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Photon-drag effect and plasma oscillations in 1D semiconductors

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Abstract: We couple the Maxwell equations to interband and intraband semiconductor Bloch equations for a laser-excited semiconductor nanowire. Results demonstrate 1D spatio-temporal plasma oscillations as well as a photon-drag current. © 2022 The Author(s)

1. Theoretical model

The Maxwell equations for a transverse propagating laser field is coupled to the two-band semiconductor Bloch equations (SBEs) that time-evolve the electron and hole occupations at momentum k and the coherences between all carrier states. [1–4]. This approach includes Coulomb corrections to single-particle energies and the Rabi frequency, as well as Coulomb scattering between carriers, diagonal and off-diagonal dephasing, and carrier-phonon collisions. [4] We solve these traditional SBEs [1,4] as well as SBEs for the intraband coherence [2,3] of the conduction electrons, C_{k_1,k_2}

$$\frac{d}{dt}C_{k_1,k_2} = \frac{i}{\hbar}(\varepsilon^e_{k_1} - \varepsilon^e_{k_2})C_{k_1,k_2} + \frac{iV^{\text{ee}}_{k_2-k_1}}{\hbar}(n^e_{k_2} - n^e_{k_1}) \sum_k C_{k+k_1-k_2,k} + \frac{i}{\hbar}\sum_{k'}\left[\mathbf{d}^{cv}_{k_2,k'} \cdot \tilde{\mathbf{E}}_T(k_2-k',t)p^*_{k_1,k'}(t) - \mathbf{d}^{cv*}_{k_1,k'} \cdot \tilde{\mathbf{E}}^*_T(k_1-k',t)p_{k_2,k'}(t)\right], \tag{1}$$

as well as analogous SBEs for the coherence between holes, D_{k_1,k_2} [2] and the coherence between electrons and holes, $p_{k,k'}$ [2]. Here, $\mathbf{d}^{cv}_{k,k'}$ is the interband dipole matrix element between conduction and valence states with momenta k and k', V^{ee}_q is the spatially Fourier transformed Coulomb potential, and $\tilde{\mathbf{E}}_T(q,t)$ is the spatial Fourier transform of $g(y)\mathbf{E}^\perp(y,t)$, where $\mathbf{E}^\perp(y,t)$ is the transverse electric field and $g(y)$ is a gating envelope function defining the borders of the nanowire length, which lies along the y-axis. With the solutions to these equations, we calculate the polarization and net free-charge density in the y-space of the wire as

$$\mathbf{P}(y,t) = \frac{\alpha}{2\delta_0\mathscr{L}}\sum_{k,k'}\mathbf{d}^{cv}_{k,k'}p_{k,k'}(t)e^{i(k'-k)y}g(y) + \text{c.c}, \tag{2}$$

$$\rho_f(y,t) = +\frac{e\alpha g(y)}{\mathscr{L}\delta_0}\left[\sum_{k'_1,k'_2} D_{k'_1,k'_2}e^{i(k'_1-k'_2)y} - \sum_{k_1,k_2} C_{k_1,k_2}e^{i(k_2-k_1)y}\right], \tag{3}$$

where $\mathscr{L}$ =500 nm is the nanowire length, and $1/\alpha$ and δ_0 are effective quantum wire thicknesses in the transverse directions [2]. We solve the SBEs coupled with the 1D Maxwell equations for the transverse laser field, $E^\perp_x(y,t)$, a 40-fs 800-nm pulse propagating in the y-direction along the axis of a GaAs nanowire oriented in the $\Gamma - X$ direction. Because this model allows for field-induced non-vertical transitions in the crystal momentum space, the excited carriers gain not only energy from the propagating laser field, but also momentum, giving rise to a measurable photon-drag current [5].

2. Results

The spatially non-uniform transverse laser field propagates through the gated wire space as shown in Fig. 1a below. This excites an e-h plasma, the distributions of which are shown in Fig. 1e-f as functions of crystal momentum

k and time t. After the initial optical excitation, the carriers relax due to Coulomb and phonon scattering after about 5 ps. The energy lost by electrons and holes (due to phonon collisions) is shown in Fig. 1d, along with the photon drag current produced in the wire that decreases over time due to momentum loss to phonons. This current arises from the spatially non-uniform field causing non-vertical transitions in momentum space, yielding a non-zero net momentum in the carriers of the nanowire. Our simulations show that the energy and momentum lost from the propagating laser field exactly matches the initial energy and momentum deposited into the *e*-*h* carriers, confirming that the current in Fig. 1d is a photon drag current.

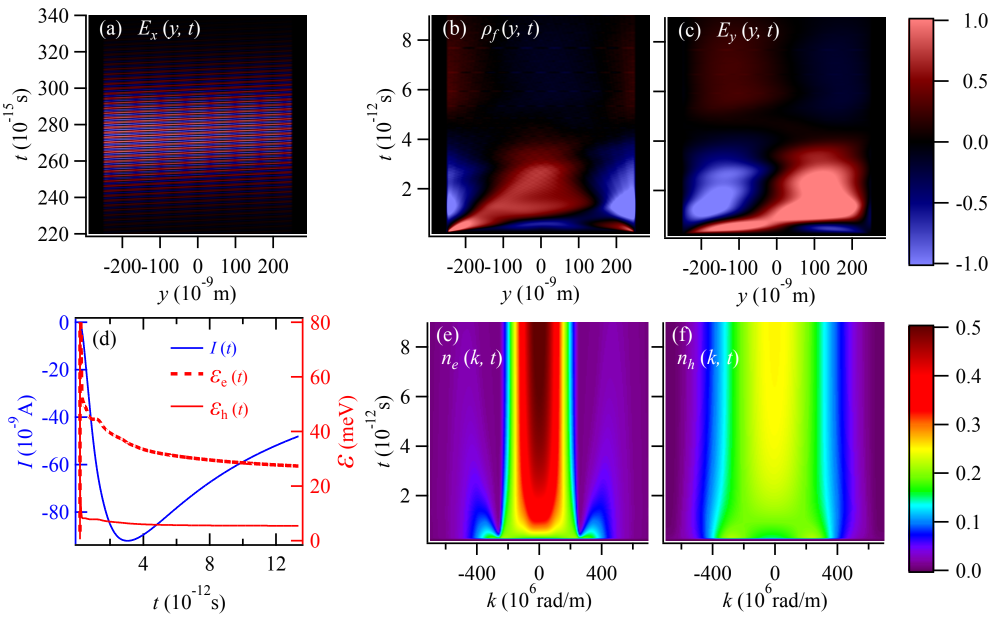

Fig. 1. (a) The normalized transverse laser electric field, (b) the net free-charge plasma density, and (c) the resulting longitudinal electric field in the wire as functions of position y and time t [2]. Also, (d) the average carrier current and average *e*-*h* carrier energies and photon-drag current as functions of time t, as well as the laser-generated (e) electron and (f) hole distributions [2] as functions of crystal momentum k and time t.

Due to the spatially non-uniform transverse field, nonzero intraband coherences (see Eq. 1) lead to spatially non-uniform distributions of electrons an holes (see Eq. 3) yielding the *e*-*h* plasma distribution in the wire space shown in Fig. 1b. Note that the plasma oscillates on the THz scale before decaying, as does the longitudinal plasma field these charges produce, see Fig. 1c. Our results further demonstrate that these plasma oscillations have an appreciable effect on the measurable photon drag current. We note that the plasma oscillations appear only for high levels of initial excitation by the laser pulse (*i.e.* only for a strong laser field), whereas the photon drag current appears for all field strengths and scales with the total pulse energy. These results allow for an experimental test of the model in Sec. 1 and give insight into the optoelectronic behavior semiconductor nanowires.

References

1. H. Haug and S. W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors* (World Scientific Publishing Co. Pte. Ltd., 2009), 5th ed.
2. J. R. Gulley and D. Huang, "Ultrafast transverse and longitudinal response of laser-excited quantum wires," Opt. Express **30**, 9348–9359 (2022).
3. J. R. Kuklinski and S. Mukamel, "Generalized semiconductor bloch equations: Local fields and transient gratings," Phys. Rev. B **44**, 11253–11259 (1991).
4. J. R. Gulley and D. Huang, "Self-consistent quantum-kinetic theory for interplay between pulsed-laser excitation and nonlinear carrier transport in a quantum-wire array," Opt. Express **27**, 17154–17185 (2019).
5. J. H. Strait, G. Holland, W. Zhu, C. Zhang, B. R. Ilic, A. Agrawal, D. Pacifici, and H. J. Lezec, "Revisiting the photon-drag effect in metal films," Phys. Rev. Lett. **123**, 053903 (2019).