The copper-doped p-Ge THz laser in the Voigt configuration: possibility of mode-locked operation.

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Abstract - **We have constructed a copper-doped germanium hot hole THz laser and studied its performance under normal - pulsed - operation, in order to investigate the possibility to create very short "quasi monochromatic" pulses through active mode-locking. The E and B field region of laser emission, emission wavelength as a function of B field and the temporal shape of the laser pulse have been studied. The results indicate that the performance of this Ge:Cu crystal can not yet compete with that of an earlier studied Ge:Ga laser under similar conditions. Nevertheless active mode-locking has been observed.**

Introduction

In p-Ge, population inversion between the light and heavy hole band is induced by the application of crossed electric- (**E**) and magnetic- (**B**) fields. The resulting Terahertz emission is strong and tunable. We have shown recently that mode locked operation of such a laser can be achieved by applying an ac electric field *parallel* to **B** at half the cavity round trip frequency. Quasi monochromatic THz pulses as short as 60 ps have been created with that technique [1,2,3]. Most of the investigations on the p-Ge laser have been performed on Ga doped material. However, the ionization energy of this single acceptor is about 11 meV, and the finite population of the acceptor levels under lasing conditions results in strong absorption of emitted light, leading to a large gap in the laser emission around 75 cm^{-1}. To avoid this gap, recently the double acceptors Be and Zn and the triple acceptor Cu have been used as dopants [4,5]. Because the ionization energies of those acceptors is larger than the highest emission energy of the Ge laser, they can not interfere with the laser action. Although the experimental evidence so far seems to indicate that Ge:Be is the best laser material, we have chosen to explore in more detail the Ge:Cu material. The reason for that being the fact that copper doped Ge can easily be fabricated in many different concentrations by simple diffusion of copper in pure Ge, whereas Ge with other dopants have to be Czochralski-grown from a doped melt.

Sample Fabrication

As starting material we have used a 5 mm thick slice, perpendicular to (100), of Czochralski-grown ultra-pure germanium from Union Minière Electro-Optical Materials. It has a dislocation density of less than 3000 per cm^2 and a p-type impurity concentration of less than 10^{12} cm^{-3}. For the fabrication of the doped samples we followed the recipe outlined in reference [5]. Apart from Hall samples, a 5x7x10mm^3 bar-shaped sample for a preliminary study of stimulated emission was made, with HV contacts such that **E** // (011). For the final laser performance study a 5x7x50mm^3 sample was made (see Fig. 1.), the same size as the Ge:Ga sample on which earlier pulsed and mode lock experiments were performed [1,2,3]. The copper diffusion for both lasing crystals was performed at 700 ^{o}C for 24 hours, because our results on Hall samples showed that in that case the resulting copper concentration, after rapid quenching of the crystal to room temperature, would be about 1.5x10^{15} cm^{-3}. After diffusion the laser sample was polish- etched and the 5x7 end faces were made parallel to each other within 30''. The high voltage excitation contacts, covering the full 5x50 sides, and the 1x10 modulation contacts at the 7x50 surfaces, were made from gold on palladium, after boron implantation. In order to remove implant damage and fully activate the boron, the samples were given a post-implant anneal. Copper wires were soldered on the contact areas with Indium.

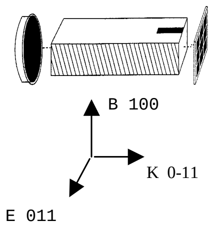

Fig. 1: Sample + cavity.

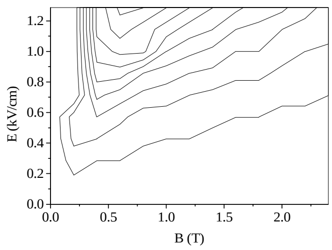

Fig. 2 E-B emission region of small crystal ; each contour line is a 4 mV signal increase from 4 to 36 mv.

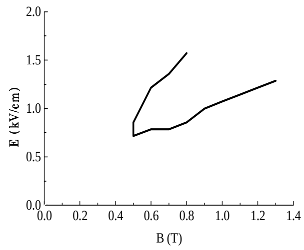

Fig. 3: E-B field region of laser action.

Experimental set up

The small laser crystal with only HV contacts was mounted without external cavity in a Helium cryostat in the bore of a superconducting solenoid Emission under pulsed HV excitation was measured with a fast cryogenic Ge:Ga detector, placed near to the crystal.The large laser crystal was mounted in a cryostat with tail window. The cavity consists of a flat gold mirror at one side and a capacitive mesh at the other, both isolated by 10 μm Teflon film, and pressed against the end fases. The crystal is studied in the Voigt configuration, i.e. both **E** // (011) and **B //** (100) are perpendicular to the (0 -11) optical axis of the laser cavity, see Fig. 1. The magnetic field, generated by a room temperature electromagnet with a maximum field of 1.3T, can be rotated with respect to **E** to optimize lasing conditions. Both the HV excitation field and the RF modulation field are applied in pulses of a few microseconds long to avoid excessive heating of the crystal. The THz emission is studied using either a relatively slow pyroelectric detector, or a very fast mm-wave Schottky diode or a GaAs/AlGaAs heterostructure detector. Using a simple reflection grating set up, the wavelength of the emitted light can be measured. The signals are monitored with either a 500 MHz digitizing oscilloscope scope or with a single shot 6 GHz bandwidth oscilloscope.

Experimental results

The experiments on the 5x7x10mm^3 crystal reveal pulsed THz emission that follows closely the high voltage excitation pulse. As evident from fig. 2, the emission also shows the peculiar dependence on the applied **E** and **B** field, with a maximum intensity centered around an E/B ratio of about 1.3kV/T. Those observations prove that the emission is not due to ohmic heating of the crystal, which increases monotonously towards higher **E** and **B** fields, but originates from the population inversion created by the crossed **E** and **B** field excitation. In view of the rather low signal intensities and the absence of sharp emission boundaries, we deal here most probably with spontaneous rather than with stimulated emission. This result shows that the low temperature density of ionized acceptors is of the right order of magnitude- $\approx 10^{14}$ cm^{-3}, about 7% of the Cu density [5] - to create population inversion.

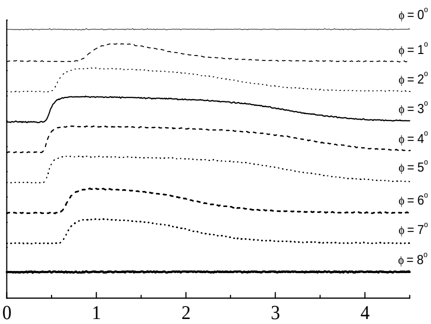

Fig. 4: Shape of the emission pulse as function of the direction of **B** and **E**.

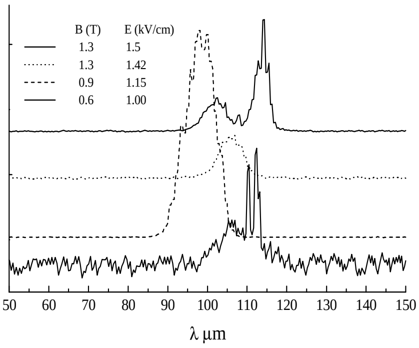

Fig. 5: Emission spectra at various B field

Introductory experiments on the 5 x7x50mm^3 sample were performed also using a Ge:Ga detector near the crystal. In fig. 4 the pulsed emission signals at B=0.9T and E=1.4kV/cm are shown for various directions of **B**; a clear minimum of the delay between start of HV excitation pulse at t=0 and start of laser action, together with the steepest growth of signal intensity is seen for $\varphi \approx 4^o$ (**E** $\perp$ **B**). In fig. 3 the E/B field region is shown for which stimulated emission is observed using a room temperature pyroelectric detector. The E/B ratio for the emission region agrees with expectations [5]. In fig. 5 emission spectra with a resolution of about 2 cm^{-1} are shown for a few **B** fields. Although these spectra differ from those reported by Reichertz et al [6] for the Be and the Cu doped Ge lasers - operated in the Faraday configuration - it is conceivable that the broadband emission originates from intervalence band transitions. Some preliminary time resolved experiments have been performed. The peculiar pulse shape shown in fig. 6 strongly resembles those observed in the Ge:Ga laser and suggests that also in the Ge:Cu system a variation in emission wavelength *during* the laser pulse occurs. The intensity variations on a 25 ns timescale are related to beating between different transverse laser modes. In general, it is found that in this Ge:Cu laser the time delay between start of the high voltage excitation and start of laser action is larger, the small signal gain is smaller, and the maximum pulse duration is shorter than observed in the Ge:Ga laser. Moreover lasing action starts at a larger **B** field. So, these first data on long pulsed operation indicate that lasing conditions in this crystal are less favorable than in Ge:Ga. Experiments on other Ge:Cu crystals, also with different Cu concentrations, have to be performed to reach a more general conclusion on this point. We have applied an RF electric field to the modulation contacts at half the cavity roundtrip frequency, to modulate the laser gain at the round trip frequency, a necessary prerequisite for mode-locking. Inspection of the electronic system showed that the Q-value of the circuit involving the modulation contacts was

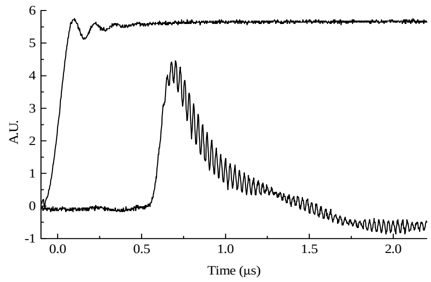

Fig. 6: Time resolved laser output at B=0.78 T observed with a fast Heterostructure detector and the high voltage pulse (upper trace).

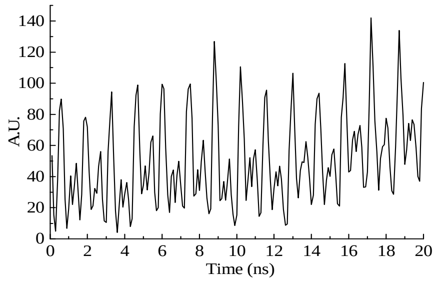

Fig. 7: Pulse train under mode-locking conditions. The 1.3 ns pulse separation equals the cavity roundtrip time.

rather low, possibly preventing the RF field to reach its optimum value. It is not clear whether this is due to bad contacts or to an intrinsic material property. Nevertheless, in these first experiments we have succeeded in operating this laser under mode locking conditions. In fig. 7 a typical result of the optical output is given. A train of pulses at a 1.3 ns time interval, the cavity roundtrip time, is observed. However, the modulation depth is not very large. Improving on the amplitude of the RF field might possibly lead to better results and shorter pulses. In summary we have shown that the copper doped germanium laser can be operated under mode-locking conditions; the present overall performance, however, does not yet equals that of the Ge:Ga laser.

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