Is CeNiSn a Kondo semiconductor? - break-junction experiments

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Abstract

We investigated break junctions of the Kondo semiconductor CeNiSn, both in the metallic and in the tunneling regime, at low temperatures and in magnetic fields up to 8 T. Our experiments demonstrate that direct CeNiSn junctions have typical metallic properties instead of the expected semiconducting ones. There is no clear-cut evidence for an energy (pseudo)gap. The main spectral feature, a pronounced $\sim 10 - 20$ meV wide zero-bias conductance minimum, appears to be of magnetic nature.

Cerium intermetallic compounds can have different ground states, depending on the hybridization between f- and conduction electrons. CeNiSn is usually classified as a Kondo semiconductor, originally because of the enhanced electrical resistivity at low temperatures. But when high quality samples became available, the low-temperature resistivity turned out to be metallic. Tunnel spectroscopy provides a direct access to the electronic density of states (EDOS). Using mechanically controllable break junctions (MCBJ), Ekino et al. observed $dI/dV$ spectra with $\sim 10$ meV broad zero-bias (ZB) minima. They assumed – without further experimental evidence – that their junctions were in the tunnel regime, and interpreted the ZB minima as being due to a gap in the EDOS. These ZB minima were found to be suppressed in magnetic fields $B \geq 14$ T only along the a-axis, indicating as a crossover from a pseudogap to a metallic heavy-fermion state. Our investigation of MCBJs of CeNiSn, both in the metallic (direct contact) and in the vacuum-tunneling regime, is based on...
Figure 1: (a) Current $I$ through a CeNiSn MCBJ in c-direction vs piezo voltage $V_{PZ}$ (curve 1) at $T = 0.1$ K and $V_{bias}=0.1$ V. Curve 2 shows the same data in conductance units, normalized to the quantum conductance $G_0 = 2e^2/h \approx 77.5 \mu S$. (b) Reduced $dV/dI$ vs $V$ for two contacts with low (28 $\Omega$) and high (5 k$\Omega$) resistance. Solid lines are fits to the Daybell formula $R = 1 - A \log(1 + (V/V_0)^2)$, with $A = 0.019(0.066)$, $V_0 = 0.357(0.345)$ mV for the bottom(top) curve. Inset shows the same curves for both polarities.

three CeNiSn single crystals with long sides in the a, b, and c-direction of the orthorhombic crystal lattice, respectively. Magnetic fields up to 8 T could be applied perpendicular to the long side of the sample (perpendicular to current flow). For further details see Refs. [6, 7].

To identify the regime of charge transport through the junctions we measured how the contact resistance depends on the distance between the two broken pieces of the sample, set by the piezo voltage $V_{PZ}$. Fig. 1a clearly shows an exponential $I(V_{PZ})$ dependence at constant bias voltage as long as $R > 100 \, k\Omega$, as expected for true vacuum tunneling. The step-like change of conductance at $R < G_0^{-1} = h/2e^2 \approx 13 \, k\Omega$ characterizes atomic-size metallic contacts [8]. Therefore, our CeNiSn junctions with $R < 13 \, k\Omega$ are made up of a metallic constriction.

Metallic MCBJs show rather similar spectra with a pronounced ZB peak (Fig. 1b, inset). $dV/dI$ decreases logarithmically between 1 and 10 mV. It can be well described by an empirical formula for the temperature dependence of Kondo scattering if $T$ is replaced by $V$ (Fig. 1b ). Fig. 2a shows the temperature and field dependence of the $dV/dI$ spectra in b-direction. In addition to the ZB peak, the background of the curves increases with voltage, resulting in a double-minimum structure similar to that found earlier [4, 5]. However, contacts
with $R < 13 \text{k}\Omega$ are not in the tunnel regime, and those ZB anomalies can not be attributed directly to the gap in the EDOS, as proposed in Refs. [4, 5]. According to Fig. 2a, the $dV/dI(V)$ spectra look like the $T$-dependence of the ZB contact resistance $dV/dI(T, V = 0)$. This characterizes the thermal and not the ballistic regime of metallic contacts [10]. A natural explanation for the ZB peak in Fig. 2a could be Kondo scattering which is indeed supported by fitting of $dV/dI(V)$ with the corresponding expression, see Fig. 2b. The enhanced low-$T$ resistance probably has the same origin as that observed earlier on less perfect (less pure) CeNiSn samples [1]. Probably the quality of the interface is degraded with respect to the bulk material, for example due to mechanical stress.

Two different type of CeNiSn tunnel junctions can be distinguished (Fig. 2b): (i) Contacts with a large (> 100%) ZB minima, similar to the $dV/dI$ - maxima of the metallic contacts in Fig. 1b. (ii) Contacts with a shallow (~ 10%) minimum. The latter have a relatively broad and also more asymmetric ZB dip. A magnetic field only slightly broadens ZB minima. If we attribute those ZB minima to a gap
of the EDOS, then its width determined by the position of the maxima is $2\Delta \sim 20 \text{ mV}$. At a characteristic temperature of $T_c \approx 10 \text{ K}$ this yields an exessively large $2\Delta/k_BT_c \sim 20$. But there are other explanations, too. The first type of spectra could be caused by magnetic scattering. For example, evaporating less than one monolayer of magnetic impurities onto thin film metal-oxide-metal planar tunnel junctions can produce either a ZB conductance maximum or a minimum, depending on the sign of the exchange integral between conduction electron spin and magnetic impurity spin. The size of those anomalies is of order 10%. A giant ZB resistance maximum similar to that in Fig. 2b and with a logarithmic variation between a few mV and 100 mV was observed in Cr-oxide-Ag tunnel junctions, and explained by Kondo scattering as well.

Another explanation could be Coulomb blockade, depending on the capacitance of the tunnel junctions. Pronounced ZB minima could result when the junctions consist of several isolated metallic (magnetic) clusters, formed accidentally while breaking the sample. Their capacitances are not shortcircuited by the distributed lead capacitances, therefore Coulomb blockade can be much stronger than at solitary junctions.

In summary, MCBJ experiments so far do not provide clear-cut evidence for an energy (pseudo)gap of CeNiSb, even when the junctions are in the true vacuum tunnel regime. The observed anomalies could equally well be produced by Kondo scattering or even by Coulomb blockade.

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