Fast relaxation of free carriers in compensated n- and p-type germanium

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***Abstract*—The relaxation of free holes and electrons in highly compensated germanium doped by gallium (*p*-Ge:Ga:Sb) and antimony (*n*-Ge:Sb:Ga) has been studied by a pump-probe experiment with the free-electron laser FELBE at the Helmholtz-Zentrum Dresden-Rossendorf. The relaxation times vary between 20 ps and 300 ps and depend on the incident THz intensity and compensation level. The relaxation times are about five times shorter than previously obtained for uncompensated *n*-Ge:Sb and *p*-Ge:Ga. The results support the development of fast photoconductive detectors in the THz frequency range.**

I. Introduction And Background

COOLED germanium (Ge) photoconductive detectors are characterized by a very low noise equivalent power and high quantum efficiency. They have been serving for decades as one of the most sensitive THz detectors in spectroscopy and imaging for laboratory research as well as for astronomy and planetary research [1]. The sensitivity of extrinsic photoconductive Ge detectors doped by shallow hydrogen-like impurity centers, such as gallium (*p*-Ge:Ga) and antimony (*n*-Ge:Sb), peaks at wavelengths around 100 µm (3 THz) and extends towards the infrared. Achieving high sensitivity requires low doped ($\sim 10^{14}/cm^3$) and weakly compensated Ge [2]. These broadband low-noise and high sensitivity operation features dominated the research on Ge photodetectors. As a rule of thumb an increased doping concentration and high compensation level increase the speed of response of these detectors while the sensitivity decreases and the dark current increases. Despite this fact the availability of intense short pulsed THz sources still demands fast, broad-band detectors. So far the shortest response times are a few ns obtained with a moderately compensated (32%) Ge in direct detector operation [3].

A more fundamental approach for determining the speed of response of extrinsic Ge photoconductors can be made with the application of the pump-probe technique providing a few ps temporal resolution which is available for example at free electron lasers [4]. In this work we present results of lifetime measurements obtained with a dedicated single-color pump-probe setup at the free electron laser FELBE. In particular we investigated the influence of the compensation level on the relaxation times in p-Ge:Ga:Sb as well as n-Ge:Sb:Ga detector material.

II. Experimental

The speed of response of an extrinsic Ge-photodetectors on a technical level is determined by parameters such as the electric bias field, the speed of the detector bias circuit or the geometry of the detector crystal, whereas the fundamental temporal limitation is determined by the lifetimes of the ionized charge carriers in the conduction/valence band. This work is a continuation of the investigation of these relaxation processes in extrinsic Ge with a dedicated single-color pump-probe setup at the infrared/THz free electron laser facility FELBE. The focus was set to the influence of the degree of compensation in Ge on the free carrier capture rate. Therefore, different samples with varying levels of compensation, i.e. relative amounts of Sb donor atoms and Ga acceptor atoms in germanium crystals, have been produced by the Institute of Crystal Growth. The samples were grown by the Czochalski method and the doping material was introduced directly into the crucible. Due to the depletion during the growth and the different segregation coefficients of Sb and Ga the concentration of the impurities changes along the growth axis of the ingot. The crystal was then sawed to samples of 10x10x0.5 mm³ size. The approximate concentration of impurity atoms obtained in the samples is shown in Tab. 1.

TABLE I.
Doping concentrations of investigated Germanium samples

Sample	N_{Ga} (cm^{-3})	N_{Sb} (cm^{-3})	N_{net} (cm^{-3})	Comp (%)
Ge-539-1	2.8×10^{16}	2.6×10^{16}	(p) 2×10^{15}	92.9
Ge-539-3	3.5×10^{16}	3.3×10^{16}	(p) 2×10^{15}	94.3
Ge-538-0	2.3×10^{16}	2.7×10^{16}	(n) 3×10^{15}	85.2
Ge-538-1	2.9×10^{16}	3.3×10^{16}	(n) 4×10^{15}	87.9
Ge-538-3	3.4×10^{16}	4.0×10^{16}	(n) 6×10^{16}	85.
Ge-538-4	4×10^{16}	4.7×10^{16}	(n) 7×10^{15}	85.1

Additionally, the absorbance spectra of these samples have been measured by Fourier transform spectrometry (FTS) at liquid helium temperatures. They show broad a absorption band at the position of impurity absorption lines (range 5-10 meV, Fig. 1) with a large absorbance (up to 100 cm^{-1}) that indicates on higher net levels of impurity concentration than those calculated from the original dopants in the crucible.

In accordance to our previous pump-probe measurements we chose a wavelength of the FEL radiation of 105 µm (photon energy of 11.8 meV or 2.85 THz).

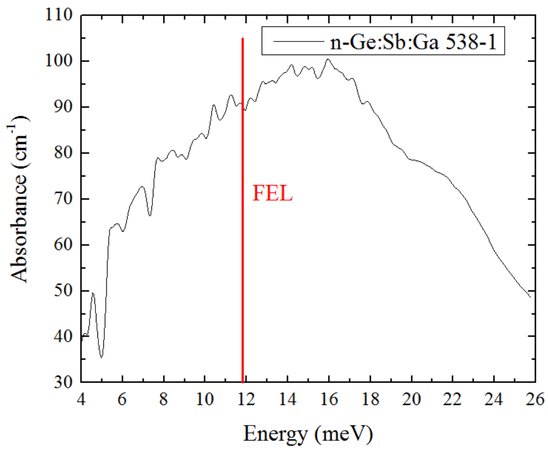

Fig. 1: Absorbance spectrum of sample Ge-538-1 shows no resonant states and very high absorbance.

This photon energy is larger than the ionization energy for both impurities and it fits to an atmospheric window. At this frequency FELBE provides bandwidth limited quasi-Gaussian pulses with pulse lengths of about 10 ps at a 13 MHz repetition rate. The maximum average power coming from the FEL was 960 mW corresponding to about 80 nJ peak pulse energy. The samples were mounted in a liquid-He flow cryostat equipped with diamond windows and cooled to about 5 K.

The pump-probe technique used is based on a time-resolved measurement of change of a probe beam transmission in the samples photo-induced by a pump beam. A Mylar beam splitter divided the incoming FEL light into pump and probe. Both pump and probe were focused onto the sample using a 10 cm focal-length off-axis parabolic mirror. Behind the sample the transmitted pump beam was blocked whereas the probe beam was detected with a silicon bolometer. The signals were recorded by chopping the pump beam mechanically at about 120 Hz and measuring the probe signal using a lock-in amplifier at this frequency.

III. Results

We report on the observation of ultrafast recombination of free electrons (n-Ge:Sb:Ga) and holes (p-Ge:Ga:Sb) in moderately doped (net concentration > 2×10^{15} cm^{-3}) with high compensation, of up to 95%. The typical range of the relaxation times for photo-induced (THz photoionization) transmittance is in the range of 20-300 ps dependent on the sample characteristics and the THz light intensity (see Fig. 2). The transmission decay times were derived by a single or double exponential fit procedure depending on the sample and pump pulse energy. Note here that the high absorption coefficient manifests itself in problems during the data analysis of pump probe signals which is usually based on a linearization approach for low absorbencies. The recombination time in compensated Ge is much shorter than that in uncompensated n-type and p-type material which has intensity-dependent relaxation times down to about 1 ns [4].

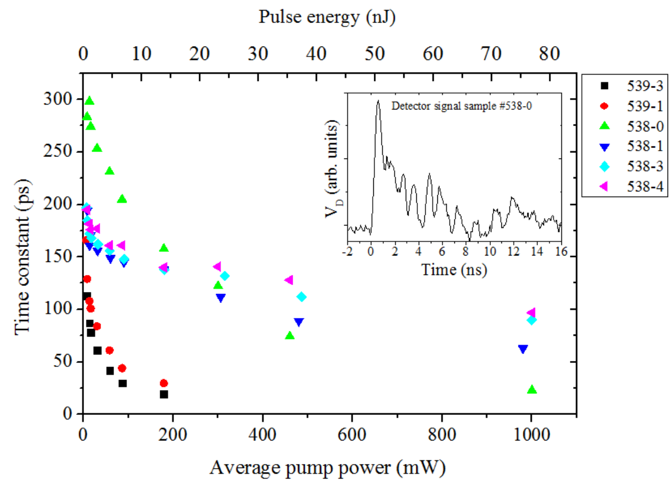

Fig. 2: Typical dependences of free electron decay times on the energy of the pump pulse (wavelength is 105 µm) for the photoinduced THz transmittance in *n*-Ge:Sb:Ga and *p*-Ge:Ga:Sb samples as measured by the pump-probe technique. **Inset:** Detector signal of a FEL pulse with a 10-90 rise time of 400 ps; no optimized bias circuit has been used.

For a fast test of this detector material for a direct photoconductivity response we soldered indium contacts along two opposing edges of the same 10×10 mm^2 facet and applied a bias voltage below the impurity breakdown. Despite the large RC value we found a 10%-90% rise time of about 400 ps (Inset of Fig. 2.).

This study indicates the potential for very fast, broad-band detection of THz pulses by extrinsic photoconductive Ge detectors with optimized doping, compensation, geometry and an appropriate electrical readout circuit.

Acknowledgement

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