“ Hot electrons ” and negative resistance of superconducting microbridges

J. Bok, C. Guthmann

► To cite this version:

J. Bok, C. Guthmann. “ Hot electrons ” and negative resistance of superconducting microbridges. Journal de Physique Lettres, 1978, 39 (12), pp.187-189. 10.1051/jphyslet:019780039012018700 . jpa-00231475

HAL Id: jpa-00231475

<https://hal.science/jpa-00231475>

Submitted on 1 Jan 1978

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Classification
 Physics Abstracts
 74.50

« HOT ELECTRONS » AND NEGATIVE RESISTANCE OF SUPERCONDUCTING MICROBRIDGES

J. BOK and C. GUTHMANN

Groupe de Physique des Solides de l'Ecole Normale Supérieure (*)
 24, rue Lhomond, 75231 Paris Cedex 05, France

(Reçu le 10 avril 1978, accepté le 2 mai 1978)

Résumé. — Nous présentons un modèle théorique permettant d'expliquer la résistance différentielle négative observée dans les microponts supraconducteurs. Ce modèle postule l'existence dans le pont d'un état hors équilibre où le gap supraconducteur est abaissé et où le courant critique diminue lorsque la tension augmente créant ainsi une résistance différentielle négative. Le modèle de *température effective* de Parker [6] est utilisé pour calculer la caractéristique courant-tension.

Abstract. — A model is presented to explain the differential negative resistance observed in superconducting microbridges. This model postulates the formation in the bridge of a non-equilibrium state where the superconducting gap is lowered and the critical current decreases as the voltage increases thus giving rise to a differential negative resistance. The *effective temperature* model of Parker [6] is used to derive the current-voltage characteristic.

1. Introduction. — We reported previously measurements of the I - V curves of superconducting thin film microbridges [1, 2]. Two different regimes were observed : the first close to T_c is well described by the so called *phase slip* process, the second appears at lower temperatures where the current voltage shows a negative slope (differential negative resistance) (D.N.R.) with a constant voltage generator. The dynamics of vortices in the bridge gave an explanation of the plateau observed with a constant current source, but gave no satisfactory description of the D.N.R.

In this letter, we propose another explanation based on the formation in the bridge of a domain where the quasiparticles are out-of-equilibrium and hence at a higher effective temperature than the lattice.

Aslamazov and Larkin [3] have already computed a I - V characteristic using a non-equilibrium electron function. Their expression failed to give the right temperature dependence of our experimental results. We propose to take into account the dissipation related to the acceleration and breaking of pairs in the bridge.

The physical picture is the following : we invoke the concept of quantum dissipation during the phase slip process, introduced by Rieger, Scalapino and

Mercereau [4]. In a one-dimensional phase-slip situation, the superconducting pairs are accelerated to their critical velocity, then break and the process repeats at the Josephson frequency. $v_j = 2eV/\hbar$ (where v is the applied voltage).

Part of the condensation energy is lost in each cycle. The power lost by this periodic dissipation is $\bar{I}_s(t) V$, where $\bar{I}_s(t)$ is the time average supercurrent. The recombination of pairs results in the emission of phonons of energy twice the superconducting gap. In a narrow bridge of thin film, a recombination phonon is far more likely to be reabsorbed by the superconductor with the creation of two quasiparticles than to escape from the superconductor [5]. We thus create a non-equilibrium region in the bridge, where the density of high energy phonons and of quasiparticles is higher than in thermal equilibrium at the ambient temperature T . The effective gap Δ^* in this region is smaller than $\Delta(T)$ and the critical current decreases, thus giving an explanation for the D.N.R. This additional superconducting dissipation means that a weak superconductor dissipates more power for a given voltage than in the normal state, because the total d-c current is given by

$$I = \frac{V}{R} + \bar{I}_s \text{ and the total dissipation by}$$

$$V \cdot I = \frac{V^2}{R} + \overline{V I_s},$$

(*) Laboratoire associé au C.N.R.S.

The normal dissipation V^2/R is heat or low energy phonons, whereas the quantum dissipation $\overline{VI}_s$ gives rise to high energy phonons and hence to a non-equilibrium superconducting region with a lower gap.

2. Development of the model. — The quantum dissipation has been calculated by Rieger *et al.* [4] using time-dependent Ginzburg-Landau equations. They computed numerically the superconducting current $I_s(t)$ at a given voltage, and hence the dissipation $\overline{VI}_s$. The d-c I - V characteristic has also been computed. It is given in figure 6 of reference [4]. A good analytical approximation to this characteristic is :

$$V = R[I(I - I_c)]^{1/2}. \quad (1)$$

We describe the out-of-equilibrium superconductor by the effective temperature T^* model due to Parker [6]. In a situation where the number of phonons of energy greater than, or equal to 2Δ is much greater than the number of phonons in thermal equilibrium, Parker proposes to characterize these high phonons by an effective temperature T^* , and to describe the superconductor with ordinary BCS theory at the temperature T^* . The critical current is given by the Ginzburg-Landau formula [7] :

$$I_c(T^*) = I_c(0) \frac{H_c(T^*)}{H_c(0)} \frac{\lambda_c(0)}{\lambda_c(T^*)}$$

where $t^* = T^*/T_c$, T_c is the critical temperature, H_c the critical field and λ_c the London penetration depth.

$I_c(T^*) = I_c(0) (1 - t^{*2}) (1 - t^{*4})^{1/2}$, for t^* of the order of unity :

$$I_c(T^*) = 4 I_c(0) (1 - t^*)^{3/2}. \quad (2)$$

Finally, we estimate the effective temperature T^* , by a balance equation (heat equation) :

$$\frac{\partial T^*}{\partial t} = D \frac{\partial^2 T^*}{\partial x^2} + \text{Generation} - \frac{T^* - T}{\tau_E}. \quad (3)$$

In the right member of equation (3), the first term represents the diffusion of high energy phonons, the second term the generation due to quantum dissipation, and the third term the decay due to inelastic phonon scattering and the escape of phonons from the bridge region. The bridge being of small dimensions ($\sim 1 \mu\text{m}$), we do not take into account variations inside the bridge and so neglect the first term. The second term is given by $\alpha \overline{VI}_s$, where α is a phenomenological coefficient representing the fraction of the quantum dissipation converted into the quasiparticles and high energy phonons system : the energy relaxation time τ_E has been estimated and measured for tin by many authors [8] and is of the order of

10^{-10} seconds. At very low voltages, where the Josephson period τ_J is larger than τ_E , the relaxation will occur quickly on the scale of τ_J and the equilibrium model at T^* is valid. Equation (3) reduces to :

$$T^* - T = \alpha \tau_E \overline{VI}_s; \quad \tau_J \gg \tau_E$$

or

$$t^* - t = \gamma VI_s \quad (4)$$

with

$$\gamma = \alpha \tau_E / T_c$$

γ is the only adjustable parameter of the theory.

Because $I_s = I - \frac{V}{R}$; equation (4) reads also :

$$t^* - t = \gamma \left[VI - \frac{V^2}{R} \right]. \quad (5)$$

By eliminating t^* and using equations (1, 2 and 5), we obtain the equation of the I - V characteristic :

$$V^2 = R^2 I \left\{ I - 4 I_c(0) \left(1 - t - \gamma VI - \gamma \frac{V^2}{R} \right) \right\}^{3/2}. \quad (6)$$

Equation (6) is valid only for $\tau_J \gg 10^{-10}$ s or $V \ll 20 \mu\text{V}$.

At high voltage, as discussed by Octavio *et al.* [8], the theory of Aslamazov and Larkin [3] is more appropriate. The heating is less effective, the effective temperature is reduced. For simplicity, we use the asymptotic value of formula (1), the temperature being that of the helium bath :

$$V = R \left(I - \frac{I_c}{2} \right). \quad (7)$$

This is valid for $V \gg 20 \mu\text{V}$ and is in agreement with the result of Rieger *et al.* [4] given by equation (1).

From equation (6), we can derive the slope dI/dV of the I - V curve at $V = 0$ and $I = I_c$. We find :

$$\frac{dI}{dV} (V = 0) = - 24 I_c^2(0) \gamma (1 - t)^2.$$

This model gives in fact a differential negative resistance. This negative slope goes to zero as T approaches T_c .

3. Comparison with experiment. — We reported experiments on tin microbridges in reference [2], showing a strong negative resistance. However, one has to be careful in analysing the precise shape of this region. Self-sustained relaxation oscillations appear in the negative resistance region. The shape of the I - V curve is completely altered in the negative region by detection of these oscillations. So direct comparison of equation (8) with experiment to obtain γ is difficult. The internal resistance of the

constant voltage source gives a minimum value for the experimental D.N.R. observed. From this internal resistance, we deduce a minimum value of γ : $\gamma > 5 \times 10^5 \text{ W}^{-1}$. We draw the I - V curves using equation (6) for low values of V , and equation (7) for high values of V (Fig. 1). The numerical values of T_c and $I_c(0)$ were taken from a sample of tin. The measurements were reported in reference [2] : $I_c(0) = 37.4 \text{ mA}$ and $T_c = 3.765 \text{ K}$, $I_c(T)$ followed equation (2) with a good precision. The two curves intersect for a value of V in the range of $10 \text{ } \mu\text{V}$ corresponding to experimental observation. For this value τ_E is greater than τ_I . The intersection of these two curves gives a value I_M for I minimum. Figure 2 shows the variation of I_M versus $T_c - T$ and a comparison with experimental values. The best fitting was obtained with $\gamma = 3 \times 10^6 \text{ W}^{-1}$. The variation with $T_c - T$

FIG. 1. — V - I characteristic deduced from equations (6) and (7) with $\gamma = 3 \times 10^6 \text{ W}^{-1}$.

FIG. 2. — I minimum versus $T_c - T$. The crosses are the experimental points, and the full line the calculated curve with $\gamma = 3 \times 10^6 \text{ W}^{-1}$.

is surprisingly good, although our procedure underestimates I_M .

In conclusion, we think that this simple model gives a good explanation for the D.N.R. observed in small superconducting microbridges. A more sophisticated theory is needed to describe the region where τ_I is of the order of τ_E .

Acknowledgments. — The authors thank Dr. A. Libchaber for very helpful suggestions and comments.

References

[1] GUTHMANN, C., MAURER, J., BELIN, M., BOK, J. and LIBCHABER, A., *Phys. Rev.* **11** (1975) 1909.
 [2] GUTHMANN, C., MAURER, J., BOK, J. and LIBCHABER, A., *Proceedings of L. T 14* (1975).
 [3] ASLAMAZOV, L. G. and LARKIN, A. I., *Zh. Eksp. Teor. Fiz.* **70** (1976) 1340.
 [4] RIEGER, T. J., SCALAPINO, D. J. and MERCEREAU, J. E., *Phys. Rev. B* **6** (1972) 1734.
 [5] SAI-HALASZ, G. P., CHI, C. C., DENESTEIN, A. and LANGENBER, D. N., *Phys. Rev. Lett.* **33** (1974) 215.
 [6] PARKER, W. H., *Phys. Rev. B* **12** (1975) 3667.
 [7] SKOCPOL, W. J., *Phys. Rev. B* **14** (1976) 3, 1045.
 [8] OCTAVIO, M., SKOCPOL, W. J. and TINKHAM, M., *Phys. Rev. B* **17** (1978) 1, 159.
 [9] VERNON, F. L. and PEDERSEN, R. J., *J. Appl. Phys.* **39** (1968) 2661.