Two-channel Kondo effects in Al/AlO_x/Sc planar tunnel junctions

Sheng-Shiuan Yeh[1,*] and Juhn-Jong Lin[1,2,†]
[1]*Institute of Physics, National Chiao Tung University, Hsinchu 30010, Taiwan*
[2]*Department of Electrophysics, National Chiao Tung University, Hsinchu 30010, Taiwan*
(Received 19 December 2008; published 30 January 2009)

We have measured the differential conductances $G(V,T)$ in several Al/AlO_x/Sc planar tunnel junctions between 2 and 35 K. As the temperature decreases to ~16 K, the zero-bias conductance $G(0,T)$ crosses over from a standard $-\ln T$ dependence to a novel $-\sqrt{T}$ dependence. Correspondingly, the finite bias conductance $G(V,T)$ reveals a two-channel Kondo scaling behavior between ~4 and 16 K. The observed two-channel Kondo physics is ascribed to originating from a few localized spin-$\frac{1}{2}$ Sc atoms situated slightly inside the AlO_x/Sc interface.

DOI: 10.1103/PhysRevB.79.012411 PACS number(s): 72.15.Qm, 64.70.Tg, 72.10.Fk, 73.40.Rw

How conduction electrons interact with local degeneracies, which is the central theme of the Kondo effect,[1] is a long-standing issue in many-body physics. In the original Kondo effect, the local degeneracies are provided by a spin-$\frac{1}{2}$ impurity antiferromagnetically coupled to a single reservoir of free electrons [the single-channel Kondo (1CK) effect]. Well below a characteristic energy, the Kondo temperature T_K, the localized moment is fully screened by the surrounding itinerant electrons to form a singlet ground state, leading to a standard Fermi-liquid behavior.[1] However, Nozières and Blandin[2] proposed that, in the multichannel case, i.e., the screening channels $M>2S$, where S is the spin of the localized moment, a non-Fermi-liquid behavior may occur at low temperatures. The simplest version of the multichannel Kondo phenomena is the two-channel Kondo (2CK) effect ($M=2$) which has recently attracted much theoretical[3–6] and experimental[7–10] attention. Apart from a physical spin, the local degeneracies may arise from orbital quadrupolar degrees of freedom or nearby atomic positions, i.e., two-level systems (TLS).[3] The magnetic and quadrupolar models have been utilized to explain the specific-heat anomalies in certain heavy fermion compounds,[3–5] while the TLS-induced 2CK physics[3,6] has recently been experimentally realized in nanoscale metal point contacts.[7] Very lately, an artificial spin-$\frac{1}{2}$ semiconductor quantum dot coupled to two independent electron reservoirs has been elegantly constructed[8] to test the 2CK physics.[9] Besides, the 2CK effect on electrical resistivity due to TLS is argued to be found in a ThAsSe single crystal.[10] Thus far, there has been no observation of the 2CK effect caused by the "simple" 3*d* magnetic transition-metal atoms. In this work, we report our finding of a non-Fermi-liquid behavior in Al/AlO_x/Sc planar tunnel junctions where a number of spin-$\frac{1}{2}$ Sc atoms are present at or slightly inside the AlO_x/Sc interface.[11,12]

Our planar tunnel junctions are composed of three layers: an Al (25 nm) film and a Sc (60 nm) film separated by an insulating AlO_x (1.5–2 nm) barrier. Both the Al and Sc films were thermally evaporated, while the AlO_x layer was grown on the top surface of the Al film by oxygen glow discharge.[13] The low-temperature resistivities of our Al (Sc) films were typically $\rho(4\ \mathrm{K})\approx 13\ (70)\ \mu\Omega$ cm. Lock-in techniques together with a bias circuitry were employed to measure the differential conductance dI/dV as a function of both bias voltage and temperature. The modulation voltages used were smaller than k_BT so that the main smearing was due to the thermal energy. The quality of the insulating barriers was checked according to the Rowell criteria[14] as well as by measuring the dI/dV curves below the superconducting transition temperature (≈2 K) of the Al films. At 0.25 K, a deep superconducting gap was evidenced in all junctions, ensuring that the conduction mechanism was governed by electron tunneling. Only the results for three representative samples (see Table I) will be discussed below. However, we stress that very similar effects have been found in a dozen of junctions, strongly suggesting that the observed 2CK physics is robust in the Al/AlO_x/Sc planar tunnel structures.

The left inset of Fig. 1 shows the raw dI/dV data for the junction A at several temperatures between 2.2 and 35 K. One clearly sees conductance peaks around zero-bias voltage sitting on an asymmetric parabolic background.[15] After subtracting this parabolic background, the excess conductance ΔG contains a dominant even contribution $G_{\mathrm{even}}\equiv\frac{1}{2}[\Delta G(V)+\Delta G(-V)]$ and a minor odd contribution $G_{\mathrm{odd}}\equiv\frac{1}{2}[\Delta G(V)-\Delta G(-V)]$, where $G_{\mathrm{odd}}\lesssim 0.1G_{\mathrm{even}}$ (Ref. 13). In this work, we focus on the even contribution and denote it as $G(V,T)$. The main panel of Fig. 1 indicates that, as T reduces, the $G(V,T)$ curves become narrower and the peaks higher. Such enhanced $G(V,T)$ cannot be expected from the disorder-induced suppression of electronic density of states at the Fermi level due to the electron-electron interaction effects.[16]

The magnitudes of the zero-bias conductance $G(0,T)$ for junctions A–C are plotted in Fig. 2. At higher temperatures (~16–32 K), $G(0,T)$ obeys a $-\ln T$ law [Fig. 2(a)], sug-

TABLE I. Relevant parameters for Al/AlO_x/Sc tunnel junctions. R_J is junction resistance at 300 K, A_J is junction area, T_{2CK} is the two-channel Kondo temperature, and T^* is a crossover temperature defined in the text.

Sample	R_J (kΩ)	A_J (mm^2)	T^* (K)	T_{2CK} (K)
A	2.2	0.5×0.8	4	72
B	1.2	0.5×1.0	5	64
C	5.0	1.0×1.0	6	56

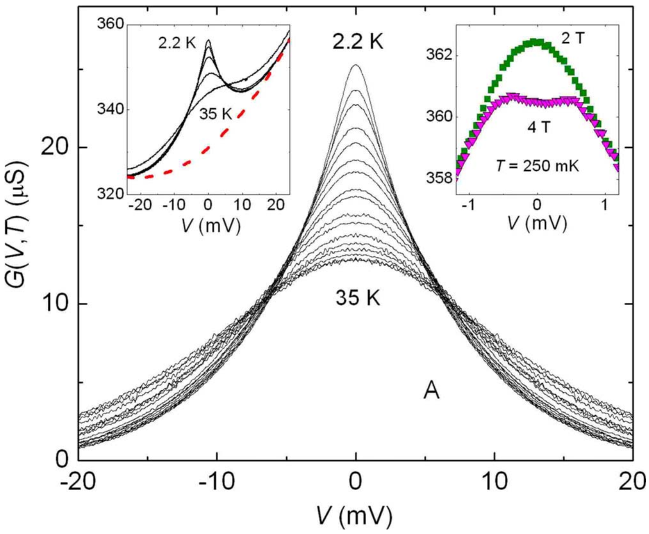

FIG. 1. (Color online) $G(V,T)$ for junction A. Left inset: Raw dI/dV data. The dotted line indicates a parabolic background conductance. Right inset: Raw dI/dV data in two magnetic fields applied normal to the plane of the junction.

gesting a Kondo-type mechanism. Notably, in our intermediate temperature regime of $\sim$5–16 K, $G(0,T)$ for all three samples obey a $-\sqrt{T}$ law [Fig. 2(b)], while a deviation from the $-\sqrt{T}$ dependence starts at about 4 K. We first notice that, in the high T regime, both the $G(0,T)\propto -\ln T$ behavior as well as our measured finite-bias $G(V,T)$ spectra[13] can be well described by a perturbative theory that considers the *s*-*d* exchange coupling between tunneling electrons and isolated localized moments which reside slightly inside the barrier.[12] This observation firmly establishes the fact that localized moments are present in our oxide barriers. The formation of localized moments in our junctions most likely arose from the diffusion of some $3d^1$ Sc atoms slightly into the AlO_x barrier, e.g., during the fabrication process.[11]

It is known that in the 2CK state the conductance

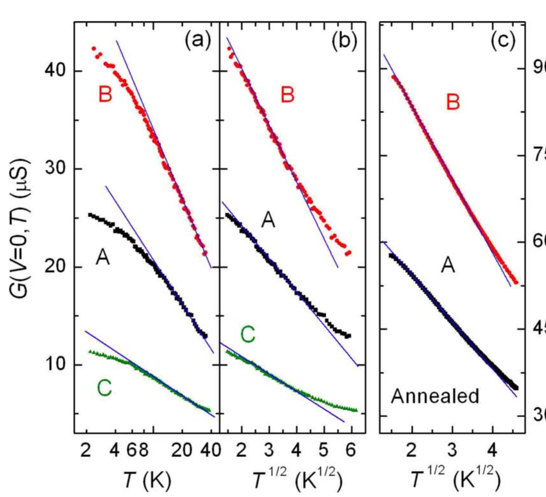

FIG. 2. (Color online) Zero-bias conductance as a function of temperature for junctions A–C. (a) Semilog plot of $G(0,T)$ versus T. (b) $G(0,T)$ versus $\sqrt{T}$ for as-prepared junctions. (c) $G(0,T)$ versus $\sqrt{T}$ after thermal annealing.

$g_{2CK}(V,T)$ due to electrons tunneling through an individual 2CK impurity residing in the barrier can be expressed by $g_{2CK}(V,T)=g_{2CK}(0,0)-B\sqrt{T}\Gamma(AeV/k_BT)$,[17–19] where A and B are nonuniversal constants which may depend on the distance of the 2CK impurity from the electrode/barrier interface. $\Gamma(x)$ is a universal scaling function of x with the asymptotes $1+cx^2$ for $|x|\ll 1$, and $\frac{3}{\pi}\sqrt{|x|}$ for $|x|\gg 1$, with $c\approx 0.0758$.[17,19,20] For macroscopic junctions, there may be a number of 2CK impurities situated inside the barrier. If the interaction between these 2CK impurities can be neglected, the total conductance $G_{2CK}(V,T)$ is additive: $G_{2CK}(V,T)=G_{2CK}(0,0)-\sqrt{T}\Sigma_i B_i\Gamma(A_i eV/k_BT)$, where $G_{2CK}(0,0)=\Sigma_i g_{2CK}(0,0)$. Therefore, the zero-bias conductance $G_{2CK}(0,T)$ has a $-\sqrt{T}$ dependence. To eliminate $G_{2CK}(0,0)$, which cannot be measured directly, it is very useful to scale the conductance as a universal function of eV/k_BT: $[G_{2CK}(0,T)-G_{2CK}(V,T)]/\sqrt{T}=\Sigma_i B_i[\Gamma(A_i eV/k_BT)-1]$. This universal function leads to the asymptotes

$$\frac{G_{2CK}(0,T)-G_{2CK}(V,T)}{\sqrt{T}}=\begin{cases} b_1\left(\dfrac{eV}{k_BT}\right)^2, & \dfrac{|eV|}{k_BT}\ll 1 \\ b_2\sqrt{\dfrac{|eV|}{k_BT}}-b_3, & \dfrac{|eV|}{k_BT}\gg 1, \end{cases} \tag{1}$$

where $b_1=c\Sigma_i B_i A_i^2$, $b_2=\frac{3}{\pi}\Sigma_i B_i\sqrt{A_i}$, and $b_3=\Sigma_i B_i$. In the low bias region ($|eV|/k_BT\ll 1$), the conductance can also be scaled into the form

$$G_{2CK}(0,T)-G_{2CK}(V,T)=f_{2CK}(T)(eV/k_BT)^2, \tag{2}$$

where $f_{2CK}(T)=b_1\sqrt{T}$.

The $-\sqrt{T}$ behavior of $G(0,T)$ in Fig. 2(b) suggests that our junctions fall in the 2CK phase in this intermediate temperature regime. In order to establish more and stronger evidences for this result, we have examined the scaling behavior of the finite bias conductance $G(V,T)$. Our measured conductances at various temperatures are scaled according to the 2CK scaling form, Eq. (1), and the results are shown in Fig. 3(a). Notice that at intermediate temperatures ($\sim$5–16 K), the data at different T all collapse onto a single curve for $(|eV|/k_BT)^{1/2}\lesssim 2.5$, with the asymptotes correctly given by Eq. (1). That is, our scaled $[G(0,T)-G(V,T)]/\sqrt{T}\propto(eV/k_BT)^2$ at low bias voltages of $(|eV|/k_BT)^{1/2}\lesssim 1.4$ (Ref. 21), while it varies linearly with $(|eV|/k_BT)^{1/2}$ at high bias voltages. Therefore, the observed $G(0,T)\propto -\sqrt{T}$ law together with the scaling behavior of the $G(V,T)$ unambiguously demonstrate that our junctions fall in a 2CK state in this intermediate temperature regime. The prefactor $f_{2CK}(T)$ in Eq. (2) can be extracted from the low bias data and is plotted in Fig. 3(b). It shows that $f_{2CK}\propto\sqrt{T}$ at intermediate temperatures, but deviates at high and low temperatures. This 2CK temperature regime for f_{2CK} is in good accord with that found in Fig. 2(b) for the $G(0,T)\propto -\sqrt{T}$ attribute.

In the high-temperature end, since the deviation of $G(0,T)$ from the $-\sqrt{T}$ law starts at $\frac{1}{4}T_{2CK}$ (Ref. 18), the two-channel Kondo temperature, T_{2CK}, for our junctions may be evaluated. In the low-temperature end, there is a crossover temperature, T^*, below which $f_{2CK}(T)$ deviates from the $-\sqrt{T}$

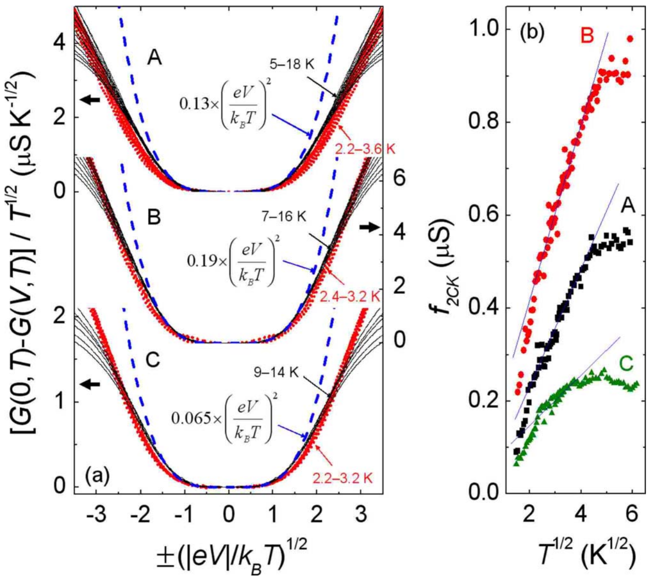

FIG. 3. (Color online) (a) 2CK scaling for junctions A–C. Solid curves stand for high T data, and dotted curves for low T data. (b) f_{2CK} as a function of $\sqrt{T}$ for the three junctions.

law. Our values of T_{2CK} and T^{*} are listed in Table I. It should be noted that, in Fig. 3(a), deviations (red dotted lines) from the 2CK scaling form are seen for data with $T \lesssim 3.6$ K.

The effect of a magnetic field H is shown in the right inset of Fig. 1. We have found $G(0,T)$ decreases with increasing H and observed a Zeeman splitting of 0.45 meV at 4 T. Such a Zeeman splitting corresponds to a g factor of 1.94, strongly indicating the presence of localized spin-$\frac{1}{2}$ moments, as discussed above. Thus, our observed logarithmic and 2CK behaviors of $G(V,T)$ can be explained as arising from the Sc d-electron impurities. The 2CK physics in our junctions should not originate from any TLS-induced effect, since the $G(0,T) \propto -\sqrt{T}$ behavior in our junctions remained intact even after thermal annealing,[22] as is depicted in Fig. 2(c). In contrast, we notice that the 2CK signals in the above-mentioned ultrasmall metal point contacts disappeared even after annealing at room temperatures.[23] On the other hand, the two-channel magnetic Kondo model developed to explain the Ce-based heavy fermion compounds should require very special symmetries in the crystal field,[3] which are unlikely to happen in our junctions. Yet, another possible candidate theory is the competition between the Kondo screening and the interimpurity interaction I proposed in the two-impurity Kondo model (2 IKM),[24,25] where the 2CK physics occurs at a critical coupling strength I_c, which separates a Kondo-screened phase from a local-singlet phase in the ground state. However, the existence of the 2CK fixed point due to the 2 IKM coupled to a single electron reservoir requires some particle-hole symmetry[24,25] which is hard to conceive in our junctions. Thus, the microscopic origin for our observed 2CK behavior as well as the deviation from the 2CK behavior below about 4 K is still not well understood in terms of available theories.

On the experimental side, it is intriguing that our 2CK effect is demonstrated in conventional planar tunnel junctions which contained $3d^1$ transition-metal impurities. These are straightforward sample structures equipped with the simplest possible dynamical impurities ($S=\frac{1}{2}$) for the Kondo phenomena.[1] Moreover, it should be noted that a deviation from the 2CK behavior has not been found in any previous experiments involving more exquisite artificial structures, such as metal point contacts[7] and semiconductor quantum dots,[8] where the characteristic Kondo temperatures are relatively low as compared with ours. The deviation could signify a crossover to a non-2CK phase as $T \to 0$ K. This issue deserves further investigations.

In summary, the 2CK non-Fermi-liquid physics has been realized in the differential conductances of $Al/AlO_x/Sc$ planar tunnel junctions. In the intermediate temperature regime, $G(0,T)$ reveals a $-\sqrt{T}$ dependence and $G(V,T)$ obeys the 2CK scaling law. At lower temperatures, a deviation in $G(0,T)$ from the $-\sqrt{T}$ behavior is found. These rich Kondo behaviors are believed to originate from a few localized spin-$\frac{1}{2}$ Sc atoms situated at or slightly inside the AlO_x/Sc interface.

The authors thank A. M. Chang, C. H. Chung, T. A. Costi, D. L. Cox, F. Guinea, T. K. Ng, J. Kroha, Z. S. Ma, G. Zarand, and A. Zawadowski for helpful discussions. This work was supported by the Taiwan National Science Council through Grant No. 96-2112-M-009-025 and by the MOE ATU Program.

*yehshengshiuan@gmail.com
†jjlin@mail.nctu.edu.tw

[1] A. C. Hewson, *The Kondo Problem to Heavy Fermions* (Cambridge University Press, Cambridge, 1993).
[2] P. Nozières and A. Blandin, J. Phys. (Paris) **41**, 193 (1980).
[3] D. L. Cox and A. Zawadowski, Adv. Phys. **47**, 599 (1998).
[4] B. Andraka, Phys. Rev. B **49**, 3589 (1994); T. S. Kim and D. L. Cox, Phys. Rev. Lett. **75**, 1622 (1995).
[5] H. R. Ott, H. Rudigier, Z. Fisk, and J. L. Smith, Phys. Rev. Lett. **50**, 1595 (1983); D. L. Cox, *ibid.* **59**, 1240 (1987); C. L. Seaman, M. B. Maple, B. W. Lee, S. Ghamaty, M. S. Torikachvili, J. S. Kang, L. Z. Liu, J. W. Allen, and D. L. Cox, *ibid.* **67**, 2882 (1991).
[6] A. Zawadowski, Phys. Rev. Lett. **45**, 211 (1980); A. Muramatsu and F. Guinea, *ibid.* **57**, 2337 (1986).
[7] D. C. Ralph, A. W. W. Ludwig, J. von Delft, and R. A. Buhrman, Phys. Rev. Lett. **72**, 1064 (1994).
[8] R. M. Potok *et al.*, Nature (London) **446**, 167 (2007); A. I. Toth, L. Borda, J. von Delft, and G. Zarand, Phys. Rev. B **76**, 155318 (2007).
[9] Y. Oreg and D. Goldhaber-Gordon, Phys. Rev. Lett. **90**, 136602 (2003).
[10] T. Cichorek, A. Sanchez, P. Gegenwart, F. Weickert, A. Wojakowski, Z. Henkie, G. Auffermann, S. Paschen, R. Kniep, and F.

Steglich, Phys. Rev. Lett. **94**, 236603 (2005).
[11] A. F. G. Wyatt, J. Phys. C **7**, 1303 (1974).
[12] J. A. Appelbaum, Phys. Rev. **154**, 633 (1967); E. L. Wolf and D. L. Losee, Phys. Rev. B **2**, 3660 (1970); This theory predicts an approximation form $G(V,T)=A'-B'\ \ln\{[(eV)^2+(nk_BT)^2]/E_0^2\}^{1/2}$, where A' and B' are constants, $n\approx 2$, and E_0 is a cutoff energy.
[13] S. S. Yeh, Ph.D. dissertation, National Chiao Tung University, 2007.
[14] J. M. Rowell, in *Tunneling Phenomena in Solids*, edited by E. Burnstein and S. Lundqvist (Plenum, New York, 1969).
[15] The background resulted from normal tunneling between two metal electrodes separated by a thin barrier; W. F. Brinkman *et al.*, J. Appl. Phys. **41**, 1915 (1970).
[16] N. S. Wingreen, B. L. Altshuler, and Y. Meir, Phys. Rev. Lett. **75**, 769 (1995).
[17] I. Affleck and A. W. W. Ludwig, Phys. Rev. B **48**, 7297 (1993).
[18] M. H. Hettler, J. Kroha, and S. Hershfield, Phys. Rev. Lett. **73**, 1967 (1994).
[19] M. Pustilnik, L. Borda, L. I. Glazman, and J. von Delft, Phys. Rev. B **69**, 115316 (2004).
[20] Y. Oreg and D. Goldhaber-Gordon, in *Physics of Zero- and One-Dimensional Nanoscopic Systems*, edited by S. N. Karmakar *et al.*, (Springer, Berlin, 2007).
[21] Recent numerical calculations (Ref. 18) indicate the scaled conductance $\propto(eV/k_BT)^2$ even for $|eV|>k_BT$.
[22] Thermal annealing of the junctions was performed in vacuum ($\sim 10^{-5}$ torr) at 100 °C for 1 h. After annealing, the R_J(300 K) of samples A and B decreased to 0.83 and 0.50 kΩ, respectively. In plotting Fig. 2(c), the background conductances had been subtracted.
[23] D. C. Ralph and R. A. Buhrman, Phys. Rev. Lett. **69**, 2118 (1992).
[24] B. A. Jones, C. M. Varma, and J. W. Wilkins, Phys. Rev. Lett. **61**, 125 (1988); J. Gan, *ibid.* **74**, 2583 (1995).
[25] G. Zarand, C. H. Chung, P. Simon, and M. Vojta, Phys. Rev. Lett. **97**, 166802 (2006); C. H. Chung and W. Hofstetter, Phys. Rev. B **76**, 045329 (2007).