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Authors
Richards, P.L.
Grimes, C.C.
Shapiro, S.

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P. L. Richards

Inorganic Materials Research Division, Lawrence Radiation Laboratory,
Department of Physics, University of California
Berkeley, California

and

C. C. Grimes and S. Shapiro

Bell Telephone Laboratories, Murray Hill, New Jersey

ABSTRACT

Two recent developments in the study of superconductivity, flux quantization and the Josephson effect, are demonstrated with relatively simple apparatus. These experiments are intended to complement the discussion in Feynman's Lectures on Physics, Vol. III.

INTRODUCTION

The Josephson effect of superconductivity has excited much theoretical and experimental interest since its discovery in 1962.[1] For example, in Lectures on Physics Feynman[2] uses it as his final example of how well we understand nature. There has been, however, no practical laboratory demonstration experiment to go with Feynman's theoretical treatment.

Josephson effects occur in the quantum mechanical tunneling current which flows between two superconductors separated by a thin insulating barrier. Usually, Josephson junctions are prepared by vacuum deposition of metal films. This procedure is too difficult and unreliable for student use. Two experiments which exhibit Josephson-type phenomena can, however, be done using a simpler point-contact junction constructed from Nb wires. The natural oxide coating on the wire provides the tunnel barrier.

In addition, tunneling effects which give a measure of the superconducting energy gap can be seen if one of the wires is anodized so as to form a thicker oxide tunnel barrier.[3] In the following, Feynman's description of the Josephson effect[2] will be assumed. The serious student should also consult the Scientific American article by Langenberg *et al.*[4] as well as the original papers referred to here.

FLUX QUANTIZATION IN SUPERCONDUCTORS

The magnetic flux threading a superconducting ring, or penetrating into a superconductor, is quantized in units of $\Phi = hc/2e$. One of the most striking demonstrations of this effect is the magnetic field dependence of the maximum zero-voltage current of a single Josephson junction, or of several such junctions in parallel. In the former case,[4,5] the current traces out the amplitude of a single slit diffraction pattern as a function of H applied in the plane of the junction. The current minima are separated by the amount of H necessary to drive one quantum of flux into the junction. Feynman[2] discusses two junctions in parallel, in which case a double slit diffraction pattern is seen. When two Nb wires are touched together and immersed in liquid He, the unavoidable roughness of the area of contact usually insures that zero-voltage current flows due to:

1. Superconducting current through points of metallic contact, and
2. d.c. Josephson tunneling current through regions where the oxide layer is thin. . . .

The portion of the zero voltage current (2) is effectively carried by several Josephson junctions in parallel, so it is a periodic function of applied field up to a few hundred Oe. It is unfortunately not possible to obtain a quantitative measure of hc/2e in this experiment since the area enclosed by the junction (s) is not known. If, however, a macroscopic loop of wire containing two point contacts is used, the quantitative experiment described by Feynman can be done.[6]

INSTRUCTIONS

Assemble the apparatus as shown in Fig. 1 to plot the current versus voltage in the junction. A current reading resistor R of 2-10 Ω and an x-y scope with ~ 50-100 mv/cm sensitivity are needed. Sharpen one Nb wire with fine file to a point of radius ~ 0.1 mm. The other contact should be flat. The oxide will form in a few minutes at room temperature.

If it is scraped off at low temperature, it may be necessary to warm the points to allow the oxide to re-form. Insert the probe into the storage vessel and adjust the contacts until a current-voltage (I-V) trace is seen like that in Fig. 2. When a permanent magnet such as a surplus magnetron magnet is moved close to the storage vessel, the portion of the zero-voltage current (vertical part of I-V trace) due to d.c. Josephson current will oscillate rapidly. This demonstrates the quantization of flux in a superconductor.

a.c. JOSEPHSON EFFECT

Josephson predicted that if a finite voltage V is imposed across a thin tunnel junction, an alternating current will flow across the junction at the frequency $\hbar\omega_J = 2eV$. This current was first observed[7] in an experiment which can be duplicated using our point-contact apparatus. If an a.c. current is induced at frequency ω_M across the junction by an external microwave source, there will be beats at $\omega_J \pm \omega_M$. Whenever the voltage V is adjusted so that $\omega_J = \omega_M$, the zero-frequency beat will appear as a vertical step on the I-V trace. Because of the non-linearity of the junction, steps also occur at harmonics of $V = \hbar\,\omega_M/2e$ as shown in Fig. 2. It can be easily shown[8] that the amplitude of the nth step varies as the nth order Bessel function J_n of the microwave voltage in analogy to conventional frequency modulation. The vertical steps on the I-V trace demonstrate the existence of the a.c. current predicted by Josephson.

INSTRUCTIONS

When an adjustment of the point contacts is found that gives large oscillations in the zero-voltage current with magnetic field, a microwave signal variable up to ~ 10 mw at k band (24 Gc/sec) or higher frequency should be coupled into the probe. For some adjustments of the contacts, the microwave power will simply destroy the zero voltage current. Adjustments can be found, however, for which the steps will appear. The recommended available power of ~ 10 mw allows for very poor coupling between the klystron and the point contacts. Actually, power levels down to ~ 10^{-13} watts can be detected using Nb point contacts making them one of the most sensitive known detectors at high microwave frequencies.[9]

A more complete description of these experiments will be published in the American Journal of Physics.

Acknowledgements

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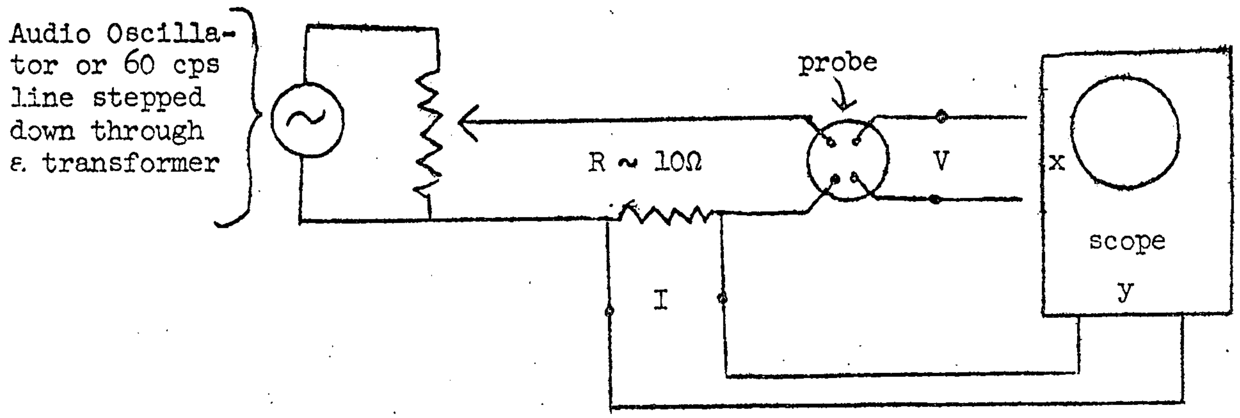
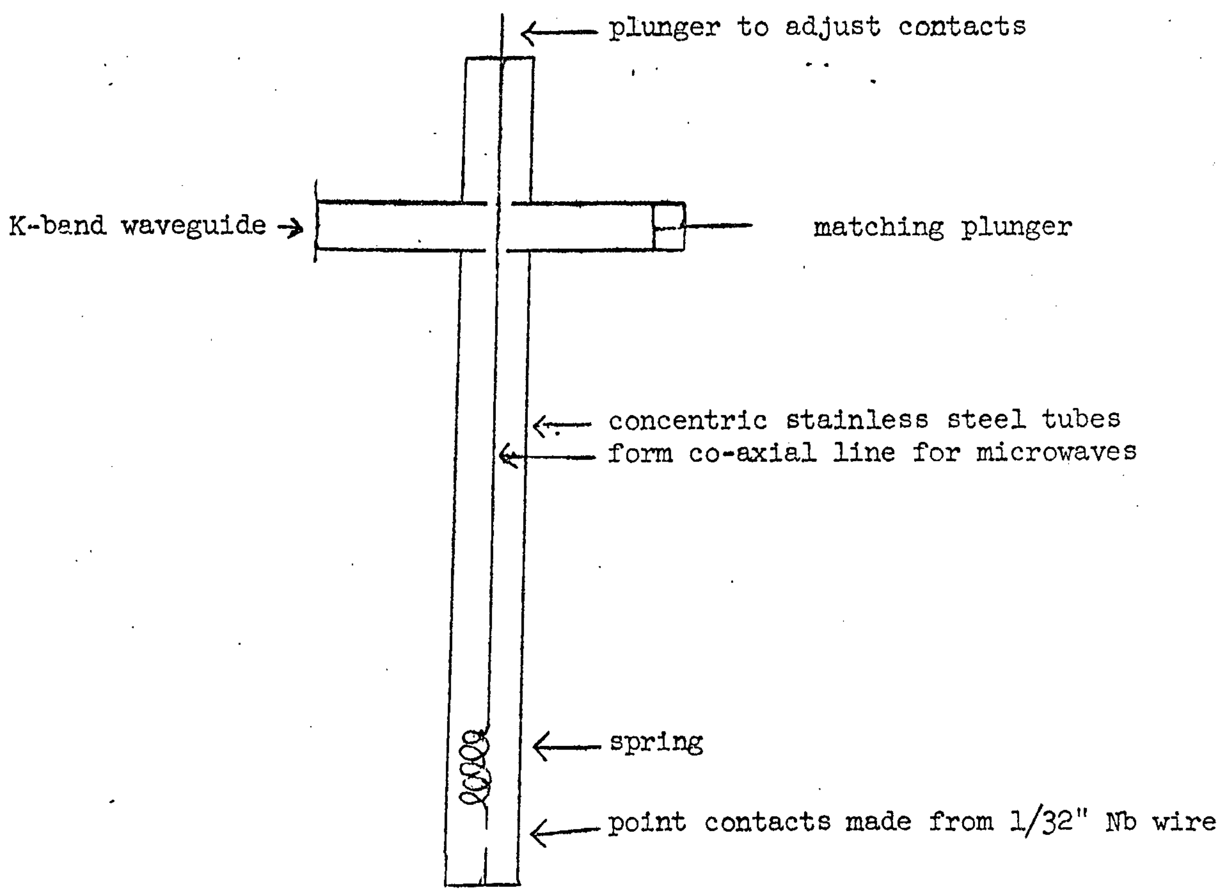
FIG. 1

CURRENT VOLTAGE PLOTTER

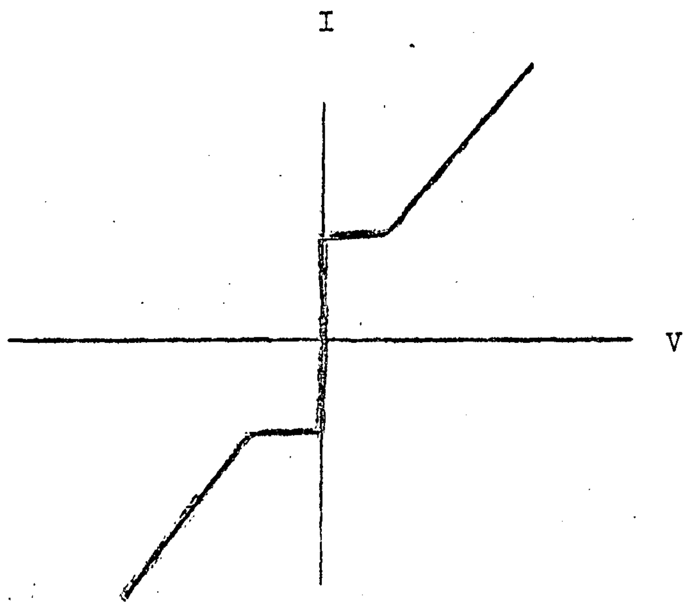


PROBE TO FIT IN He STORAGE DEWAR

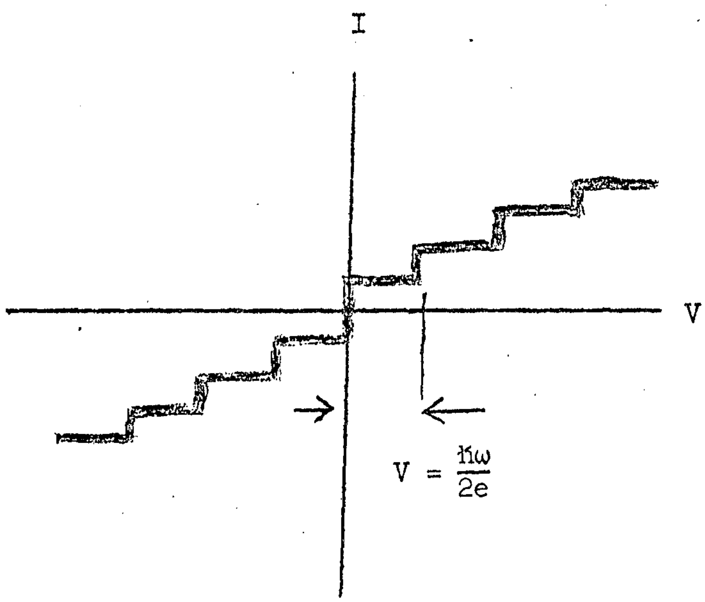


current and potential leads to each point contact are not shown on diagram

FIG. 2



I-V trace in absence of microwaves. Vertical region is "zero-voltage current"



I-V trace with microwaves applied. Amplitude of various vertical steps will depend on microwave power.

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