OPTICS, LASERS, AND QUANTUM ELECTRONICS

PHASE CONJUGATION IN InSb(Cu)

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It is shown that the doping of narrow-band semiconductor InSb by copper leads to an enhancement of the phase conjugation efficiency at low intensities of laser radiation.

The appearance of thermal lenses in high-power gas-discharge lasers and the scattering of radiation by the gradient of the refractive index of an active medium in high-power gas-dynamic CO_2 lasers restrict considerably the possibilities of their wide technical application. Wavefront aberrations related to temperature inhomogeneities of the refractive index of the active medium can be corrected with the help of phase-conjugate mirrors (PCM) [1, 2]. One of the most promising materials for fabricating such mirrors is semiconductors. The mechanism of phase conjugation (PC) of radiation from solid-state and CO_2 lasers in various nonlinear media and, particularly, in narrow-band semiconductors of the InSb- and InAs-type has been extensively studied [3–5]. It was shown that the small value of two-photon absorption coefficient, strong absorption of the radiation of a CO_2 laser by nonequilibrium holes, and fast diffuse spreading of electrons and holes in InSb reduce substantially the PC efficiency [3]. At large powers of laser radiation, an increase of the two-photon absorption coefficient, as well as a decrease of the lifetime and the diffuse spreading length of nonequilibrium charge carriers, result in the significant growth of the PC efficiency. At the same time, at low excitation intensities (in particular, for longitudinal-discharge CO_2 lasers), the PC efficiency in narrow-band InSb and InAs semiconductors remains small and insufficient for their use as PCMs.

This work reports the results of investigations demonstrating that, similarly to the above-mentioned studies of the doping with multicharge deep Ge impurities [6], one can noticeably weaken the effect of the listed factors and enhance the PC efficiency at low powers of laser radiation by introducing, e.g., copper to InSb. Copper forms singly and doubly charged acceptor levels closely (23 and 56 meV, respectively) to the edge of the InSb valence band [7]. In this case, the monopolar conduction ($\tau_n \gg \tau_p$, where τ_n and τ_p are the lifetimes of electrons and holes, respectively) prevents the spreading of the nonequilibrium lattice, while the impurity absorption increases significantly the absorption coefficient at low laser intensities.

We studied an undoped InSb single crystal and InSb films of the n-type undoped and copper-doped. The phase conjugation was studied on a set-up depicted in Fig. 1. A nonequilibrium lattice in the InSb samples was formed by reference wave I generated by a TEA CO_2 laser (*1*) with a power of 2 MW and a pulse duration of 200 ns, as well by wave II reflected from mirror *6*. Test wave III reflected from Ge mirror (*3*) coated from one side was directed to sample (*5*) at an angle of $\approx 10°$ and formed an additional lattice there that generated back wave IV. The radiation from the CO_2 laser (*1*) was attenuated using CaF_2 filters (*2*). The difference between the optical paths of the reference and test waves was compensated by a thick Ge plate (*9*). The radiation was registered by a $Cd_{0.2}Hg_{0.8}Te$ receiver (*8*). The absorption of the radiation of a single-mode CO_2 laser by nonequilibrium charge carriers was measured with the use of a technique similar to that used earlier for other semiconductors [8, 9].

Figure 2 presents the results of investigation of the undoped InSb single crystal (curve *1*). One can see that the absorption signal $\Delta M = M \left(1 - \exp\left(-\sigma_{n+p}\Delta p d\right)\right)$ at low radiation intensities of a CO_2 laser (*I*) is caused by the two-photon absorption and that the concentra-
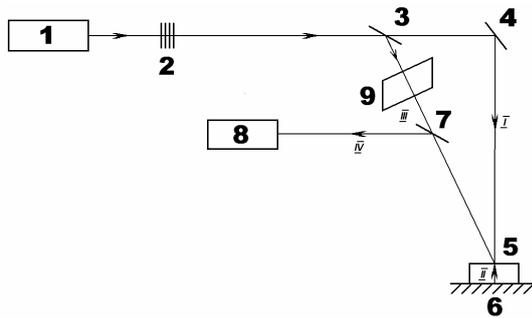
Fig. 1. Diagram of PC measurements: 1 – CO_2 laser, 2 – CaF_2 filters, 3, 7 – semitransparent mirrors, 4 – 99-% mirror, 5 – InSb sample, 6 – 99-% mirror evaporated onto InSb, 8 – IR radiation detector, 9 – Ge plate, I, II – reference waves, III – test wave, IV – back wave

tion of nonequilibrium carriers $\Delta n = \Delta p \sim I^2$. At high intensities, ΔM tends to the signal M obtained under a mechanical modulation of the radiation of a probing CO_2 laser.

At "low" intensities, the phase conjugation signal (curve 2) in the same sample ultralinearly increases with the intensity and saturates at the same value as the absorption signal $\Delta M = f(I)$ (curve 1). This testifies to the fact that the saturation mechanisms of phase conjugation and absorption signals in undoped thick ($d \gg \lambda$) InSb samples are equivalent. Moreover, they are not caused by a change of the mechanisms of phase conjugation and recombination but are related to an increase of the coefficient of absorption of the CO_2 laser radiation by nonequilibrium charge carriers $k = \sigma_{n+p}\Delta p$, where the capture cross section $\sigma_{n+p} \approx 10^{-15}$ cm^2 at $T = 300$ K. That is why, in order to expand the dynamic interval of PC signals with respect to the radiation intensity, we performed the basic measurements with thin samples (the sample thickness d was equal to approximately 0.8 mm (curves 1, 2) or 0.012 mm (curve 4)), i.e., in the linear region of the Bouguer–Lambert law, where $\sigma_{n+p}\Delta pd \ll 1$. Figure 2 (curves 3, 4) also demonstrates the results of investigation of the phase conjugation in doped (curve 3) and undoped (curve 4) InSb. The doping was carried out with the use of the known method of diffusion of Cu atoms at a temperature of ~ 400 °C and an annealing time of 40 min. According to [10], the limit solubility N_0 of copper in InSb under these conditions reaches $\approx 10^{16}$ cm^{-3}. In this case, the Cu$^-$ energy level is completely occupied by electrons. Under the condition $N_D \gg N_0$, it captures additionally electrons from the conduction band and passes to the level Cu^{2-}. To reduce the obtained results to equal initial conditions,
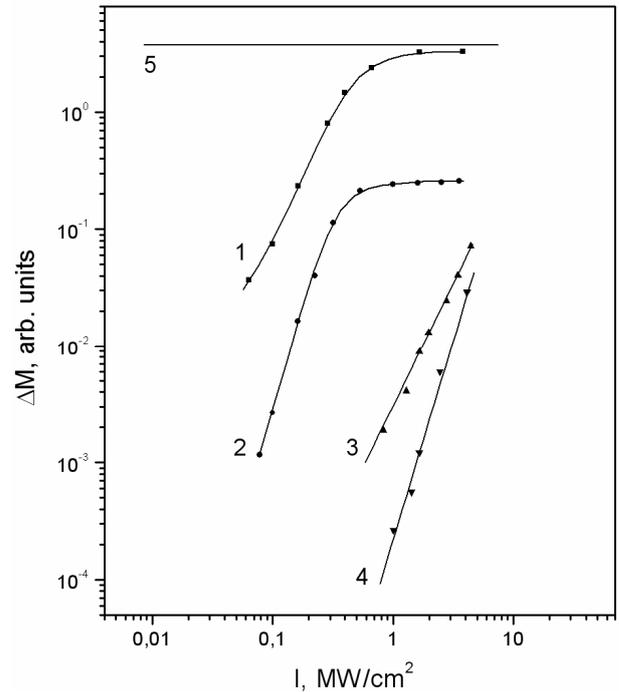

Fig. 2. Intensity dependence of the absorption ΔM (1) and PC (2–4) signals at 300 K: InSb single-crystal with $d = 0.8$ mm (1, 2), copper-doped InSb film with $d = 12$ μm (3), and undoped InSb film (4). Curve 5 – M-signal ΔM at the total overlap of the probing IR radiation

the InSb film ($n \approx 7 \times 10^{17}$ cm^{-3}, $d \approx 0.012$ mm) grown on a GaAs substrate ($\oslash$ 20 mm) was cut in two, and one part was doped with copper.

One can see that the slope of the intensity dependence of a PC signal in the film (curve 4) is practically the same as that in bulky InSb (curve 2). The difference is that the excitation of nonequilibrium charge carriers (ncc) at the two-photon absorption of the CO_2 laser radiation realized in bulky InSb is nonstationary ($\tau_{ncc} \gg t_u$), and the PC signal is saturated at $\sigma_{n+p}\Delta pd \gg 1$, whereas it is stationary ($\tau_{ncc} \approx 10^{-8}$ s $\ll t_u$) in InSb films, and the PC signal is not saturated because $\sigma_{n+p}\Delta pd \ll 1$. Moreover, the slope of the intensity dependence of a PC signal on the log-log scale is equal to 3 in both cases, which corresponds to the phase conjugation under two-photon absorption in the presented measuring scheme. At the same time, the slope of the intensity dependence of a PC signal in InSb (Cu) (curve 3) is equal to 2, which is possible in the case of the one-photon absorption of radiation in this measuring scheme.

Indeed, the energy gap width in InSb at $T = 300$ K amounts to 0.167 eV, and the energy of the second dou-

bly charged level Cu^{2-} is equal to ~ 0.056 eV [7]. In other words, the one-photon absorption requires a quantum with an energy of 0.111 eV, whereas the energy of the radiation quantum of a CO_2 laser is equal to 0.117 eV. Thus, the doping of n-InSb with copper atoms, which form two levels in the energy gap, allows one to significantly influence the properties of films related to the processes of absorption, recombination, and diffusion of nonequilibrium charge carriers and, respectively, the efficiency of phase conjugation, especially at low powers of a laser. This phenomenon can be used for developing the PCMs for CO_2 lasers produced on the basis of narrow-band semiconductors.

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ОБЕРНЕННЯ ХВИЛЬОВОГО ФРОНТУ В InSb(Cu)

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Р е з ю м е

Показано, що легування вузькозонного напівпровідника InSb атомами міді спричиняє збільшення ефективності обертання хвильового фронту при малих інтенсивностях лазерного випромінювання.