Time scale for the semiclassical terahertz gain in a semiconductor superlattice with optically excited charge carriers

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Abstract— **We report on a Monte Carlo study of the interplay between terahertz radiation and an electron ensemble in a GaAs/AlGaAs superlattice after ultra-short optical excitation. We found that the time, the electron ensemble needs to reach the state ensuring the steady terahertz gain, is determined by the dephasing time of Bloch oscillations. The stationary state with the terahertz gain may be attained faster for the special initial distribution of electrons in *k*-space.**

Index Terms—**Bloch oscillations, gain of terahertz radiation, Monte Carlo simulations, semiconductor superlattice.**

I. INTRODUCTION

ONE of the approaches for realizing a room-temperature electrically pumped terahertz (THz) emitter is based on the property of a biased semiconductor superlattice to amplify THz radiation within a wide frequency range [1]. As it has been pointed out theoretically a superlattice shows gain values comparable and even exceeding those for THz quantum cascade lasers [2]. However, in addition to the superlattice gain media, the emitter requires a cavity which couples the THz radiation back to the superlattice providing the feedback. In principle in this THz emitter already a weak THz field, present in the thermal background radiation, should be amplified giving rise to the further amplification until a steady state is reached. On the other hand the preparation of states with Bloch oscillating electrons using femtosecond laser pulses [3] is accompanied by the emission of THz radiation which might also serve as a seeding field for the laser start. The development of the steady-stationary state in the emitter is closely related to the question of the evolution time of the electron ensemble from the initial state to the state corresponding to the gain of the coupled THz field.

In our theoretical study we focus on the dynamics of the THz gain in a superlattice, namely we discuss the question of the time of gain buildup after an optical injection of charge carriers into a superlattice, which has been left without attention so far.

We simulate the transport of electrons excited in an undoped biased superlattice by an ultra-short pulse of a femtosecond laser. In order to analyze the development of the gain in the superlattice after the excitation we consider one period T of a high-frequency field (‘probe’ field) which interacts with the electrically biased superlattice beginning at a time τ after the optical pumping event (Fig. 1). This situation simulates a THz amplification experiment where a THz pulse is coupled to the superlattice after a waiting time. We show that the interaction between Bloch oscillating electrons and the applied THz field right after the excitation can cause either amplification or damping of the THz field. The steady-stationary THz gain sets in only after the Bloch oscillations die out. Thus, the buildup time for the gain is determined by the dephasing time of the Bloch oscillations (from 0.15 to 1 ps) and depends on the efficiency of electron scattering.

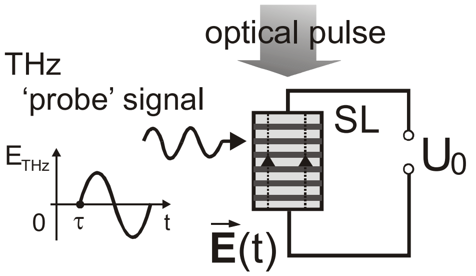

Fig. 1. Sketch of the principle of the experiment on a biased superlattice (SL) exposed to a ‘probe’ THz field (E_{THz}).

II. MATHEMATICAL MODEL

We consider a GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice (period (d) of 8.4 nm and a width of the first electron miniband of 38 meV) which is subject to an electric field applied along the superlattice axis. The charge carriers are assumed being introduced into the superlattice instantaneously at the time t=0 with the density (n) of 10^{15} cm^{-3}. We assume the excitation of the electrons at the bottom of the first electron miniband in

Manuscript received March 19, 2007. This work was supported in part by the Russian Agency of Education and CRDF (grant BF5M01), the Federal Agency of Science and Innovations (contract No. 02.444.11.7093), and RFBR.

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accordance with the Gaussian distribution in the Brillouin zone with the average wave vector equal to zero and the dispersion corresponding to the half-frequency maximum width of the optical pulse of 14 meV. The previous detailed experimental and theoretical studies [4, 5] have enabled us to assume the electric field being homogeneous in the superlattice and neglect the hole contribution into the THz superlattice response. Therefore, we employ a single-particle Monte Carlo technique to describe the motion of electrons which interact with acoustic and optical phonons and interface roughness (for details of the calculation of the scattering rates see Ref. [6, 7]). The simulations have been performed for the lattice temperature of 10 K.

III. RESULTS AND DISCUSSION

We describe the interplay between an electron ensemble in the superlattice subject to a static field (E_0) and a THz field, ($E_\omega \sin\omega t$), by an average power absorbed by the electron ensemble over a period of the THz field, $T=2\pi/\omega$. The power depends on the time instant, the THz field has been applied at and is given by $P_{\sin}(\tau)=(qn/T)\int_{\tau}^{\tau+T}\upsilon_{\sin}(t)E_\omega \sin\omega t dt=\frac{c\sqrt{\varepsilon}E_\omega^2}{8\pi}\alpha(\tau)$, where $\alpha(\tau)=4\pi qn(\upsilon_{\sin\omega}(\tau)/E_\omega)/c\sqrt{\varepsilon}$ is the instantaneous amplification coefficient, $\upsilon_{\sin\omega}(\tau)=\frac{1}{T}\int_{\tau}^{\tau+T}\upsilon_{\sin}(t)\sin\omega t dt$, ε is the dielectric constant of GaAs, and q is the elementary charge.

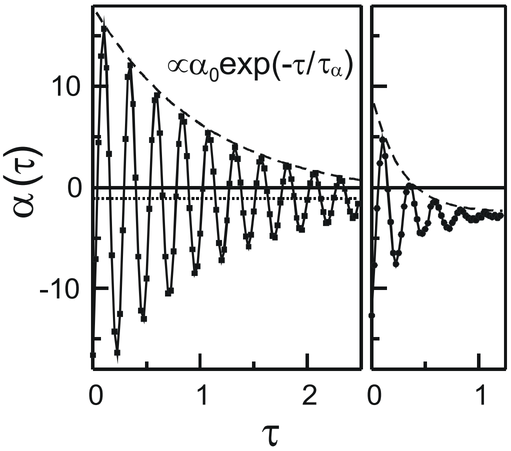

Fig. 2. Left: Time-dependent amplification coefficient (solid line) in the superlattice with electrons subject to scattering at optical and acoustic phonons and the exponential fit of its envelope function (dashed line); Right: the same as the left but electrons are assumed to be additionally scattered at interface roughness with the fluctuation of the layer thickness of 0.28 nm and the correlation length along the layer surface of 3 nm.

A positive value of the average power or the amplification coefficient implies damping of the THz field over the period while the negative value corresponds to the THz field amplification. Fig. 2 (left) shows the time-dependent amplification coefficient for the superlattice subject to the static and high-frequency fields (E_0=20 kV/cm, E_ω=5 kV/cm, and $\omega/2\pi$ = 2.5 THz). In this case we assume electron scattering only at optical and acoustic phonons. The amplification coefficient is an oscillatory function of time and it becomes negative after about 2.5 ps. The latter indicates that after 2.5 ps the electron ensemble is capable to amplify external THz radiation. We also performed simulations of the superlattice response when electrons experience strong elastic scattering at interface roughness. The amplification coefficient is displayed in Fig. 2 (right) and shows that the stable THz gain is established in the superlattice already after 0.5 ps. We fitted the envelope function of the time-dependent amplification coefficient with the exponential function $\alpha(\tau)=\alpha_0\exp(-\tau/\tau_\alpha)+\alpha_\infty$ where α_∞ is the amplification coefficient in the stationary state and we denote the time of the gain buildup as τ_α. The oscillatory behavior of the amplification coefficient right after the excitation is due to the Bloch oscillations of the electrons in the Brillouin zone. Therefore the time of the gain buildup in a superlattice after the optical excitation is in fact a dephasing time of the Bloch oscillations and it depends on electron scattering and changes from 0.15 to 1 ps. However, if the initial conditions for electrons eliminate Bloch oscillations and the electron ensemble is in the state determined by the applied static field, which in our case corresponds to τ larger than a few picoseconds, then already the first period of the external radiation with an appropriate frequency will be amplified. The amplification coefficient over the first period will then be slightly smaller than its stationary value. The latter can be reached after one or several periods of the THz field which depends on both scattering mechanisms and the frequency of the THz field.

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