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BRIEF COMMUNICATIONS

Effect of Superconductivity–Magnetism Interaction on the Differential Conductivity in $Ho(NiB)_2C$/Ag Point Contacts

I. N. Askerzade[1, 2] and B. Tanatar[3]

[1] *Institute of Physics, Academy of Sciences of Azerbaijan, ul. Dzhavida 33, Baku, 370143 Azerbaijan*

e-mail: solstphs@lan.ab.az

[2] *Physics Department, Ankara University, Tandogan, 06100 Ankara, Turkey*

[3] *Physics Department, Bilkent University, 06533 Bilkent, Ankara, Turkey*

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Abstract—In terms of the Blonder–Tinkham–Klapwjik theory, the differential conductivity of $Ho(NiB)_2C$/Ag point contacts is explained by the coexistence of magnetic ordering and superconductivity in holmium boron carbides. © *2002 MAIK "Nauka/Interperiodica".*

The measurement of the differential conductivity in normal metal–superconductor junctions is a sensitive method for studying superconductor properties [1–3]. It was applied to study the order parameter symmetry in cuprate semiconductors [4, 5], as well as the properties of recently discovered semiconductor MgB_2 [6]. Investigation into the superconducting properties of exotic boron carbide–(boron nitride–) based semiconductors of the RTBC(N) class, where R is a rare-earth element and T = Ni, Pd or Pt, is also of great importance for the elucidation of a microscopic mechanism of superconductivity in these compounds [7]. Point contact spectroscopy of boron carbides is needed for the detailed study of the order parameter symmetry and is also dictated by the coexistence of superconductivity and magnetism in magnetic boron carbides. Andreev spectroscopy of $Y(La)(NiB)_2C$ nonmagnetic boron carbides gives peak values at the gap value of the order parameter [3]. Similar behavior was observed in $Dy(Er)(NiB)_2C$ magnetic boron carbides. The compound with Dy exhibits superconductivity in the presence of antiferromagnetic ordering at a temperature T_N = 10.5 K and is the only boron carbide–based compound with the Néel temperature exceeding the superconducting transition critical temperature, $T_N > T_c$ = 6 K. In the Er-containing compound (the critical temperature T_c = 10.8 K), antiferromagnetic ordering takes place below T_N = 5.9 K. $Ho(NiB)_2C$ compounds have a more complex magnetic structure. Here, antiferromagnetic ordering arises below the Néel temperature $T_N \approx$ 5 K and is associated with a commensurate magnetic structure modulated along the *z* axis with a wave vector $\mathbf{Q}_{AF} = \mathbf{c}^* = 2\pi/c$. Other magnetic structures were discovered in the temperature range $T_N < T < T_m$ = 6 K. In this interval, an incommensurate phase helical along the *z* axis with a wave vector $\mathbf{Q}_C = 0.91\mathbf{c}^*$ and an incommensurate phase modulated along the *x* axis with a vector $\mathbf{Q}_a = 0.55\mathbf{c}^*$ form. The reentrant or almost reentrant behavior of superconductivity was detected in the magnetic ordering range [8]. $Ho(NiB)_2C$/Ag point contacts were experimentally studied in [9], but the suppression of Andreev features remained unexplained. In this work, we concentrate on the effect of the helical structure on the differential conduction in $Ho(NiB)_2C$/Ag point junctions, invoking the Blonder–Tinkham–Klapwjik (BTK) formalism [10].

First, let us turn to the effect of the helical structure on the superconductivity. For the first time, this point was considered by Morozov in [11]. Recently, he has extended his approach for holmium boron carbides [12]. Applying the Bogoliubov transformation, one can show that the gap parameter in the quasi-particle spectrum becomes highly anisotropic and disappears at the line of intersection between the Fermi plane and Bragg planes, which are generated by magnetic ordering. The conventional BTK theory for isotropic semiconductors can be generalized for the anisotropic case by introducing the dependence of the gap on the momentum $\Delta(\mathbf{k})$ into the expressions for the Andreev reflection probability $A(\varepsilon, \Delta(\mathbf{k}))$ and normal tunneling probability $B(\varepsilon, \Delta(\mathbf{k}))$. Then, the normalized zero-temperature con-

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ductance of a point junction is given by

$$\frac{G_{NS}}{G_{NN}} = \frac{\partial I_{NS}/\partial V}{\partial I_{NN}/\partial V}$$
$$= \frac{\partial/\partial V\int d^3k v_z\{1 + A(\varepsilon, \Delta(\mathbf{k})) - B(\varepsilon, \Delta(\mathbf{k}))\}}{\partial/\partial V\int d^3k v_z\{1 - Z^2/1 + Z^2\}}, \quad (1)$$

where v_z is the velocity positive component normal to the *NS* interface and *Z* is the potential barrier height at the interface. In this approximation, the proximity effect can be neglected although the effect of the surface on the order parameter is significant in purely *d*-wave and *p*-wave superconductors.

The differential conductivity for *N*/*d*-wave superconductors was calculated in [13] with Eq. (1). Similar calculations for ferromagnet/*d*-wave structures were carried out in [14]. The dependence of the intragap structure on the orientation of the *d* wave with respect to the interface was found. Of interest also are calculations performed within the same approach for Sr_2RuO_4 in view of the *p*-wave symmetry of the order parameter [15]. For the UPt_3 heavy-fermion system, the oddness of the order parameter was taken into account [16]. In all the cases, the anisotropy of the order parameter causes the plateau in the (–Δ, Δ) interval to transform into a triangular peak of the conductance inside the gap.

As was shown by Morozov [11, 12], the order parameter in the presence of the helical structure is given by

$$\Delta(\mathbf{k}, T) = (u_{\mathbf{k}}^2 - v_{\mathbf{k}}^2)\Delta(T),$$

where

$$u_{\mathbf{k}}^2 - v_{\mathbf{k}}^2 = \left\{\frac{(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{k}+\mathbf{Q}})^2}{(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{k}+\mathbf{Q}})^2 + I^2S^2}\right\}^{1/2}, \quad (2)$$

I is the exchange integral, *S* is the averaged spin, $\varepsilon_{\mathbf{k}}$ is the dispersion relation in the paramagnetic phase,

$$\Delta(T) = \int_0^\omega d\varepsilon \frac{\Delta(T)(1 - 2n_{\mathbf{k}})}{\varepsilon^2 + \Delta^2(T)}$$
$$\times\left(\int_{MFS} \frac{dS'}{(2\pi)^3}\frac{(u_{\mathbf{k}'}^2 - v_{\mathbf{k}'}^2)^2}{|\nabla_{\mathbf{k}'}\tilde{\varepsilon}_{\mathbf{k}'}|}\right), \quad (3)$$

$\tilde{\varepsilon}_{\mathbf{k}}$ is a new dispersion relation, and n_k is the Fermi distribution function. Equation (4) corresponds to the conventional BCS equation with the effective parameter of interaction in parentheses. The dependence $\lambda_{\text{eff}}(T)$ depends on the Bogoliubov coefficients and on the Fermi surface slope. Since anomalies of the vector dependence are observed near the intersections of the Fermi surface with Bragg planes, the difference between the actual interaction constant and its effective value $\Delta\lambda = \lambda - \lambda_{\text{eff}}(T)$ can be expanded in units of IS/E_F. The difference $\Delta\lambda$ was estimated at $\Delta\lambda/\lambda = 0.12$ [17] from the data for the band structure of boron carbides. This value was used to explain the reentrant behavior of the upper critical field in holmium boron carbides.

Experimental data [9] indicate the insensitivity of the curve $G_{NS}(V)$ to the orientation of the contact plane with respect to crystallographic axes. This fact supports the isotropy of the electronic structure of these compounds. Thus, the possibility of *d*-wave or *p*-wave pairing in helicoidal superconductors should be excluded; otherwise, the current–voltage characteristic would be sensitive to the contact plane orientation.

The evolution of the $G_{NS}(V)$ shape with the barrier height is analyzed in the BTK theory [10]. Clearly, the intragap plateau in the absence of the barrier changes to peaks for $\pm\Delta$ as the barrier grows. For $Ho(NiB)_2C$/Ag at $T < 5$ K, where the helicoidal structure transforms into the antiferromagnetic phase, the current–voltage characteristic has two peaks.

However, in the temperature interval $5 < T < 8.1$ K, which is equivalent to $\Delta T/T \approx 3/4 = 0.4$, the gapless behavior is observed (note that this parameter equals 0.2 for $Er(NiB)_2C$ compounds). In our opinion, the broadening and the gapless behavior are due to the decline of the order parameter when the helical structure is present in the system. As was noted [17], the decrease in the interaction constant to $\Delta\lambda/\lambda \approx 0.12$ is insufficient for the order parameter to be suppressed completely. On the other hand, when calculating the differential conductivity, we must include the additional factor $u_{\mathbf{k}}^2 - v_{\mathbf{k}}^2$. Since this factor is less than unity, we have one more channel for suppressing the order parameter.

Thus, the broadened gapless behavior of $G_{NS}(V)$ for $Ho(NiB)_2C$/Ag point contacts at near-critical temperatures can be explained by the order parameter suppression. In experiment [9], the suppression is incomplete because $Ho(NiB)_2C$ samples were extrapure. It was shown [18] that nonmagnetic impurities heavily destroy superconductivity in helicoidal systems. We can thus conclude that helicity "retards" the emergence of two peaks in the $G_{NS}(V)$ curve.

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