Infrared and terahertz transmission properties of germanium single crystals

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Abstract. Experimental transmission spectra of samples fabricated of germanium single crystals doped with stibium were registered in the infrared 2.5-25 µm and terahertz 130 µm regions of spectrum. It is shown that doping concentration and treatment of the crystals surface have a noticeable influence on the samples absorption.

1. Introduction

Terahertz (THz) radiation is widely used in modern and traditional fields of science and technology such as optics, material science, medicine, biology, biochemistry, and etc. [1, 2]. As for optical devices operating in the THz spectral domain, it is very important to ensure development of their basic elements including radiation sources, detectors and transparent media. Special requirements on the THz optical elements are related to the peculiar character of the spectral range.

Usually crystalline silicon, crystals of quartz and sapphire as well as the polymers (polymethylpentene (TPX), polyethylene (PE), teflon (PTFE)) are applied in THz technology [3]. High-resistivity single crystal silicon grown by zone melting without crucible technology is the example of a transparent and well investigated medium. Germanium as well as silicon are also typical semiconductor materials applied in the THz spectral region. As known, crystalline germanium is widely used at the wavelengths 2.5-14 µm in mid-infrared (IR) optics, in photodetectors, detectors of ionized radiation and photovoltaic transducers [4-6]. P-type germanium served as a matrix of a monopolar THz laser [7]. The only acousto-optic crystalline material that has been used at the THz frequencies is the single crystal germanium. A wide-angle THz beam deflector has been developed and successfully tested on the base of this crystal [8].

Investigations of optical properties of germanium in the THz region is of a considerable interest in optics and acousto-optics. In this paper, a comparative analysis of IR and THz transmission spectra measured in the germanium crystals is carried out. The germanium samples were characterized by various concentrations of stibium and different treatment of their surfaces.

2. Objects of investigations and experimental techniques

In this research, a detailed investigation of germanium single crystals grown along the direction [111] by the Czochralski method was performed. We also examined properties of the germanium single crystals doped with stibium Sb or with both stibium and gallium Ga (compensated crystals). The...

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treatment of the samples included polishing ($N < 1$; $\Delta N < 0.5$) and grinding (by abrasive M10). Thickness of all samples was equal to $l = 1.0$ cm. Transmission spectra of the samples in the THz range were measured using the Novosibirsk free-electron laser operating at the wavelength $\lambda = 130$ $\mu$m. We also employed the Golay cell as a detector of the THz radiation. In the IR spectral domain 2.5-25 $\mu$m, the study was carried out by means of the Fourier transform spectrometer Tensor-27.

3. Results and discussions

The detailed characteristics of the samples as well as their determined absorption coefficients $\alpha$ and the refractive indexes $n$ at the wavelengths 10.6 $\mu$m and 130 $\mu$m are summarized in Table 1. The recorded transmission spectra $T$ in the frequency range from $\nu = 4500$ $\text{cm}^{-1}$ to $\nu = 375$ $\text{cm}^{-1}$ are shown in Fig. 1. The curves in Fig. 1 are numbered from 1 to 5 according to the sample numbers in Table 1. It was found that the transmission of the samples in the THz range depended on the concentration of doping. As for the IR transmission properties, they are mainly related to the free-carrier absorption.

As follows from data in Table 1, absorption of the samples in the THz range is substantially stronger than in the IR. For example, transmission is equal to $T = 0.47$ at the wavelength $\lambda = 10.6$ $\mu$m and it is about 0.15 at the wavelength $\lambda = 130$ $\mu$m. The minimal value of the absorption coefficient $\alpha = 1.04$ $\text{cm}^{-1}$ was registered in the sample number 3 having the smallest dopant concentration. In the reference [8], the reported absorption coefficient of a pure high-resistivity germanium crystal was equal to $\alpha = 0.75$ $\text{cm}^{-1}$. However, we found that the IR transmission of the doped germanium was similar to that in the THz region. We propose that this feature originates from high concentration of the free-carriers $n_e$ even in the pure germanium. For example, the pure germanium samples have the intrinsic carrier concentration $n_e = 2.5 \times 10^{13}$ $\text{cm}^{-3}$ and the resistivity of about $\rho = 47$ $\Omega\cdot\text{cm}$, whereas for the pure silicon, these parameters are the following $n_e = 5 \times 10^{10}$ $\text{cm}^{-3}$ and $\rho = 2$ $k\Omega\cdot\text{cm}$.

Table 1. Determined absorption coefficients and detailed sample characters.

| Property                        | $\lambda$, $\mu$m | Number of the sample ($l = 1.0$ cm) |
|---------------------------------|-------------------|-------------------------------------|
| Transmission $T$ ($n = 4.0000$) | 130               | 1.3841·10^{-3} 5.5882·10^{-3} 0.1469 0.050 0.1375 |
| Absorption coefficient $\alpha$, cm$^{-1}$ | 10.30 8.90 1.04 2.11 1.11 |
| Transmission $T$ ($n = 4.0048$) | 0.135 0.364 0.456 0.451 0.447 |
| Absorption coefficient $\alpha$, cm$^{-1}$ | 1.122 0.207 0.024 0.032 0.041 |
| Dopant concentration, $\text{cm}^{-3}$ | 8.0·10^{15} 8.0·10^{15} 1.3·10^{14} 3.0·10^{14} 5.5·10^{13} |
| / impurity                      | /Sb /Sb /Sb /Sb /Sb-Ga |
| Resistivity $\rho$, $\Omega\cdot\text{cm}$ | 0.26 0.26 13.5 5.0 33.0 |
| Type of conductivity           | n n n n p |
| Surface treatment              | grinding polishing polishing polishing polishing |
| Dislocation density , $\text{cm}^{-2}$ | < 10 < 10 $10^4$ $10^4$ $10^4$ |

* - concentration difference (Sb concentration 7.0·10^{15} $\text{cm}^{-3}$; Ga concentration 12.5·10^{13} $\text{cm}^{-3}$).
As one can see from data presented in Table 1, the transmission of the polished sample (number 2) is substantially higher than that in the grinding sample (number 1). The ratio of the transmission coefficients at the wavelength $\lambda = 130 \mu m$ is equal to $T_1/T_2 = 4$. This feature may be explained in the following way. Optical path $d$ of a THz beam is increased by an increment $\Delta d$ due to oblique incidence of the radiation on each microfacet forming microtopography of a polished sample surface. In case of high absorption this leads to strong intensity reduction. The relative value $\Delta d/d = 15\%$ was found using the Bouguer-Lambert law. Therefore, mean angle of incidence of the beam on the fracture-squares equaled to $29^\circ$. The averaged angle of microfacet orientation with respect to the vertical forming the surface microrelief of the polished sample was estimated making use of the law of refraction for $n = 4.0$ and $\lambda = 130 \mu m$. This angle was about $55^\circ$ and it was close to the magnitude of the angle between the cleavage plane (111) in germanium and the optical input surface of the samples under investigation.

As follows from the Fig. 1, transmission of polished samples decreases at the absorption edge whereas that of the grinding sample (number 1) increases. Under certain relations between the average angle of the microfacet and the refractive index of the sample, beams multiply reflected by the fracture-squares do not go backwards and give a contribution to the transmitted radiation mimicking the blooming effect of grinding surfaces the greater the less is refractive index. In the spectral range 5-10 $\mu m$, the decrease of refractive index revealed in our measurements. As for the blooming effect, it manifested itself right up to the phonon absorption edge.

4. Conclusion

Transmission of doped single crystal germanium in the THz range is sufficiently lower as compared to the IR range. This trend originates from high concentration of free-carriers even in the pure germanium. Roughness of the grinding surface in the samples leads to a stronger THz absorption at the wavelength 130 $\mu m$. It is concluded that this absorption is related to the increase of the optical path in the doped germanium. On the contrary, in the IR spectral range, the blooming effect takes place on grinding surfaces of germanium. The effect is due to multiple reflections accompanied by small absorption.
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