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H. Ohta, M. J. Feldman, P.T. Parrish, R.Y. Chiao. Semimetal barrier planar Josephson junction. *Revue de Physique Appliquée*, 1974, 9 (1), pp.187-190. 10.1051/rphysap:0197400901018700 . jpa-00243735

HAL Id: jpa-00243735

<https://hal.science/jpa-00243735>

Submitted on 1 Jan 1974

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SEMIMETAL BARRIER PLANAR JOSEPHSON JUNCTION (*)

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Résumé. — La jonction plane à barrière semi-métallique est un excellent dispositif pour détecter des ondes millimétriques. Elle présente une résistance élevée, une faible capacité, est mécaniquement et électriquement stable et peut facilement être fabriquée avec de petites dimensions. Nous décrivons la fabrication et les caractéristiques de ces jonctions.

Abstract. — The semimetal barrier planar junction is an excellent candidate for a millimeter-wave detector. It has a high resistance and a very small capacitance, it is electrically and mechanically stable, and it can easily be made in the small-junction limit. We describe the fabrication and characteristics of such junctions.

1. Introduction. — We have developed a superconductor - semimetal - superconductor (S-SM-S) Josephson junction which has both a high resistance and a low capacitance, and which is impervious to electrical and mechanical shock. The combination of these qualities recommends using this junction as a millimeter-wave detector. In our experiments we have used bismuth as the semimetal and lead, tin, or niobium nitride as the superconductor. Bismuth was chosen as the barrier material because it has a high resistivity even though it has a very large mean free path. As expected, we find that these junctions do indeed have all the characteristics of Josephson elements.

The geometry of our S-SM-S junctions is original in that the superconductor on one side of the barrier does not overlap that on the other side, as shown in figure 1. Below the critical temperature the semimetal strip lying upon the superconductor has no effect on the electrical characteristics because a negligible current flows in the semimetal other than in the barrier itself. The current essentially flows

in a single plane. This geometry allows a very small barrier cross-sectional area, and hence a very small junction capacitance.

By adjusting the length, width, and thickness of the semimetal barrier, the resistance of Pb-Bi-Pb junctions has been experimentally varied from $10^{-3} \Omega$ to 40Ω . This is much larger than the resistance of normal metal barrier (S-N-S) junctions [1], which can be $2 \times 10^{-6} \Omega$. Because this low resistance shunts the AC currents, radiation-induced constant-voltage steps have been observed on S-N-S junctions only at frequencies below 2 MHz [1]. High resistance S-SM-S junctions can better couple to millimeter-wave radiation. The cross-sectional area seen by the current in a S-SM-S planar junction is typically 30 to 3 000 times that in a microbridge, making the former proportionally more resistant to unavoidable electrical pulses. The thin film geometry is extremely mechanically stable. The mechanical and electrical stability of S-SM-S planar junctions is a great advantage when compared to point contacts and thin-film microbridges respectively.

FIG. 1. — Geometry of a semimetal barrier planar Josephson junction.

(*) Work partially supported by National Science Foundation Grant GP 38586 and National Aeronautics and Space Administration Grant NGL 05-003-272.

2. Theoretical considerations. — There is no microscopic theory of semimetal-barrier Josephson junctions. We use the theory of the proximity effect in a normal metal, N, in contact with a superconductor, S, to estimate the supercurrent through a semimetal barrier. According to proximity effect theory [2], the probability amplitude for finding a Cooper pair in the normal metal at so far a distance as κ^{-1} from the N-S boundary is still considerable. In the clean limit,

$$\kappa^{-1} = \frac{\hbar v_F}{2 \pi k T} \quad (2.1)$$

Assuming for bismuth a Fermi velocity $v_F = 6 \times 10^7$ cm/s at a temperature $T = 4.2$ K, we find that $\kappa^{-1} = 1\,720 \text{ Å}$.

We can then certainly expect to observe a large supercurrent through a 3 000 Å long bismuth barrier.

Let us calculate the impedances for a typical Pb-Bi-Pb junction. We assume, as in figure 1, that the bismuth barrier has a length $l = 3\,000\text{ Å}$, a width $w = 40\text{ }\mu\text{m}$, and a thickness $t = 3\,000\text{ Å}$, and that the length of the lead film $L = 6\text{ mm}$. Polycrystalline bismuth films 1 000 Å thick evaporated upon a liquid-nitrogen-cooled glass substrate have a measured resistivity of $2\,500\text{ }\mu\Omega/\text{cm}$ at 4.2 K. Using these parameters,

$$R = \rho \frac{l}{wt} = 0.63\text{ }\Omega. \quad (2.2)$$

The capacitance can also be calculated [3]. It is dominated by the stray capacitance between the superconducting strips far from the barrier. Again using the above parameters,

$$C = \frac{2\epsilon w K(k)}{K(\sqrt{1-k^2})} = 0.012\text{ pF} \quad (2.3)$$

$$k = \frac{L}{L+2l}$$

where $K(k)$ is the complete elliptic integral and we have assumed $\epsilon = 1$. This capacitance is smaller than that of a point contact because the length of the bismuth barrier, l , is much larger than that of the « barrier » of a point contact. Note that the cut-off frequency, $1/RC$, for this junction is extremely high. Were it not for energy gap limitations, this junction could respond to frequencies as high as 30 μm . We can expect our junction to be free of capacitive-induced hysteresis [4] because

$$RC\omega_J = RC \sqrt{\frac{2eI_m}{\hbar C}} = 0.038 \quad (2.4)$$

is much smaller than unity. We have assumed the critical current is

$$I_m = J_m wt = 100\text{ }\mu\text{A}.$$

For junctions in the small-junction limit no excess supercurrent is seen at large voltages [1]. To achieve this we must have

$$w \lesssim 4\lambda_J$$

$$\lambda_J = \sqrt{\frac{\epsilon_0 \hbar c^2}{2eJ_m l}}. \quad (2.5)$$

For the parameters assumed above a junction having $w \simeq 40\text{ }\mu\text{m}$ can be considered « small ». That this width is so large is experimentally convenient.

3. Fabrication. — In making Pb-Bi-Pb junctions, we first wash the cover glass substrates with detergent in an ultrasonic cleaner, and then expose them to an oxygen glow discharge for thirty minutes. To enable the lead to adhere to the clean glass, a 40 Å

lead oxide layer is deposited at the rate of an Ångström per second by evaporating lead in an oxygen atmosphere of 2.5×10^{-4} torr. A pure lead film is then evaporated to desired thickness. To protect the film from corrosion, a 50 Å bismuth layer is then evaporated at a few Ångströms per second. During all of these evaporations the substrates are kept at liquid nitrogen temperature. The resulting films are very shiny and adhere strongly to the glass substrates. These films are kept in liquid nitrogen to avoid alloying and to prevent corrosion. Whenever water drops form on the film surface they must be removed immediately, for example with a blast of compressed gas. Lead, and to a lesser extent bismuth, are corroded by water drops, presumably by dissolved atmospheric oxides of nitrogen.

A number of grooves of the desired width, for instance 3 000 Å, are made on one of these films with a diamond stylus. We use ethanol to reduce the friction between the film and the diamond, to give a regular, straight groove. If the resistance across the groove is not infinite, a ten volt pulse can usually burn off tiny short circuits. We then solder across the groove at one point (using low-temperature solder) to prevent destructive arcing during the subsequent glow discharge.

99.999 9 % pure bismuth is evaporated through a mask with one millimeter wide slits. The intersection of one of these slits with one of the grooves in the substrate defines a junction. Before evaporating the bismuth, though, we found it necessary to perform an argon glow discharge to remove the oxide layer and any oil accumulated along the grooves. Without this the bismuth strip had poor electrical contact and even poor mechanical adhesion to the lead film. Care must be taken to avoid oxygen or water vapor contamination of the glow discharge. We experimentally adjusted the glow discharge pressure, voltage, and duration for our evaporator geometry in order to remove the oxide layer without damaging the grooves. The melting point of lead is lower than the evaporation temperature of bismuth at a pressure of 10^{-6} torr. Because of this low melting point we found it necessary to cool the substrates with liquid nitrogen during both the glow discharge and the bismuth evaporation, and to evaporate the bismuth at a rate less than 10 Å/s.

Sn-Bi-Sn junctions are made in essentially the same way. Some of the above steps are unnecessary as tin is less liable to corrosion (in our situation) and has a higher melting temperature than lead.

Four copper leads are soldered to each junction, eliminating the large induction voltage at the tip of the soldering iron by disconnecting the iron or by using a regulated DC power supply. We manually reduce the junction width as desired, to as narrow as 30 μm , with a diamond needle under a 30 power microscope. With practice we can avoid the junction being shorted by the superconductor. That this

parameter is so readily accessible is an advantage. The junctions are kept in liquid nitrogen to avoid alloying.

4. Characteristics of S-SM-S junctions. — Bismuth, although it is a conductor, has an extremely high resistivity. The resistivity of bismuth thin films increases with decreasing temperature from 300 K to 4.2 K, in contrast to all other conductors and to bulk bismuth. Because of these facts, the bismuth barrier contributes perceptibly to the room temperature junction resistance, and significantly or even dominantly to the junction resistance at 77 K and below, even though the barrier aspect ratio is very much less than that of the background film. By measuring the ratio of a junction's resistance at two temperatures, then reducing its width and doing the same, we can easily calculate the effective length of the junction. We need to know only the resistance ratio $R(T)/R(T')$ of the background film and the resistivity of the bismuth at these temperatures. We must assume the geometry is in fact planar. This technique is more precise for tin than for lead junctions because we can use 4.2 K as well as 77 K, whereas at 300 K the effect of the bismuth is small. A typical result for a Sn-Bi-Sn junction is: in six independent determinations of the junction length, consecutively reducing its width, we calculate a length of $3\,400 \pm 300 \text{ \AA}$. A scatter this large is to be expected from the 2 % accuracy of the resistance measurements. We expected a length of about $3\,000 \text{ \AA}$ from scanning electron microscope observations of similar grooves without an overlaid bismuth film. These results tell us that: 1) the geometry is indeed planar (i. e. the currents flow as we expect); 2) the bismuth of the barrier has the same resistivities as that evaporated on clean glass, and there are no unexpected quantum size effects; 3) the groove is regular on a large scale; 4) we have not induced tin shorts in reducing the width. The results for lead junctions are similar except that the effective junction length seems too large, about one micron. We believe this indicates our glow discharge is not optimum for lead films.

It is easy to tell if the bismuth barrier has been shorted while reducing its width. If so the junction resistance ratio with temperature becomes almost exactly that of the background film. Also, the supercurrent becomes very much larger.

Without evaporating an overlay, we can measure the capacitance between the lead films on either side of a $3\,000 \text{ \AA}$ groove with standard equipment. We find 2.5 pF for a 1 cm long groove. This implies 0.01 pF for a $40 \text{ \mu m}$ long groove, in striking agreement with the calculated value of eq. (2.3).

We observe very clear microwave-induced constant-voltage steps on the voltage-current I - V curves of S-SM-S junctions, as shown in figures 2 and 3. The asymptotic resistances of tin junctions are consistent

with values calculated as in eq. (2.2). Those for lead junctions are a few times larger than the calculated values, indicating again a larger than expected effective junction length. The I - V curve of figure 4 has no excess supercurrent at large voltages, so that the junction must be in the small-junction limit. From figure 4 we can calculate

$$\frac{2eI_m R}{\pi\Delta(0)} = 0.6 \quad (4.1)$$

FIG. 2. — X-band microwave-induced current steps in the I - V curve of a Pb-Bi-Pb junction at $T = 4.2 \text{ K}$. The vertical and horizontal scales are $50 \text{ \mu V/div}$ and $500 \text{ \mu A/div}$ respectively. The junction parameters are $l = 3\,000 \text{ \AA}$, $w = 100 \text{ \mu m}$, $t = 1\,000 \text{ \AA}$.

FIG. 3. — X-band microwave-induced current steps in the I - V curve of a Pb-Bi-Pb junction at $T = 4.2 \text{ K}$. The vertical and horizontal scales are $20 \text{ \mu V/div}$ and $100 \text{ \mu A/div}$ respectively. The junction parameters are $l = 3\,000 \text{ \AA}$, $w = 300 \text{ \mu m}$, $t = 2\,500 \text{ \AA}$.

which is close to unity. The larger this ratio the higher sensitivity a junction will have *in video* detection, heterodyne detection and parametric amplification of microwave and millimeter-wave radiation.

We expect any effects of alloying to be unimportant as the junctions are at liquid nitrogen temperature, except for perhaps an hour total exposure to room temperature.

FIG. 4. — The I - V curve of a Pb-Bi-Pb junction at $T = 4.2$ K. The vertical and horizontal scales are 2 mV/div and 500 μ A/div respectively. Evidence indicates that the junction parameters are $l = 4\,000$ Å, $w = 20$ μ , $t = 2\,500$ Å. No excess supercurrent exists for this junction at high voltages, above the energy gap.

5. NbN-Bi-NbN junctions. — Niobium nitride [5] has many properties that recommend it for use in a practical Josephson junction radiation detector, and especially, in a semimetal barrier junction. Its critical temperature is 15.6 K, allowing the use of a closed-cycle helium refrigerator. Its energy gap is 4.5 meV, corresponding to a wavelength of 278 μ m. Thus, with its extremely small capacitance, a NbN-Bi-NbN junction can sensitively detect radiation far into the infrared. The melting point of NbN is 2 573 °C. We could make a single-crystal bismuth barrier by heating a NbN substrate during the bismuth evaporation. NbN is extremely mechanically strong and chemically

stable, making NbN-Bi-NbN junctions very easy to prepare and maintain. There is no danger of an alloy forming. Ultrasonic cleaning and most abrasives will not disturb the NbN surface.

In one aspect NbN junctions are harder to prepare. It is difficult to cut a very narrow groove in a NbN film. We have used both a diamond stylus and an electron beam sensitive photo-resist for this purpose. The I - V curve of a NbN-Bi-NbN junction made with a 1 μ wide groove is shown in figure 5.

FIG. 5. — The I - V curve of a NbN-Bi-NbN junction at $T = 4.2$ K. The vertical and horizontal scales are 200 μ V/div and 50 μ A/div respectively. The junction parameters are $l = 1$ μ m, $w = 500$ μ m, $t = 8\,000$ Å.

Acknowledgments. — The authors gratefully acknowledge several helpful discussions with Dr. J. Clarke in the early stages of this work.

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