Semiconductor-based carrier-envelope phase detector

Christian Jirauschek, Lingze Duan, Oliver D. Mücke, and Franz X. Kaertner
Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139
Tel: 617-253-4186, Fax: 617-253-9611, Email: jirau@mit.edu

Klaus D. Hof, Thorsten Tritschler, and Martin Wegener
Institut für Angewandte Physik, Universität Karlsruhe (TH), Wolfgang-Gaede-Straße 1, 76131 Karlsruhe, Germany

Abstract: We study the carrier-envelope phase sensitivity of the inversion in a two-band semiconductor and the influence of rapid dephasing of higher-lying states. The application of this effect for constructing a solid-state phase detector is investigated.

OCIS codes: (190.7110) Ultrafast nonlinear optics; (320.7130) Ultrafast processes in condensed matter, including semiconductors

Summary:

Detectors based on solid-state effects are of special interest for measuring the carrier-envelope (CE-) phase φ_{CE}, due to their compactness. For interaction of a semiconductor with a strong electric field, the carrier dynamics becomes phase-sensitive, resulting in a phase-dependent polarization and inversion. The phase signal in the polarization can be extracted by detecting the emitted radiation [1]. The inversion can be probed optically or read out electronically by an applied bias voltage, resulting in a compact electronic phase detector. For a two-level system, the phase dependence of the inversion has already been discussed and experimentally demonstrated for radiofrequency pulses [2,3]. In this paper, we extend the discussion to include effects which arise due to the quasi-continuum level structure in the semiconductor bands.

Our calculations are based on a two-band semiconductor model. The interaction with the electric field is described by the semiconductor Bloch equations [4], the Coulomb interaction among carriers and propagation effects are neglected. Our model includes energy-dependent dipole moments and dephasing rates. For the energy bands, we choose the highest valence band and the conduction band of GaAs or respectively InGaP, obtained with a tight-binding method [5].

We assume sinc-shaped pulses with a FWHM pulse duration T and a carrier frequency $\omega_0=2\pi f_0$. $\Omega_g= d_g E_{max}/\cong$ is the Rabi frequency at the Γ point, with the maximum field strength E_{max} and the dipole matrix element d_g.

In Fig. 1, various densities are displayed as a function of the interband transition energy E. Fig. 1(a) shows the density of states $\rho(E)$ in the conduction band. In Fig. 1(b), the electron-hole pair density $n_E(E,\varphi_{CE}=0)$ after interaction with a two-cycle Ti:sapphire pulse is displayed for $\Omega_g/\omega_0=1$. Fig. 1(c) shows the phase-related inversion difference $\Delta n_E(E)=n_E(E,0)-n_E(E,-\pi/2)$. Only the near-band-gap transitions contribute to the phase signal. The population of the higher-lying states is phase-insensitive, mainly because of the increased dephasing for higher energies.

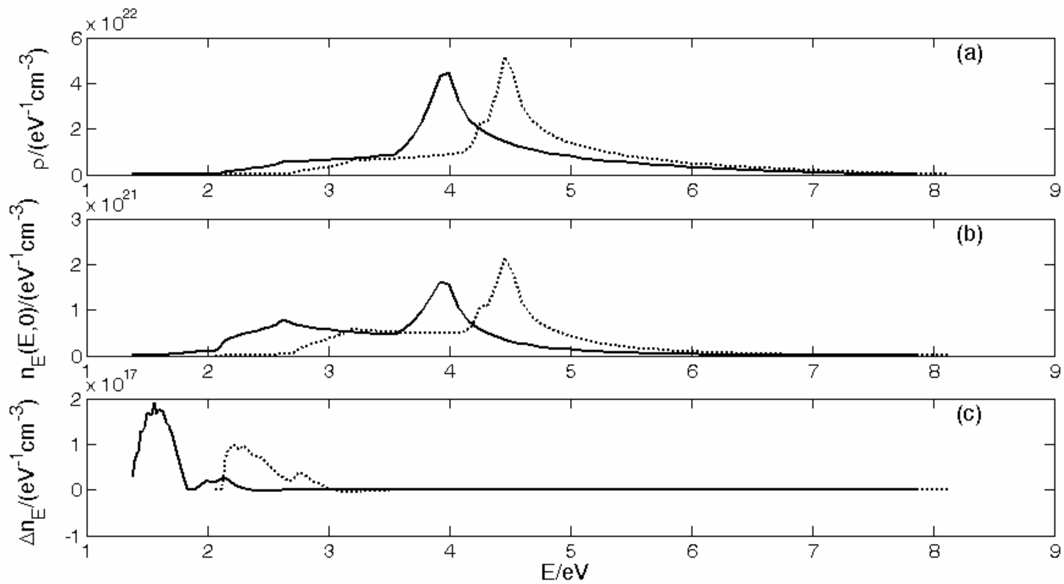

Fig. 1. Energy dependence of density functions for GaAs (solid line) and InGaP (dotted line). (a) Density of states in the conduction band. (b) Electron-hole pair density after interaction with a two-cycle Ti:sapphire pulse for $\varphi_{CE}=0$ and $\Omega_g/\omega_0=1$. (c) Phase-related inversion difference after interaction with the pulse.

The phase-dependent modulation of the population occurs at twice the CE phase. Fig. 2 shows the modulation depth $\delta=[N(0)-N(-\pi/2)]/[N(0)+N(-\pi/2)]$, where $N(\varphi_{CE})$ is the total number of electron-hole pairs after the pulse. For single-cycle pulses ($f_0T=1$), where the phase dependence of the field is more pronounced than for two-cycle pulses ($f_0T=2$), δ is larger. Overall, the relative modulation grows strongly for increasing Rabi frequencies, but intervals with positive and negative δ alternate.

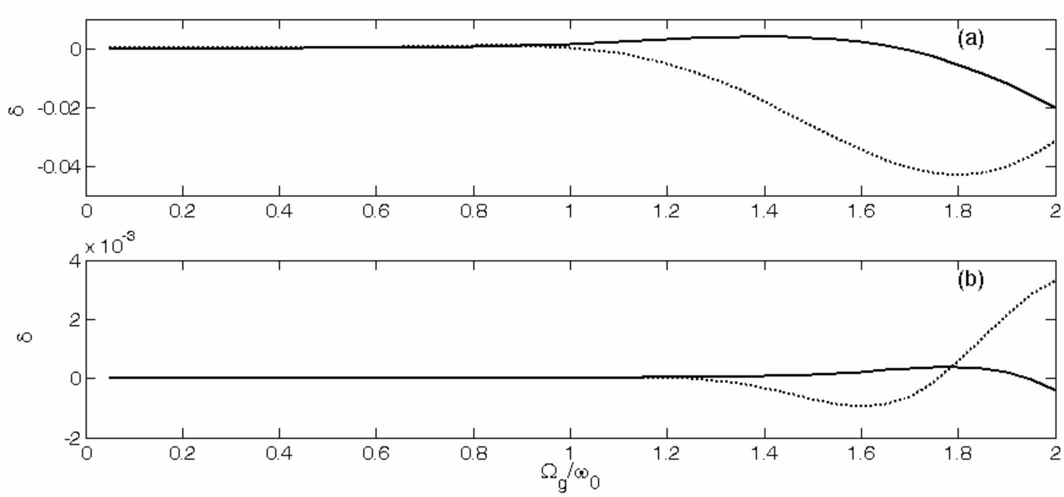

Fig. 2. Modulation depth δ in GaAs (solid line) and InGaP (dotted line) for (a) single-cycle and (b) two-cycle pulses.

Coulomb interaction, energy relaxation, and alternative models for the dephasing of the higher-energy states might lead to quantitative changes of these results. Nevertheless, these theoretical findings suggest several intriguing experiments. In the case of electronic detection, where the inversion is read out after carrier relaxation to the conduction band minimum, the signal-to-noise ratio is considerably decreased, but the phase dependence may still be observable for large Rabi frequencies. Increased phase sensitivity can be expected from materials that come closer to two-level systems, i.e., have narrower energy bands and in particular a smaller dephasing, e.g., artificial materials like superlattices and quantum dots. In the case of optical probing, the population close to the band edge can be monitored, avoiding contributions from phase-insensitive higher-lying states, if the probing occurs on a time scale shorter than the intraband relaxation processes. Such an experiment could give useful information on relaxation and dephasing processes in semiconductors. Simple analytical calculations within a perturbative approach or within the so-called square-wave approximation allow for an intuitive understanding of the underlying physics.

References

[1] O. D. Mücke, T. Tritschler, M. Wegener, U. Morgner, and F. X. Kaertner, "Role of the carrier-envelope offset phase of few-cycle pulses in nonperturbative resonant nonlinear optics," Phys. Rev. Lett. **89**, 127401 (2002).
[2] W. M. Griffith, M. W. Noel, and T. F. Gallagher, "Phase and rise-time dependence using rf pulses in multiphoton processes", Phys. Rev. A **57**, 3698-3704 (1998).
[3] A. Brown and W. J. Meath, "On the effects of absolute laser phase on the interaction of a pulsed laser with polar versus nonpolar molecules," J. Chem. Phys. **109**, 9351-9365 (1998).
[4] H. Haug and S. W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors* (World Scientific, Singapore, 1993).
[5] A.-B. Chen and A. Sher, "Electronic structure of III-V semiconductors and alloys using simple orbitals," Phys. Rev. B **22**, 3886-3896 (1980).