Letters to the Editor

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Modulation of Light Reflected from Germanium by Injected Current Carriers

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IT has been found that it is possible to modulate the light reflected from germanium by injecting current carriers.

A beam of light from a tungsten lamp was focused on the surface of a germanium monocrystal diode. The reflected light was analyzed by a spectrophotometer with a cathode-ray tube. A PbS photoconductive cell connected to a 1000-cps narrow-band amplifier was used as a detector. When a sine-wave voltage was applied to the diode a modulated component in the reflected light appeared, the degree of modulation depending on the size of the alternating current flowing through the diode and on the wavelength of the light. A modulation depth of up to 0.5% was observed.

Samples of n-type germanium of resistivity 6–20 ohm cm and intrinsic Ge of resistivity 60 ohm cm were used.

The current carriers were injected either by metal point contacts or by a p-n junction produced by a diffusion method.

The Ge surface, upon which the effect was observed, was obtained by cleavage, etching, and polishing.

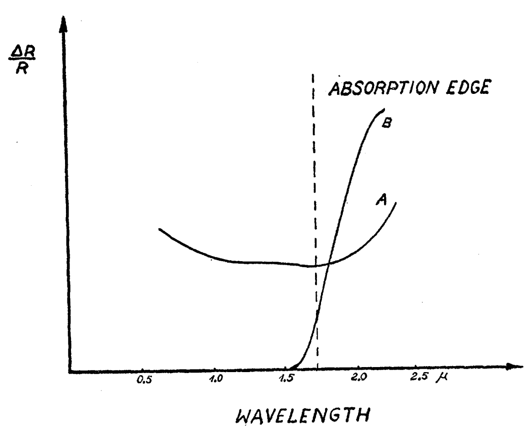

FIG. 1. Spectral distributions of the fractional change in reflection coefficient in germanium.

Two essentially different types of spectral distributions were found; these correspond to curves A and B of Fig. 1. The occurrence of modulation of strong absorption in the short-wavelength region in germanium is characteristic of type A. Type B modulation occurs only beyond the absorption edge of germanium. Type A occurs for point-contact diodes illuminated near the contact. The type B spectral distribution occurs for junction diodes when the reflecting germanium surface is opposite to the indium-doped region. Spectral distributions of a type intermediate to A and B were also observed.

Special care was taken to ensure that the observed effects were not the result of the additional absorption of light due to injected carriers. This was done by eliminating the possibility of reflection from the rear surface of the crystal. By placing a germanium filter (0.3 mm thick) between the light source and the reflecting surface one can eliminate the generation of hole-electron pairs by the incident radiation. Under these conditions the modulation in the long-wavelength region was essentially unaffected.

A full account of this work will be published in the *Acta Physica Polonica*.

Contribution of Current Carriers in the Reflection of Light from Semiconductors

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A NEW electro-optical phenomenon has been found by Filiński,[1] namely a modulation of the reflection of light from germanium by the injected current carriers. In the present note an attempt is made to interpret this effect.

The reflection coefficient R at normal incidence is connected with the complex index of refraction $n_c = n - ik$ by the well-known formula:

$$R = [(n-1)^2 + k^2]/[(n+1)^2 + k^2].$$

On the other hand, n_c may be expressed by the microscopic polarizability α_c:

$$\frac{n_c^2 - 1}{n_c^2 + 2} = \frac{4\pi}{3}\alpha_c = \frac{e^2}{3\pi m}\sum_{kK}\frac{f_{kK}}{(\nu_{kK}^2 - \nu^2) + i\gamma_{kK}\nu}. \qquad (1)$$

The summation (or integration) is taken over all occupied states represented by the wave vector k. Terms of the sum with $K \neq 0$ correspond to interband transitions, whereas terms with $K=0$ correspond to transitions within one band (contribution of free carriers).

For further semiquantitative discussion we shall represent the polarizability of the medium by a one-term expression. The crystal will be represented by N oscillators per unit volume. We assume that their frequency equals ν_0, that f is the oscillator strength, and that γ is the damping constant. Formula (1) may, with these assumptions, be reduced to

$$\frac{n_c^2-1}{n_c^2+2}=\frac{e^2}{3\pi m}\left(\frac{Nf}{(\nu_0^2-\nu^2)+i\gamma\nu}\right). \tag{2}$$

Any change in the number of holes or electrons will correspond to an equivalent change in N. Thus n and k, and consequently R will be functions of N. Assuming small variations of N and restricting the calculation to the region of small absorption ($k \ll n$) one obtains for the change of the refractive index and reflection coefficient:

$$\Delta n=\frac{(n+2)^2}{18n}\left(\frac{fe^2}{3\pi m(\nu_0^2-\nu^2)}\right)\Delta N; \quad \frac{\Delta R}{R}=\frac{4}{n^2-1}\Delta n.$$

With a reasonable estimate of the numerical values involved, $f \simeq 1$, $\nu_0^2-\nu^2 \simeq 10^{28}$ sec^{-2}, $n_{\mathrm{Ge}}=4$, one obtains $\Delta n \simeq 3\times10^{-20}\Delta N$; $\Delta R/R \simeq 10^{-20}\Delta N$.

To explain the magnitude of the effect observed by Filiński ($\Delta R/R$ up to 1%), one has to permit ΔN to be as large as 10^{18} cm^{-3}. A change of volume concentration of this order of magnitude due to injection of minority carriers is out of the question. The presence of a surface layer, however, changes the situation. The difference in concentration of electrons (or holes) between a thin surface barrier region of p type, for instance, and the bulk of the Ge crystal of n type, might well be of this order of magnitude. Under the influence of a voltage applied to the diode, the barrier may be almost completely leveled. Thus the applied field might change the surface concentration by an amount sufficient to explain the Filiński effect.

The spectral distribution corresponding to the curve A of Filiński's paper is thus considered to be due to a primary effect. The occurrence of modulation of reflection in the region of strong absorption in germanium directly establishes the surface character of the effect.

It remains to explain the type B spectral distribution. The lack of modulation beyond the absorption edge of germanium suggests that in this case the reflected light has to pass through some layer of germanium. In fact one can obtain a curve of type B from A if a germanium filter is placed somewhere in the light path. One is thus led to the conclusion that in this case the modulated light is reflected by some surface lying deep within the germanium. Actually in some cases the overlapping of both types was observed.

The additional reflection due to a sharp jump Δn of the refractive index over some plane parallel to the crystal surface is given by $\Delta R/R=4(\Delta n)^2/(n^2-1)^2$ in the case of negligible absorption. To obtain a value for $\Delta R/R$ of one percent, one has to assume a corresponding ΔN of the order of 10^{19} cm^{-3}. Such a value seems to be permissible for the p-n junctions formed in indium-doped germanium crystals for which the type B effect was observed.

Thus the hypothesis that the Filiński effect is due to the influence of the current carriers on the refractive index and that the modulation takes place in the region of either surface or internal p-n junctions seems to explain its main features. The quantitative theory and an explanation of the spectral distribution require knowledge of the oscillator strength and damping constants over the entire range of the absorption spectrum. The effect should not be restricted, of course, to germanium, and the investigation of other substances is under way.

[1] I. Filiński, preceding Letter [Phys. Rev. 107, 1193 (1957)].

Detection of Submillimeter Solar Radiation*

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PRELIMINARY results are given here of experiments aimed at finding regions in the submillimeter wavelength range at which solar radiation is appreciably transmitted by the earth's atmosphere.

Figure 1 shows a spectrum of the sun observed at the Jungfraujoch, Switzerland (altitude 3450 meters). In the wavelength range shown (1 mm to 300μ) there are several maxima which indicate regions of transmission and which extend the observed wavelength range of

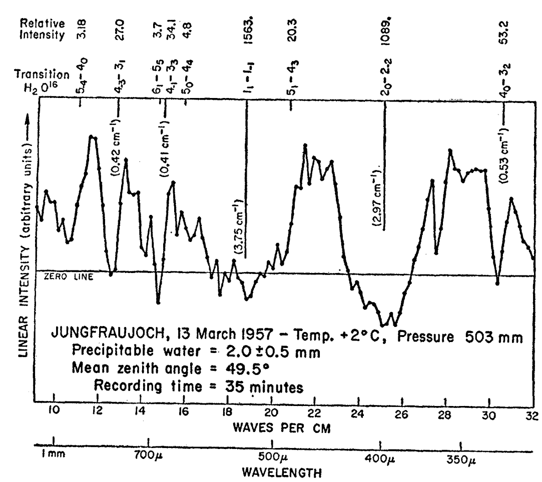

FIG. 1. Submillimeter spectrum of solar radiation showing regions of atmospheric transmission and absorption. The calculated positions and intensities of pure rotation lines of H_2O are given. The numbers in parentheses are calculated half-widths for selected lines.