TRUE PHOTOELECTROMAGNETIC EFFECT IN BULK BISMUTH AT 4.2°K

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The photoelectromagnetic (PEM) effect[1] has been measured in monocrystalline bismuth at 4.2°K by using a superconducting transformer[2,3] to match amplifier impedance to the very low impedance of the sample. Comparison of the PEM spectral response with reflectivity data indicates that a true internal photoeffect (electron-hole pair creation by photons) is being observed as opposed to thermal excitation of carriers. This is the first definite report of an internal photoeffect in a semimetal. Responses in antimony and gallium also have been observed, and the sensitive technique used here should have some success with some pure metals.

From the data, one can deduce for the first time a fairly definite value of a recombination time[4] in bismuth: $\sim 2\times10^{-8}$ sec, roughly 25 times larger than the carrier relaxation times in the sample. This means that intravalley scattering among electron ellipsoids and among hole ellipsoids predominates over electron-hole intervalley scattering (recombination). It should be pointed out that recombination in semimetals is of some interest because of a qualitative difference from that in semiconductors; between the overlapping bands of a semimetal, recombination presumably occurs <u>without</u> energy emission and with only a change in crystal momentum.

Most important, there is the possibility here of a new experimental tool to complement reflectivity data. Reflectivity measures total absorption, and in cases where free-carrier absorption is large, the absorption due to interband transitions may be masked, whereas the PEM effect tends to ignore the free-carrier "background" and instead shows the effects of interband transitions.

In the present experiment a simple all-Pyrex Dewar was used with a band of silvering deleted for the admission of light. An etched bismuth sample, 2.5×10 mm^3, with a resistivity ratio $\rho_{300°}/\rho_{4.2°} = 360$, was immersed in helium and oriented so that illumination fell on a face perpendicular to the trigonal axis, with the magnetic field along a binary axis and current connections (from the superconducting transformer) to the ends of the long dimension (along a bisectrix). The ends were masked to prevent their illumination, and an additional wire was connected near each end of the sample just under the edges of the mask. A known ac current from outside the Dewar could be sent through these probes to simulate a photocurrent and therefore calibrate the system. Light from a Bausch and Lomb grating monochrometer with a linewidth of ~50 Å was chopped at a 1-kc/sec rate, and the amplified photosignals were synchronously detected.

Figure 1 shows that the spectral response at constant photon flux is generally proportional to the absorbance $1-R$, where R is the reflectivity measured by Cardona and Greenaway[5] on cleaved bismuth at 77°K for the same crystal orientation. Since a thermal effect would be proportional to $(1-R)/\lambda$, we conclude that a true photocurrent is being observed. Reflectivity data at 4.2°K are not yet available, but it is doubtful that reflectivity changes grossly for this spectral range between 4.2 and 77°K, since interband transitions (not free-carrier or lattice absorptions) predominate.

The vertical arrows in the figure locate maxima in the reflectivity and signify energies assigned by Cardona and Greenaway at which various interband transitions commence. The PEM curve also shows maxima, but perhaps slightly displaced. What needs to be done, de-

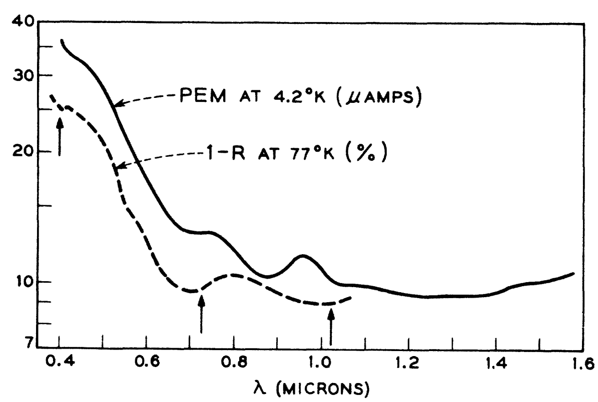

FIG. 1. Photoelectromagnetic current at constant photon flux vs wavelength of incident light, and absorbance (one minus the reflectivity R) vs wavelength.

spite the difficulties, is a simultaneous measurement of reflectivity and PEM current.

We have derived expressions[6] for the PEM effect when there are many-valleyed bands and anisotropic mobilities. For bismuth in the present orientation, the PEM current through the second order in magnetic field B is

$$i \cong weI(\mu_1+\nu_1)B(2\nu_3E_0\tau/3)^{1/2}, \qquad (1)$$

where w is the sample width, e the electronic charge, I the absorbed photon flux density, μ_1 and ν_1 the binary-axis components of the equilibrium electron and hole mobility tensors, respectively, ν_3 is the trigonal component of hole mobility, E_0 the band overlap, and τ the electron-hole recombination time. [Mks units are used in (1)]. Mobility components quite small compared to others have been ignored in (1); hence, the approximation sign. Also, surface recombination is assumed to be negligible,[7] and the quantum efficiency of absorbed photons is taken to be unity. The square-root term is the effective diffusion length.

The next term after (1) is of order B^3. We confine ourselves to the small-field case because of certain unexplained transport phenomena at higher fields.[3] The PEM current is found to be linear with B up to ~1 gauss, and even the earth's field is detectable.

Mobility values from reference 3, corrected for the resistivity ratio of the present sample, are inserted in (1) and give the recombination time $\tau \sim 2\times10^{-8}$ sec, with an uncertainty factor of 3; this is mainly due to the uncertain value of ν_3 in bismuth and the estimate of the absorbed light flux I. Electron and hole relaxation times[3] for this sample are probably about 4×10^{-10} and 8×10^{-10} sec, respectively.

Two previous claims of observation of the PEM effect in bismuth are doubtful. The first,[8] for a deposited film at 300°K, reports a spectral response (between 1 and 4 μ) which apparently is proportional to radiant power, not photon flux. The second case,[9] for very thin crystals at 300°K that only give a voltage when intensely illuminated edgewise, is almost certainly a magnetothermal effect due to a temperature gradient, particularly since the sample temperature climbed to 28°C under illumination.

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ENERGY LEVELS OF He^4 †

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A number of recent experiments[1-6] using the reactions $T(d,n)He^{4*}$, $T(p,p)T$, and $He^3(d,p)He^{4*}$ have indicated the existence of an excited state in He^4 about 20 MeV above the ground state. Because this state lies above the threshold for breakup into a proton and a triton, reactions such as $T(d,n)He^{4*}$ and $He^3(d,p)He^{4*}$ actually lead to three-body final states, e.g., $T+D \to T+p+n$, where excited states in He^4 are seen as final-state interactions between the outgoing proton and triton. In order to remove the ambiguity which can be introduced by measuring the energy of only one member of such a three-body system, we have extended the in-