RADIATION-INDUCED CHANGE OF POLARIZATION OF TERAHERTZ RADIATION IN n-Ge

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We investigated the angular dependence of the polarization of terahertz (THZ) radiation of hot electrons in weakly doped (10^{14} cm^{-3}) n-Ge at 5 K, as well as its change due to the irradiation with 1-MeV electrons. It is established that, at the expense of irradiation, the THZ radiation phase changes by 90°. That is, if the radiation polarization is directed along the electric field in the initial samples, then the direction of the polarization vector becomes normal to the direction of the electric field after the introduction of radiation defects.

Work [1] presents the experimental results of measurements of the polarization direction of the terahertz radiation of n-Ge hot electrons for various concentrations of charge carriers.

In a heavily doped material (ρ =0.3–0.05 Ohm·cm), the radiation polarization is normal to the direction of the electric field. For a weakly doped material (ρ =40–45 Ohm·cm), the polarization is parallel to this direction. Since the dominant types of charge-carrier scattering in heavily and weakly doped materials at helium temperatures are, respectively, the scattering by charged impurities and by acoustic vibrations of the lattice, a hypothesis was proposed, according to which the form of the polarization characteristic is related to the mechanism of charge-carrier scattering.

In order to check this hypothesis, it was decided to introduce additional charged centers into weakly doped n-Ge, where the scattering of charge carriers takes place mainly due to their interaction with acoustic phonons, while the radiation polarization is parallel to the direction of the electric field. In this way, one reaches the conditions, under which the scattering by charged defects becomes the dominant type of charge-carrier scattering. In this case, the polarization direction becomes normal to that of the heating electric field.

Additional scattering centers were introduced by means of the irradiation of n-Ge samples (ρ=10 Ohm·cm) by 1-MeV electrons at room temperature. It is known that, in this case, the dominant radiation defects are those of the acceptor type with the electron level E_C=0.20 eV. The effectiveness of the appearance of such effects $\Delta N/\Delta\Phi$ (the concentration of defects created by one high-energy electron) amounts to 0.10 cm^{-1}. The polarization dependences of radiation (Fig. 1) were measured using the samples with dimensions of $1 \times 1 \times 7$ mm at a temperature of about 5 K. The signal from a receiver (gallium-doped germanium) corresponded to the zero angle of rotation of the polarizer, where the polarizer lines were parallel to the electric field. The short-wave part of the radiation below 50 μm was cut by a black polyethylene filter. The pulsed (0.8 μs) electric field with a repetition frequency of 6 Hz was applied along the large size of the samples cut off in the $\langle 111 \rangle$ crystallographic direction. The magnitude of applied voltage amounted to 50–200 V.

Figure 2 presents the polarization dependences of the samples before the irradiation (upper curve) and after the irradiation with a dose of 6×10^{14} cm^{-2} (lower curve). One can see that, in the initial samples, the signal reaches a maximum at the rotation angle of the polarizer of 90°, i.e. the polarization direction is parallel to the electric field. In the irradiated samples, the polarization direction has changed to the opposite one. The experimental curves are well described by the sine (initial sample) and cosine (irradiated sample) functions. Moreover, one should operate with the absolute values of the functions as the magnitude of the signal is repeated in 180°.

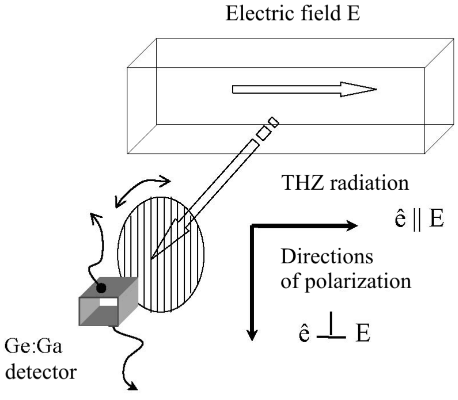

Fig. 1. Diagram of experimental conditions and principal elements of the registration of radiation

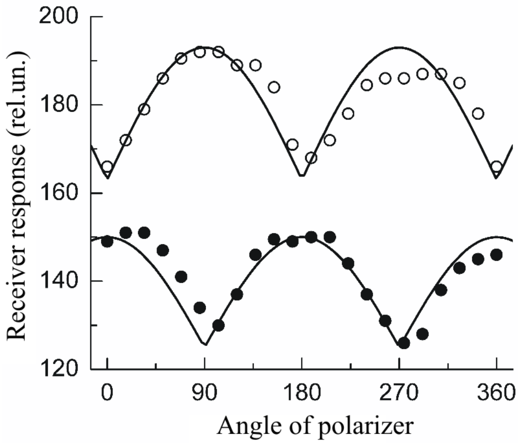

Fig. 2. Dependence of the radiation intensity on the rotation angle of a polarizer. Dots – experiment, solid curves – model functions. Upper curve – before irradiation, lower curve – after irradiation with a dose of 6×10^{14} electrons/cm^{-2}

The concentration of equilibrium electrons in the initial samples amounted to 10^{14} cm^{-3}. The compensation degree of the conductivity did not exceed 20%. That is, the concentration of alloying donors $\leq 1.25 \times 10^{14}$ cm^{-3}, that of compensating acceptors $N_{\rm A} \leq 2.5 \times 10^{13}$ cm^{-3}, while the concentration of charged centers at the helium temperature $(N_{\rm D}^{+} + N_{\rm A}^{-}) \leq 5 \times 10^{13}$ cm^{-3}. Due to the ionization of donor levels by the electric field, the concentration of charged centers will increase up to $(N_{\rm D} + N_{\rm A}) \leq 1.5 \times 10^{14}$ cm^{-3}. The irradiation with the used dose allowed one to additionally introduce compensating acceptors with the concentration $N_{\rm CA}$ of 6×10^{13} cm^{-3}. At the helium temperature (and the ionization of donors by the electric field), the density of charged defects will be $(N_{\rm D} + N_{\rm A} + N_{\rm CA}) \leq 2.1 \times 10^{14}$ cm^{-3}.

Is it enough to change the scattering mechanism?

As follows from results in [1], the scattering of charge carriers by charged defects becomes the dominant mechanism at doping impurity concentrations $>10^{15}$ cm^{-3} (for ρ=0.7 Ohm·cm). One can see that even the maximally possible concentration of scattering centers in the irradiated samples is less than the required magnitude. But the defects $E_{\rm C}$–0.20 eV created at the expense of irradiation have unusual properties. The estimation of the charge-carrier scattering by these defects demonstrates that their cross section exceeds the scattering cross section by singly ionized centers at least by a factor of 16 [2]. It is considered that the increase of the scattering cross section is determined by the interaction of charge carriers with elastic stress regions created by defects [3]. In this case, we obtain that the effectiveness of the scattering of charge carriers by radiation defects formed by irradiation (6×10^{13} cm^{-3}) corresponds to at least the sixteenfold greater concentration of usual singly charged scattering centers. Under such conditions, the effective concentration of scattering centers will be approximately equal to 10^{15} cm^{-3}. This value becomes close to the concentration of a doping impurity, at which the scattering by acoustic phonons was replaced by the impurity scattering [1].

Thus, the experimental results (Fig. 2) indicate that, in the case of the transition from the charge-carrier scattering by acoustic phonons (weakly doped n-Ge) to the scattering by additionally introduced radiation defects, there occurs the inversion of the polarization dependence of terahertz radiation. That is, it changes from the case, where the radiation polarization direction coincides with that of the electric field, to the opposite case, where the direction of the polarization vector is normal to the latter.

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1. V.M. Bondar, N.F. Chernomorets', Ukr. Phys. Zh. **48**, 51 (2004).
2. V.V. Emtsev and T.V. Mashovets, *Impurities and Point Defects in Semiconductors* (Radio i Svyaz, Moscow, 1981) (in Russian).
3. V.V. Emtsev, M.I. Klinger, and T.V. Mashovets, Pis'ma Zh. Eksp. Teor. Fiz. **19**, 575 (1974).

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РАДІАЦІЙНО НАВЕДЕНА ЗМІНА ПОЛЯРИЗАЦІЇ ТЕРАГЕРЦОВОГО ВИПРОМІНЮВАННЯ В n-Ge

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Резюме

Досліджено кутову залежність поляризації терагерцового (ТГЦ) випромінювання гарячих електронів в слаболегованому (10^{14} см$^{-3}$) n-Ge при 5 К та її зміну в результаті опромінення електронами з енергією 1 МеВ. Встановлено, що в результаті опромінення спостерігається зміна фази ТГЦ випромінювання на 90°. Тобто, якщо у вихідних зразках напрямок поляризації випромінювання збігається з напрямком електричного поля, то після введення радіаційних дефектів напрямок вектора поляризації стає перпендикулярним до напрямку електричного поля.