SUPERCONDUCTORS AS QUANTUM DETECTORS FOR MICROWAVE AND SUB-MILLIMETER-WAVE RADIATION*

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Giaever[1] and Nicol, Shapiro, and Smith[2] have reported experiments on electron tunneling through metal oxide barriers between a metal and a superconductor, $M|B|S$, and between two superconductors, $S_1|B|S_2$. The tunneling process which involves "unpaired" charge carriers can be simply described in terms of a quasi-particle energy band picture in which the superconductor is represented, at temperatures below its transition temperature, as an intrinsic semiconductor with a temperature-dependent energy gap, $E_G = 2\epsilon_0$, and equal effective masses for electrons and holes [Fig. 1(a)].

For small bias voltages, V_b, such that $|eV_b|$ is less than $E_G/2$ in the case of $M|B|S$ and less than $(E_{G_1}+E_{G_2})/2$ in the case of $S_1|B|S_2$, the tunneling current depends on the density of thermally excited carriers. For larger bias voltages, the tunneling current is essentially independent of the density of thermally excited carriers and results in the "injection" of electrons and holes into the conduction and filled bands of the superconductor. The concept of "photo-injection" of carriers by optical excitation across the energy gap of the superconductor follows quite naturally. These considerations suggest the use of "low-voltage" tunneling in $M|B|S$ and $S|B|S$ structures for the quantum detection of microwave and sub-millimeter-wave radiation in a manner which is analogous to the detection of visible and near infrared radiation by p-n junctions in semiconductors [Fig. 1(b)]. Such superconductor photodetectors would have long-wavelength limits, λ_{max}, determined by the energy gap of the superconductor used. Thus, for aluminum $\lambda_{max} = 3.9$ mm corresponding to $E_G = 3.2\times10^{-4}$ ev, and for lead $\lambda_{max} = 0.46$ mm corresponding to $E_G = 2.7\times10^{-3}$ ev.[1,2]

The magnitude of the tunneling current due to optically excited carriers will depend, among other things, on the lifetime of the carriers. The processes which limit the lifetime include (a) the recombination of electrons and holes across the gap, (b) the pairing of electrons in the conduc-

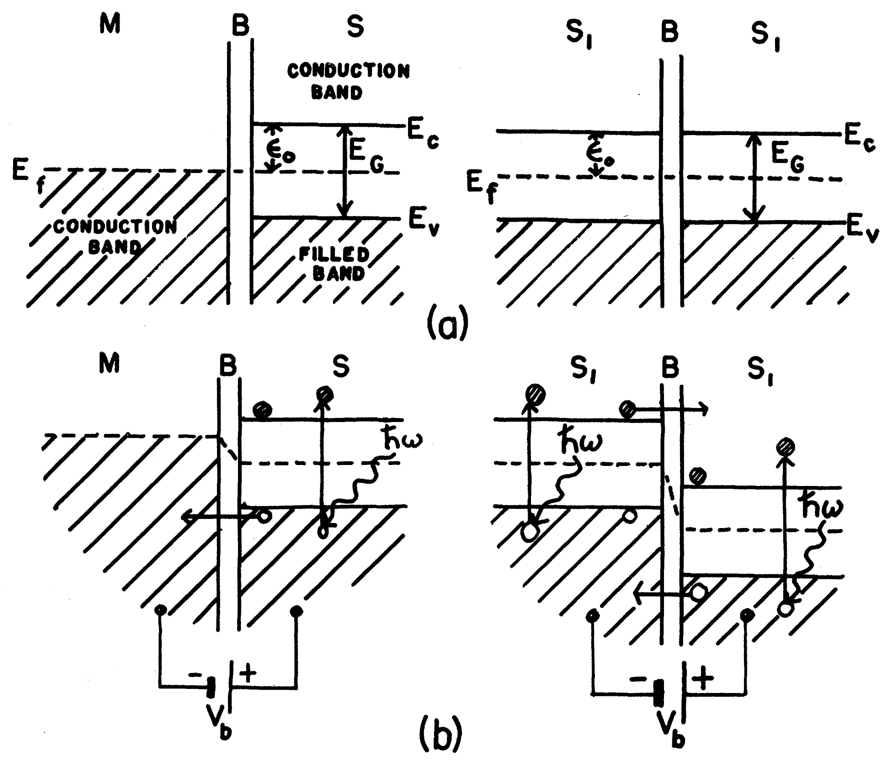

FIG. 1. (a) Quasi-particle energy band diagrams for an $M|B|S$ structure and an $S_1|B|S_2$ structure in which the two superconductors are the same. (b) Tunnelling of optically excited carriers in $M|B|S$ and $S_1|B|S_1$ structures under "low bias voltage" conditions.

tion band and the corresponding pairing of holes in the filled band, and (c) in the case of $M|B|S$ structures, the simultaneous tunneling of electrons and holes into the metal from the superconductor and their subsequent transition to the Fermi surface of the metal. At the present time, estimates for the lifetimes for these processes which may be radiative or nonradiative are not available. We have carried out an estimate of the electron-hole radiative recombination lifetime, τ_{opt}, for lead at 2°K using the theory of van Roosbroeck and Shockley[3] (Fig. 2). The dependence on frequency of $\eta^2\kappa$, where $\eta+i\kappa$ is the complex refractive index, was derived from theoretical expressions for $\sigma_1+i\sigma_2$, the complex conductivity, obtained by Mattis and Bardeen,[4] while the density of thermally generated carriers, n_i, was calculated from the quasi-particle density of states of superconductors given by the Bardeen, Cooper, and Schrieffer theory[5] and a value of $N(0) = 2.2\times10^{22}/\text{cm}^3$ which Gold[6] proposed for the density of states at the Fermi surface of lead in the normal state. The theoretical values of σ_1 and σ_2 are in reasonable agreement with the experimentally determined values obtained by Glover and Tinkham[7] and Ginsberg and Tinkham[8] but do not show any of the structure near the

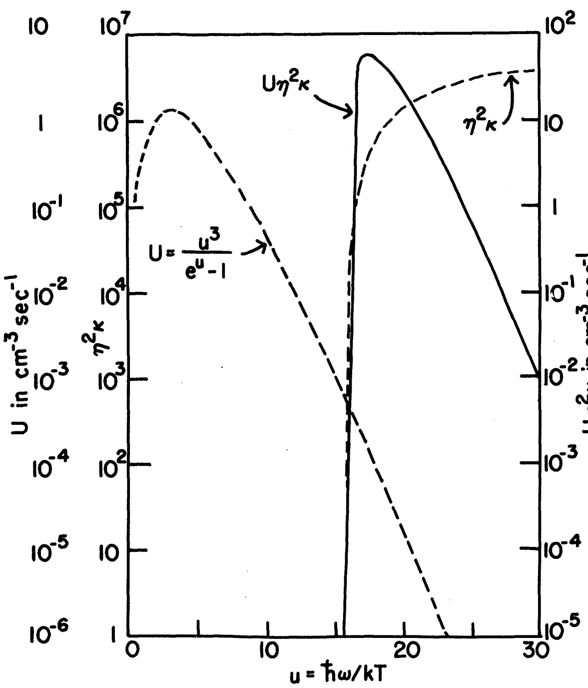

FIG. 2. The dependence of $\eta^2\kappa$ and of $U\eta^2\kappa$, which is proportional to the radiative recombination rate per unit frequency interval, on $u=\hbar\omega/kT$ for lead at 2°K.

band gap which is present in the experimental spectrum. We obtain $n_i = 5.5\times10^{15}/\text{cm}^3$ and $\tau_{opt} = 0.4$ sec. It is, therefore, very unlikely that the radiative recombination of electrons and holes is the dominant process which determines the lifetime. Measurements of the tunneling current due to optically and electrically injected carriers should provide an effective means for obtaining information about the lifetime, and, in appropriate configurations, about the diffusion length of the unpaired carriers in superconductors.

B. Rosenblum of RCA Laboratories has pointed out that photoexcited carriers in the metal of the $M|B|S$ structure may also contribute to the tunneling current. This would extend the photoresponse to longer wavelengths with λ_{max} controlled by the bias voltage. The magnitude of the photoresponse of the metal would be expected to be much smaller than that of the superconductor since the lifetime of the excited carriers in the metal is very much shorter than the corresponding lifetime in the superconductor.

The metal and superconductor films used in the superconductor photodetectors must be much smaller than the wavelength of the radiation in the films in order to decrease the reflection and, thereby, to increase the absorption of the incident radiation by the superconductor. An $S_1|B|S_2$ structure is an ideal configuration for such detectors. On the one hand, it avoids the annihilation of electrons and holes by simultaneous tunneling of electrons and holes from the superconductor into the metal which can occur in $M|B|S$ structures, and on the other hand it allows an optimum absorption of the incident radiation by the superconductor layers. The absorption of radiation by an $S_1|B|S_1$ structure can be calculated by considering the composite structure as a single superconductor film. Curves of the absorptivity, A, and of $A/(\hbar\omega/E_G)$ which is proportional to the number of photons absorbed per unit intensity of incident radiation, are plotted as a function of $\hbar\omega/E_G$ in Fig. 3 for lead films having thicknesses of 5, 15, and 150 angstroms. We see that the absorptivity of the 15-angstrom film approaches the maximum value of 0.5 at $\hbar\omega/E_G\approx2.5$. However, the 150-angstrom film still exhibits an appreciable absorptivity, having a value of 0.15 at $\hbar\omega/E_G\approx3$. The photoresponse of the $S_1|B|S_1$ structure may be expected to differ somewhat from the photon absorption spectrum as a result of two effects: (a) a dependence of the lifetime of the excited carriers on energy,

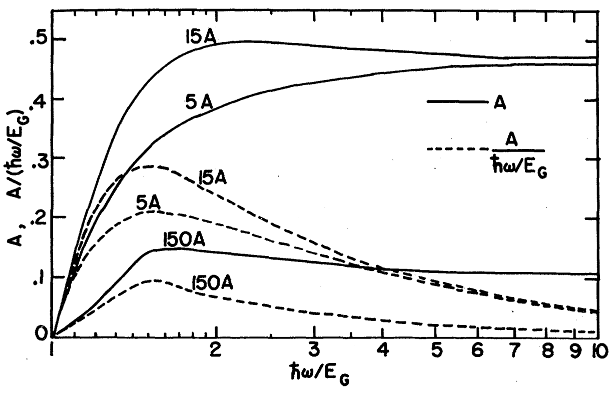

FIG. 3. Absorptivity and photon absorption spectra for superconducting lead films of 5, 15, and 150-angstrom thicknesses.

and (b) an increase in quantum efficiency for high-energy photons due to secondary impact ionization processes, as has been observed in the case of photoconductors.[9] The latter effect would increase the photoresponse at the higher frequencies and, thereby, would compensate for the decrease in photoresponse resulting from the decrease in the number of photons absorbed per unit intensity of radiation with increase in frequency. However, the photoresponse may also be expected to exhibit a sharp drop-off at frequencies greater than the "collision" frequency of the carriers (not shown in Fig. 3) where σ_1 exhibits a $1/\omega^2$ dependence.

Operating conditions for the superconductor photodetector are straightforward. The superconductor should be maintained at a temperature well below its transition temperature in order to diminish the thermal generation of carriers. Under these conditions ($kT \ll E_G$) the thermally excited carriers obey Maxwell-Boltzmann statistics and the equilibrium density of excited carriers is, to a good approximation, given by $n_i = N(0)(\pi E_G kT)^{1/2} \exp(-E_G/2kT)/2$ which has the same temperature dependence as a one-dimensional intrinsic semiconductor. For optimum response the temperature is lowered to a point where the rate of optical generation of carriers by background radiation is greater than the rate of thermal generation.[10] Under these conditions the fractional change in carrier density produced by a small radiation signal is given by $\Delta n/n_i = G_s/G_b$, where G_s is the rate of generation by the radiation signal and G_b is the rate of generation by the background radiation accompanying the radiation signal. The frequency response of the photodetector should be limited only by the lifetime of the excited carriers. It should also be noted that the photodetector can be operated with bias voltages of either polarity, as contrasted to the semiconductor photodiode.

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