Far-IR emission in narrow-gap semiconductors in the magnetoplasma transparency window

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Emission in the far-IR range, with wavelengths up to 49.1 μm, in the magnetoplasma transparency window of the semiconductor, has been achieved in $(\mathrm{PbSe})_{1-x}(\mathrm{SnTe})_x$-$\mathrm{PbSe}_{0.32}\mathrm{Te}_{0.68}$ $(x \leqslant 0.2)$ laser heterostructures in a magnetic field.

The plasma resonance, which leads to a strong damping of electromagnetic waves with frequencies below the plasma frequency (ω_p) is one of the primary obstacles to the development of sources of coherent emission in the far-IR range from semiconductors with a narrow band gap. It is nevertheless known that in the presence of a magnetic field, for certain propagation directions and polarizations of the radiation, the plasma becomes optically transparent $[\mathrm{Re}\,\epsilon(\omega) > 0]$, and this also happens at frequencies $\omega \leqslant \omega_p$. For linearly polarized electromagnetic radiation which is propagating through a magnetized plasma in the direction perpendicular to the external magnetic induction **B**, for example, with **E**⊥**B**, where **E** is the electric field of the electromagnetic wave, there exists a transparency window in the frequency band between the hybrid resonance ω_0 and the lower cutoff frequency ω_-. In the collisionless limit, the corresponding frequencies are[1]

$$\omega_0 = \sqrt{\omega_p^2 + \omega_c^2},$$

$$\omega_{\mp} = \sqrt{\omega_p^2 + (\omega_c/2)^2} \mp \frac{\omega_c}{2},$$

where ω_c is the cyclotron frequency. If the width of the band gap of the semiconductor is such that allowed optical transitions fall in the magnetoplasma transparency band,

$\omega_- < \omega < \omega_0$, we can expect the onset of lasing at frequencies below the plasma frequency.

To pursue this possibility, we studied laser diodes using $(PbSe)_{1-x}(SnTe)_x$-$PbSe_{0.32}Te_{0.68}$ ($x \leqslant 0.2$) heterostructures at low temperatures ($T \leqslant 6$ K) in magnetic fields up to 20 kG. These laser diodes had been used previously to achieve the record longest emission wavelength for a laser using a *p-n* junction: 46.2 μm, which is close to the plasma wavelength according to our estimates.[2]

The emission of the laser diodes in a magnetic field is studied in the transverse propagation geometry described above. The plane of the active region of the laser diodes is oriented perpendicular to the external magnetic induction **B**. The diode is pumped with current pulses 2 μs long. The emission is detected by a Ge⟨Be⟩ photodetector. The output frequencies are measured with a KSDI-82 spectral complex.

The results show that the basic effects of the magnetic field on the nature of the emission occur in comparatively weak magnetic fields ($B < 5$ kG). The threshold current density begins a sharp decrease (by a factor of nearly two) at fields of about 1.5 kG; simultaneously, the output spectrum splits into short-wave and long-wave components (Fig. 1). A slight increase in the magnetic field leads to a quenching of the short-wave component, and at fields as low as $B \gtrsim 2$ kG the output spectrum contains only the long-wave component. At these values of the magnetic field we detect an emission at the longest wavelength, 49.1 μm (Fig. 2). A further increase in the magnetic field has only a slight effect on the threshold current density. The minimum threshold current density is reached at about 3 kG. Above 5 kG, the threshold current density begins to rise sharply. Over the entire range of magnetic fields we observe a linear polarization of the radiation in the plane perpendicular to **B**.

All of these experimental results provide evidence that when the magnetic field is applied, the frequency of the allowed interband optical transitions lies in the magnetoplasma transparency window. Only transitions between Landau states in the valence band and the conduction band with opposite spin orientation participate in the emission (Fig. 3). Numerical analysis of the experimental emission frequencies and calculations to fit the energies of the magnetooptical transitions for the lower Landau bands

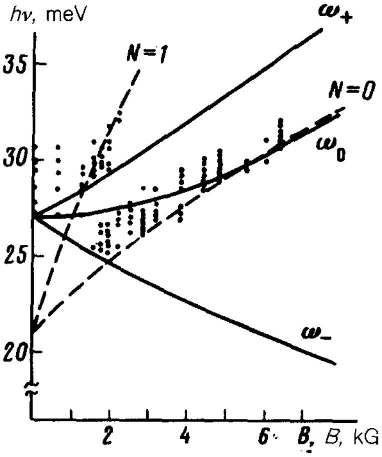

FIG. 1. Photon energy of the emission from the $(PbSe)_{0.8}(SnTe)_{0.2}$-$PbSe_{0.32}Te_{0.68}$ laser diode vs. the magnetic field. Points—Observed emission frequencies; solid lines—energies of the hybrid magnetoplasma modes calculated in the collisionless limit; dashed lines—energies of interband transitions ($\Delta s = \pm 1$) between the zeroth ($N = 0$) and first ($N = 1$) Landau bands calculated in the Kane approximation.

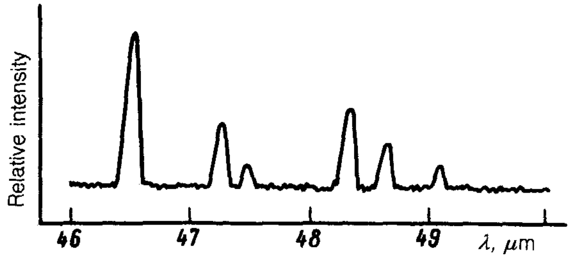

FIG. 2. Output spectrum of the $(PbSe)_{0.8}(SnTe)_{0.2}$-$PbSe_{0.32}Te_{0.68}$ laser diode in a magnetic field. The working current of the diode is 5 A, its temperature is 6 K, and the magnetic field is 2 kG.

$(N = 0,\ 1)$ in the Kane approximation,[3] along with calculations of the energies of hybrid magnetoplasma modes, yield the following values for the band parameters of the narrow-gap semiconductor $(PbSe)_{0.8}(SnTe)_{0.2}$: a gap width $\epsilon_g = 21 \pm 0.5$ meV, an effective cyclotron mass $(m_c/m_e) = 0.005 \pm 0.0002$, and a spin-splitting factor $|g| = 390 \pm 10$. According to the calculations, the minimum emission frequency in the absence of a magnetic field is close to the plasma frequency ($\hbar\omega_p = 27$ meV; Fig. 1). In a magnetic field, the output spectrum shifts into the transparency window $(\omega_- < \omega < \omega_0)$. The lowest emission frequencies are achieved in the region in which the magnetooptical transition frequencies for $N = 0$ intersect the lower cutoff frequency ω_-. In strong magnetic fields, where the frequency of the hybrid resonance, ω_0, approaches the frequency of electronic transitions (Fig. 1), we observe an emission at frequencies $\omega > \omega_0$, despite a band of strong damping of electromagnetic waves. This result may be evidence of a resonant nature of the interaction of photons with the hybrid mode ω_0 and of the formation of magnetoplasma polaritons.[4]

We also see that the emission on transitions with opposite spin orientation occurs only in a limited interval of magnetic fields, since the spin-induced splitting increases with increasing magnetic field, while the population of the upper Landau subbands decreases. On the other hand, emission does not arise on transitions between lower filled Landau subbands (Fig. 3), since the medium has a negative dielectric constant $[\mathrm{Re}\,\epsilon(\omega) < 0]$ for electromagnetic waves with a longitudinal polarization $(\mathbf{E}\|\mathbf{B})$.

In summary, emission in narrow-gap semiconductors with frequencies below the plasma frequency is possible in a magnetic field. The lowering of the energy of longitu-

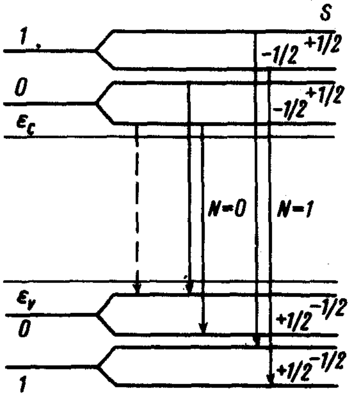

FIG. 3. Allowed transverse $(\Delta s = \pm 1,\ \mathbf{E}\perp\mathbf{B})$ interband transitions in $(PbSe)_{0.8}(SnTe)_{0.2}$. The dashed line is a longitudinal $(\Delta s = 0,\ \mathbf{E}\|\mathbf{B})$ interband transition which does not occur in the magnetized plasma. It is assumed here that the g-factor of the conduction band is positive.

dinal optical phonons due to screening effects in the plasma[4] and the renormalization upon a decrease in the gap width[5] raise the hope that it will be possible to use magnetic fields to produce transparency windows suitable for emission over essentially the entire far-IR range.

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