a nondegenerate spatial state), the parameters $V_1 = -5.6$ mV, $\Delta V_1 = 4.4$ mV, and $V_2 = 8.8$ mV lead to the prediction $T_K \sim 25$ mK, while using instead the value $V_2 = 15$ mV gives $T_K \sim 30$ mK. Uncertainty in the prediction of T_K is thus dominated by uncertainty in the ratio $|V_1|/\Delta V_1$, not V_2. The value for T_K based on the resonant tunneling peaks, ~ 30 mK, is nicely consistent with the experiment limit $T_K < 50$ mK, determined from the T and V dependence of the Kondo-assisted tunneling peak.

We note that if we assume values for $N \neq 2$, the results for T_K are significantly greater than the experimental upper bound on T_K. For $N=4$, $T_K \sim 280$ mK, and for $N=6$, $T_K \sim 570$ mK.

Using Eqs. (1), (2), and (4), we may also determine the ratio $N\Gamma/(\pi |\varepsilon_0|) \approx 0.1$, directly from the resonant tunneling peaks. By the Schrieffer-Wolff transformation [15,25] (assuming $N=2$), this is equal to the expansion parameter in perturbation theory calculations of Kondo-assisted tunneling: $-2J\rho$, where J is an exchange coupling and ρ the density of electron states in the leads.

The data in Fig. 3 were measured for T a factor of 6 lower than previous measurements of Kondo-assisted tunneling in a planar tunnel junction [26], and a factor of 20 lower than previous measurements of Kondo-assisted tunneling from a single defect [12], allowing an improved and exacting comparison with perturbation-theory calculations [27,28]. Following the analysis procedure used in Ref. [26], we determine the coefficient of the Kondo tunneling term (third order in perturbation theory) using the $B=0$ data. Then we make two alternative fits for the coefficient of the spin-flip scattering term (second order) using the 2.55 T data. (The same coefficients are then applied to the 0.85 and 1.7 T data.) For the Lande g factor, we use $g=1.9$, given by $g=2+2J\rho$ [11], using $2J\rho = -0.1$, as found above. This provides a good fit to the positions of the peaks. We allow T to vary as a function of B, to model the field-induced broadening suggested by Wolf and Losee [26,28]. Despite multiple free parameter, the shape of the high-B curves cannot be adequately fitted using the coefficient for the Kondo contribution determined at $B=0$. The two alternatives for $B=2.55$ T in Fig. 3 show that one cannot simultaneously

fit both the onset of the Kondo peak at low $|V|$ and the slowly decaying conductance at large $|V|$ using low-order perturbation theory.

A similar failure of perturbation theory has been described previously for the Kondo signal due to many impurities in planar junctions [29]. Because our signal is from a single defect, our measurements show that this disagreement is not due to sampling a distribution of impurities having different g factors or T_K, nor due to interactions between impurities.

Recent nonperturbative calculations [5–8] are not yet sufficiently quantitative to make a detailed fit to data, but the qualitative results are in good agreement with our measurements. The B-field splitting of the Kondo-assisted tunneling peak is in accord with predictions that, in a magnetic field, Kondo peaks in the electron density of states shift away from the chemical potentials of the leads by the Zeeman energy, producing peaks in $G(V)$ for eV equal to the Zeeman splitting [6]. The asymmetric broadening and suppression of the measured Kondo signals at large B is also in qualitative agreement with predictions of a finite dissipative lifetime for nonzero V [6].

In summary, we have studied assisted tunneling due to a single charge trap using lithograpically fabricated point contacts of nm dimensions. These have provided the best spectroscopic information to date concerning assisted tunneling via one electronic state. For the first time we have measured both Kondo-assisted and resonant tunneling due to a single trap, and have obtained quantitative consistency with predictions of the Anderson model out of equilibrium. The observed Kondo signal in large magnetic fields is found not to be in accord with perturbation theory calculations, but is in agreement with the qualitative predictions of recent nonperturbative calculations.

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in these papers is twice that of the present Letter.