EMC Simulation of THz Emission from Semiconductor Devices

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Abstract

We report on several ultrafast electron transport phenomena occurring in wurtzite InN which are considered as the physical mechanisms responsible for the THz electric field radiation. We apply the ensemble Monte Carlo (EMC) method to simulate the streaming transport caused by (a) optical phonon emission and (b) impact ionization. Under specific conditions, in both streaming regimes the electron drift velocity reveals the sub-picosecond oscillations which are an indication of "readiness" of the semiconductor system to radiate an electric field in the THz range. We also investigate the electric field emission from InN and InAs surfaces induced by femtosecond laser excitation.

1 Introduction

In recent time, the terahertz (THz) electric field radiation associated with different ultrafast carrier transport phenomena has attracted much attention [1,2]. Such increasing interest stems from the ability of THz electromagnetic waves to safely penetrate into soft tissues of human body and other organic materials without damages that occur, for example, by X-ray radiation. Other areas of the use of THz radiation sources such as defence and security applications, as well as sensor techniques are also envisaged. From the viewpoint of practical applications, the most perspective devices are, probably, solid-state THz sources due to their ability to be easier integrated with other optoelectronic devices within a single chip. In this concern, several physical mechanisms, associated to specific ultrafast transport phenomena, such as the optical-phonon transit-time resonance due to streaming transport [3], are considered as possible candidates to obtain THz emission. In addition, the THz radiation from semiconductor surfaces is currently under extensive investigation. The physical mechanisms of THz surface emission are associated with the transient transport of photogenerated carriers governed by a built-in surface electric field or due to the different diffusion of electrons and holes towards the bulk (photo-Dember effect) [4]. However, the realization of solid-state THz sources is still a challenge and several aspects of the physics of THz emission are not fully understood. Therefore, simulations of the THz emission and related ultrafast electron transport phenomena in semiconductors are urgently needed.

First, we discuss the streaming transport in wurtzite InN induced by polar optical phonon (POP) emission and impact ionization as suggested in our previous work [5]. Then, the THz surface emission driven by the photo-Dember effect is investigated for InN and InAs.

2 Electron Streaming Transport in Wurtzite InN

Electron streaming is specified as an ultrafast transport phenomenon in polar semiconductors when electrons, by applying a constant electric field, perform periodically repeated ballistic flights ended by energy dissipation due to optical phonon emission. However, the latter energy relaxation mechanism is not unique and another mechanism, such as impact ionization in wurtzite InN, can be responsible for the quasi-periodic motion of electrons in the momentum space as well.
By streaming transport, the electron drift velocity exhibits an oscillatory behavior in the time domain, which is drastically affected by the temperature and the doping level. Such oscillations can serve as a physical operation principle for THz radiation [3]. As shown in Fig. 1(a), the THz drift velocity oscillations induced by POP emission are present only at relatively low temperatures and are entirely quenched at room temperature. Next, ionized impurity scattering at high doping levels also strongly damps the drift velocity oscillations due to very rapid loss of synchronization in the POP emission by individual electrons (Fig. 2).

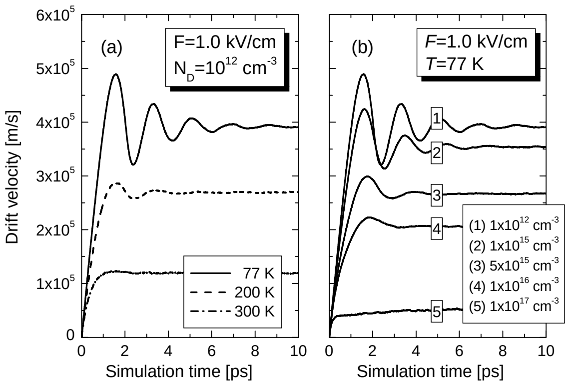

Fig. 1. Transient drift velocity in InN simulated by the EMC method at (a) different temperatures and for (b) different doping levels. The frequency of the damped oscillations is 600 GHz.

In contrast, when streaming transport is induced by impact ionization the drift velocity oscillations at significantly higher frequencies survive even at room temperature and doping level of 10^{17} cm^{-3} (see Fig. 2).

3 THz Surface Emission from InN and InAs

The THz surface radiation is understood as the emission from a small oscillating electric dipole induced by optical pulse excitation of the semiconductor surface. Such electric dipole is formed due to a spatial separation of photogenerated carriers, i.e. electrons and holes. Up to date, different semiconductors have been experimentally probed as THz surface emitters. However, the main parameters limiting the efficiency of the field surface emission are not fully clarified.

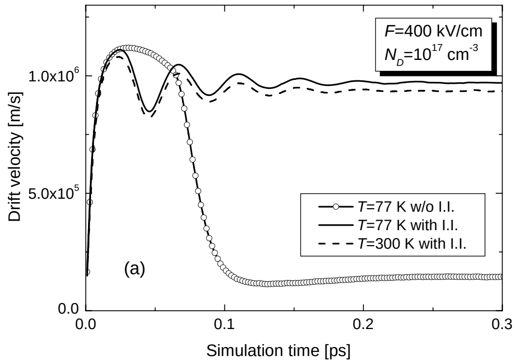

Fig. 2. Transient drift velocity in InN with and without impact ionization simulated by the MC method at different temperatures. The frequency of the damped oscillations is 23 THz.

We simulated the THz field radiation as a function of laser excitation energy and laser fluence for InN and InAs. Figure 3 shows the electric field pulses (waveforms) radiated from InN and InAs surfaces by 100 fs laser excitation with photon energy of 1.55 eV. As illustrated, the nonparabolicity of the central valley drastically influences the waveform amplitude for both semiconductors.

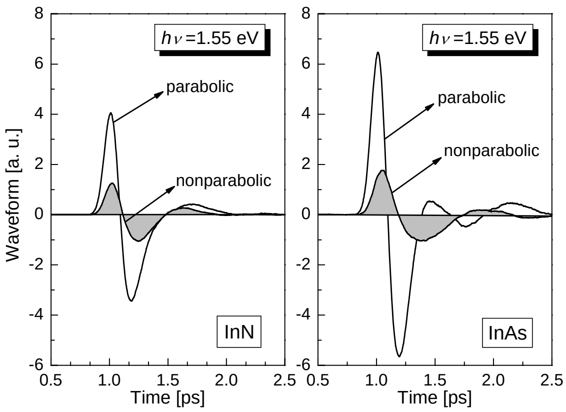

Fig. 3. Temporal THz electric field waveforms for InN (a) and InAs (b) simulated for the laser excitation energy $h\nu = 1.55$ eV.

The calculated THz waveform amplitudes as a function of the laser excitation energy in the range from 0.85 eV up to 1.55 eV are plotted in Fig. 4. For the nonparabolic case, InN exhibits a slight increase of the THz field with the photon eenrgy, whereas a reduction of the amplitude is observed for InAs. The latter finding is associated with the electron transfer to the heavier effective mass satellite valley for higher excitation energies. The laser fluence dependencies of the THz radiation are shown in Fig. 5. As expected, we observe a monotonic increase of the THz field amplitude with increasing laser excitation power. This result is attributed to the fact that a spatial separation of photogenerated carriers at the higher densities leads to an enhancement of the photo-Dember electric field.

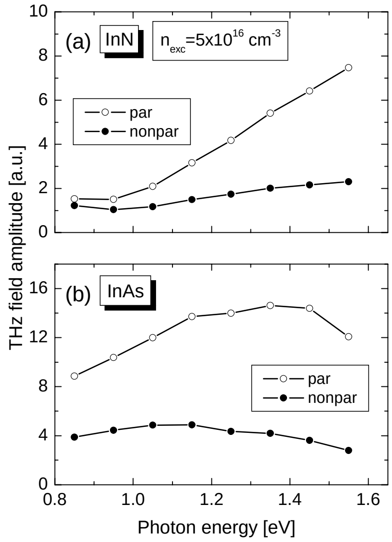

Fig. 4. THz waveform amplitudes for InN (a) and InAs (b) as a function of laser excitation energy.

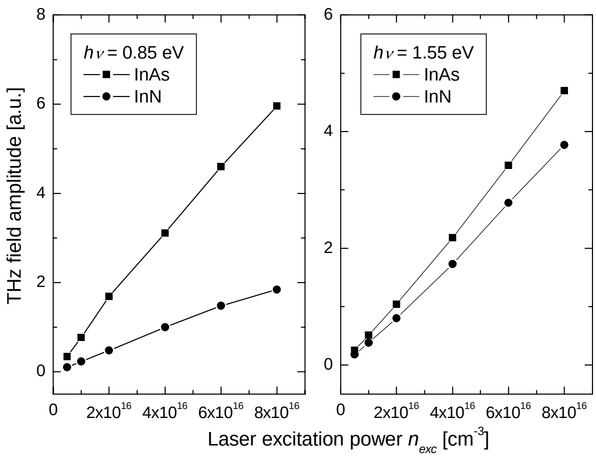

Fig. 5. THz waveform amplitudes for InN and InAs as a function of laser excitation power for photon energies (a) $h\nu = 0.85$ eV and (b) $h\nu = 1.55$ eV.

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