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 picosecond free electron laser emission. Different relaxation processes can be observed by an accurate analysis of the results of the pump-probe technique, including interband, intraband and intraconductor 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-band 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 \(10^{18}/\text{cm}^3\)) 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 \(10^8/\text{cm}^3\)) 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 \(10^{17}/\text{cm}^3\). Samples with the wedged optically polished faces have cooled down to \(-5\) 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.
Towards Active Silicon Photonics – strain engineering and hybrid approaches

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Over the last decades silicon photonics showed remarkable success in the development of passive integrated optical components like waveguides, splitters and gratings. However, to introduce active fast switching and modulation, parasitic wavelength generation and signal transfer nonlinear optical properties have to be exploited. Unfortunately Si does not show a sizeable bulk second order nonlinearity and its third order nonlinearity is plagued by strong two photon absorption in the near IR. Therefore here 2 approaches are discussed which can solve/overcome these issues: the generation of a $\chi^{(2)}$ in Si mainly due to inhomogeneous strain engineering and breaking of centrosymmetry of Si-lattice and a hybrid approach which uses a chalcogenide glass with large $\chi^{(2)}$ but negligible two photon absorption in the near IR.

Generation of $\chi^{(2)}$ in Si-waveguides

The lack of a dipolar second order susceptibility $\chi^{(2)}$ in silicon due to the centrosymmetry of its diamond lattice usually inhibits efficient second order nonlinear optical processes in the silicon bulk. However, recently the deposition of stressed silicon nitride layers lead to the demonstration of second harmonic generation and electro-optic modulation in silicon waveguides. The predominant cause of this observed second order nonlinearity was nevertheless not completely clear. On one side the breaking of the centrosymmetry of the silicon lattice due to the extending inhomogeneous strain in the silicon was discussed. On the other side the impact of the SiN-layer and its interface with Si was stated as the possible source of a strong $\chi^{(2)}$. To clarify this, we prepared several silicon strip waveguides with differently stressed silicon nitride and silicon dioxide coatings. Applying finite-element simulations the inhomogeneous stress/strain fields inside the silicon waveguides were calculated and an integrated stress gradient was defined as measure for symmetry breaking of the Si-lattice. This theoretical stress/strain field was experimentally verified using X-ray diffraction. Specifically the experimentally observed distortion of the symmetric Si(111) reflex in the reciprocal space map was accurately described by the calculated diffraction pattern based on the simulated inhomogeneous stress field. Subsequently second harmonic generation was measured in these waveguides at a pump wavelength of 2200 nm (fig. 1). The results show, that indeed an enhancement of the second order nonlinearity occurs for waveguides with increasing integrated stress gradient $\Sigma$ (larger inhomogeneous strain in the silicon).

Fig. 1. SHG conversion efficiency for differently coated Si-waveguides having comprising different levels of inhomogeneous strain. SiN-coated waveguides show always a higher $\chi^{(2)}$ signal than SiO$_2$ coated ones.

This strain-related $\chi^{(2)}$ appears for both, SiN, and SiO$_2$-covered waveguides and does therefore not depend on the chemical nature of the stressing cover layers. However for SiN$_2$-coated waveguides an additional two-fold enhancement is observed, even if the SiN$_2$-coating is basically unstrained and the inhomogeneous strain in Si is negligible. Capacitance-Voltage measurements on similarly coated metal-insulator-silicon-structures indicate that this SiN$_2$-related effect is caused by fixed positive charges at the SiN$_2$/Si interface. These charges lead to an electric field on the order of 10$^5$ V/cm at the interface and can elect...