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A. F. Ioffe Physico-Technical Institute,
Academy of Sciences of the USSR, Leningrad

Effect of Weak Electric Fields on the Absorption Edge in Doped Germanium

By

V. M. Asnin, G. L. Eristavi, and A. A. Rogachev

Results of the investigation of a new effect, the great change in the absorption spectra near the direct band edge of germanium in a relatively weak electric field, are presented. The effect is assumed to be due to the screening of the Coulomb interaction by the carriers which are freed by avalanche breakdown of shallow impurities.

Es werden die Ergebnisse von Untersuchungen eines neuen Effekts mitgeteilt, der in einer Änderung des Absorptionsspektrums in der Nähe der direkten Bandkante von Germanium in einem schwachen elektrischen Feld besteht. Es wird angenommen, daß der Effekt durch die Abschirmung der Coulombwechselwirkung durch Ladungsträger verursacht wird, die durch Lawinendurchschlag aus flachen Verunreinigungszentren befreit werden.

The shape of the absorption edge in semiconductors is determined to a considerable extent by Coulomb interaction between the electrons and holes created by light [1]. This interaction is responsible, in the first place, for the appearance of the exciton maxima in absorption.

If free current carriers are present at a sufficiently large concentration, the electron-hole interaction becomes reduced due to screening. As the current carrier concentration increases, the shape of the absorption edge should change from that characteristic for the presence of this interaction to another one obtained for non-interacting particles [1, 2].

A study of the absorption in germanium in the region of direct transitions has shown an increase in current carrier concentration to result in a broadening and disappearance of the exciton peak [3]. The critical concentration corresponding to destruction of the exciton turned out to be about 10^{16} cm^{-3} ($T = 77$ °K). These results permit to predict the existence of a new phenomenon consisting in a strong modulation of the absorption coefficient of a doped semiconductor in relatively weak electric fields.

Indeed, at sufficiently low temperatures the current carriers are on the impurity centres and there is no screening of the field of the electron–hole pairs created by light. However already a quite weak electric field applied to the specimen is sufficient to produce impact ionization of the impurity centres [4]. As a result, the absorption spectra should undergo changes similar to those resulting from thermal ionization of impurities [3]. As for the magnitude of breakdown field, for lightly-doped germanium, for instance, it is only 5 V/cm and increases slowly with increasing impurity concentration [4, 5].

A study was made of the effect of external electric field on the absorption edge of antimony-doped germanium in the concentration range $N_d = 10^{14}$ to

10^{16} cm^{-3} in the direct-transition region. The specimen thickness was 5 to 10 μm, contacts being made by fusing the In+As alloy at $T = 400$ °C. To ensure an adequate mechanical rigidity, thin plates of doped germanium were fixed during the contact alloying to a thicker frame of high-resistivity germanium. Each contact was simultaneously fused to the specimen and the frame thus fixing the specimen to the frame. To avoid possible thermal stress, the frame and the specimen were cut in the same crystallographic directions. All measurements wer carried out on specimens immersed in liquid helium or nitrogen. To reduce overheating, the electric field was applied to the specimens in pulses 1 to 3 μs long.

Fig. 1 to 3 show germanium absorption spectra obtained at $T = 4.2$ and 77 °K. At 77 °K the shape of the absorption edge depends on the degree of doping. An increase of concentration results in a broadening of the exciton line and in a decrease of its intensity. At $N \approx 10^{16}$ cm^{-3} there is no exciton peak in absorption [3], and an application of electric fields of up to 200 V/cm does not produce any marked changes in the shape of the absorption edge.

At 4.2 °K, when all electrons are on the impurity levels, the absorption edge in all specimens has practically the same shape as in pure germanium, as this should be expected [3]. However, if we apply an electric field to such specimens,

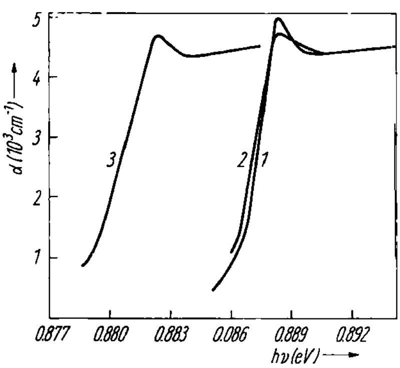

Fig. 1. Absorption spectra of antimony-doped germanium with $N_d = 6 \times 10^{14}$ cm^{-3}. (1) $T = 4.2$ °K, without field; (2) $T = 4.2$ °K, with field $E = 20$ V/cm; (3) $T = 77$ °K

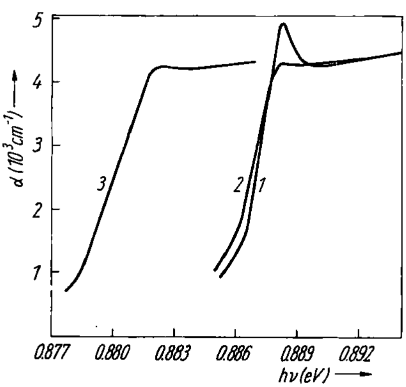

Fig. 2. Absorption spectra of antimony-doped germanium with $N_d = 2 \times 10^{15}$ cm^{-3}. (1) $T = 4.2$ °K, without field; (2) $T = 4.2$ °K, with field $E = 50$ V/cm; (3) $T = 77$ °K

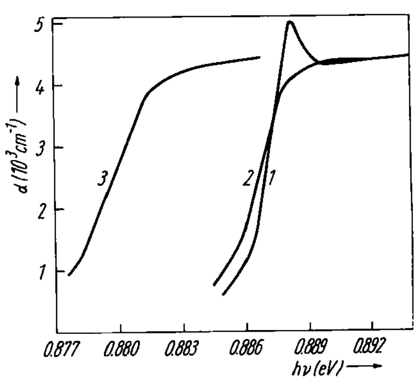

Fig. 3. Absorption spectra of antimony-doped germanium with $N_d = 8 \times 10^{15}$ cm^{-3}. (1) $T = 4.2$ °K, without field; (2) $T = 4.2$ °K, with field $E = 100$ V/cm; (3) $T = 77$ °K

the light passing through them will exhibit modulation near the absorption edge. The modulation spectra are shown in Fig. 4. At the wavelength corresponding to the exciton peak one observes much stronger transmission whereas at energies corresponding to the wings of the exciton line the transmission becomes weaker. Such pattern of the modulation spectrum indicates that the exciton line becomes diffuse in an electric field.

In order to clarify the nature of the observed effect, we have determined the dependence of the percentage of modulation of the absorption coefficient near the exciton peak on electric field applied to the specimen. The current–voltage characteristics of the specimens were obtained simultaneously. It has been found (Fig. 5) that modulation of the absorption coefficient appears at the same fields at which impact ionization of impurity centres occurs. Besides, the region of steep increase in the modulation percentage vs. field curves coincides with that of a superlinear current increase in the current–voltage characteristics of impurity breakdown, and saturation occurs at fields corresponding to a complete ionization of the impurity centres. This indicates that the onset of modulation is indeed associated with the appearance of free carriers.

Fig. 1 to 3 (curve 2) display the absorption spectra of specimens with different degree of doping obtained at fields corresponding to complete ionization of the impurity centres. The absorption edge is seen to have practically the same shape as at $T = 77$ °K when all impurities are thermally ionized. This indicates that in both cases the mechanism responsible for the destruction of the exciton absorption is apparently the same, namely, a screening of the electron–hole interaction by free current carriers.

Generally speaking, a similar change in the shape of the absorption edge in germanium in an electric field can be due to two other mechanisms.

The first of them is associated with impact ionization of $\boldsymbol{K} = 0$ excitons created by light by electrons in the [111] minima. The broadening of the exciton line due to this process will be evidently proportional to electron concentration.

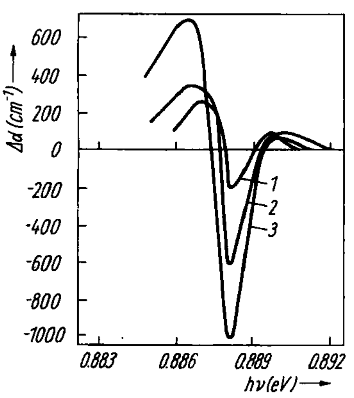

Fig. 4. Spectra of germanium absorption coefficient modulation at 4.2 °K in electric fields corresponding to total ionization of impurity centres. (1) $N_d = 6 \times 10^{14}$ cm^{-3}; (2) $N_d = 2 \times 10^{15}$ cm^{-3}; (3) $N_d = 8 \times 10^{15}$ cm^{-3}

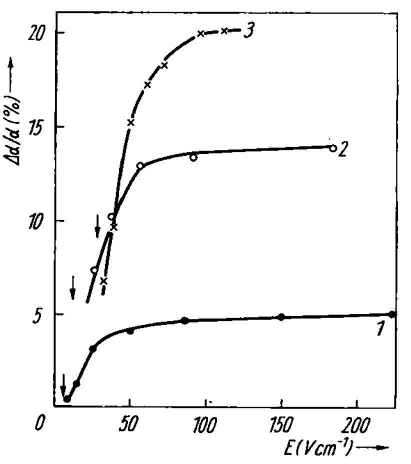

Fig. 5. Dependence of modulation percentage of germanium absorption coefficient near exciton peak on electric field at $T = 4.2$ °K. (1) $N_d = 6 \times 10^{14}$ cm^{-3}; (2) $N_d = 2 \times 10^{15}$ cm^{-3}; (3) $N_d = 8 \times 10^{15}$ cm^{-3}. The arrows mark the magnitude of breakdown field for each of the specimens

Since the dependence of modulation percentage on carrier concentration observed experimentally is much weaker than that (Fig. 5), it can be suggested that impact ionization of excitons in these experiments does not play an important role.

Another mechanism whereby electric field could affect the exciton absorption is due to the ionization of excitons in a static electric field. This effect has been experimentally studied in germanium for the case of direct exciton [6], where the disappearance of the exciton line in absorption was shown to occur at fields of $\approx 10^3$ V/cm so that at fields used by us this effect could not be significant.

It is of interest to compare the percentage of absorption coefficient modulation in electric field obtained in our experiments, with the modulation caused by an electrostatic ionization of excitons. According to [6], this effect results in a decrease of the absorption coefficient near the exciton peak by about 4% in fields of ≈ 140 V/cm. Now in our experiments (Fig. 5) such modulation is observed in germanium with $N_d = 6 \times 10^{14}$ cm^{-3} at ten times weaker fields. At the same time in specimens with an impurity concentration $N_d = 8 \times 10^{15}$ cm^{-3} modulation reaches 20% already at a field ≈ 100 V/cm.

The evidence presented indicates that the observed effect of weak electric fields on the absorption edge of doped germanium is indeed associated with the screening of electron–hole interaction by current carriers liberated in the process of impact ionization of the impurity centres.

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