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Role of the optical pulse repetition rate in the efficiency of terahertz emitters

Antanas Reklaitis

Semiconductor Physics Institute, Center for Physical Sciences and Technology, A. Goshtauto 11, Vilnius 01108, Lithuania

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ABSTRACT

Excitation of *n*-GaAs and *p*-InAs terahertz emitters by the series of optical pulses is studied by ensemble Monte Carlo simulations. It is found that the spatial separation of photoexcited electrons and holes dramatically reduces the recombination intensity in *n*-GaAs emitter, the operation of which is based on the surface field effect. The spatial separation of carriers does not affect the recombination intensity in *p*-InAs emitter, the operation of which is based on the photo-Dember effect. Therefore, the recovery time of equilibrium state after optical pulse in *n*-GaAs emitter significantly exceeds the corresponding recovery time in *p*-InAs emitter. This fact leads to a substantial reduction of photocurrent amplitude in *n*-GaAs emitter excited by the optical pulse series at high repetition rate.

1. Introduction

Terahertz (THz) radiation from semiconductor surface is generated using the series of femtosecond optical pulses [1,2]. The transient photocurrent, which generates THz pulse, is induced by the surface electric field [3] and by the photo-Dember effect [3,4]. The emitter made of *n*-type GaAs is the one of THz emitters which are based on the surface field effect [5,6]. The (100) oriented *p*-InAs is a typical THz emitter, which is based on the photo-Dember effect [7,8]. The experimental studies show that emitters based on the photo-Dember effect are much more efficient than the emitters based on the surface electric field effect [9,10].

After each optical pulse, the dynamics of electron–hole system in a freestanding THz emitter involves two stages of different duration. The transient photocurrent of excited electrons and holes generates a pulse of THz radiation during the first stage. The duration of the first stage does not exceed few picoseconds. The equilibrium momentum distribution of photoexcited carriers is recovered after the first stage. However, the spatial distribution of carrier density remains nonequilibrium. During the second stage, the carrier recombination tends to restore the equilibrium spatial distribution of carrier density. The duration of the second stage depends on the recombination intensity of photoexcited carriers which is determined by several factors including the rates of radiative and trap-assisted nonradiative recombination, as well as the extent of spatial separation of electrons and holes. The intensity of both recombination channels can be substantially reduced if the spatial separation of electrons and holes is significant.

The response of THz emitters to the optical pulse series has not yet been investigated theoretically. The transient photocurrent induced by a single optical pulse has been analyzed, i.e., only the first stage has been considered in the theoretical studies of THz emitters (see, for instance, [11–15]). The response of the emitters to a single optical pulse has been studied assuming that the emitters are in equilibrium state before the optical excitation. This approach is reasonable given the time interval between the pulses is sufficiently large for a complete recovery of the equilibrium distribution of carrier density after each optical pulse.

However, the efficiency of the THz emitter may be significantly reduced if the time interval between the optical pulses is less than the recovery time of equilibrium state. In this case, the response of the emitter to the subsequent optical pulse is started from some intermediate state which differs from the equilibrium. Let us consider, for instance, *n*-GaAs. Due to the built-in surface electric field, the excited electrons are swept out from the surface towards the bulk during the first stage, while the excited holes move towards the surface. The holes are collected at the surface and screen the built-in electric field. The recombination rate of holes is substantially decreased because the region near the surface is depleted of electrons. Consequently, the carriers excited by the next optical pulse are accelerated by the reduced electric field. As a result, the amplitude of photocurrent is lowered. A similar situation may develop in *p*-InAs due to the photo-Dember effect. In this case, electrons and holes are spatially separated after the first stage due to different diffusion rates. The electric field induced by

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E-mail address: reklaitis@pfi.lt

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the separated carriers can significantly reduce the diffusion current of electrons excited by the next optical pulse.

In the present work, the excitation of *n*-GaAs and *p*-InAs THz emitters by the series of optical pulses is studied using ensemble Monte Carlo (EMC) simulations. The mechanism of the recovery of equilibrium state after the optical pulse is analyzed. The dependence of the efficiency of THz emitters on the intensity of carrier recombination is investigated.

2. Models of *n*-GaAs and *p*-InAs emitters

The semiclassical motion of extrinsic and photoexcited carriers in freestanding THz emitters is simulated by EMC method. The spatio-temporal variation of electric field is obtained from the solution of Poisson equation which is self-consistently coupled with the space charge distribution of electrons, holes, ionized impurities, and charged traps. The simulations are performed in a one-dimensional real space and in a three-dimensional momentum space. The one-dimensional real space approach is a good approximation as long as the size of the laser beam is significantly larger than the absorption depth. The details of the applied EMC method as well as the simulation of the carrier photoexcitation are given elsewhere [12].

The models of the conduction band structure of GaAs and InAs consisting of nonparabolic Γ, L, and X valleys are considered. For the valence band, the heavy, light, and split-off nonparabolic subbands are taken into account. The band structure and material parameters for GaAs and InAs are taken the same as in [16] and [17], respectively. The electron scattering mechanisms considered in the simulations include polar optical, inelastic deformation acoustic, intervalley, and ionized impurity scattering, as well as electron-electron and electron–hole interactions. The interaction of holes with polar optical phonons, deformation optical and acoustic phonons is considered for intrasubband and intersubband scattering of holes taking into account the overlap between *p*-like wave functions of the valence band. The ionized impurity scattering as well as the hole-hole and hole-electron interactions are also taken into account. The calculations are carried out for the lattice temperature of 300 K.

The electron–hole pairs are generated by the series of three Gaussian optical pulses. The full width at half maximum of each optical pulse is set to 100 fs. The central photon energy is taken 1.55 eV. At this photon energy, the light absorption coefficients α in GaAs and InAs are 1.25×10^4 cm^{-1} [6] and 7×10^4 cm^{-1} [18], respectively. The thickness of the doped to 10^{16} cm^{-3} *n*-GaAs and *p*-InAs layers is taken 3 μm, which substantially exceeds the optical absorption depth in GaAs and InAs. The substrate doping is taken the same as in the surface layer. The simulations are started from the equilibrium ensemble of charge carriers. At equilibrium, the surface Fermi level F_s is pinned at 0.71 eV below the conduction band edge in GaAs [5], and at 0.2 eV above the conduction band edge in InAs [19].

The typical repetition rate of the optical pulses is 80 MHz in the experimental studies of THz emission. The optical pulses are separated by the time interval of 12.5 ns at this repetition rate. In order to reduce the simulation time, the time interval between the optical pulses is set to 125 ps, i.e., the repetition rate is increased by 100 times. Accordingly, the rates of the recombination processes are also artificially increased by 100 times.

The trap-assisted Shockley-Read-Hall (SRH) and radiative recombination processes are considered for electrons and holes. The details of EMC simulation of SRH recombination are given in [20]. The density of donor-type traps is set to $N_T=2\times10^{15}$ cm^{-3} in *n*-GaAs and *p*-InAs emitters. The calculations show that the potential profile is not affected by the charged traps at this trap density. It was assumed that the energy levels of traps are located at the middle of GaAs and InAs energy gap, i.e., at E_c–0.71 eV and E_c–0.17 eV, respectively, where E_c is the energy of the conduction band bottom. The carrier capture cross section σ of different traps in GaAs varies from 10^{-17} cm^2 to 5×10^{-14} cm^2 [21,22]. The capture cross section of 10^{-14} cm^2 results in SRH recombination lifetime of several nanoseconds at the trap density $N_T=2\times10^{15}$ cm^{-3}. In the simulations, the capture cross section of SRH recombination is increased to $\sigma=10^{-12}$ cm^2 for electrons and holes in *n*-GaAs and *p*-InAs to match the enhanced repetition rate of optical pulses.

The radiative recombination of electrons and holes is described by the rate equation

$$\frac{dn(z,t)}{dt}=\frac{dp(z,t)}{dt}=-B[n(z,t)p(z,t)-n_i^2] \tag{1}$$

where n and p are the electron and hole density, respectively, B is the coefficient of radiative recombination, and n_i is the intrinsic carrier density. In EMC simulations, the radiative recombination is considered as the conventional scattering process. The rates of radiative recombination for electrons and holes are given by

$$\lambda_{re}=Bp(z,t) \tag{2}$$

and

$$\lambda_{rh}=Bn(z,t), \tag{3}$$

respectively. The distribution of electron and hole densities are calculated after each time step. The electron–hole pair is removed from the subsequent simulation after each event of radiative recombination, which is selected randomly using (Eqs. (2) and 3). According to Eq. (1), the electron–hole pairs are generated at a constant rate Bn_i^2 during each time step. The carriers are generated with the equilibrium momentum distribution. The coefficients of radiative recombination in GaAs and InAs are 1.7×10^{-10} cm^3 s^{-1} [23] and 6×10^{-11} cm^3 s^{-1} [24], respectively. Following the time scaling scheme adopted in the present work, the simulations are carried out for 100 times increased coefficients of radiative recombination. The coefficients of radiative recombination for GaAs and InAs are set to 1.7×10^{-8} cm^3 s^{-1} and 6×10^{-9} cm^3 s^{-1}, respectively.

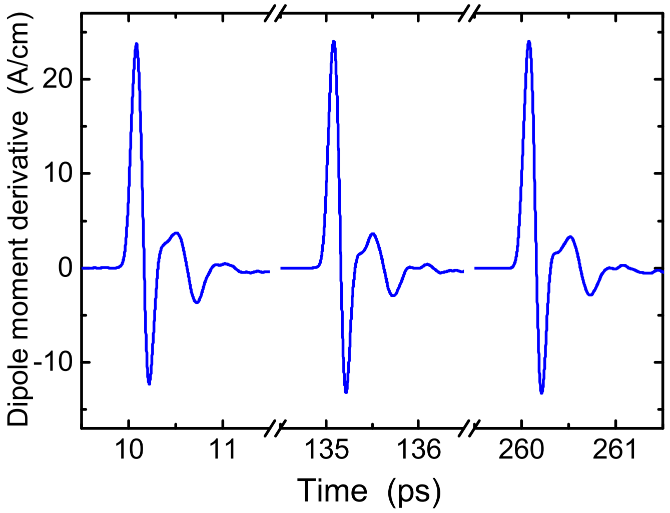

Fig. 1. Waveforms of the temporal derivative of the dipole moment in *p*-InAs excited by the series of three optical pulses. The intensity peaks of the first, second and third optical pulses are centered at 10 ps, 135 ps, and 260 ps, respectively. The fluence of each optical pulse is 5 μJ/cm^2.