REALIZATION OF AN $N$-SHAPED IVC OF NANOSCALE METALLIC JUNCTIONS USING THE ANTIFERROMAGNETIC TRANSITION.

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Abstract

We have observed at low temperatures ($\leq 8$ K) hysteretic $I(V)$ characteristics for sub-$\mu$m ($\sim 200$ nm) metallic break-junctions based on the heavy-fermion compound UPd$_2$Al$_3$. Degrading the quality of the contacts by in situ increasing the local residual resistivity or temperature rise reduces the hysteresis. We demonstrate that those hysteretic $I(V)$ curves can be reproduced theoretically by assuming the constriction to be in the thermal regime. Our calculations show that such anomalous $I(V)$ curves are due to the sharp increase of $\rho(T)$ of UPd$_2$Al$_3$ near the Néel temperature $T_N \approx 14$ K. From this point of view each metal with similar $\rho(T)$ should produce similar hysteretic $I(V)$ curves. As example we show calculations for the rare-earth manganite La$_{0.75}$Sr$_{0.25}$MnO$_3$, a system with colossal magnetoresistance. In this way we demonstrate that nano-sized point contacts can be non-linear devices with $N$-shaped $I(V)$ characteristics, i. e. with negative differential resistance, that could serve like Esaki tunnel diodes or Gunn diodes as amplifiers, generators, and switching units. Their characteristic response time is estimated to be less than 1 ns for the investigated contacts.

Keywords: point contacts, negative differential resistance, UPd$_2$Al$_3$, La$_{0.75}$Sr$_{0.25}$MnO$_3$.

Point-contact (PC) spectroscopy is widely used to study the interaction of conduction electrons with elementary excitations or quasiparticles in conducting solids [1]. On the other hand, PC investigations can shed light on peculiarities of the electronic transport in nano-scale devices at ultrahigh current densities. The latter matters for mesoscopic
or nanoscale physics, and especially for applied research where electronic devices have already reached this sub-μm scale.

Electron transport in nanostructures can be distinguished by basically three different current regimes, depending on the relationship between the elastic $l_{el}$ and the inelastic $l_{in}$ mean free path of electrons, and the constriction or point-contact diameter $d$ (for a review see [1], Chapter 3). The constrictions are either ballistic ($l_{el}, l_{in} \gg d$), diffusive ($l_{el} \ll d \ll \sqrt{l_{in}l_{el}}$), or thermal ($l_{el}, l_{in} \ll d$).

A priori it is not trivial to determine the specific current regime, which is important to further characterize the nano-object: first, because the nano-sized object needs a well-defined geometry; second, to evaluate the electronic mean free path, especially the inelastic one, can be rather speculative. To investigate the non-linear $I(V)$ curves using PC spectroscopy seems to be the best method to solve this problem.

Here we present experiments on PCs between two pieces of the heavy-fermion compound UPd$_2$Al$_3$, using the technique of mechanically-controllable break junctions (see [1], Chapter 4.1.5). UPd$_2$Al$_3$ becomes antiferromagnetic (AFM) at $T_N \simeq 14$ K [2]. We have observed huge nonlinearities of the PC resistances and even hysteretic $I(V)$ characteristics (Fig.1). We derived the contact size and the residual resistivity in the PC region as described in [3]. We found that the very short elastic

![Figure 1](image-url)
Realization of an $N$-shaped IVC in nanoscale metallic junctions

mean-free path in the constriction $l_{cl} \ll d$ points to at least the diffusive regime of electron transport through the PC. Considering also the small inelastic mean-free path in UPd$_2$Al$_3$, reflected by the steep $\rho(T)$ rise with temperature around the AFM transition in Fig. 1(b), we applied the thermal model developed in Refs. [4, 5]. In this case the excess electron energy $eV$ dissipates within the constriction, increasing the temperature inside the contact when a bias voltage $V$ is applied. As a result $I(V)$ is governed by the resistivity $\rho(T)$ via [4, 5]

$$I(V) = V d \int_0^1 \frac{dx}{\rho(T\sqrt{1-x^2})},$$

where the temperature $T$ in the center of the constriction is set by $T^2 = T_{bulk}^2 + V^2/4L$ and $L$ is the Lorenz number.

The calculated $I(V)$ curve at $T = 1K$ in Fig. 1(c) has maximum at around 2.5 mV, resulting in a hysteresis for up- and downward sweeps when the junction is driven by a current source. Figure 1(c) shows that the theoretical $I(V)$ describe well the experimental data, including the width of the hysteresis, using $d = 200$ nm and $\rho_0 = 10 \mu\Omega\text{cm}$, where $\rho_0$ is the additional residual resistance: $\rho(T) = \rho_0 + \rho_{bulk}(T)$. These are the only two adjustable parameters which have been derived independently from the measured contact resistance $R(T)$ in [3]. This agreement strongly supports our interpretation that local thermal effects at the PC determine the behavior of our UPd$_2$Al$_3$ break-junction conductivity.

The UPd$_2$Al$_3$ junctions presented here are non-linear devices. Their $N$-shaped $I(V)$ characteristics have a negative differential resistance at very high current densities up to $5 \times 10^{10}$ A/m$^2$. Those devices could be applied – in principle – like an Esaki tunnel diode or a Gunn diode [7, 8] as amplifiers, generators, or switching units. Of practical interest is therefore the possible minimum response time. We estimate [3] a thermal relaxation time $\tau \approx 100$ ps for a $d = 100$ nm wide contact. This is three orders of magnitude larger than for a standard tunnel diode, but it could be reduced by using smaller contacts as long as they remain in the thermal regime.

Obviously UPd$_2$Al$_3$ is not such a unique material for creating $N$-shaped IVCs – each metal with a similar $\rho(T)$ should also produce similar $I(V)$ characteristics. This can be expected for many materials which order magnetically, since their resistivity typically increases steeply when the magnetic order is destroyed by thermal fluctuations.

An example for this behaviour is the well known rare-earth manganite La$_{0.75}$Sr$_{0.25}$MnO$_3$, a system with colossal magnetoresistance as shown in Fig. 2(a). Indeed, the calculated $I(V)$ curves in Fig. 2(b) are $N$-shaped up to room temperature. Even enhancing disorder by increasing the
residual resistivity up to $\rho_{\text{add}} = 1000 \mu \Omega \text{cm}$ as in Fig. 2(c) does not suppress the hysteresis at low temperatures.

On the other hand, the position of the current maxima shift to higher voltages with increasing temperature (or residual resistivity), contrary to what has to be expected for a simple AFM transition. Thus it would be very interesting to study $I(V)$ for constrictions of this compound experimentally.

The partial support of the complex program "Nanosystems, nanomaterials and nanotechnologies" of the National Academy of Sciences of Ukraine are acknowledged.

References

[1] Yu. G. Naidyuk, I. K. Yanson, Point-contact spectroscopy (Springer, N.Y., 2004).
[2] C. Geibel, C. Schank, S. Thies, H. Kitazawa, C. D. Bredl, A. Böhm, M. Rau, A. Gräuel, R. Caspary, R. Helfrich, U. Ahlheim, G. Weber, and F. Steglich, Z. Phys. B 84, 1 (1991).
[3] Yu. G. Naidyuk, K. Gloos, I. K. Yanson, and N. K. Sato, J. Phys.: Condens. Matter 16, 3433 (2004).
[4] B. I. Verkin, I. K. Yanson, I. O. Kulik, O. I. Shiklyarevskii, A. A. Lysyk, and Yu. G. Naidyuk, Solid State Commun. 30, 215 (1979); Izv. Akad. Nauk SSSR, Ser. Fiz. 44, 1330 (1980).
[5] I. O. Kulik, Sov. J. Low Temp. Phys. 18, 302 (1992).
[6] J. Mitra, A. K. Raychaudhuri, N. Gayathri, and Ya. M. Mukovskii, Phys. Rev. B., 65, 140406 (2002).
[7] L. Esaki in: Nobel lectures in Physics 1971-1980 (edit. Stig Lundquist), (World Scientific Publishing Company 1992); Science 183, 1149 (1974).
[8] P. J. Price in Handbook on Semiconductors (edit. T. S. Moss and P. T. Landsberg), (Elsevier Science Publishers B. V. , Amsterdam, 1992), Volume I, Chapter 12.