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Measurements of the dc Josephson current in light-sensitive junctions

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The temperature dependence of the light-induced dc Josephson current in asymmetric (Pb-CdS-In) and symmetric (In-CdS-In) tunnel junctions has been measured. A rather simple theoretical model, in the framework of the proximity effect, has been adopted. A reasonable agreement with the experimental data has been found giving a consistent picture of the whole behavior of such light-sensitive structures.

I. INTRODUCTION

Superconducting tunnel junctions using a semiconductor film as tunneling barrier were realized by Giaever for the first time in 1968.[1-4] In this context, junctions employing a light-sensitive material (cadmium sulphide) as barrier layer deserve particular attention, because it is possible to realize tunneling structures with a "light-adjustable" effective barrier. The main features of such junctions may be summarized as follows: at low temperature and before illumination they show high-tunnel-resistance values, whereas under light exposure a decrease of the resistance is observed. The degree of the variation depends, among other factors, upon the light-exposure time. At liquid-helium temperature the low-resistance state is stable, for all practical purposes. Moreover, because of the light-sensitive character of the barrier, it is possible to increase the tunnel probability by suitable illumination and thereby, induce dc Josephson current even though such current is absent in dark conditions. To recover the original conditions one may either warm the structures to high temperature (about 100 K) and then recool them, or apply a suitable voltage pulse to the junctions. The difference between the actual mechanism involved in the two methods is not yet clear.

These structures have been investigated by many authors[5-18] also using other semiconductors;[19,20] however, at the present time, light-induced Josephson current has been observed through CdS barriers only.

In this paper experimental results concerning the temperature dependence of light-induced dc Josephson current, I_J^L, in symmetrical (In-CdS-In) and asymmetrical (Pb-CdS-In) junctions are reported.

Although these structures share a number of features with oxide junctions, an interpretation of their light-sensitive behavior in terms of the lowering of a rectangular barrier in a superconductor-barrier-superconductor sandwich appears to be inappropriate. In fact, this picture is in contrast with two important experimental facts: (i) Typically, the semiconductor film thickness s, which allows light-induced Josephson current, strongly depends on the superconductors employed as electrodes;[8,10] in fact, for this purpose suitable thicknesses are: in Pb-Pb junctions $s \simeq 200$ Å, in Pb-In $s \simeq 400$ Å, and in In-In $s \simeq 800$ Å; (ii) The temperature dependence of the light-induced Josephson current markedly deviates from that calculated by Ambegaokar and Baratoff[21] for oxide barrier junctions. The former circumstance strongly suggests that the superconductor-semiconductor interfaces play a fundamental role in limiting the tunneling current. The explanation of the experimental results is probably related to the In-CdS contact. It is well known[22] that interdiffusion between In and CdS occurs, leading to a stable ohmic contact; consequently, the interface may be, at least approximately, considered as a degenerate layer. On the contrary, at the Pb-CdS boundary, due to the difference in the work functions, a potential barrier is built in. From such peculiarities of the two contacts it follows that in Pb-CdS-In junctions a highly asymmetric barrier exists that after illumination, should be essentially confined to the Pb-CdS boundary. This implies that the semiconductor film thickness should not play a dramatic role on the tunneling current.[10] In the case of the In-CdS-In structure, the barrier is symmetrical and the junction behavior is bulk rather than surface (contact) dominated. This circumstance leads to a very small barrier height after illumination.

Since the transport properties of the degenerate layer at the In-CdS interface may be approximately considered as metal-like, it seems reasonable to discuss the experimental data in terms of proximity effect.

A similar approach, although in a quite different physical situation, was used by Seto and Van Duzer[23,24] to interpret I_J vs T and I_j vs s dependences of Pb-Te-Pb junctions. Aside from their interesting results, no further work on this subject is available in the literature, to our knowledge. On the other hand, much theoretical and experimental work has been developed on proximity-effect tunnel junctions,[25] leading to a reasonable assessment of this topic.

II. JUNCTION FABRICATION AND EXPERIMENTAL TECHNIQUES

The junctions are realized by conventional thin-film deposition technique. The metal films are evaporated from current heated Mo boats at a pressure in the range of 10^{-6} Torr in a turbomolecular pump system, and deposited on microscope glass slides held at room temperature. The selected geometry is obtained using stencil masks patterned by conventional photoresist techniques and a movable substrate holder. The thickness of the metal films ranges from 500 to 5000 Å. The metals used, Pb and In, have an initial purity of 99.999%. After the metal-base layer evaporation, the semiconductor (CdS ultrapure powder, Alfa Inorganics) deposition is realized by evaporation from a single source onto the substrate at room temperature. Before deposition, the semiconductor is preheated for a few minutes. During the evaporation the pressure is about $(6-8)\times 10^{-6}$ Torr, and the deposition rate is approximately 10 Å $\sec^{-1}$. After the barrier deposition pure oxygen is introduced into the bell jar at a pressure of about 500 Torr to fill the pinholes occurring in the thin CdS films.[2] Although in the literature it is reported that pinholes occur even in thick films ($\approx$1000 Å), in the present experiments the oxidation seems to be useful only for film thicknesses $s < 500$ Å; for thicker films the junctions are pinhole free and the oxidation step is avoided. This point is relevant, considering that the oxygen atmosphere can modify the surface properties of the semiconductor. The metal counterelectrode is evaporated with the same procedure as that for the base layer. The two electrodes cross each other at right angles. The junction areas are about 0.2×0.4 mm^2. All fabrication steps are made without breaking the vacuum. With this procedure followed, junctions exhibiting a ratio $R_{NN}^{\text{dark}}/R_{NN}^{\text{light}}$ up to about 10^4 have been obtained. Moreover, it is worth pointing out that the use of In electrodes leads to a significant improvement in the properties of the junctions; in particular, a longer lifetime and a rather good cyclability have been obtained.[10]

The junctions are tested in a He^4 cryostat down to a limiting temperature of about 0.9 K. The Josephson current was measured following the technique reported in Ref. 26; the applied magnetic field was provided by a pair of Helmholtz coils assembled in the cryostat (1 G $\simeq$ 6 mA); a quartz iodine lamp was used as optical input. The whole cryostat was surrounded by two coaxial μ-metal shields. It is worth noting that all data reported in this paper refer to junctions showing I-V characteristics clearly exhibiting the gap structure and no zero-bias current in dark conditions. This guarantees the absence of any other pair transfer mechanism but through the illuminated semiconductor. Ad hoc measurements have also shown the absence of any appreciable time decay of the light-induced Josephson current.

Fourteen measurements of I_J^L vs T on Pb-CdS-In and In-CdS-In structure are considered. After each run, measurements of I_J^L versus the external magnetic field H_e have also been performed. The last results almost completely reproduce Fraunhofer-like patterns, which guarantees (within the limits of the light-exposure levels considered) that one is dealing with "small" junctions. This is an important point, since a transition to "large" junction behavior by long enough light-exposure time can occur, as demonstrated in Ref. 11.

A typical experimental I_J^L vs H_e curve (the reported data are relative to sample 2; see Table I) is reported in Fig. 1. This dependence exhibits only slight deviations from a Fraunhofer-like pattern. There are present a small superimposed modulation and an enhancement of the first secondary maxima, which suggests[12,15] the occurrence of a current density peaking at the edges of the junction. This assumption, on the other hand, is physically realistic since higher illumination is expected at the junction edges not covered by the top film layer.

III. RESULTS AND DISCUSSION

In order to render this section self-contained, let us outline some basic theoretical considera-

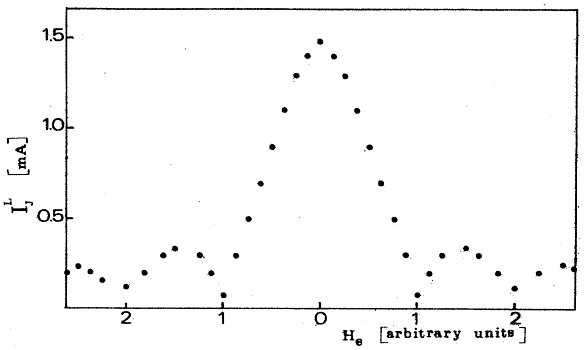

FIG. 1. Magnetic field dependence of the light-induced dc Josephson current of a Pb-CdS-In junction. The data refer to sample 2; see Table I.

tions that will provide a plausible explanation of the experiments and justify the choice of a suitable fitting.

A. Theoretical background

Following the arguments given in the Introduction, a simple one-dimensional model of the junction can be considered in which proximity effect occurs at the In-CdS interface. In this scheme the Pb-CdS-In and In-CdS-In sandwiches can be regarded as superconductor-(1)-barrier-normal-layer-superconductor-(2) and superconductor-normal-layer-barrier-normal-layer-superconductor structures, respectively. The present treatment of these proximity-effect structures essentially follows the approach given in Ref. 27.

The maximum dc Josephson current has been deduced in the framework of the Ginzburg-Landau theory by de Gennes[28]:

$$I_J \propto F^R(T)F^L(T)\,, \tag{1}$$

where F^R and F^L are the condensation amplitudes on the two sides of the barrier. In the asymmetrical case, assuming that the thickness of the In film, d_S, is of the order of its coherence length ξ_S, the condensation amplitude is given by[29]

$$F_S^R(x,T) = F_{\rm BCS}^R(T)\cos[k_S(x-d_S)]\,, \tag{2}$$

where

$$k_S = (2/\pi)(1/\xi_S)(T_{cS}/T-1)^{1/2} \tag{3}$$

and T_{cS} is the critical temperature of the superconductor.

The condensation amplitude induced in the finite normal-metal layer is written, in the "dirty-limit" hypothesis,

$$F_N(x,T) = F_N(0^-,T)\frac{\cosh[k_N(x+d_N)]}{\cosh(k_N d_N)}\,, \tag{4}$$

where d_N is the normal-layer thickness, $x=0$ is the normal-metal-superconductor plane of contact, and $k_N^{-1} \simeq \xi_N$ is the coherence length in the normal layer, assuming that $T_{cN} \ll T$.

By using the de Gennes boundary conditions for the condensation amplitudes at the N-S interface[30] and taking into account that $F^L(T)$ essentially coincides with the spatially independent $F_{\rm BCS}^L(T)$, the maximum dc Josephson current is given by[31]

$$I_J(T) \propto \frac{F_{\rm BCS}^L(T)F_{\rm BCS}^R(T)}{\cosh(k_N d_N)[1+\tan^2(k_S d_S)]^{1/2}}\,. \tag{5}$$

Equation (5) can be written in a form in which the temperature dependence of the terms involved appears explicitly. The coherence length in the superconducting layer is

$$\xi_S = \left(\frac{\hbar v_{FS} l_S}{6\pi k_B T}\right)^{1/2} = \xi_{S0} t^{-1/2}\,, \tag{6}$$

where v_F is the Fermi velocity, l is the electron mean free path, and t is the reduced temperature of the sandwich. Within the framework of the free-electron model, the coherence length in the degenerate layer is

$$\xi_N = \left(\frac{\hbar^3 \mu}{6\pi k_B T e m^*}\right)^{1/2} (3\pi^2 n)^{1/3} = \xi_{N0} t^{-1/2}\,, \tag{7}$$

where μ is the electron mobility, m^* is the electron effective mass, and n is the carrier density.

Using Equations (6) and (7), relation (5) becomes

$$I_J(t) \propto F_{\rm BCS}^L(t')F_{\rm BCS}^R(t)/\cosh\left(\frac{d_N}{\xi_{N0}}t^{1/2}\right)\left[1+\tan^2\left(\frac{2}{\pi}\,\frac{d_S}{\xi_{S0}}(1-t)^{1/2}\right)\right]^{1/2}, \tag{8}$$

where t' is the Pb reduced temperature.

An obvious extension of the above procedure leads to the following expression for the temperature dependence of the dc Josephson current in the symmetrical (In-CdS-In) case:

$$I_J(t) \propto \frac{F_{\rm BCS}^2(t)}{\cosh^2(k_N d_N)[1+\tan^2(k_S d_{SL})]^{1/2}[1+\tan^2(k_S d_{SL}\rho)]^{1/2}}\,, \tag{9}$$

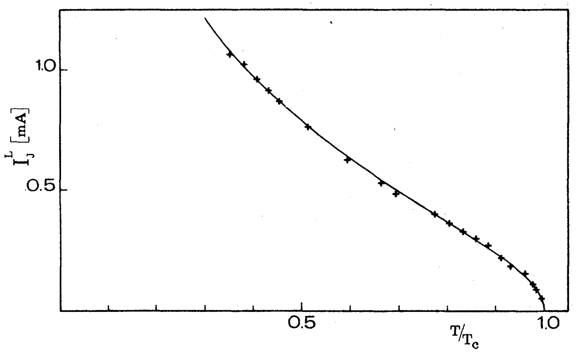

FIG. 2. Temperature dependence of the light-induced dc Josephson current in a Pb-CdS-In junction. Experimental data are compared with the theoretical behavior (solid curve) predicted by Eq. (8) using $d_N/\xi_{N0}=3.48$ and $d_S/\xi_{S0}=1.67$.

where $\rho = d_{SR}/d_{SL}$. It is worth noting that in deriving Eq. (9), the junction is considered as strictly symmetric, i.e., with interfaces described by the same values of the parameters.

B. Experimental results and discussion

A typical temperature dependence of the light-induced dc Josephson current for a Pb-CdS-In junction is shown in Fig. 2. The data clearly exhibit two main features: a sudden increase of the current near T_c, followed by a nonsaturating behavior at low temperatures. The experimental I_J^L vs T for an In-CdS-In junction is shown in Fig. 3; an analogous nonsaturating behavior is exhibited, but in this case, the dependence near T_c is essentially linear.

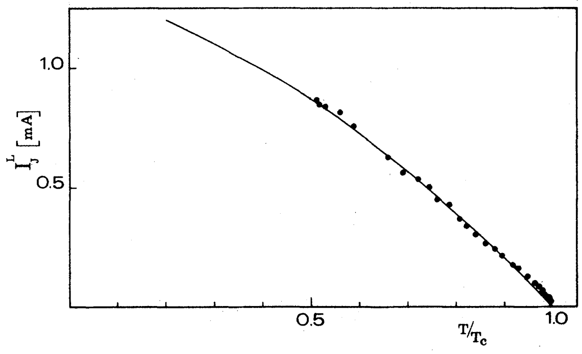

FIG. 3. Temperature dependence of the light-induced dc Josephson current in an In-CdS-In junction. Experimental data are compared with the theoretical behavior (solid curve) predicted by Eq. (9). The best-fitting parameters are $d_N/\xi_{N0}=1.45$ and $d_S/\xi_{S0}=0.26$; the experimentally determined ratio between the metal film thicknesses is 2.1.

The experimental data relative to the asymmetrical and symmetrical structures are characterized by a common feature, both showing, near T_c, a behavior similar to that calculated by Ambegaokar and Baratoff[21] for oxide barrier junctions. At lower temperatures their behavior markedly deviates from that expected for an oxide structure, and, in particular, no saturation level is attained.

The theoretical curves, reported in Figs. 2 and 3, have been calculated following Eqs. (8) and (9). Only measurements of I_J^L vs T and of the superconducting film thicknesses have been performed on the present structures, so that the quantities d_N/ξ_{N0} and d_S/ξ_{S0} are considered as free parameters. The values of these parameters have been determined by a least-mean-squares fit to the experimental data. It is worth noting that the use of a parametric fit is essential because some of the quantities involved are not accessible to direct measurement. An overall coefficient is also introduced in the fitting of each set of experimental data; these coefficients are unessential for the interpretation of the data, but they account for a normalization in Eqs. (8) and (9), which gives the maximum critical current versus T, apart from a factor.

The existence of other pairs of values for the parameters that give a better fit to the experimental data has been excluded by performing a random search on the whole region of the physically plausible values. All the sets of experimental data have been analyzed using the above procedure; in all cases, good agreement has been found between the experimental and theoretical curves.

By varying the illumination time, various levels of critical current have been induced in the same sample. Measurements of I_J^L vs T have been performed for each level obtained. A typical behavior of a Pb-CdS-In junction for two illumination levels is shown in Fig. 4. The results obtained by fitting the experimental data are reported in Table I. Some relevant features emerging from these results deserve further comment. As it is physically plausible, the parameter d_S/ξ_{S0} is unaffected by the light exposure; in fact, the values obtained show only a small scattering (not exceeding 3%) in spite of the drastic change (up to a factor of 8) in the critical current. The effect of the light input appears to be observable only in the critical current level and in the value obtained for d_N/ξ_{N0}, which increases with the illumination level. This trend has been observed in all cases except in the fourth illumination level of sample 2, see Table I. It is worth noting that no interpretation of the behavior of this parameter with light exposure can be attempted until an independent measurement of the quantities involved

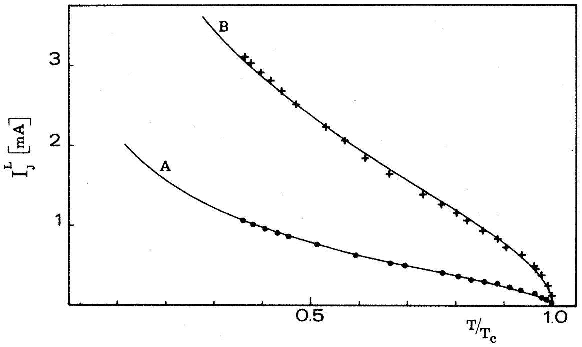

FIG. 4. Temperature dependence of the dc Josephson current at two different values of light-induced critical current in the same sample. The experimental data are compared with the theoretical behavior (solid curve). The fitting parameters are reported in Table I (sample 2, third and fourth light level).

TABLE I. Junction parameters related to different light-induced current levels.

Sample	Light level	d_N/ξ_{N0}	d_S/ξ_{S0}	$[I_J^L(0)]_{th}$ (μA)
1	1	1.49	0.87	87
	2	1.52	0.92	476
	3	2.10	0.88	727
2	1	2.67	1.59	2925
	2	2.88	1.59	5025
	3	3.48	1.67	6664
	4	3.06	1.61	14713

or a detailed model of the sandwich becomes available.

IV. CONCLUSIONS

Detailed experiments have been performed on the temperature dependence of both symmetrical (In-CdS-In) and asymmetrical (Pb-CdS-In) light-sensitive Josephson junctions which contribute to the understanding of the behavior of these structures.[32] An exhaustive theoretical interpretation of the data appears to be extremely difficult. A rather simple model has been adopted that allows a reasonable correlation among the experimental data. In spite of the crudeness of this approach, the results strongly suggest that the behavior of light-sensitive junctions can be well explained in the framework of the proximity effect.

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[1] I. Giaever, Phys. Rev. Lett. 20, 1286 (1968).
[2] I. Giaever and H. R. Zeller, J. Vac. Sci. Tech. 6, 502 (1969).
[3] I. Giaever and H. R. Zeller, Phys. Rev. B 1, 4278 (1970).
[4] I.Giaever and H. R. Zeller, Physica 55, 455 (1971).
[5] R. C. Dynes and T. A. Fulton, Phys. Rev. B 3, 3015 (1971).
[6] M. Russo, in *Proceedings of the Congresso di Cibernetica* (Casciana Terme, Italy, 1971), Vol. 1, p. 424.
[7] J. Josefowicz and H. J. T. Smith, J. Appl. Phys. 44, 2813 (1973).
[8] A. Barone, P. Rissman, and M. Russo, Rev. Phys. Appl. 9, 73 (1974).
[9] C. J. Magee and M. Russo, Vuoto Sci. Tecn. 7, 4 (1974).
[10] A. Barone and M. Russo, Phys. Lett. A 49, 45 (1974).
[11] A. Barone, G. Paternò, M. Russo, and R. Vaglio, Phys. Lett. A 53, 393 (1975).
[12] A. Barone, G. Paternò, M. Russo, and R. Vaglio, in *Proceedings of the Fourteenth International Conference on Low Temperature Physics*, edited by M. Krusius and M. Vuorio (North-Holland, Amsterdam, 1975), Vol. 4, p. 88.
[13] M. Mehbod, W. Thijs, and Y. Bruynseraede, Phys. Status Solidi A 32, 203 (1975).
[14] T. Tsuboi, Phys. Lett. A 56, 472 (1976).
[15] A. Barone, G. Paternò, M. Russo, and R. Vaglio, Phys. Status Solidi A 41, 393 (1977).
[16] M. Russo, Phys. Lett. A 61, 191 (1977).
[17] A. Barone, G. Paternò, M. Russo, and R. Vaglio, Zh. Eksp. Teor. Fiz. 74, 1483 (1978).
[18] M. Russo and R.Vaglio, Phys. Rev. B 17, 2171 (1978).
[19] G. Lubberts and S. Shapiro, J. Appl. Phys. 43, 3958 (1972).
[20] P. Rissman, J. Appl. Phys. 44, 1893 (1973).
[21] V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. 11, 104(E) (1963).
[22] R. H. Bube, *Photoconductivity of Solids* (Wiley, New York, 1963).
[23] J. Seto and T. Van Duzer, Appl. Phys. Lett. 19, 488 (1971).
[24] J. Seto and T. Van Duzer, in *Proceedings of 13th International Conference on Low Temperature Physics*,

edited by K. D. Timmerhaus, W. J. O'Sullivan, and E. F. Hammel (Plenum, New York, 1972), Vol. 3, p. 328.

[25] A. Gilabert, Ann. Phys. 2, 203 (1977), and references reported therein.

[26] E. P. Balsamo, A. Barone, G. Paternò, P. Rissman, and M. Russo, Phys. Rev. B 10, 1881 (1974).

[27] N. L. Rowell and H. J. T. Smith, Can. J. Phys. 54, 223 (1976).

[28] P. G. de Gennes, in *Superconductivity of Metals and Alloys* (Benjamin, New York, 1966).

[29] N. R. Werthamer, Phys. Rev. 132, 2440 (1963).

[30] P. G. de Gennes, Rev. Mod. Phys. 36, 225 (1964).

[31] F. Andreozzi and M. Russo (unpublished).

[32] A. Barone, M. Russo, and R. Vaglio, AIP Conf. Proc. 44, 340 (1978).