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Improving the efficiency of photopiezoelectric induction acoustic waves in semi-insulating single crystals of gallium arsenide

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The work is devoted to the analysis of the influence of acoustic losses on the efficiency of inducing resonant acoustic waves in single-crystal gallium arsenide plastids using infrared light pulses. It is established that the amplitude of the excited mechanical vibrations depends on the magnitude and position of the internal friction in the crystal on the temperature scale due to acousto-electronic relaxation. Recommendations on the choice of the element of the alloying admixture of gallium arsenide are formulated.

Keywords: optical absorption, piezoelectric effect, relaxation, optical pulses.

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The work [1] describes the effect of photopiezoelectric induction of resonant acoustic waves in single-crystal plates of semi-insulating gallium arsenide containing no specially introduced impurities. The effect is based on the conversion of the optical pulses energy with their own absorption wavelength in the semiconductor into a pulsating photo-emf, which, through the inverse piezo effect, generates mechanical oscillations of the piezoelectric cut plate. If the repetition frequency of the optical pulses is close to the resonant mode frequency (bending, longitudinal, etc.) of the acoustic wave in the plate, there will be a parametric amplification of the mechanical vibration amplitude. The oscillating plate in this case can be seen as a semiconductor piezoelectric optically pumped resonator, which can be used as a receiver of optical signals and has the selectivity of the modulation frequency of the optical signal [2]. Further studies of the properties of such a resonator have shown that its selective properties, determined by the mechanical quality factor of the resonator plate, depend on external factors such as losses at the plate fixing points, damping by the environment and also, to a large extent, on internal friction in the semiconductor crystal. The latter component of the loss cannot be eliminated by design methods, as it is determined by the internal properties of the material. In this connection, the dependence of efficiency of induction of resonant mechanical oscillations in GaAs plates with the most often used deep Cr and Fe impurities on internal friction in the operating temperature range of optoelectronic devices was investigated.

The amplitude of the resonant bending oscillations of a GaAs plate under the optical pulses impact and the internal friction were determined [1] to measure the internal friction of solids on the same samples. Single-crystal gallium arsenide plates grown by the Czochralski method were used, alloyed with iron or chromium impurities in the melt, providing high resistivity (10^3 and $4 \cdot 10^5\,\Omega \cdot$ m, respectively) through compensation of small background impurities. Rectangular shaped samples of size $18 \times 6 \times 0.4$ mm had a $\{100\}$ plane orientation and a long face direction along the $\langle 110 \rangle$, at which bending deformation causes piezoelectric charges in the maximum volume. The plates were mounted horizontally in a vacuum chamber on two $50\,\mu$m thick quartz strands attached to a quartz base with film electrodes serving as a capacitive sensor. The support points coincided with the plate oscillation points. Pulsed optical irradiation of the test samples was performed through a transparent window using a L-7113SF6C LED with a wavelength of 860 nm and a power of up to 100 mW. The repetition rate of the optical pulses was chosen to be equal to the frequency of the first bending mode. The oscillations were recorded using a capacitive sensor. Internal friction was measured by free oscillation damping using electrostatic excitation.

Figure 1 shows the results of measuring the temperature dependence of the amplitude of bending oscillations induced by optical pulses in the studied gallium arsenide plates.

The curves in Fig. 1 show that the maximum vibration amplitude of the Fe impurity plate (curve *1*) is 4 times greater than the vibration amplitude of the Cr impurity plate (curve *2*). The presence of Cr in GaAs creates a deeper energy level (0.76 eV) in the band gap compared to Fe impurity (0.52 eV) [3,4] and provides higher resistivity and optical sensitivity of semiconductor [5]. In addition,

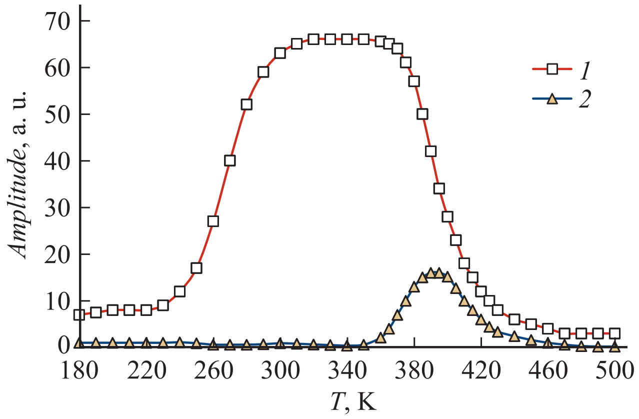

Figure 1. Temperature dependence of bending oscillation amplitude with frequency of 6.3 kHz induced by optical pulses in GaAs plates with Fe (*1*) and Cr (*2*) impurities.

the piezoelectric effect is stronger in high resistivity semiconductors. Therefore, it was logical to assume that the Cr impurity should provide a larger oscillation amplitude than the Fe impurity. However, the opposite ratio is observed (Fig. 1). The explanation for this lies in the results of measurements of the temperature dependence of the internal friction in GaAs plates with the above impurities (Fig. 2).

It can be seen from Fig. 2 that in the absence of optical irradiation in both types of samples there are Debye peaks of internal friction (curves *1* and *3*), which are caused by acoustic electronic relaxation of free charge carriers in an alternating piezoelectric field like Maxwell relaxation [6]. Their activation energy is close to the ionization energy of the corresponding impurity level. Under pulsed optical irradiation with a wavelength of 860 nm, both peaks widen in the low temperature region (curves *2* and *4*), which is typical of peaks of this nature. This broadening is due to the appearance of a relaxation time spectrum of non-equilibrium conduction near the optical absorption region in the presence of a sign-variable piezoelectric plate bending deformation field, i.e., radiation-activated charge carriers become participants of the relaxation process along with equilibrium free carriers. A paradoxical feature of the described processes is that the same non-equilibrium charge carriers generated near the irradiated GaAs surface induce mechanical oscillations of the plate and at the same time, they are partially damped as a result of relaxation redistribution in the alternating piezoelectric field generated by these vibrations. The degree of damping can be judged from the change in internal friction Q^{-1}, the inverse of the mechanical quality of the plate, which increases by almost two orders of magnitude: from a value of $Q^{-1} = 10^{-5}$ (the background value) to $Q^{-1} = 10^{-3}$ at the maximum of the relaxation curves. This leads to a significant deterioration in the selectivity of optical signal receivers based on this principle.

If the data in Figs. 1 and 2 are compared, it can be seen that the maximum amplitude of vibration of the plates takes place in the temperature range where the values of internal friction and natural conductivity are small at the same time. The high-temperature dip of *1* and *2* curves in Fig. 1 occurs in the same interval (above 400 K) and is associated with an increase in intrinsic conductivity in GaAs [3], which causes screening of photo-emf. In this case, the decrease in amplitude of excited oscillations in the low-temperature region of the curves *1* and *2* in Fig. 1 is due to damping associated with the presence of internal friction. It is noteworthy that in GaAs⟨Fe⟩ samples, the amplitude of excited oscillations in the temperature range of 280–350 K is approximately 100 times greater than in GaAs⟨Cr⟩ samples (Fig. 1), at equal irradiation intensity, despite the fact that the Cr impurity provides resistivity and optical sensitivity two orders of magnitude higher. This is due to the fact that the temperature regions of internal friction and intrinsic conductivity for GaAs⟨Cr⟩ overlap, while for GaAs⟨Fe⟩, the interval between regions is over 100 K. Thus, the lower the acoustic electronic absorption region on the temperature scale, the higher the amplitude and wider the temperature range of the acoustic oscillations excited by the optical pulses. This means that it is necessary to choose a doping impurity in GaAs that has an acoustic electronic absorption region at a lower temperature and at the same time provides satisfactory optical sensitivity of the semiconductor. The operating temperature range, in which devices based on the principle of photopiezoelectric induction of acoustic oscillations for GaAs⟨Fe⟩ can be realized, is 240–440 K (Fig. 1), which almost corresponds to the operating temperature range of opto-electronic devices.

The main conclusion to be drawn from the results is that the efficiency of photopiezoelectric induction of acoustic oscillations and the frequency selectivity of optical signal receivers based on the described effect depend more on the damping effect of internal friction than on the resistivity and optical sensitivity of gallium arsenide.

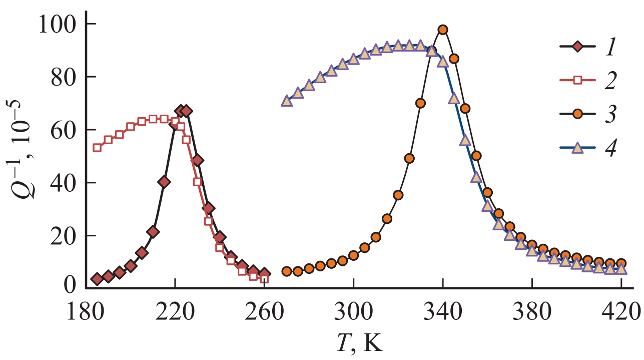

Figure 2. Temperature dependence of internal friction Q^{-1} in GaAs plates with Fe (*1*,*2*) and Cr (*3*,*4*) impurities. Curves *1* and *3* were obtained with darkened samples, curves *2* and *4* — with pulsed optical irradiation at a wavelength of 860 nm. Bending frequency is 6.3 kHz.

Conflict of interest

The authors declare that they have no conflict of interest.

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