Subnanosecond kinetics of photoionized carriers in n- and p-type germanium probed by a far-infrared free electron laser

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Fast relaxation dynamics of photoexcited charge carriers in n- and p-type germanium crystals have been probed using far-infrared ps-pulsed free electron laser emission. Different relaxation processes can be observed by an accurate analysis of the results of the pump-probe technique, including intersubband, intraband and intracenter energy relaxation. The characteristic time constants lie in the broad range from 30 ps up to a few ns depending on the pump intensity and doping concentrations.

Introduction

Intense short pulsed THz sources, such as infrared free-electron lasers (FEL), demand fast, broad-band, wide-dynamic-range detectors. Cooled germanium (Ge) photoconductive detectors have been serving for decades as one of the most sensitive and at the same time robust THz detectors in spectroscopy and imaging for laboratory research as well as for astronomy and planetary research [1]. So far the shortest response times in direct detector operation are a few ns obtained with neutron transmutation doped (acceptor concentration are above $10^{15}/cm^3$) and compensated (32-52%) Ge for frequencies between 1.5 and 3.1 THz [2]. On the other hand, in undoped Ge crystals (residual donor and acceptor concentration less than $10^{13}/cm^3$) longer lifetimes for electrons in lower excited states have been derived from the submillimeter photoconductivity spectroscopy [3]. The question of fundamental limits in speed of Ge photoconductive detectors requires a direct study of the kinetics of free carriers as well as charge carriers bound to an impurity. A time-resolved pump-probe experiment, registering pump-induced changes in probe transmission through a sample, at the free-electron laser (FEL) FELBE facility of the Helmholtz-Zentrum Dresden-Rossendorf has been used to determine relaxation dynamics of free holes and electrons in germanium doped by gallium (Ga) and antimony (Sb).

Experimental

Different Ge crystals were grown and doped to typical levels of ~ $10^{15}/cm^3$. Samples with the wedged optically polished facets have cooled down to ~ 5-6 K in a liquid helium flow cryostat. At such temperatures, impurity electrons are bound to their centers and can be photoionized in the band state continuum by photons with the energies exceeding the binding energy of a particular impurity center. An FEL emission at 105 μm (11.8 meV) providing photoionization of both antimony (n-Ge:Sb) and gallium (p-Ge:Ga) centers has been used for pump-probe experiments (Fig. 1).

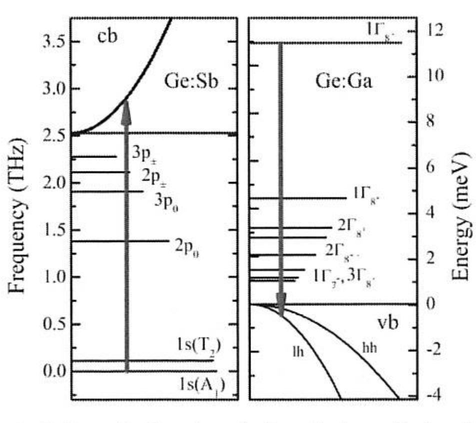

Figure 1. Schematic band and discrete impurity level structures for n-type (a) and p-type (b) germanium. Arrows indicate the FEL pump-probe optical transitions.

Data analysis

The analysis of pump-probe experimental data taking into account all relevant effects is crucial in order to obtain correct results. Their study with regard to intensity dependencies of the pump light, varying sample temperature, as well as an external electric field on the time-resolved pump-induced change of the probe transmittance can reveal the physical principles of the relaxation mechanism [4]. For a proper interpretation of such signal we analyze a time-dependent pump-probe signal in a convolution form of a Gaussian function, describing the FEL pulse shape, and a sum of exponential functions with a scaling factors describing different contributions in the absorption by the sample:

$$S(t) = e^{\frac{(t-t_0)^2}{2\Delta t^2}} * (a \cdot e^{-\frac{t}{\tau_+}} + b \cdot e^{-\frac{t}{\tau_i}})$$

where t_0 is the time of maximum overlap between pump and probe pulses, Δt is the full width at half maximum of the FEL pulse, a_i and τ_i are the partial contribution and the time constant for a particular recombination process i. Analysis shows that for most cases a two-exponential fit to the experimental dependences $S(t)$ is satisfactory (Fig. 2).

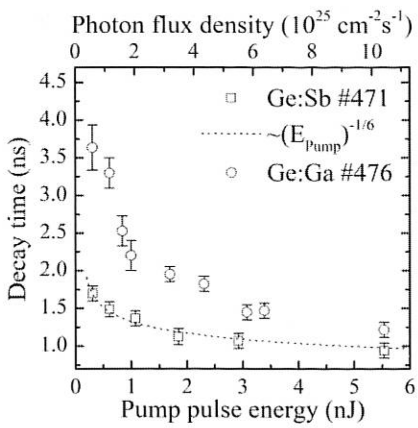

Figure 2. Decay time constants derived from the experimental pump-probe data for n-type (Si:Sb) (a) and p-type (Si:Ga) (b) germanium as function of the FEL pump pulse energy.

The decay of free electrons in a moderately doped and low-compensated n-Ge:Sb shows a good agreement with the well-known cascade capture model [5] and can be accurately described by a single-exponential decay. The typical capture time is between 1 and 2 ns (Fig. 2a). At high pump intensities a better fit can be provided using a two-exponential function $S(t)$. The typical time constants around of ~ 200 ps indicate on intraband relaxation of highly excited free electrons in the conduction band, the process governed by intervalley electron scattering and intervalley phonon emission.

The degenerate valence band in a moderately doped and low-compensated p-Ge:Ga leads to a strong intraband contribution to the relaxation times. That makes a free hole capture time strongly dependent on excitation and decreases with increasing pump power from approximately 4 ns to 1 ns (Fig. 2b). It decreases with increasing pump energy and increasing compensation, because of the higher concentration of Coulomb recombination centers. The weaker and faster, τ_{IVB} ~ 50 ps, contribution is likely for intersubband (light-to-heavy hole subband scattering).

In conclusion, we have carried out and analyzed the data offar-infrared pump-probe experiments for determination of key characteristics of fast relaxation processes in doped germanium. The times for moderately doped and low compensated samples lie in a few ns scale for electronic capture and intracenter relaxation, while intraband decay is an order of magnitude shorter.

Acknowledements

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References

1. E. E. Haller // Infrared Physics, V. 25, 257 (1985).
2. F. A. Hegmann, J. Williams, B. Cole, M. Sherwin, J. W. Beeman, and E. E. Haller // Applied Physics Letters, V. 76, 262 (2000).
3. E. M. Gershenzon, G. N. Gol'tsman, N. G. Ptitsyna // Letters to the Journal of Experimental and Theoretical Physics, V. 25, 539 (1977).
4. N. Deßmann, S. G. Pavlov, V. N. Shastin, R. Kh. Zhukavin, V. V. Tsyplenkov, S. Winnerl, M. Mittendorff, N. V. Abrosimov, H. Riemann, and H.-W. Hübers // Physical Review B, V. 89, 35205 (2014).
5. V. N. Abakumov, V. I. Perel', and I. N. Yassievich // Soviet Physics: Journal of Experimental and Theoretical Physics, V. 45, 354 (1977).