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Non-linear self-oscillations in normal–superconducting contacts

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Abstract. The non-linear properties of mechanical normal–superconducting contacts are investigated. It is shown that the near-boundary superconductor conductivity jump due to direct current through the heterosystem would induce not only the known N-shaped non-linearity in *I–V* characteristics (Ta–(SnPb) heterosystems) but also the *S*-shaped non-linearity in *I–V* characteristics (In–Bi heterosystem). This conclusion follows from the conditions required to observe self-oscillations. The nature of the non-linearity in the In–Bi heterosystem which is non-traditional for conductors is analysed using self-oscillation parameters.

1. Introduction

It is well accepted that good-quality non-Josephson normal–superconducting (NS) interfaces offer almost no resistance to electrical current because of the Andreev reflection of electrons with an excitation energy T less than the superconducting gap $\Delta(T)$.

Commonly this is the situation if it is supposed that some of the well known mechanisms disturbing the electron transparency of the NS interface are negligible. Indeed, one of these mechanisms is due to non-equilibrium effects (through electric field penetration into superconductor) and it makes the resistance always less than the normal resistance of the superconductor [1]. Another mechanism is connected with the non-Andreev nature of the electron reflection when the electron momentum component normal to the NS interface is less than $[2m\Delta(T)]^{1/2}$ (m is the electron mass). Electrons with such momenta are those whose angle of incidence on the interface is equal to $(T/\varepsilon_F)^{1/2}$ at most and so they might be referred to as sliding electrons. Such electrons reflect specularly from the NS interface as from the usual potential wall (see, e.g., [2]). Their maximum relative contribution to resistance is of the order of $\alpha = \delta R/R \simeq [\Delta(T)/\varepsilon_F]^2$ [3]. For an NS system with well conducting metals as the 'normal' part this is also insignificant.

However, it is like this only for $\varepsilon_F \simeq 1$ eV. Kadigrobov [3] found that the contribution of the specularly reflected electrons to the resistance should essentially increase in the case of low ε_F of the conductor forming the NS system together with a superconductor. In particular the above-mentioned contribution should be enhanced by a factor of about 10^4 for the In–Bi pair and so should become quite easily measurable as was experimentally shown [4].

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We sought to ascertain whether the discussed mechanism would lead to S-shaped I–V characteristics which could cause non-linear self-oscillations (SOS) under certain conditions predicted in [3]. If the predictions are confirmed, this should provide a new method for studying some electron characteristics such as the gap, the mean free path and the Fermi energy in conductivity band.

2. Experiment

The resistance of the NS system can be thought of as a sum: $R_X = R_N + R_{NS} + R_S$, where R_N is the total resistance of the normal metal part of the system, R_S the superconductor resistance and R_{NS} the NS interface resistance. The latter is equal either to αR_N (when $\Delta(T) \neq 0$ and $R_S = 0$) or to 0 (when $R_S = R_S^{(N)}$, where $R_S^{(N)}$ is the normal resistance of a superconductor). If we take into account the considerations in the previous section, it will be easily understood that the inequality $R_{NS} > R_S^{(N)}$ is one of the necessary conditions for the appearance of S-shaped I–V characteristics in the NS system. Since R_{NS} and $R_S^{(N)}$ are independent of each other, this can be attained by increasing α (i.e. R_{NS}) through choosing a normal metal with a low ε_F and reducing the sample dimension along the current. If the condition $R_{NS} > R_S^{(N)}$ exists, there will be a negative discontinuity in the resistance, $\delta R_X = R_S^{(N)} - \alpha R_N$ in switching over from the NS to the NN state at some critical (for the superconductor) current value i_c. This takes place because the specular electron reflection from the potential wall vanishes when the current destroys the superconductivity. This effect will lead to S-shaped I–V characteristics only if the resistance transition has a finite width. Kadigrobov [3] has mentioned that the non-linearity width in this case should be of the order of magnitude of $\alpha^2 i_c$.

It is essential that this occurs to the same extent when a positive discontinuity in resistance, $\delta R_X > 0$, takes place (i.e. $R_{NS} < R_S^{(N)}$) as the current increases. This is generally known as N-shaped I–V characteristics and leads, as a consequence, to non-linear SOS which are often observed in superconducting channels, films, etc (Josephson contacts may be concerned here).

According to the general vibration theory, non-linearities in both S- and N-shaped characteristics must lead to SOS but under electrical circuits embodying different concepts. In figure 1 the inset (a) shows the circuit that we used. Depending on the shape of the I–V characteristic it may be converted to observe either 'N'- or 'S'-type SOS merely by changing the connections of the same fixed-current source.

The case of S-shaped I–V characteristics is of the greatest interest. It appears that a circuit self-capacitance of the order of several picofarads is sufficient for SOS to occur. In fact, with such a capacitance and the time taken for superconductor transition to a resistive state of the order of the pair relaxation time τ_1, the discontinuous change in sample current is

$$\delta i_x \simeq i_{x0}(e/\tau)\alpha R_X \gg i_{x0} - i_c \simeq \alpha^2 i_c \tag{1}$$

(i_{x0} is the working point bias current in figure 1(a)). This is sufficient for a SO cycle to occur. The cycle time is $\tau = 2(\tau_1 + \tau_2) \simeq \tau_2 \simeq L/R_X$.

In the common case of S- and N-type oscillations the amplitude of SOS measured on the inductance L is

$$u_L \sim i_{x0}\beta \sim i_c(T)\beta(T) \tag{2}$$

where β is either αR_N (S-type oscillations) or $R_S^{(N)}$ (N-type oscillations).

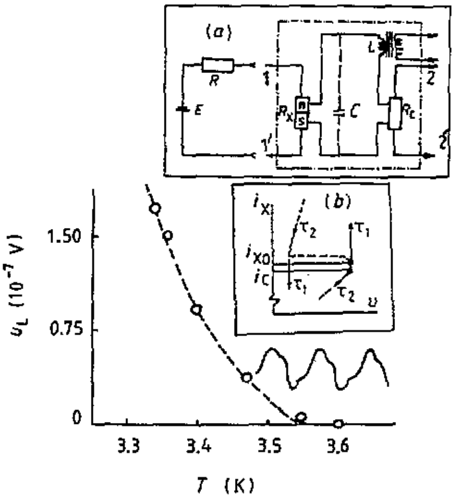

Figure 1. Temperature dependence of the S-type oscillation amplitude for an In–Bi sample. The broken curve is due to equation (3). The shape of the oscillations is also shown. Inset (*a*) presents the measuring circuit. S-type oscillations have been excited when the NS system R_X possesses an S-shaped *I–V* characteristic (inset (*b*)) and is connected in parallel to the capacitor *C* and the fixed-current source. The DC source *E* with the internal resistance *R* will be the fixed-current source for R_X when it is joined with terminals 1, 1′ and $R \gg R_X$, R_C (R_C is the calibrating resistor). In this method of connection, N-type oscillations cannot be generated. S-type oscillations are also absent with the connection described in figure 2 caption.

The following metal combinations were investigated: In–Bi (S-shaped *I–V* characteristics), Ta–(Sn + Pb) and Ta–In (N-shaped *I–V* characteristics). Altogether 50 contacts including those restored after degradation were used. About 40 of these exhibited SOs. In In–Bi systems the resistance R_X also includes the resistance of the mechanical contact. The test samples were chosen so that their ohmic resistances coincided in the order of magnitude with the resistance of the macroscopic normal component. The preparation technique of NS contacts with S-shaped *I–V* characteristics is the same as described elsewhere [4]. NS contacts with N-shaped *I–V* characteristics were prepared in the following way. Ta–(Sn + Pb) samples were made by passing a tantalum wire (0.05 mm in diameter; $i_c \simeq 0.5$ A; $T_c = 4.13$ K) through a solder drop or tightening the wire with a solder-coated steel screw. The Ta–In contacts were made by tightening a tantalum wire of the same diameter with an indium-coated steel plate.

Since according to the evaluation the generation region width expressed in terms of current ranges within $(10^{-6}\text{–}10^{-7})i_c$, the search for the region with our $i_c = 0.2\text{–}1$ A is not simple. The problem was solved by using a highly stabilized DC source ($\delta i/i \simeq 10^{-7}$) combined with a current scanner operating in a wide range of rates down to $\mathrm{d}i/\mathrm{d}t \simeq 5 \times 10^{-8}\ \mathrm{A\,s^{-1}}$.

To eliminate the effect that possible thermopower fluctuations in the leads have on the working point stability, transformer removal of the measured signal was employed. The primary (one-turn) inductance *L* of a miniature low-temperature transformer was 10^{-6} H. For typical values of R_X ($\simeq 10^{-2}\text{–}10^{-3}\ \Omega$) this should lead to SO frequencies of about $10^3\text{–}10^4$ Hz, which were observed in our experiment.

In fact the maximum frequencies of the described non-Josephson SOs are restricted by inductances close to the internal inductance in the best designed circuit (no less than 10^{-8} H). It should be recalled that for Josephson oscillations due to N-type non-linearity the 'inductive' constant is about $2e/\hbar$, which corresponds to oscillation frequencies of about 10^8 Hz [5]. It was verified by experiment that the SO frequency changed with *L*.

Finally, note that detailed measurements of the *I–V* non-linear region on such a scale (either figure 1(*b*) or the inset in figure 2) cannot be made by the static four-probe method since the main part of voltage is α^{-1} ($= 10^3\text{–}10^4$) times as high as the voltage of interest within the current range of about $10^{-6}i_c$.

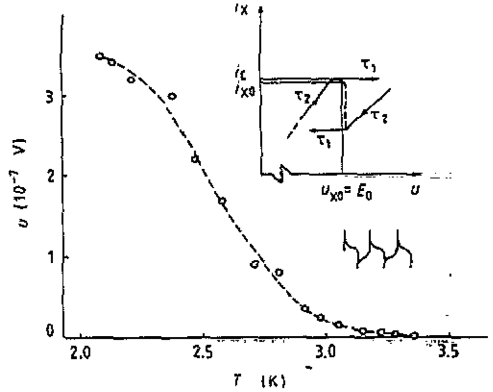

Figure 2. Temperature dependence of the N-type oscillations amplitude for a Ta–In sample. The broken curve is due to equation (2) and $R_n^{(N)} \simeq$ constant. The shape of oscillations is also shown. The same measuring circuit (figure 1(a)) is used. It exhibited N-type oscillations when the NS system has an N-shaped I–V characteristic (inset) and is connected in series to the inductance L and the fixed-voltage source. The same source E together with R_C forms the fixed-voltage source (with the internal resistance R_C) for R_X when it is connected to terminals 2, 2′ and $R_C < R_X$ (R is arbitrary). In this method of connection, S-type oscillations cannot be generated. N-type oscillations are also absent with the connection described in figure 1 caption.

3. Results and discussion

3.1. S-type oscillations

Under the generation conditions with the S-type non-linearity (the source is connected to terminals 1, 1′; see figure 1(a)), SOs were only observed in the In–Bi systems. The shape of oscillations and the temperature dependence of their amplitude near T_c of the In channel are shown in figure 1. Depending on the contact quality the total current through the system at which the critical current density in the In channel and SOs occurred was 0.2–0.5 A, $T - T_c$ being 0.5 K. The connection pattern, the working point control, a single value of the bias current and the temperature dependence of the SO amplitude point to an S-type non-linearity entailing SOs. In addition, the oscillation amplitude corresponds to the δR_X-value statically measured in our previous study [4]:

$$\delta R_X = \alpha R_N = 10^{-6}\text{–}10^{-7}\ \Omega.$$

If it is regarded that $\Delta(T) \sim (1 - T/T_c)^{1/2}$ and $i_c \sim 1 - (T/T_c)^2$, the temperature dependence of the oscillation amplitude over a fairly narrow temperature range, where the mean free path length can be considered as being constant, according to (2) should be described by the function

$$u \sim (1 - T/T_c)^2(1 + T/T_c) \qquad (3)$$

which corresponds to the broken curve in figure 1 with $T_c = 3.55$ K.

Thus, the data on SOs give independent evidence that, in In–Bi systems technologically similar to those investigated previously [4], the excess NS interface resistance due to the elastic scattering of sliding electrons exceeds the resistance of the superconductor in its normal state, causing predominating S-type non-linearity.

3.2. N-type oscillations

In the generation regime with the N-type non-linearity (the source is connected to terminals 2, 2′; see figure 1(a)), oscillations were observed in the systems with the SS interface in the pairs Ta–(Sn + Pb) and Ta–In (figure 2).

In the Ta–In systems, SOs were successively excited at currents corresponding to the critical values for both Ta and In, if the sample temperature was below T_c for indium.

The oscillation amplitude (figure 2) due to the resistive transition in indium (N-type non-linearity) was an order of magnitude less than the amplitude of the S-type oscillations (figure 1) in the In–Bi systems when a corresponding correlation between the excess NS interface resistance in the latter and the resistance of the contacting normal indium layer was considered.

The temperature dependence of the oscillation amplitude in Ta–In pairs should be described by equation (2) with $R_{\mathrm{In}}^{(\mathrm{N})} \simeq$ constant as observed (the broken curve in figure 2).

The excitation of SOs with the N-type non-linearity appearing in a jump-like resistive transition was repeatedly observed both under non-thermal destruction of the order parameter in the superconductor (the AC Josephson effect; generation in wide films [6]) and under thermal mechanisms of resistance jump (generation in microbridges [7] and superconductors connected in parallel [8]). We do not exclude that the many-times-repeated generation observed by us for numerous values of bias current is related to the successive formation of phase slip centres in the near-contact region of the superconductor (Ta).

4. Conclusions

Here we suggest a method for studying some electron characteristics of metals which form the NS system. It is based on the use of non-linearities in the resistivity of the NS contact which can lead to non-linear SOs. The SO parameters contain useful information on the nature of the non-linearity entirely determined by the electron characteristics of the metals forming the NS system. For the first time we realized and studied an S-type non-linearity due to the non-Andreev reflection of the electrons sliding along the NS interface.

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