Photo-emf at a cleaved germanium surface in liquid helium

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Illumination with light at a wavelength $\lambda \lesssim 1.6\ \mu$m produces a significant photo-emf directed along a germanium surface which has been produced by cleaving a crystal in liquid helium and heating it in helium vapor. The effect stems from a quasi-2D diffusion of photoinduced current carriers in a high gradient of the surface resistivity.

The surface conductivity σ_s of germanium immediately after a crystal is cleaved in liquid helium is vanishingly low and is masked by the bulk conductivity[1] $\sigma \sim 10^{-9}$ S, but σ_s can be increased by a factor of hundreds of thousands by an intermediate annealing in He vapor at[1,2] $T_i \lesssim 40$ K. This increase in σ_s is evidently due to an adsorption of impurities, since σ_s remains vanishingly small when adsorption is illuminated, e.g., after a high-temperature annealing in a vacuum chamber at a pressure $p \lesssim 10^{-2}$torr (Ref. 3). After annealing in He vapor, however (as can be seen from the inset in Fig. 1), σ_s increases extremely sharply, in a very narrow interval of T. This behavior suggests that the metal-insulator transition at the Ge surface is a complex transition with a significant involvement of processes other than adsorption.

In an effort to study these effects, we have carried out experiments on cleaved surfaces of Ge crystals during illumination by visible and near-IR light.

The samples are cut from n-type and p-type germanium bars with donor (or acceptor) concentrations on the order of 10^{14}–10^{15} cm^{-3}. The ends of the samples are electroplated with Ni; the electrodes are small strips of indium alloyed along lateral faces. Fresh surfaces are obtained by cleaving the crystals in liquid helium; the dimensions of the samples are $\sim 1 \times 4 \times 10$ mm, and the area of the fresh surface is 1×8 mm^2. After cleavage, a diaphragm with a slit 0.5×1 mm in size is positioned in front of the newly formed surface, and the surface is scanned with monochromatic light at a wavelength $0.8 \leqslant \lambda \leqslant 1.8\ \mu$m and with an intensity $\sim 10^{14}$ cm$^{-2} \cdot$ s^{-1}.

During the annealing, the sample and the heaters are exposed to gaseous helium at $T \simeq 5$ K. The sample temperature is raised to a certain T_i over a time $t = 2$–3 min and then held there for 1 min. The value of T_i is increased from one annealing step to the next. This procedure of "brief" annealing steps yields the behavior σ_s (4.2 K) $= f(T_i)$ shown in the inset in Fig. 1. After each annealing at $T = 4.2$ K, we measure the current-voltage characteristics (in darkness and with illumination). These measurements yielded the following results.

1) There is no photo-emf at a freshly cleaved surface. The short-circuit current is $I_{sc} \leqslant 10^{-9}$ A during illumination of smooth parts of the surface, without any noticeable cleavage defects and at a reasonable distance from the contacts. This result remains the same after intermediate annealings at temperatures T_i below 30 K.

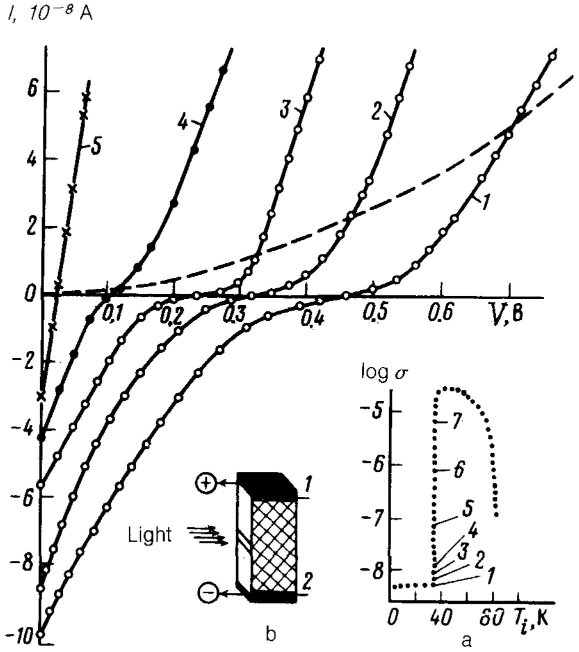

FIG. 1. The I–V curves measured at $T = 4.2$ K during illumination with light at a wavelength $\lambda = 1.2$ μm of a cleaved surface of a p-Ge crystal. The dashed line corresponds to the freshly cleaved surface, while the other lines correspond to surfaces which have been annealed in He vapor at several temperatures T_i: 1—34 K; 2—34.5 K; 3—35 K; 4—35.5 K; 5—36 K; 6—36.5 K; 7—37 K. Inset a: The surface conductivity σ_s (at $T = 4.2$ K, in the absence of illumination) as a function of the temperature T_i. Inset b: Shape of the sample after cleavage of the crystal. The new surface is the unhatched surface. The positions of the light spot and of the electrodes (1 and 2) are shown.

2) With a further increase in T_i, the photocurrent I_{sc} arises and increases rapidly during illumination of the Ge surface. The increase in this current in the temperature interval $31 \leqslant T_i \leqslant 34$ K is accompanied by an increase of the voltage V_{ph} which completely cancels this current. For example, after annealing at T_i values ~31 K, ~32 K, and ~33 K, the current I_{sc} takes on the values $\sim 0.2 \times 10^{-9}$ A, $\sim 1 \times 10^{-9}$ A, and $\sim 6 \times 10^{-9}$ A in succession, and the corresponding voltages V_{ph} are ~20 mV, ~50 mV, and ~180 mV. We see that the intermediate annealing leads to important changes in the properties of the Ge surface, even in the T_i region in which the "dark" characteristics of the samples are indistinguishable from those exhibited immediately after cleavage.

3) After annealing steps in the interval $34 \leqslant T_i \leqslant 38$ K, the cleaved Ge surface undergoes an abrupt insulator-metal transition, accompanied by an increase in σ_s four or five orders of magnitude. During illumination of any part of the Ge surface under these conditions, we observe a significant photocurrent I_{sc}, reaching $\sim 10^{-7}$ A.

At the very beginning of this interval, at $T_i = 34$ K, the quantities I_{sc} and V_{ph} remain proportional, as is characteristic of annealing conditions in the region $T_i < 34$

K: Values $I_{sc} \simeq 10^{-7}$ correspond to voltages $V_{\rm ph} \simeq 500$ mV. Later on, during the transition of the surface from the insulating state to the metallic state, the voltage V_{ph} falls off greatly, spanning the interval 500–0.2 mV as σ_s increases. The photocurrent I_{sc}, on the other hand, remains the same in order of magnitude. Figure 1 shows some typical $J(V)$ curves, measured in the interval $34 \leqslant T_i \leqslant 38$ K during illumination at $\lambda = 1.2$ μm. The labels on the $I(V)$ curves give the number of intermediate annealing steps and their sequence; the same labels in the inset show the values of σ_s measured after each annealing step, in the absence of illumination. It can be seen from Fig. 1 that with increasing σ_s the values of $V_{\rm ph}$ decrease; beginning with annealing step No. 6, they become so low that the corresponding $I(V)$ curves merge with the ordinate axis.

In this T_i region we see yet another structural feature: As σ_s, increasing, approaches the minimum metallic conductivity in a $2D$ medium, $\sigma_{\rm min} \simeq e^2/h$, the photocurrent I_{sc} changes direction, and the voltage $V_{\rm ph}$ changes sign.

Finally, the currents and voltages induced by the light at the annealed Ge surfaces are significant in magnitude not only at $\lambda = 1.2$ μm but also over nearly the entire range of intrinsic optical absorption of the Ge crystals. It can be seen from Fig. 2 that the photocurrent arises at the very edge of indirect transitions; increasing smoothly, it reaches a maximum near $\lambda = 1.4$ μm where direct optical absorption is dominant.

We know that the total current during illumination is

$$I_{\rm sc} = \sigma(E + E^*) = \sigma E + e\left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right), \qquad (1)$$

where σ is the total conductivity, E is the external field, E^* is the field of the "external" forces which are induced by the photoexcitation and diffusion of carriers, D_n and D_p are the diffusion coefficients of electrons and holes, and n and p are their concen-

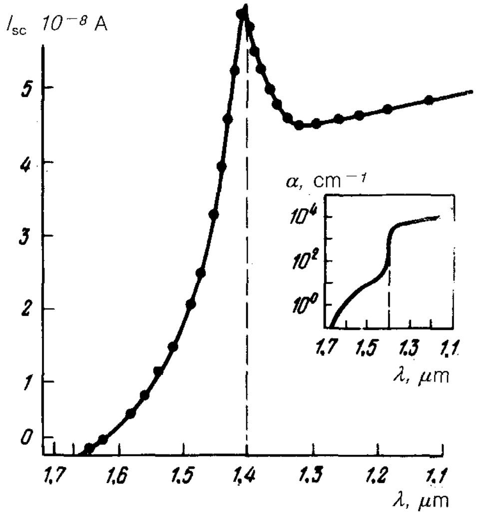

FIG. 2. The photocurrent I_{sc} versus the wavelength of the incident light (the current was measured after one of the intermediate annealings of the surface). The inset shows the absorption coefficient α as a function of the light wavelength.

trations. During illumination of inhomogeneous conductors, a nonzero photocurrent

$$I_{sc} \sim e\left(D_n \frac{dn}{dx} - D_p \frac{dp}{dx}\right)$$

and a nonzero photo-emf $V_{\text{ph}} \sim I_{sc}/\sigma$ will naturally arise.

The values $I_{sc} \leqslant 10^{-9}$ found in our experiments during illumination of freshly cleaved Ge crystals are evidence of the homogeneity of not only the cleaved surfaces but also the interior of the crystal, where the current carriers are generated by the light and then diffuse. The crystals obviously retain their homogeneity after they are heated in helium vapor. Consequently, the significant photoeffects observed in our experiments (currents $I_{sc} \sim 10^{-7}$ A and voltages $V_{\text{ph}} \sim 500$ mV) are related to the properties of the "warmed" surfaces and are caused by processes of a 2*D* or quasi-2*D* nature. Evidence for the latter assertion comes, in particular, from the fact that the dependence of the photo-emf on the surface conductivity is of the form $V_{\text{ph}} \sim I_{sc}/\sigma_s$, characteristic of 2*D* diffusion conditions. (The values of V_{ph}, as we have already mentioned, fall from 500 to 0.2 mV as σ_s increases over the interval $2\times10^{-8} \leqslant \sigma_s \leqslant 5\times10^{-5}$ S in the course of the heating steps.)

The effect seen in these experiments is a 2*D* analog of a phenomenon linked with the names of Lashkarev and Tauc[4]: the appearance of a "distributed" photo-emf during the illumination of a conductor with a nonuniform distribution of the resistivity (in our case, the surface resistivity). This effect can be exploited to study the degree of homogeneity of surfaces. Our experiments show, for example, that a sharp (brief) heating of the surfaces in helium vapor gives rise to significant inhomogeneities and associated high values of the photocurrent $I_{sc} \sim 10^{-7}$ A. In cases in which the heating is uniform and prolonged (lasting times on the order of several hours at lower values of T_i), the value of I_{sc} can be reduced by a factor of 20–50.

The results found in these experiments support the suggestion[3] that the increase in σ_s after annealing in He vapor results from an adsorption of gaseous impurities. The concentration of these impurities at low values of T falls of by a factor of tens as T is lowered by a degree, so that the adsorption of impurities during a time-varying heating is of a nonuniform nature. The heating of the surface under these conditions leads to significant inhomogeneities in the distribution of adsorbed impurities and of the holes bound to them in conducting surface layers.

Spectral measurements (Fig. 2) show that significant photocurrents and photo-emf's arise during illumination at wavelengths $\lambda \lesssim 1.6\ \mu$m, which usually cause a bulk excitation of Ge crystals. It follows from these results that the "annealing-activated" germanium surface acquires the capability to retain photoexcited current carriers in thin surface layers. This interesting result requires further experiments and a theoretical analysis.

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