Table I. Band energies in Bismuth.

References	Fermi energy (meV) For electrons	For holes	Energy gap (meV) For electron band	For hole band
a	...	...	24	...
b	25	...	15	...
c	...	12	...	...
d	27.6	11	15.3	...
e	27 for sum of both		...	...
Present work	15	15	20	15

[a]W. E. Engeler, Phys. Rev. 129, 1508 (1963).
[b]R. N. Brown, J. C. Mavroides, and B. Lax, Phys. Rev. 129, 2055 (1963).
[c]Y.-H. Kao, Phys. Rev. 129, 1122 (1963).
[d]G. E. Smith, G. A. Baraff, and J. M. Rowell, IBM J. Res. Develop. 8, 228 (1964).
[e]A. L. Jain and R. L. Jaggi, IBM J. Res. Develop. 8, 233 (1964).

when tunneling into a semimetal. However, the observed structure is quite large. It is felt that the WKB approximation is not applicable for semimetals and degenerate semiconductors as the electron and hole wavelengths are larger than the junction width. In fact, at a band edge, the wavelengths are extremely large in any material, and one would expect a complete breakdown of the WKB approximation at this point.

One possible explanation for the observed structure is that proposed by Harrison[1] for the case of the sharp boundary which illustrates a dependence of tunneling current on the one-dimensional density of states.

In this study we have detected many bands in Bi, most of which have never been seen with other experimental methods. This demonstrates that this technique of tunneling spectroscopy has great potential for band-structure studies in semimetals and degenerate semiconductors and, in particular, in the study of the Bi_xSb_{1-x} alloy system.

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[1]W. A. Harrison, Phys. Rev. 123, 85 (1961).
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DETECTION OF THE ac JOSEPHSON EFFECT

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Josephson[1] made two startling predictions in 1962 of effects which have become known as the ac and dc Josephson effects. The dc effect, which allows supercurrent to flow between the ground state of two superconductors in an electron tunneling experiment,[2] is now well established experimentally.[3] The ac effect, which allows current flow between the ground states of two superconductors when there is a small potential difference V between them, has found only indirect experimental support.[4-6] This current flow is accompanied by photon emission; the frequency ν of the photons is given by $h\nu = 2eV$ where h is Plancks constant, e the electronic charge, and V the potential difference between the two superconductors. The frequency is related to twice the electronic charge as the two superconductors exchange

Cooper pairs[7] rather than single electrons.

For some time it has been the ambition of many to detect the electromagnetic fields in a tunnel junction operating in the ac Josephson mode. The frequency range is in the far infrared, and the junction offers some promise as a tunable infrared source. So far, to my knowledge, all attempts to get the electromagnetic fields out of the junction and into a conventional detector have failed, presumably because of the bad impedance match between the junction and free space. In the experiment I shall describe, I have succeeded in detecting the electromagnetic fields, using a highly unconventional spectrum analyzer. Dayem and Martin[8] showed that when a conventional tunnel junction of two equal superconductors is subjected to a microwave field, current steps occur at voltages given by $(1/e)(2\Delta \pm nh\nu)$, where ν is the frequency of the microwave field and 2Δ is the energy gap of the superconductors. Thus a superconducting tunnel junction is indeed a crude spectrum analyzer.

Now consider the following experimental arrangement shown schematically in Fig. 1. First a Sn film (marked 1 in the figure) is evaporated onto a microscope glass slide. This film is oxidized in the laboratory air overnight to form a thick oxide. Second, another Sn film (2) is evaporated over the first one, forming a T-like structure. This film is oxidized from 5 to 30 min to form a thin oxide layer, and finally a third Sn film (3) is evaporated on top of the other two films. The films (1) and (2) are separated by an oxide layer thick enough to

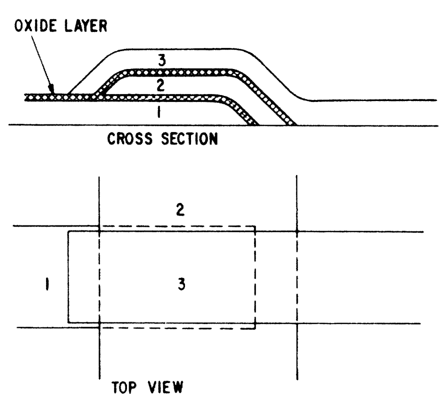

FIG. 1. Schematic drawing of the experimental arrangement. All films are made of Sn, and the oxide layers between them are thought of as cavities for the radiation.

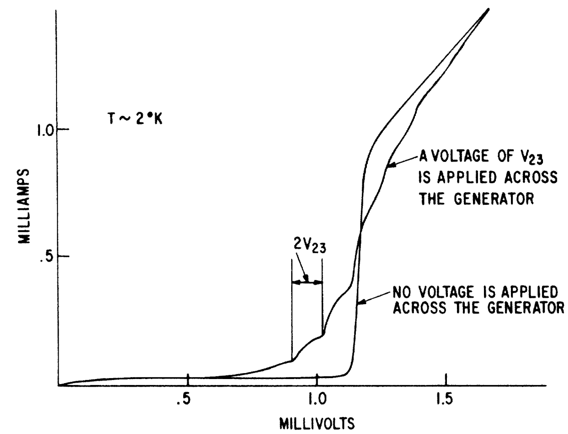

FIG. 2. This figure shows the current-voltage characteristic of the detector, with no voltage and with a voltage V_{23} applied across the generator junction.

quench out most, if not all, Josephson effects. These two films comprise the detector. Films (2) and (3) are separated by a thin oxide and exhibit the Josephson effects. These two films act as the generator of the microwaves. There also is a "sneak path" between films (3) and (1); however, the area of this junction can be made small enough so that it does not interfere appreciably with the dc measurements. This overlap of film (3) on film (1) is necessary to obtain a tight coupling between the two cavities, represented by the oxide layers between films (1) and (2) and films (2) and (3).

By applying a voltage V_{23} across the films (2) and (3), a microwave field of frequency $h\nu = 2eV_{23}$ is produced. Then by measuring the current-voltage characteristic of the junction between films (2) and (1), current steps are obtained at voltages $V_{12} = (1/e)(2\Delta \pm nh\nu) = (1/e) \times (2\Delta \pm n2eV_{23})$ in a precisely similar fashion to what happened in the experiment carried out by Dayem and Martin. One of the better samples is shown in Fig. 2, where steps can be seen at least to $n = 3$. There can be two reasons for the steps which occur for $n > 1$; either they are due to multiple photon absorption (emission), or they are due to higher harmonics in the Josephson ac effect.

Figure 3 shows a different sample with various voltages applied to the generator junction. Figure 4 shows this same sample in a slightly different magnetic field, but this time, at one specific voltage across the generator, a subharmonic of the Josephson ac frequency is present. No definitive reason for this subhar-

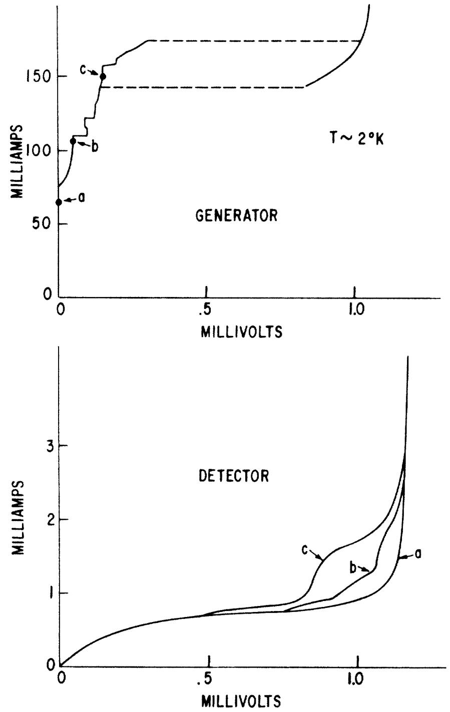

FIG. 3. Current-voltage characteristics of the generator as well as the detector. Three different characteristics are shown for the detector depending upon the bias applied to the generator, as indicated.

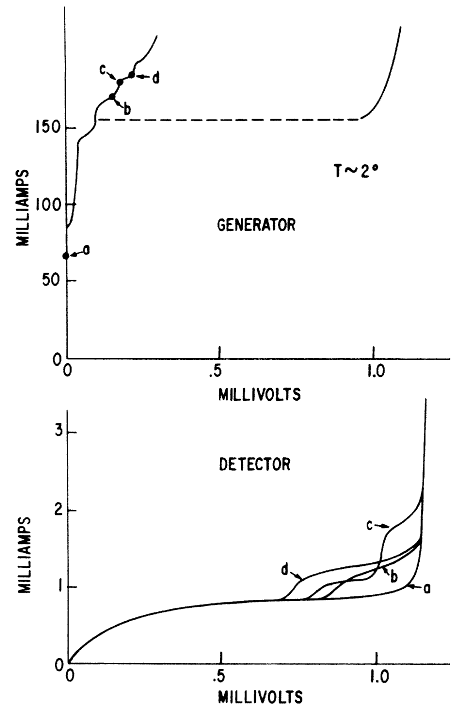

FIG. 4. This is the same sample as in Fig. 3; however, now a small magnetic field is applied. Note the appearance of a subharmonic when the generator is biased to point *c*.

monic can be given at this time; however, it is believed that it may be due to nonlinear effects present in the Josephson equations when these are solved taking proper care of boundary conditions in the cavity. Subharmonics of $\frac{1}{3}$ of the Josephson frequency have also been observed.

No attempt has been made to shield out the earth's magnetic field in these experiments. The characteristics do depend upon the magnetic field present, but apparently not in any simple way. When the magnetic field gets sufficiently large, the current-voltage characteristic of the detector does not depend appreciably on the voltage applied across the generator. When the resistance of the detector is sufficiently small to allow some Josephson effect in the detector as well, it is possible to detect the ac field produced by the generator by the inverse Josephson effect on the detector. This is completely analogous to the experiment done by Shapiro,[4] which first established the existence of the ac effect.

In summary, this experiment helps confirm the Josephson ac effect. An appreciable amount of ac power is produced when a junction is put in this mode; to date the order of 10^{-7} W have been extracted from the generator without affecting it to any appreciable degree.

It is a pleasure for me to acknowledge many helpful discussions with M. D. Fiske.

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