Relation between microwave absorption fluctuations and surface defects of germanium crystals containing electron-hole drops

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(Submitted 31 December 1981)
Zh. Eksp. Teor. Fiz. **83**, 1058–1064 (September 1982)

It is found that the strains present in many cases in the surface layer of crystals are responsible for the appearance of fluctuations in the absorption of microwaves by germanium crystals containing electron-hole drops. It is suggested that an electron-hole plasma that absorbs microwave radiation strongly appears as a result of formation of large electron-hole drops in the strain region and of their subsequent Auger recombination. Estimates show that the major mechanism of microwave absorption by a plasma is intraband absorption involving hole transitions in the valence band.

PACS numbers: 71.35. + z, 78.70.Gq, 78.50.Ge

INTRODUCTION

One of the most puzzling phenomena observed in earlier studies of microwave absorption by germanium crystals with electron-hole drops is the instability that manifests itself in the form of large absorption-fluctuation spikes.[1] Many attempts were made to explain this phenomenon, but its character is not clear to this day. It has been recently reported that a definite role in the formation of the instability is played by the surface of the crystal.[2,3] In particular, it was observed that the fluctuations occur only when certain regions or points of the crystals are excited.[3]

In the present study we investigated the connection between the fluctuations in the absorption of microwaves and volume and surface damage to germanium crystals. Two series of experiments were performed. In the first we investigated the absorption of microwaves when the surface of a crystal is scanned by a focused laser beam. The main purpose of these experiments was to determine the coordinates of the active regions of the crystal. Next, in the second series of experiments, the same germanium plate was investigated by x-ray topography methods to determine the locations of the local strains in the crystal. A comparison of the pictures of the stresses with the coordinates of the crystal regions that are active in the microwave absorption has shown that absorption spikes arise only when the strained regions are illuminated.

We present below a brief description of the procedures used to register microwave absorption and lattice deformation of the crystals. This is followed by a discussion of the causes of the onset of large absorption of electromagnetic waves in the millimeter band. Estimates of the values of the absorption are presented. These estimates suggest that the most probable cause of the absorption is the electron-hole plasma produced in the strain regions.

EXPERIMENTAL PROCEDURE

The microwave radiation was registered in the following manner. A plate of the investigated crystal was placed in the discontinuity of a quasi-optical waveguide, in which radiation of wavelength $\lambda = 2$ mm propagated. The microwave source, rated ~ 10 mW, was an avalanche transit time diode, followed by a ferrite gate, a high-speed modulator based on a silicon *p-i-n* diode, microwave-to-optical waveguide junction, and a polarization-plane rotator. The radiation receiver (*n*-InSb crystal) was placed behind the investigated germanium crystal. The surfaces of the samples were processed in the standard manner. The plate was first ground, polished, and etched in H_2O_2. The electron-hole drops were excited by light from an argon laser of power ~ 0.5 W at a crystal temperature ~ 1.9 K.

To observe the surface and volume damage to the crystal lattice of the investigated germanium sample, we used Lang's x-ray topography method.[4]

The method consists of photographing the x-ray diffraction reflection of the crystal in transmission geometry, when the diffraction conditions are satisfied for the system of the atomic planes almost perpendicular to the crystal surface. By scanning the crystal and the photographic plate in the incident x-ray beam under diffraction conditions it is possible to obtain a topogram from a specified crystal area containing the images of the defects in the "trans-illuminated" volume.

The defect images are of diffraction origin. These images are produced by a strain mechanism. This means that the intensity and the width of the image of the defects contain information on the magnitude and distribution of the local strain (disorientation) of the crystal lattice of the investigated sample, although the extraction of this information constitutes a difficult and not always solvable problem.

In the case when $\mu t > 1$, where μ is the linear absorption coefficient for the employed x-ray wavelength and t is the crystal thickness, it is possible to determine the sign of the strain from the sign of the contrast of image if the diffraction vector direction is known.[5]

We investigated both dislocation-free crystals as well as a crystal with growth dislocations having an average density $\sim 10^3$ cm^{-2}. From the dislocation-free crystals we obtained a series of topograms in a set of reflections corresponding to one and the same sample area. It was necessary to obtain a

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series of topograms in order to verify the absence of dislocations and, thus, exclude their influence on the investigated phenomenon.

In all the samples we observed regions of local disturbances of the crystal structure, due to surface damage of the crystals. In connection with the high sensitivity of the employed methods to local damage of the crystal lattice, we observed in the investigated samples not only "fresh" scratches introduced into the crystal after etching, but also "old" ones, which were not etched out and constituted the "memory" in the form of fields of residual stresses.

MoK_α radiation was used. The sample thickness ranged from 200 to 450 μm, corresponding to values of μt from ~ 7 to ~ 16. Therefore the crystal photography conditions made it possible to determine the sign of the strain at the location of the damages. As a rule, the contrast of the image of the scratches was such that both tension (dark field) and compression of the lattice (light field) are observed at the location of the scratch. It is much more difficult to estimate the stress level in the deformation regions. Of help in the estimate of this level can be experience in investigation of x-ray diffraction contrast of dislocations, and also of the boundaries of amorphous films on surfaces of semiconductor crystals.[6] In the case of fresh shallow scratches, and also of residual stresses due to old deep scratches incompletely removed by chemical polishing, the minimum relative deformation of the crystal lattice, taken to mean the change of the interplanar distance $\Delta d/d$ observable by this method, is $\sim 10^{-6}$. From Hooke's law we obtain hence for germanium the minimum recordable compression (tension) stress $P = 1$ kgf/cm^2.

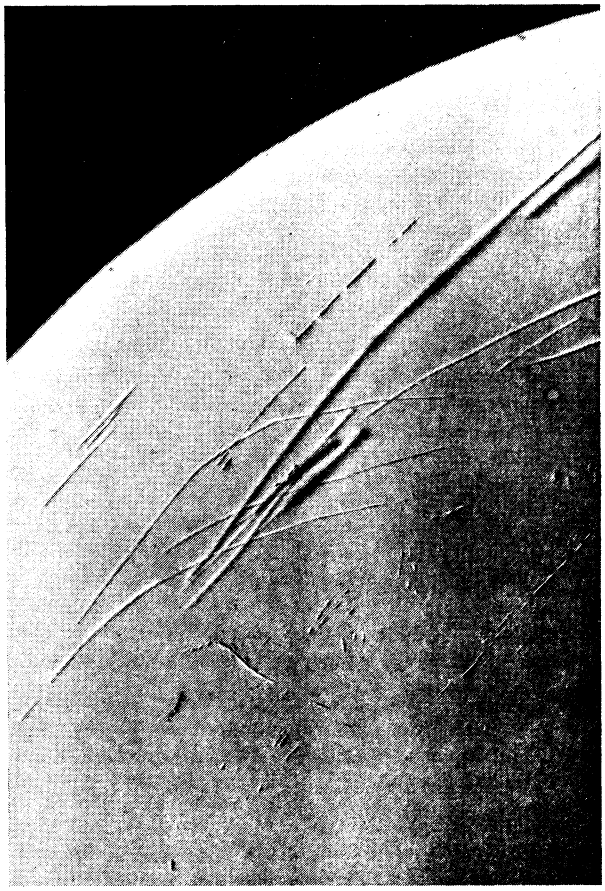

FIG. 1. X-ray topogram of germanium crystal. Crystal thickness 220 μm. Magnification 16$^\times$. The explanation is in the text.

RESULTS AND THEIR DISCUSSION

Figure 1 shows an x-ray topogram of a pure germanium crystal ~ 200 μm thick with an electrically-active-impurity density $N_D - N_A = 10^{11}$ cm^{-3}. There are no growth dislocations in this crystal, but one can see clearly deformation regions in the form of filaments, which exist at the locations of the scratches. Figure 2 shows an oscillogram of the fluctuations of a microwave radiation, observed upon excitation of the crystal in the deformation region. The modulation depth M of the microwave radiation passing through the crystal is large, $M = \Delta I/I_0 = 0.1$–0.5%, where I_0 is the radiation intensity registered by the receiver in the absence of electron-hole drops in the crystal, ΔI is the amplitude of the absorption spikes, and I_0 is determined from the 100% modulation of the radiation by a diode.

Comparing the pictures of the x-ray topogram with the regions of the crystal that absorb the microwave radiation strongly, we arrive at the conclusion that the crucial factor in the understanding of the nature of the large value of the fluctuating microwave absorption is the residual deformation of the crystal surface ($P \gg 1$ kgf/cm^2). This raises the following questions. What is the mechansim that determines so large an absorption and why does the absorption fluctuate in time?

We present below some arguments and estimates which allow us to suggest that the absorption spikes are the result of the appearance of plasma upon Auger recombination of large drops ($R \sim 40$ μm) on the crystal surface, and that the microwave absorption by the plasma is determined by the holes, namely, by direct transitions between subbands of the heavy and light holes in the valence band of germanium.

We consider first the possible cause of the fluctuations in the absorption of microwaves. It is known that the locations of the strains, particularly the region where the lattice is compressed, are potential wells for the drops and for the excitons. Therefore, when the strained region is illuminated with light, one or several large drops with diameters up to ~ 0.5 mm can be produced.[7] This phenomenon can be ob-

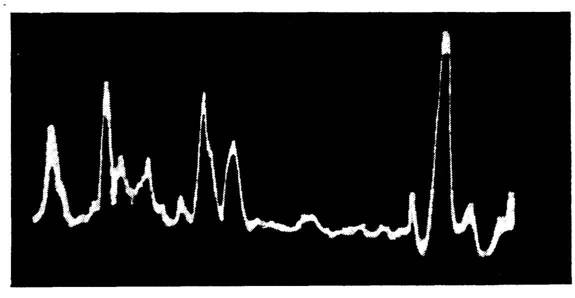

FIG. 2. Oscillograms of absorption spikes of microwave radiation absorption upon excitation of strained regions of the crystal; $\lambda = 2$ mm, $T = 1.9$ K. The horizontal scale is 1 cm = 1 μsec.

served if the region of the maximum pressure is inside the crystal, and the drops do not touch the surface of the sample. If, however, the crystal is subject to surface tension, for example as a result of scratches, these conditions are not satisfied and the drop, without reaching its maximum size can be pushed out by the field of the elastic stresses to the surface, where it will recombine rapidly. Since we have previously observed the boiling of helium on scratches,[3] it can be assumed that the recombination of the electron hole drops in a crystal surface causes not only boiling of helium, but also evaporation of the drop itself and the appearance of plasma.

We assume that the short lifetime of the drops on the crystal surface, $\tau_s \approx 10^{-7}$ sec, is determined by the onset of new recombination mechanisms in which the surface participates, such as Auger recombination with momentum transferred to the surface, or else Auger recombination with participation of the impurities on the surface.[8] Both mechanisms lead to effective heating[9] and to direct ejection of some of the carriers from the drop.

No fluctuations in the absorption of the microwaves were observed in dislocation-free germanium crystals 200 μm thick, thoroughly polished mechanically and chemically, in which there is no surface tension in accord with x-ray topography. The absorption increased smoothly with increasing pump up to a light intensity ~ 10 W/cm^2. We were able to observe in such crystals reversible absorption fluctuations by inhomogeneously deforming the crystal in the [111] direction, directly in the liquid helium, using a Teflon plunger. The removal of the strain led to vanishing of the fluctuations.

Thus, deformation of the crystal surface leads principably to the onset of absorption fluctuations, which we assume to be due to the possibility of formation of large drops under these conditions. On the other hand, microwave absorption is caused by the plasma that appears when an EHD recombines on the surface. The drop can be pushed out to the surface not only by a non-uniform strain, but also, for example, by a phonon stream or, in thin samples, by self-expansion of the drops. If there are no strains on the crystal surface and the drops are small ($R \sim 1\ \mu$m), no fluctuations in the absorption are observed in this case inasmuch as, first, the amplitude of the spikes is small and, second, the frequency of the impacts of the drops against the surface is very high, $\sim 10^8$ sec^{-1}, and the emergence of the electron-hole drops to the surface manifests itself in the appearance of a time-constant background absorption of the microwaves.

We proceed now to discuss the microwave-absorption mechanism. It is known that neither the drops, nor the excitons that are at thermodynamic equilibrium with them at $T = 2$ K, nor the free electrons, nor the holes absorb any significant radiation in the millimeter band.[10] However, if a plasma with a density $\sim 10^{14}$–10^{15} cm^{-3} appears in the crystal, then at low temperatures intense absorption of microwaves will occur on account of direct transitions between the subbands of the heavy and light holes in the valence band of the germanium.[11]

Estimates show that this absorption mechanism, for a plasma with density lower than 10^{15} cm^3, at a frequency $\omega \approx 10^{12}$ Hz and at $T = 2$ K is more effective than the usual Drude mechanism, in which the relaxation time of the carrier momentum is determined by electron-hole scattering.[12]

Let us estimate the cross section for the absorption of microwaves by a plasma filament of length $l > \lambda$, or by a plate, under conditions when the wave vector lies in the plane of the plate or is directed mainly along the filament; this agrees with our experimental conditions. Since $\omega > \omega_p$, the field acting on the electrons and holes in the plasma will not differ in magnitude from the incident-wave field. In this case the depolarizing factor is zero.

An electromagnetic wave passing through a body of volume V loses, on the average per second, an energy

$$Q = \tilde{\sigma}(\omega) E^2 \overline{\cos^2 \omega t}\, V,$$

where $\tilde{\sigma}(\omega) = \omega\varepsilon''/4\pi$ is the high-frequency conductivity of the body, ε'' is the imaginary part of its dielectric constant, and E and ω are the amplitude and frequency of the wave. The effective absorption cross section σ is determined by the ratio of the average dissipated energy Q to the incident-flux density $(n_0 c/4\pi)E^2\, \overline{\cos^2 \omega t}$ (Ref. 13). Hence

$$\sigma = \omega\varepsilon''\, V/cn_0. \tag{1}$$

To calculate σ we must know ε'' and V.

The plasma volume can be roughly estimated from Fig. 1 by assuming that the plasma is restricted to a strain region with dimensions $\sim 200 \times 200\ \mu$m, and the length is specified by the diameter of the exciting-light beam, ~ 0.2 cm.

The imaginary part of the dielectric constant ε'' for the case of intraband transitions was calculated in many papers[14]

$$\varepsilon'' = \frac{\sqrt{2}\, e^2}{\hbar(\hbar\omega)^{1/2}} \left\langle I(\Omega) \left(\frac{m_e m_h}{m_h - m_e}\right)^{1/2} [f(a) - f(b)] \right\rangle; \tag{2}$$

$$f(a) = \left[1 + \exp\left(\frac{a-\mu}{kT}\right)\right]^{-1}, \quad a = \frac{\hbar\omega}{(m_h/m_e - 1)}$$

$$f(b) = \left[1 + \exp\left(\frac{b-\mu}{kT}\right)\right]^{-1}, \quad b = \frac{\hbar\omega}{(1 - m_e/m_h)}$$

$m_e = 0.042 m_0$ is the effective mass of the light holes; $m_h = 0.35 m_0$ is the effective mass of the heavy holes; μ is the Fermi level of the holes in the valence band.

At low quantum energies $\hbar\omega$, corresponding to millimeter waves, we can disregard the corrugation of the valence band and put $I(\Omega) = 1$. It follows from (1) and (2) that intense absorption will be observed in the frequency band from $\hbar\omega_{\min} = \mu(1 - m_e/m_h) = 0.88\ \mu$ to $\hbar\omega_{\max} = \mu(m_h/m_e - 1) = 7.26\mu$ or, if the frequency is constant, in a range of μ from $\mu_{\max} = \hbar\omega/(0.8$–$1.0)$ to $\mu_{\min} = \hbar\omega(5$–$7)$. Intense absorption of electromagnetic waves with $\lambda = 2$ mm ($\hbar\omega = 0.62$ meV) can occur if the hole density lies in the range 10^{15}–$2\cdot 10^{16}$ cm^{-3}. For waves with $\lambda = 8$ mm ($\hbar\omega = 0.15$ meV) the density of a strongly absorbed plasma is in the region with $p = 10^{14}$–$2\cdot 10^{15}$ cm^{-3}. For example, the value of ε'' for a plasma with $p = 10^{14}$ cm^{-3} at $T = 2$ K is

$$\varepsilon''(\lambda = 2\ \text{mm}) \approx 70\,[f(a) - f(b)]. \tag{3}$$

Substituting $\varepsilon'' = 2$ and $V = 8\cdot 10^{-5}$ cm^3 in (1) we obtain $\sigma = 10^{-3}$ cm^2.

The absorption cross section is connected with the experimentally measured modulation depth M by the simple relation $\sigma = MS$, where $S = 0.5$ cm^2 is the area of the microwave-radiation beam incident on the crystal. In our experiments, the measured absorption cross section was $\sigma = (0.001\text{–}0.005)\cdot 0.5$ cm$^2 = (5\text{–}25)\cdot 10^{-4}$ cm^2, which is of the same order as the theoretical estimate.

We now estimate the absorption cross section by another method. We rewrite (1) in the form

$$\sigma = \omega\varepsilon'' N/n_0 cp = \sigma_1 N, \tag{4}$$

where N is the total number of holes released upon recombination of an electron-hole drop on the surface; $\sigma_1 = \alpha/p$ is the absorption cross section per hole. It follows from (2) and (4) that the absorption cross section σ_1 changes very little when the hole density changes in the range $p = 10^{13}\text{–}10^{15}$ cm^{-3}, and amounts to $\sigma_1 = (0.7\text{–}2)\cdot 10^{-13}$ cm^2 at $T = 2$ K and $\omega = 10^{12}$ Hz. Consequently, to obtain the experimental value $\sigma = 10^{-3}$ cm^2 it is necessary that $N = 10^9\text{–}10^{10}$ free carriers be released on the surface upon recombination of the drop, i.e., the radius of such a drop should be not less than $R = (3N/4\pi n)^{1/3} \approx 15\text{–}30$ μm, where $n \sim 10^{17}$ cm^{-3} is the carrier density in the drop in a deformed crystal.[10]

We note in conclusion that raising the crystal temperature above the critical value $T > 6$ K produced a strong time-invariant microwave absorption ($\alpha d > 1$). This is not surprising within the framework of the considered mechanism, inasmuch as at $T > 4$ K the crystal contains a high density of holes capable of absorbing electromagnetic waves.

Recently, Ashkinadze and Bel'kov[15] have proposed another explanation of the large absorption, wherein it is assumed that a layer of electron-hole liquid ~ 1 μm thick is produced on the surface of the crystal. This assumption is easily verified in experiments with a magnetic field directed along the crystal surface. If the microwave absorption is due to formation of the layer and to strong scattering of the carriers by the surface, as assumed by Askhinadze and Bel'kov,[15] the absorption should decrease strongly with increasing magnetic field, owing to the twisting of the carrier trajectories.[16] Actually the necessary experiments was carried out earlier for another purpose in Ref. 17, but no substantial decrease of the absorption was observed up to fields ~ 20 kG. It is precisely such a result that would be expected if the absorption were to be connected with hole transitions in the valence band.[18]

Thus, if we take into account the possibility of Auger recombination of electron-hole drops on the surface and the intraband absorption effect, we can explain in natural fashion also the results of Ref. 15.

The authors are grateful to M. I. D'yakonov and Yu. T. Rebane for helpful discussions.

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Translated by J. G. Adashko