Induced hot-hole millimeter emission in germanium in fields E||H (cyclotron-resonance negative-effective-mass amplifier and generator)

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Stimulated electromagnetic emission has been observed in the short-wavelength part of the millimeter range ($\lambda \approx 1.5$–2.2 mm) from p-type Ge cooled down to liquid-helium temperature in fields **E**||**H**||[100].

The concept of a negative-effective-mass amplifier and generator[1,2] (NEMAG) was discussed widely more than two decades ago, but it has so far not been realized. Interest in the concept has been revived by developments in research on the anisotropy and inversion of the hot-carrier distribution function in a semiconductor (see, for example, Ref. 3). Calculations[4] have shown that a cyclotron-resonance NEMAG would be feasible in p-type Ge at low temperatures in fields **E**||**H**||[100] at wavelengths $0.2\text{ mm} < \lambda < 4.00\text{ mm}$. When the inelastic scattering of hot holes by optical phonons is dominant, a static electric field stretches the distribution function out in p space (a streaming effect). When streaming occurs along the axis of the negative-cyclotron-mass cone, an inversion arises in the distribution of holes with a negative cyclotron mass in the direction transverse with respect to **E** (this is an inversion in Landau levels in the case **H**||**E**). Under these conditions, circularly polarized radiation at resonance with holes with a negative cyclotron mass can be amplified.[4] The absorption of holes with a positive cyclotron mass, whose distribution function is not inverted, will be a nonresonant absorption (cf. Ref. 1). The maximum inversion and the maximum amplification are achieved in the case of a slight anisotropy of the distribution function, which arises in p-type Ge at liquid-helium temperature at fields $E \sim 100$–200 V/cm (Ref. 3). The maximum gain corresponds to a negative cyclotron mass $m_c \sim 0.5 m_0$ (Ref. 4; m_0 is the mass of the free electron).

In the present experiments we studied the emission from samples cut in the [100] direction with current contacts on opposite faces. These samples were made from weakly compensated Ge(Ga). The sample is held in a liquid-helium cryostat at the center of a superconducting solenoid, so that the **E** and **H** directions in the sample are the same. The emission is detected by a cooled n-type InSb detector inside the cryostat and by a Schottky-barrier diode outside the cryostat at the time at which the electric field pulse is applied (Fig. 1; $\tau_{\text{pulse}} \sim 5\ \mu\text{s}$, $f_{\text{rep}} = 3$–30 Hz). The measurement procedure is similar to that of Ref. 6. The signal received by the n-type InSb detector is five orders of magnitude stronger than the spontaneous emission from p-type Ge, detected previously in stronger fields,[5] $E \sim 1$ kV/cm. The most intense emission (the signal at the Schottky diode reached 20 mV) was observed at the beginning of the pulse; the intensity then fell off, presumably due to a heating of the sample (Fig. 1).

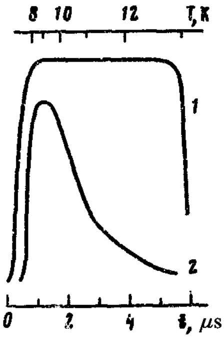

FIG. 1. Oscilloscope traces of the voltage pulse across the sample (1) and of the emission pulse (2). The upper abscissa scale is the temperature of the sample during the voltage pulse, estimated from adiabatic heating.

It can be seen from Fig. 2 that the emission arises after thresholds are reached in E and H. In electric fields $E > 250$ V/cm the emission is observed only at the leading edge of the electric field pulse, because E is swept through the value $E \sim 100$–200 V/cm. Emission is observed at magnetic fields up to $H \cong 50$ kOe.

As the magnetic field is strengthened, we observe a shift of the emission frequency (Fig. 3). The wavelengths in the range 2.2 mm $> \lambda >$ 1.5 mm are measured with a Michelson interferometer and a Schottky diode. Extrapolation of the data in Fig. 3 to the extreme magnetic fields at which the emission is still detected indicates that the wavelength can be tuned over the range 0.8 mm $< \lambda <$ 2.3 mm.

All these results—the existence of emission fields $E \cong 100$–200 V/cm, the tuning of the wavelength in a magnetic field corresponding to cyclotron masses $m_c \cong (0.45$–$0.49)m_0$, the suppression of the emission by heating of the crystal, and the fading of the emission in strong magnetic fields (which can be explained in a natural way as due to a decrease in the negative conductivity with increasing H; Ref. 4)—suggest that a cyclotron-resonance NEMAG has been achieved in the short-wavelength part of the milli-

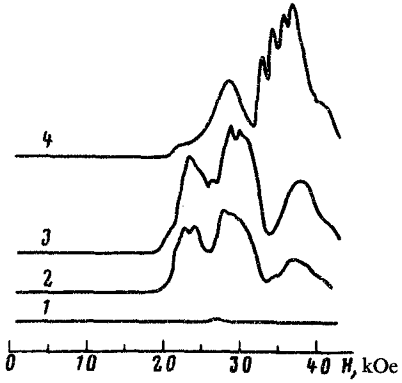

FIG. 2. Intensity of the emission from the p-type Ge versus the magnetic field in the band of the n-InSb detector. 1—$E = 90$ V/cm; 2—$E = 120$ V/cm; 3—$E = 140$ V/cm; 4—$E = 195$ V/cm. The curves have been shifted along the ordinate axis.

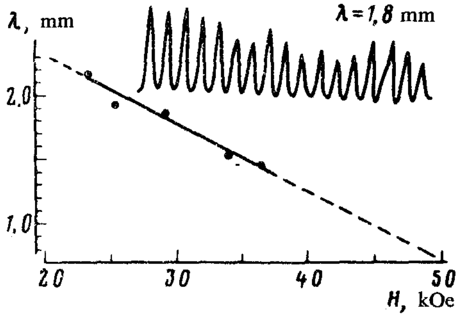

FIG. 3. Emission wavelength versus the magnetic field. Points—Experimental values (one of the interferrograms is shown in the inset); dashed lines—approximation in the range of magnetic fields in which the emission is observed.

meter range for the first time in these experiments. The results of Ref. 4 indicate that it is possible in principle to extend the wavelengths into the submillimeter range.

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