Heat Transport Across the Interface Between Normal Metal and d-wave Superconductor

I.A.Devyatov and M.Yu.Kupriyanov
Institute of Nuclear Physics, Moscow State University 119899 GSP Moscow, Russia

A.A.Golubov
Department of Applied Physics University of Twente P.O.Box217, 7500AE Enschede, The Netherlands

L. Kuzmin and M. Willander
Chalmers University of Technology S-412 96 Goteborg, Sweden

Abstruct **Heat conductance and heat current across normal metal/*d*-wave superconductor (NID) interface are calculated in framework of quasiclassical equations. The calculations was performed for different values of boundary transparencies and crystal axis orientation. It is shown that in contrast to N/*s*-wave boundary the heat conductance of transparent (D=1) NID interface is considerably larger and has nonactivated form. Electronic heat current across NID structures is also calculated for different interface models taking into account the midgap states and possibility of generating of gapless s-wave state in the vicinity of rough NID interface. It is shown that NID junctions can not compete with analogous NIS devices [1,2] in microrefigarating and bolometer applications.**

I. INTRODUCTION.

There are two thermoelectric effects that are widely used in modern cryoelectronic devices [1,2]. The first of them is the existence of the heat transfer from the normal metal into superconductor in NIS junctions that accompanied the flow of electric current across the NS interface. The second one is the overheating of the electron gas in SNS structures due to low value of the thermal conductance of the SN interfaces.

The first effect is used for refrigerating of electrons in the normal metal [1,3]. The mechanism of refrigerating in NIS junctions [4] is the same as that of the Peltier effect in metal-semiconductor contacts. Due to the energy gap in the superconductor, electrons with higher energies ε (above the gap Δ) are removed from the normal metal more effectively than electrons with lower energies. This makes the electron energy distribution sharper, thus decreasing the effective temperature of electron gas in the normal metal. In contrast to NISm structures in SIN junctions refrigerating effect across NS interface is suppressed due to existence of the coherent Andreev reflection channel [5]. This channel effectively removed the electrons inside the energy gap from N to S metal making the electron distribution function in N smother and resulting in increase of the effective temperature of electron gas in the N-metal. The effectiveness of this process is proportional to D^2, where D is the transparency of the boundary.

On the other hand the coherent Andreev reflection provides the low thermoconductivity κ of the transparent SN interface. It is the second thermoelectric effect that is used in the modern far infrared detectors [2].

Previously the heat transfer in NIS contacts was studied in the case of usual S-wave isotropic superconductors [4]. It was shown that in the tunnel limit $D \ll 1$ maximal refrigerating power is proportional to Δ. The heat conductance of transparent NS interface is proportional to $\exp\{-\Delta/T\}$. Thus both effects became more pronounce with increasing the energy gap in S.

The goal of this work is to analyze these two effects in the structures with high-Tc superconductor electrode. The energy gap in high-Tc superconductor larger than that of low-Tc one. But the advantage is not so obvious due to anisotropic pairing in high-Tc materials, especially if the pairing have d-wave symmetry (NID junctions).

In the last case for the sharp clean NID interface there is several additional channels (mid gap states [6,7], Andreev bound states [8]) for the heat transfer across the boundary. Moreover in the vicinity of rough interface with diffusive electron scattering [9] the gapless s-wave superconducting component is generated due to proximity effect with the bulk d-wave superconductor. All these effects will be taken into account analyzing the thermoeffects.

II. MODEL OF THE NID JUNCTION.

To avoid the suppression of superconductivity in S-electrode due to proximity effect with the N-metal we will assume that NID structure has the form of clean constriction with the geometrical sizes much smaller than the coherence length of superconductor, inelastic and elastic scattering lengths in the electrodes. In this case the electron motion across junctions is naturally decomposed into several decoupled transverse modes. During the calculations we will also assume that the Fermi surface of HTS material has cylindrical form.

Under these restrictions the electron transport properties of the structure can be describe by the probabilities of normal $B(\varepsilon,\theta_-)$, and Andreev $A(\varepsilon,\theta_+)$, reflection from the N-S interface [10,7]:

$$A(\varepsilon,\theta_+) = \frac{|a_+(\varepsilon)|^2 \cos^4(\theta)}{\left|\cos^2(\theta) + z^2(1 - a_+(\varepsilon)a_-(\varepsilon))\right|^2}, \tag{1}$$

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$$B(\varepsilon,\theta_-)=\frac{|1-a_+(\varepsilon)a_-(\varepsilon)|^2(\cos^2(\theta)+z^2)z^2}{|\cos^2(\theta)+z^2(1-a_+(\varepsilon)a_-(\varepsilon))|^2}.$$

Here $\theta_+=\theta$ is the angle of incidence of incoming electron on N-S interface, $\theta_-=\pi-\theta$ is angle correspondent to specula reflected electron, parameter $z=mH/\hbar^2k_0$ control the transparency D of the interface $D=1/(1+z^2)$, H is the strength of the δ-functional barrier at the interface, k_0 is Fermi wave vector. Functions $a_{\pm}(\varepsilon)$ in (1) are the amplitudes of Andreev reflection from the ideal N-S interface with $D=1$ at angles $\theta_{\pm}$. The energy dependence of the coefficients $a_{\pm}(\varepsilon)$, must be find for every model of the superconductor side of the constriction independently.

Using the reflection probabilities (1) we write the balance equation for energy distribution functions of electrons moving to and from NS interface in the direction having the angle θ with the interface normal. For electrons moving from the bulk N-metal to the NS interface the distribution function coincides with the Fermi one $f^+(\varepsilon)=f(\varepsilon-eV)$ shifted by eV, where V is the voltage drop across the junction.

Electrons moving from the interface into the normal metal with angle θ are produced in three processes. Holes incident with angle θ are Andreev reflected as electrons with probability $A(\varepsilon,\theta_+)$, electrons incident with angle π-θ are specula reflected with probability $B(\varepsilon,\theta_+)$, quasiparticles incident from the superconductor are transmitted into the normal metal with the probability $1+A(\varepsilon,\theta_+)-B(\varepsilon,\theta_+)$. Thus, the energy distribution $f^-(\varepsilon,\theta)$ of electrons moving into the normal metal with angle θ has :the form

$$f^-(\varepsilon,\theta)=A(\varepsilon,\theta_+)(1-f^+(-\varepsilon))+B(\varepsilon,\theta_-)f^+(\varepsilon)+ \\ +(1-B(\varepsilon,\theta_-)+A(\varepsilon,\theta_+))f(\varepsilon) \quad (2)$$

Heat current j across NS interface can be calculated in the similar way as in [4]. Taking into account specific to NID junction angular dependence of distribution function (2) we arrived at:

$$j=\frac{k_0}{2\pi^2\hbar}\int d\varepsilon(\varepsilon-eV)\int_{-\pi/2}^{\pi/2}d\theta\cos\theta(f^+(\varepsilon)-f^-(\varepsilon,\theta)). \quad (3)$$

Equations (2,3) give the heat current as a function of bias voltage, temperature, orientation angle α and transparency D for different interface models. From (2), (3) it follows that the problem reduce to the determination of the θ and energy dependencies of the Andreev coefficients.

We will calculate also the heat conductance $\kappa=j/\delta T$ of perfect N-d-wave superconductor boundary with transparency $D=1$ (Andreev's problem [5]), where δT is small temperature difference between S and N metals. From (3) it follows:

$$\kappa=\frac{k_0}{2\pi^2\hbar k_BT^2}\int\frac{\varepsilon^2\exp(\varepsilon)d\varepsilon}{(1+\exp(\varepsilon))^2}\int_{-\pi/2}^{\pi/2}d\theta\cos\theta(1-|a_+(\varepsilon)|^2) \quad (4)$$

Eq. (4) coincides with the same equation for usual anisotrpic superconductor, since (4) depends on only single angle θ_+. The same situation take place in current-voltage calculations in the N -d-wave junctions with transparency $D=1$ [7].

III. ANDREEV COEFFICIENTS

For the sharp specula interface the form of the $a_{\pm}(\varepsilon)$ dependencies is different for different misorientation angles a. At $\alpha=0$ there is no suppression of the order parameter $\Delta_{\pm}=\Delta(\theta_{\pm})=\Delta_0(T)\cos(2(\theta\mp\alpha))$ in the vicinity of the interface and only anisotropy effects must be taken into account. In this particular case the Andreev coefficients have the usual BCS form (see, for example, [4], [7]).

At arbitrary a the coefficients $a_{\pm}(\varepsilon)$ was calculated numerically in two steps (see [10] for the detailes). First, in the framework of quasiclassical Eilenberger equations space dependence of the order parameter $\Delta(x)$ was found for different misorientation angle a. At the second step the analytical continuation in was made by changing $\omega\to -i\varepsilon$ and the resultant set of equations was solved numerically with $\Delta(x)$ defined on the previous step. Rough interface was modeled by the thin disordered layer contacted with the bulk clean d-wave superconductor [9].

The energy dependencies of $|a_{\pm}(\varepsilon)|$ for different misorientation angles α are shown on Fig 1. For the case of specula interface and $\alpha=0$ the $|a_{\pm}(\varepsilon)|$ dependencies (4) have usual BSC form with θ-dependent order parameter $\Delta\propto\cos 2\theta$. At $\alpha\neq0$ the suppression of the energy gap in the vicinity of the interface take place (see Fig. 1a) resulting in formation the Andreev bound states [8] for the quasiparticles trapped between the interface and the point L where their energy $\varepsilon=\Delta(L)$. The closer angle θ to $\pi/2$, the longer is the trajectory L of quasiparticles in the "potential well" with smaller Δ, and therefore the larger is the number of Andreev bound states (see the increase the number of peculiarities in $|a_{\pm}(\varepsilon)|$ with increasing θ in Fig. 1a)

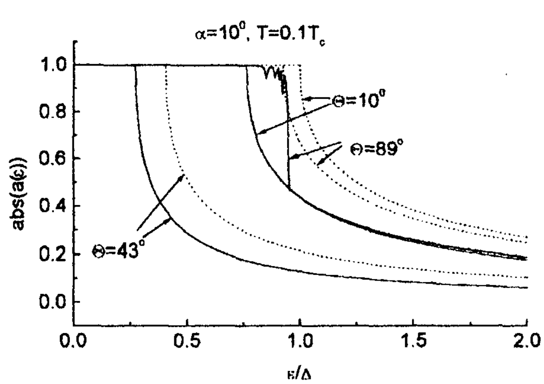

Fig. 1a. Andreev coefficients for specula reflected N-D interface at T=0.1Tc. for misorientation angle α=10, 43, 89. Solid lines are the results of selfconsistent conculations, while dotted correspond to Andreev coefficients calculated with the bulk value of the order parameter (non-selfconsistently).

In the case of the interface with disordered layer the gapless s-wave state is generated at the free surface resulting in $|a(\varepsilon)|\sim\varepsilon$ at small energies (see Fig.1b). The maximum value of $a(\varepsilon)$ is significally smaller compare to the values for the clean specula interface.

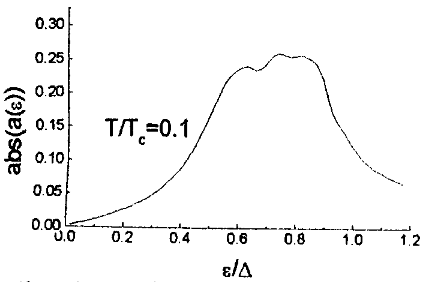

Fig. 1b. Andreev coefficients for rough N-D interface

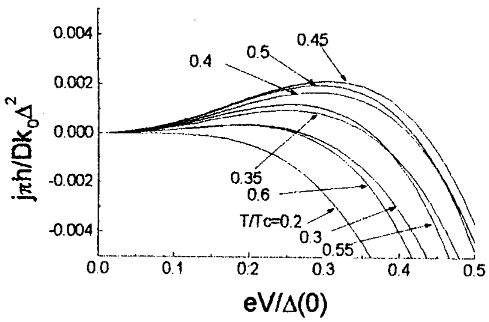

Fig.2 Heat current j in the NID contact with specula reflecting boundaries versus bias voltage V for several temperatures T calculated for misorientation angle α=0 and D=0.0001.

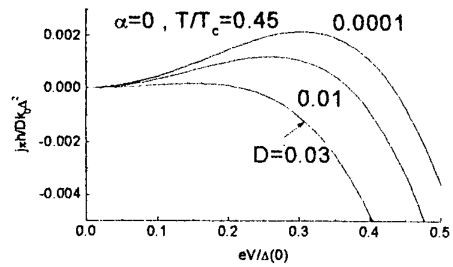

Fig.3. Heat current j in the NID contact with specula reflecting boundaries versus bias voltage V for set of transparencies D=0.0001 (tunnel limit); 0.01; 0.03. T/T_c=0.45 and misorientation angle α=0.

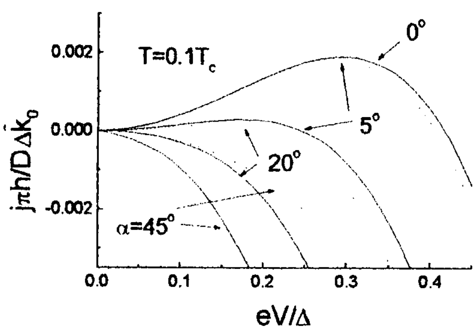

Fig.4. Heat current j in the NID contact with specula reflecting boundaries versus bias voltage V for several values of misorientation angle α=0, 5, 20, 45, D=0.0001 and T/T_c=0.45. Dotted lines are $j(V)$ calculated with the use of (3) with the bulk value of the order parameter (non-selfconsistently)

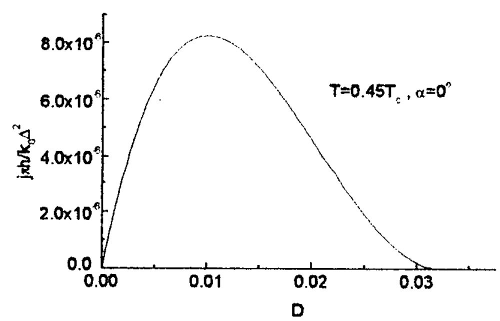

Fig. 5. The maximum heat current density of NID junction with as a function of transparency D for α=0, and T= 0.45T_C.

IV. NID JUNCTIONS WITH SPECULA REFLECTING INTERFACE

Properties of NID junctions with specula reflecting boundary essentially depends on mutual orientation between principal axis of the HTS material a and interface normal. Figure 2 shows the heat current j as a function of bias voltage V across the junction for different temperatures T calculated numerically for α=0 and D=10^{-4}. We see that for each temperature there is an optimal bias voltage which maximize the heat current j. The heat current has maximum at T/T_c=0.45. This value is close to the optimum temperature obtained for N-S-wave junction (NIS) [4], but maximal normalized j in NID case is more than one order of magnitude smaller than in NID junctions [4]. The reason of the difference lays in the strong anisotropy nature of HTS superconductors.

Increase of D suppress the refrigerating power of the NID junction due to Andreev reflection starts dominate be the electron transport in the same manner as in NIS case [4]. Figure 3 shows how this suppression occurs for the optimal set of the parameters α=0, T/T_c=0.45.

Figure 4 shows $j(V)$ for the different α and optimal temperature T/T_c=0.45. Increase of the misorientation angle α results in significant suppression the refrigerating power. The reasons of this effect are the midgap states [6,7] and suppression of the order parameter at the vicinity of the interface. Both of these factors decrease the value of the energy gap and, hence diminish the refrigerating power.

Figure 5 shows heat current of NID junction as a function of junction transparency D. At small D heat current increases linearly with D as in the isotropic case [4]. At larger D, j starts to decrease with D because of increasing contribution to heat transport from coherent Andreev reflection. It is important that maximum normalized heat current is more than two orders smaller than in isotropic case [4] and achieved at smaller D.

Heat conductance κ_S as a function of Δ/k_BT for different values of orientation angle $\alpha=0$, $\pi/8$, $\pi/4$ is plotted on Fig.6. In inset in Fig.6 depicted $\kappa_S(\Delta)$ of N-isotropic 2D s-wave superconductor, which has the usual [5] exponential form:

$$\kappa_s = \frac{\sqrt{2}}{\pi^{3/2}}\frac{k_0}{\hbar}\Delta k_B\sqrt{\frac{\Delta}{k_BT}}\exp(-\Delta/k_BT), \Delta/k_BT >> 1 \qquad (6)$$

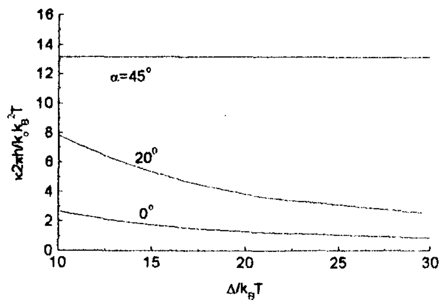

Fig.6.The heat conductance as a function of Δ/k_BT for $\alpha=0$, $\pi/8$ and $\pi/4$.

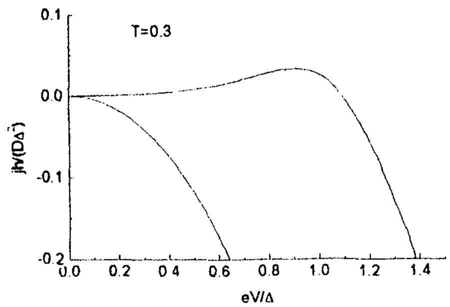

Fig. 7. The heat current across N-disorder layer-d-wave superconductor junction. The upper curve corresponds to the heat current across NIS junction

From Fig.6 it follows that heat conductance of the NID junction for all values of orientation angle α are approximately two order higher than heat conductance of the NIS structure. This is the consequences of significant (not exponential small) heat flow across d-wave order parameter nodes. At α=45 the order parameter equals to zero at the interface, effectiveness of this channels achieve maximum and heat conductance are practically independent on Δ and close to its value for 2D N-N junction.

$$\kappa \approx 4\frac{k_0 k_B^2 T}{\pi\hbar}\int_0^\infty dx \frac{x^2}{\cosh^2(x)} \approx 13.159\frac{k_0 k_B^2 T}{\pi\hbar}, \quad (7)$$

At α=0 there is no suppression of Δ at the boundary and we have usual decreasing of the heat conductance with increase of Δ.

IV. NID JUNCTIONS WITH DIFFUSIVE INTERFACE

In the model of the diffusive interface suggested in [9] Andreev coefficients are gapless and relatively small (see Fig.1b) compare to them of specula reflecting boundaries.

Numerical calculations leads in this case to the negative value of the heat current in NID junction for all values of junction parameters (see Fig.7) which is practically coincides with the heat current across N-N junction. The corresponded normalized (for 1D case) value of the heat conductance is close to its value (7) for N-N structures.

Thus, in contrast to NIS devices (see upper curve on Fig.7) in NID junctions we have heating effect at all voltages

V. CONCLUSION

Our analysis have shown that the refrigerating effect in NID junctions with specula reflecting boundaries is possible only for the small values of α, when the suppression of the order parameter is not crucial. Nevertheless, even in this case the corresponded normalized values of the refrigerating power is more than two order smaller than for NIS structures. It means that the advantage of large values of the order parameter in HTS materials is overweighing by anisotropy nature of pairing. Thus in HTS-N-HTS structures it is impossible to make noticeable overheating of electron gas and hence there will be no any practical advantages in substitution LTS material by HTS one in bolometers [1,2] employ the Andreev reflection.

From Fig.4 it follows that for optimal set of the parameters (α=0 and T=0.45T_c, D=0.01) refrigarating power of NID junction can be 4 times larger than in Nb based NIS structures. Unfortunately, for practical applications it is interesting to cool electron gas at T < 1K. In this temperature domain there is no any advantage of HTS based refrigerator compare to LTS one.

So we can conclude that there are no reasons for using NID junctions for microrefigarating and bolometer applications. This is especially true for NID devices with diffusive reflection of electrons at the interface. The generated in this case gapless s-state in the vicinity of the boundary makes the structure close to N-N contacts, which have not any refrigerating effects and suppression of the heat conduction, typical for NIS junctions

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