Towards a life-time-limited 8-octave-infrared photoconductive germanium detector

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Abstract. Ultrafast, ultra-broad-band photoconductive detector based on heavily doped and highly compensated germanium has been demonstrated. Such a material demonstrates optical sensitivity in the more than 8 octaves, in the infrared, from about 2 mm to about 8 μm. The spectral sensitivity peaks up between 2 THz and 2.5 THz and is slowly reduced towards lower and higher frequencies. The life times of free electrons/holes measured by a pump-probe technique approach a few tenths of picoseconds and remain almost independent on the optical input intensity and on the temperature of a detector in the operation range. During operation, a detector is cooled down to liquid helium temperature but has been approved to detect, with a reduced sensitivity, up to liquid nitrogen temperature. The response time is shorter than 200 ps that is significantly faster than previously reported times.

1. Introduction

Broad-band infrared detectors are requested for the in-situ diagnostic of power and quality of broad-band wavelength tunable pulsed infrared free electron lasers. Usually such lasers deliver picosecond pulses separated with typical temporal intervals of a few nanosecond (1/20/40 ns at the FELIX Facility in the Radboud University, Nijmegen, The Netherlands; 9.2 ns at the FEL Facility, the Institute of Scientific and Industrial Research, Osaka University, Japan; 16 ns at the CLIO Facility, the Universite Paris-Sud, Orsay, France; 77 ns at the FELBE Facility, Helmholz Zentrum Dresden-Rossendorf, Germany; 180 ns at the NovoFEL Facility, the Budker Institute for Nuclear Physics, Novosibirsk, Russia).

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Germanium photoconductive detectors (GeD) are known for their very broad-band high spectral sensitivity in infrared [1]. The detector utilizes photoconductivity of free electron/holes optically excited from the ground state of dominating impurity. Since conventional applications of GeDs are in sensitive low-noise detection, they are usually from low doped (~ 10^{14} cm^{-3}) and low compensated crystals, standard dopants for p-type is gallium (p-Ge:Ga) and for n-type is antimony (n-Ge:Sb). The responsivity of such a material peaks at wavelengths around 100 μm and the long-wavelength cut-off is determined by the binding energy of the dopant to the valence band or the conduction band, respectively (figure 1, left). For time-resolved detection of optical pulses, significant reduction of conductivity recovering times is required. This can be achieved, for instance, by increasing of number of traps for free charge carriers. Such an effect can result from compensation of a dominant impurity in germanium by doping with centers causing opposite conductivity. As a rule, reduction of the recombination time of free charge carriers occurs proportionally to the number of attracting Coulomb centers [2]. Response time of ~2 ns in the far-infrared was observed for neutron transmutation doped high-compensated (N_D/N_A = 0.32-0.52) p-Ge:Ga:As:Se samples with a moderate acceptor (Ga) concentration of N_A = (1-2)×10^{15} cm^{-3} and a total compensating donor (As+Se) concentration of N_D = (5.2-12)×10^{14} cm^{-3} [3]. Similar response times have been obtained under special electrical bias of conventionally compensated GeD with $N_D/N_A < 0.7$ near impurity breakdown [4]. The speed of such detectors is set by technical limitations such as the bias circuit, the geometry of the detector crystal, and the electric field applied to the detector.

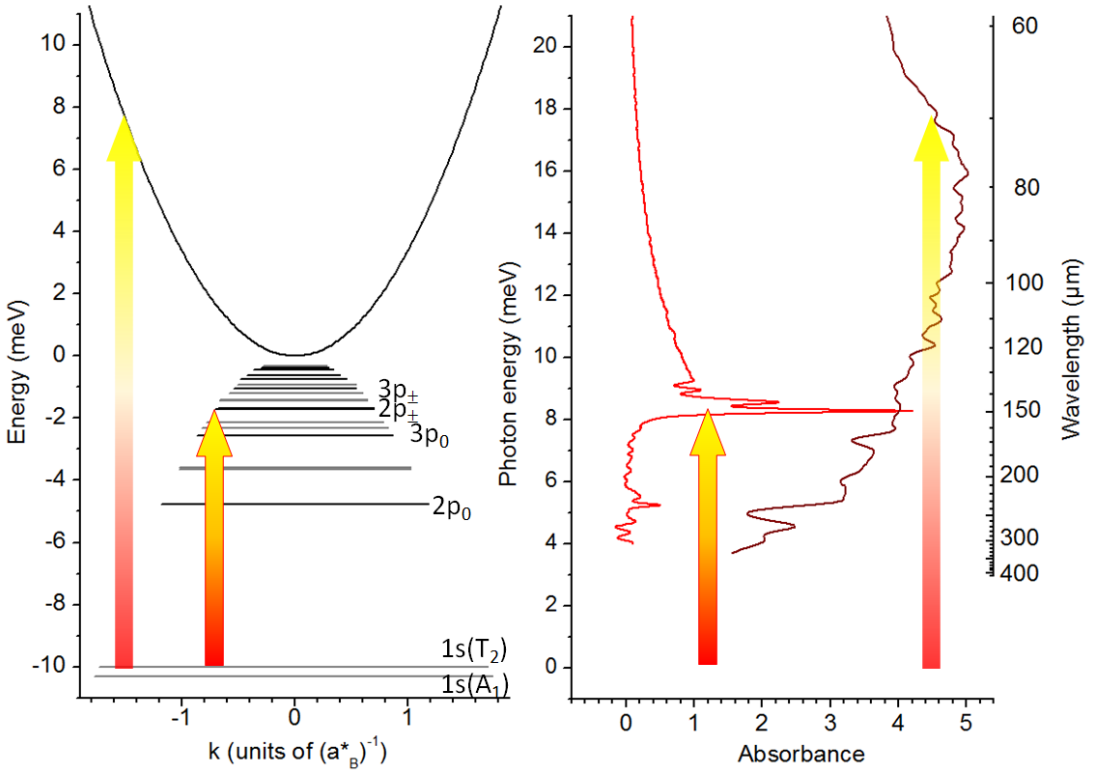

Figure 1. Left: Band structure of electronic states of germanium in vicinity of the bottom of the conduction band. Discrete line are ground (1s(A_1)) and excited levels (marked are few of odd-parity states serving as terminating states for the dipole allowed optical transitions from the ground state) of antimony donor atoms in the germanium bandgap. Right: Impurity absorption spectra of two germanium crystals: low doped low compensated n-Ge:Sb #471 (discrete intracenter optical transitions are clearly seen) and heavily doped highly compensated n-Ge:Sb:Ga #538 taken at low crystal temperature, 6 K. Vertical bold arrows indicate intracenter (bound-bound) and impurity-continuum (bound-free) optical transitions.

2. Experimental

2.1. Germanium detectors

Dedicated doping of germanium crystals by dominating and compensating atoms, gallium and antimony, has been performed in specially designed gradient germanium crystals up to almost a critical concentration of metal-insulate transition for shallow impurities. Different samples with different level of compensation cut from these crystals have been characterized by absorption spectroscopy at ~6 K with a Fourier transform infrared spectrometer (FTIR) in the range from 4 to 400 μm. The spectra of heavily doped samples reveal an absorbance of up to five (absorption coefficient up to 100 cm^{-1}) (figure 2, right). Ohmic contacts have been prepared by evaporation of metal (Au+Sb for n-Ge and Al for p-Ge) on the opposite 2×0.5 mm^2 surfaces of the 4×2×0.5 mm^3 samples. The samples were attached to a cold finger of a liquid helium flow cryostat. Connections to the outer circuit were made by the coaxial stainless steel cables.

2.2. Fast detection

Detection of the ~10 ps infrared pulses at different wavelength has been carried out at the FELBE facility in the Helmholtz Zentrum Dresden-Rossendorf. We used a conventional DC biasing with a 7 ps rise time bias tee. Photocurrent has been directly fed into the input of a 20 GHz band oscilloscope, a DPO72004C model. Typical photoresponse on the FEL pulse is shown in figure 2. Dynamic range of detection exceeds 15 dB and was limited by a digital noise of the scope. Response signal dropped with increasing temperature but remained until liquid nitrogen temperature of 77 K [5].

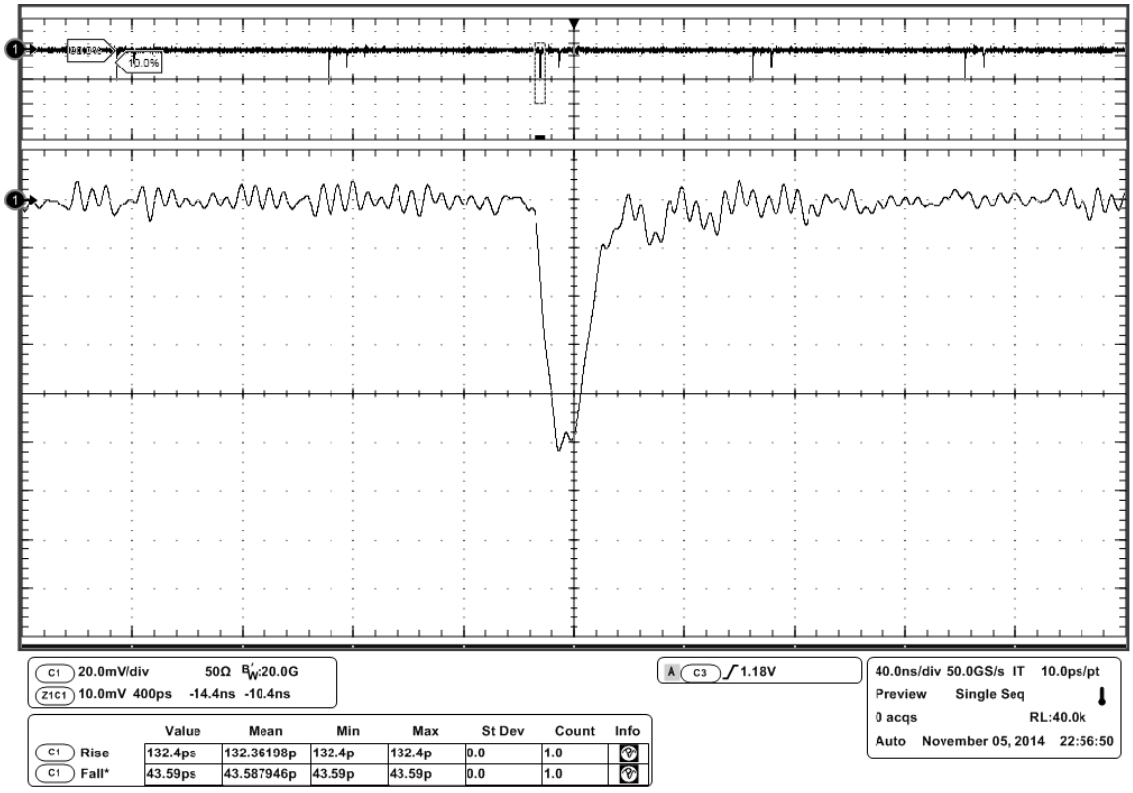

Figure 2. Response of the p-Ge:Ga:Sb # 539-4 detector on a FELBE pulse @ 19 μm taken with a fast scope, no amplifier. Upper signal (multi-pulse response) has a vertical resolution of 20 mV/division and time scale of 40 ns/division; the lower signal (single pulse): 10 mV/div and 400 ps/div, correspondingly. Rise time is 132 ps. FWHM is about 160 ps. The sample is at T ~ 10 K.

Both, uncompensated and compensated GeD resolve single FEL micropulses (separation is 77 ns). Uncompensated samples demonstrate significantly longer response, the shortest response times have been obtained for the heavily doped ((2-3)×10^{16} cm^{-3}) p-Ge:Ga:Sb samples with ~97% compensation.

2.3. Fast detection

Lifetimes of nonequilibrium electrons/holes have been measured by a pump-probe technique at the FELBE. These measurements show significant drop of recombination times (under 200 ps) in the samples with the large number of attracting recombination centers (figure 3) achieved by high level of compensation. Low compensated samples have lifetimes longer than 1 ns.

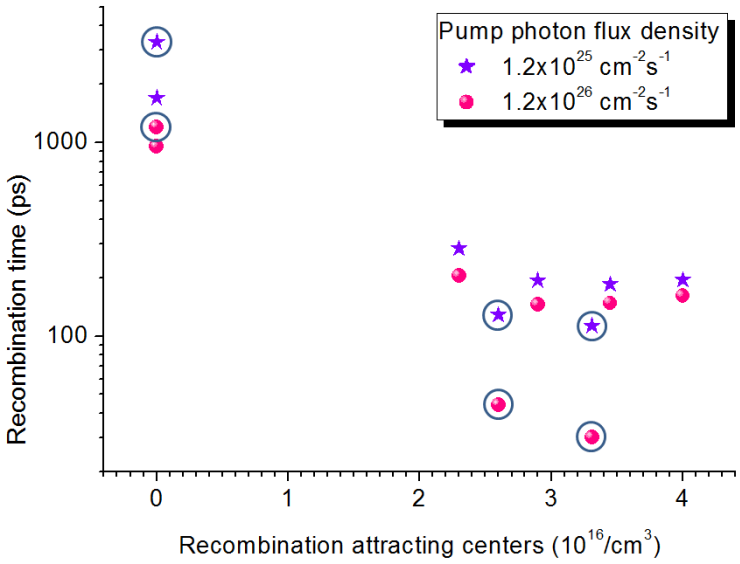

Figure 3. Dependence of the lifetime for p-Ge:Ga:Sb (data points shown in the circles) and n-Ge:Sb:Ga samples with a different concentration of domi-nant and compensating centers on a number of attracting centers for different pump photon flux densities. Pumping is in the state continuum (in the bottom of the conduction or valence bands, corres-pondingly). The samples were held at T ~ 10 K.

3. Conclusions

We have demonstrated ultrafast, ultra-broad-band (from millimeter waves to infrared) GeD based on heavily doped and highly compensated crystals. The response time of around 200 ps corresponds to the lifetime of nonequilibrium charge carriers as measured for the same semiconductors.

4. Acknowledgements

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5. References

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