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Finite size arrays of proximity effect bridges (*)

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Résumé. — Nous avons étudié des réseaux 20×20 bidimensionnels de jonctions à effet de proximité en Au/In. La résistance statique à l'origine en fonction de la température montre une transition à T_c (In) et une autre à T_c^* , inférieure à T_c (In), mais supérieure à T_c (Au/In). A T_c^* , le système passe dans un état où il n'y a plus de résistance même s'il est composé de jonctions SNS. Chaque région de température est caractérisée par différentes formes de courbes courant-tension.

Abstract. — We have studied devices consisting of 20×20 two dimensional arrays of proximity effect junctions of Au/In. The DC resistance at the origin as a function of temperature shows a transition at T_c (In) and another one at T_c^* , below T_c (In) but above T_c (Au/In). At T_c^* the devices go into a resistanceless state even though they are composed of SNS junctions. Different shapes of the current-voltage curves characterize each temperature region.

1. **Introduction.** — In the last years attention was paid to interaction between individual junctions that show themselves Josephson type effects. Rosenblatt and coworkers [1] worked on a possible collective interaction that may appear in a lattice of junctions made of spheres of Nb pressed together. They proposed that the weak Josephson coupling between Nb spheres gives rise to a sort of dynamic phase transition from a state of phase disorder to a state of phase coherence at a temperature T_c^* lower than T_c (Nb).

Work done on granular films of NbN [2] and AlGe [3] may also be interpreted as evidence of a phase transition occurring well below T_{cG} of each grain. Gubser and Wolf [2] explained their results as a transition from a phase incoherent state to a coherent one coming from Josephson coupling between grains. The problem has been recently studied theoretically by Barnes [4] and by Giovannini and Weiss [5]. The main inconvenience with pressed spheres and granular films consists in the irregularity of the lattice formed by those systems.

More regular one dimensional lattices were done by either proximity effect bridges [6] or lamellar eutectic alloys [7]. The goal of those experiments was mainly the study of the transport properties of the samples themselves. The analyses were done based on the de Gennes' model [8] for the dirty limit and the Kulik's model [9] for the clean limit. Dupart *et al.* [10] made a one dimension band structure

calculation, using the Kulik's model to describe a single junction, to account for their observations in the Pb-Sn eutectic alloy. A recent paper by Spencer *et al.* [7] on Pb-Cd laminar eutectics shows the complexity of the behaviour of these samples, where flux pinning and flux flow are reported to show up in the transport properties.

With the aim of studying possible collective effects coming from Josephson coupling we investigated finite two dimensional arrays of proximity effect bridges made of Au/In. We report here results concerning the properties of arrays composed of 20×20 squares of In separated by Au/In.

2. **Experimental.** — The samples were made by application of a projection photolithographic technique developed by us [11]. A film of 230 Å of gold is evaporated on a sapphire substrate. A coat of photoresist (P.R.) AZ-1350 is applied on it and a mask having the design of figure 1a projected. The unprotected regions of the film are chemically etched with a solution composed of

1 part of a mixture made of
 400 g KI
 100 g I₂
 400 ml distilled H₂O
 40 parts distilled H₂O.

This leaves in the middle of the substrate a film of gold having the replica of the mask reduced by a factor given by the objective chosen ($16 \times$ or $40 \times$). After

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Fig. 1. — *a*) Mask projected onto the Au film. The blacks correspond to the regions that will stay after etching of the Au film and will become the Au/In regions when the In film is evaporated. The whites are the regions unprotected by the photoresist and etched away in the Au film. They become the In squares when the second evaporation is made. *b*) Mask projected onto the In film that covers the Au design. The blacks are the protected regions and the whites

the regions to be etched. There are two horizontal contacts for the current, and four vertical ones for the voltage. The array is placed in the middle. *c*) Photograph made of the R16G sample ($400\times$) after repeated recycling between low and room temperature. *d*) Schematic drawing showing the dimensions of the arrays presented in this work.

removing the P.R. with pure acetone a second evaporation is made of $500\text{ \AA}$ of In. The samples are recoated with P.R. and the mask shown in figure 1*b* projected with an objective $4\times$. The unprotected regions are chemically etched with a solution composed of

2 parts NO_3H (67 %)
1 part ClH (32 %)
6 parts distilled H_2O .

The resulting sample is shown in figure 1*c* for a reduction $16\times$. In figure 1*d* we give the dimensions for the R16G and R40G, which are the two examples that we want to discuss here.

The mean free path for each material was measured in films evaporated simultaneously with the samples.

For the film of gold we got $l_{\text{FILM}}(\text{Au}) \approx 0.04\text{ }\mu\text{m}$ and for the indium $l_{\text{FILM}}(\text{In}) \approx 0.6\text{ }\mu\text{m}$.

The devices were mounted inside a variable temperature cryostat and four terminal resistance and current-voltage (I - V) measurements done [12].

3. Results. — In figure 2*a* we show the variation of the DC resistance at the origin as a function of temperature for the R16G sample. One can observe that there are two different transitions, one occurring at about $T_c(\text{In})$ and another one occurring at a lower temperature T_c^* . This second T_c^* is found to be at a higher T than the one expected for the regions Au/In. In figure 2*b* we show the variation of the DC resistance

Fig. 2. — *a*) The DC resistance at the origin as a function of temperature showing the transitions at $T_c(\text{In})$ and T_c^* for the R16G sample. The results are similar for the R40G. *b*) *Idem* for the sandwich Au 220 Å/In 510 Å.

at the origin of a sandwich of Au (220 Å)/In (510 Å) (sample C16G).

We were able to determine T_c^* within 0.005 K from the critical current I_c vs. T curves (Fig. 3) which corresponds to an $I_c < 0.5 \mu\text{A}$. These results show clearly two things. First $T_{c\text{Au/In}}$ (C16G) = 1.705 K is below T_c^* (R16G) = 1.795 K and T_c^* (R40G) = 1.820 K. Second, T_c^* (R40G), the array for which the distance between In squares is shorter, occurs at a higher T

Fig. 3. — Variation of the critical current I_c versus temperature for the R16G sample. The results are similar for the R40G sample. The insert shows the situation for the sandwich Au/In.

than that of T_c^* (R16G), the array for which the separation is larger.

These observations imply that the arrays go into a resistanceless state at a temperature T_c^* before the Au/In regions become superconducting. The shorter the separation distance between In squares the higher T_c^* .

In figure 4 we show the V - I characteristics as a function of temperature. Below $T_c(\text{In})$ the V - I curves are ohmic with reducing slope. When the jump in T_c^* starts the characteristics are ohmic only very near the origin. Finally below T_c^* a resistanceless state is observed giving the V - I curves shown in figure 4a for the R16G sample.

When $T_c(\text{Au/In})$ is approached, the V - I curves for the R40G sample show a different behaviour (Fig. 4b). We believe the same happens with the R16G but it was outside the range of our equipment to measure its V - I characteristic lower than 1.68 K due to the fast increase of I_c with lowering T for a sample of those dimensions.

Fig. 4. — *a*) Voltage versus current for different temperatures sample R16G. *b*) *Idem* sample R40G. Notice the change in the V scale and the different behaviour below $T_c(\text{Au/In})$.

4. Discussion. — We will discuss first the way the DC resistance R at the origin approaches T_c^* . Our results resemble those of Gubser and Wolf [2] where the $V = V(I, T)$ curves are described by an expression based on scaling laws of critical phenomena suggested to them by Pr. Y. Imry.

We found that our R vs. T curves can be described within 10 % error when $T \rightarrow T_c^*$ by the formula

$$R = R_0 \frac{L}{W} \left(\frac{T - T_c^*}{T_c^*} \right)^\alpha \quad (T > T_c^*) \quad (1)$$

where R_0 is a square resistance equal to 0.82Ω , L is the length and W the width of a section of the Au/In region shown in figure 1d, and α a critical exponent equal to (0.85 ± 0.15) . In a similar way the V - I curve for $T = T_c^*$ can be described by a relation of the type

$$V = AL \left(\frac{I}{W} \right)^\beta \quad (T = T_c^*) \quad (2)$$

where V is measured in μV , I in μA , A is a constant equal to $0.011 [(\mu V/\mu m)]/[(\mu A/\mu m)^\beta]$, and β a second critical exponent equal to (1.58 ± 0.30) .

Equations (1) and (2) are particular cases of a more general expression that describes the V - I characteristics above T_c^*

$$V = BI^\beta \chi \left(\frac{\Delta T}{T_c^*} \right) \quad (T > T_c^*) \quad (3)$$

Fig. 5. — Gubser and Wolf's [2] type analysis of the approaching to T_c^* of the DC resistance at the origin (top); voltage versus current at $T = T_c^*$ (middle); and χ function plotting for different $(T - T_c^*)$ above T_c^* (bottom).

where χ is a function having the specific limits [2]

$$I \rightarrow 0 \quad \chi \rightarrow \left(\frac{\Delta T}{T_c^*} \right)^\alpha \quad (4a)$$

$$(T - T_c^*) \rightarrow 0 \quad \chi \rightarrow 1 \quad (4b)$$

and γ , the third critical exponent, is found to be equal to $(\beta - 1)/\alpha = (0.71 \pm 0.30)$. The results of this type of analysis are shown in figure 5, where one sees that in fact the data show a clear tendency to fall into an universal curve. We want to remark that the determination of α , β and γ , can be made with a much higher precision for each sample. But at present we preferred an overall view giving the general tendencies on the way the transition T_c^* is approached from above.

In the temperature region between T_c^* and T_c (Au/In) our samples are formed by SNS junctions, that can be considered as being in the clean limit (l FILM (In) = $0.6 \mu m$). In fact attempts to fit de Gennes' theory proved unsuccessful.

Bardeen-Johnson (BJ) [9, 10] calculated the variation of the critical current J_c as a function of T . Their result well below T_c (In) can be written as

$$J_c = J_0 \exp - [2 d^* k_B / \xi_0 \Delta(T = 0)] T \quad (5)$$

where

$$J_0 = 6 n_e \hbar e / md^* \quad (6)$$

and the distance $d^* = d_N + \pi \xi_0$, where d_N is the width of the normal region (Au/In) between two In squares. When the temperature dependence of the gap is taken into account [10], d^* is given by

$$d_N + \pi \xi_0 [\Delta(T = 0) / \Delta(T)]$$

and the BJ expression (Equations (5) and (6)) is still valid. Using the values of $[\Delta(T = 0) / \Delta(T)]$ for a BCS superconductor [13] it is possible to show that the correction is small in our case.

Figure 6 shows a plot of I_c versus T for both samples, together with the BJ prediction for 20 single junctions in parallel calculated using equation (5) and [14] ξ_0 (In) = $2600 \text{ \AA}$, $\Delta(0) = 1.82 k_B T_c$ (In); T_c (In) = 3.407 K and $n_e = 11.5 \times 10^{28} \text{ electrons/m}^3$.

It can be graphically seen that the experimental results do not follow the BJ temperature dependence prediction near T_c^* , and for the R16G one observes a larger current than allowed by BJ while for the R40G is smaller. Well below T_c^* our data could be fitted to $I_0 \exp(-\beta T)$: with β (fit) $> \beta$ (BJ). This has been interpreted in linear arrays [6] as coming from the fact that l (FILM) $< d_N$, which is the case of our samples. The BJ theory applies only to situations where l (FILM) $> d_N$, and β and J_0 (Eq. (6)) may change otherwise. But we should remark that near T_c^* we observe deviations from an exponential fitting.

Fig. 6. — a) Variation of the critical current versus temperature between T_c^* and T_c (Au/In) for the R16G sample. b) *Idem* for the R40G sample where the solid line shows the prediction of 20 parallel junctions that follow Bardeen Johnson theory.

5. Conclusions. — We have shown the V - I characteristics of 20×20 lattices of proximity effect bridges. These samples show two different transition temperatures in their DC resistance at the origin vs. temperature curve, one occurring at T_c (In) and the other at T_c^* above T_c (Au/In). Below T_c^* the samples go into a resistanceless state and are composed of a lattice of SNS junctions. Each temperature region is characterized by a particular shape of the V - I curve. These curves resemble those of granular films permitting us to make the same type of formal analysis as Gubser and Wolf [2] did for their NbN films [15].

But the resemblance cannot be pushed further at the moment unless a theory valid for proximity effect bridges is constructed.

The examples shown in this work look to us as the best to present the general features of the temperature behaviour. But perhaps it will be convenient to recall that T_c^* can be changed also by changing the thickness of the films. For example a $40 \times$ sample made on a film of $240 \text{ \AA}$ of gold and $650 \text{ \AA}$ of indium shows a transition at $T_c^* = 3.25 \text{ K}$, while a sandwich of Au/In made simultaneously shows a single transition at T_c (Au/In) = 1.62 K . This sample has similar V - I curves for each temperature region as the ones discussed in this work. We believe this is a good example to discourage the idea that T_c^* is simply an enhancement of T_c (Au/In).

At present we do not have any solid idea to explain the I_c vs. T results. The possibility of a transition from a state of phase disorder to one of phase order, even though it is an appealing one, is not proved for the moment. The theoretical approach of Barnes [4] applies specifically to granular films and should be generalized to SNS junctions if any serious attempt to test it with our results is made. On the other hand the treatment of Giovannini and Weiss [5] is the subject of our present research.

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- [19] WOLF et al., *Phys. Rev. Lett.* **42** (1979) 324, obtain the following critical exponents $\mu = 3.9 \pm 0.3$ (as compared to our $\alpha = 0.85 \pm 0.15$); $\lambda = 0.5$ ($\gamma = 0.71 \pm 0.30$) and $\nu = 3.0 \pm 0.2$ ($\beta = 1.58 \pm 0.30$). The exponent α (or μ) is related to the critical index z , which is difficult to calculate accurately for two dimensional systems. Preliminary calculations yield α (or μ) $\simeq 1$ (B. Giovannini, private communication).