An Atomistic Insight on Hot Carrier's Nonlinear Dynamics

Praveen Saxena (✉ a.saxena@technextlab.com)

Tech Next Lab

Fanish Gupta

Tech Next Lab

Anshika Srivastava

Tech Next Lab

Pankaj Srivastava

Tech Next Lab

Anshu Saxena

Tech Next Lab

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Abstract

An innovative atomistic approach for deeper understanding of the ultrafast THz spectroscopy experiments is reported. The coupled Boltzmann transport equation (BTE) with the various nonlinear scattering mechanisms is solved through the Monte Carlo (MC) technique under the influence of the single-cycle THz pulses to observe the ultrafast carrier nonlinear dynamics. The proposed technique is capable to explain the various effects based on the rigorous physics at the atomistic scale. It has the capabilities to overcome the limitations and challenges pose by various density functional theories (DFT) e.g., RT-TDDFT and molecular dynamics based methods used for the demonstration of the hot carrier dynamics. A clear advantage of the proposed real-time approach is shown by no use of any priori assumptions regarding specific nonlinear scatterings which are chosen as the fitting parameters in the relaxation time approximation (RTA) methods. The method has capabilities to capture the full real-time ultrafast carrier dynamics with the inclusion of the superposition of the electron–electron, electron-lattice and electron–phonon scatterings etc. No such method with advances in the theoretical treatments to explain the ultrafast carrier dynamics is reported previously as per the author's knowledge. The output results of the proposed technique are compared against the experimental findings. The theoretical free carrier absorption spectra are found to be in good agreement with the experimental ones at room temperature.

I. Introduction

Terahertz (THz) spectroscopy is a key technology, used for contact-less conductivity measurements of the metals, semiconductors, 2D materials, and superconductors. The interaction of the THz energies with the charge carriers in semiconductors are responsible for inter- and intra- valley carrier transitions and provide valuable information about the the quasi-particle dynamics. [1] - [6]. The typical ultrafast pump-probe experiments, which are carried out by the generation of the hot carriers with the optical photon energies exceeding the band gap. The THz probe pulses are used to predict the hot carrier's dynamics during and after the excitation process. However, this method suffers with several limitations. Also, it is incapable to accurately predict the hot carrier dynamics in the bulk and nano- materials through the optical excitation method [1].

Several theoretical treatments for the predictions of the THz conductivities in the thin films and nano-materials have been reported previously. The Drude model is most widely used for the same. The Drude model is based on the confined gas of the classical non-interacting electrons which requires the several fitting parameters in order to calibrate the experimental results. Also, the incompetence of the Drude model to explain the low-frequency conductivities suppression, poses significant challenges. Especially for the nano-systems where the physical boundaries on the nano-scales provide a conceptually clear source of the directional biased carrier scattering mechanisms. [6] - [9]. Explicitly the first-principles (DFT) based methods are used to study the real-time electron thermalisation dynamics [10] – [11]. These methods are much less common. Few methods based on the real time time-domain density functional theory (RT-TDDFT) have only been reported for the laser-excited nickel, chromium, and copper [2], [9] [12].

On the other hand, the few researchers have attempted to explain the ultrafast carrier dynamics exploiting the solution of the Boltzmann transport equation (BTE) [2]. However, these BTE solutions through Monte Carlo (MC) technique reported previously considered relaxation time approximation (RTA) approach, in which the carrier scattering rates are chosen as the fitting parameter on the arbitrary basis without giving any physics based justification [2], [6], [11]. Also, the contribution of various types of different scattering mechanisms responsible for conductivity degradation is also non-distinguishable in these methods [11] – [13].

To address all these above issues and as given in the ref [2], the authors are reporting an innovative solution with a solid atomistic physics based foundations to demonstrate successfully the nonlinear carriers dynamics of the hot electrons. The Ge thin film is chosen in the present study due to its material optical properties (high refractive indices and large third-order nonlinearities), e.g. Ge based core optical Fibre (GCOF) exhibit more advantages compared to silica-based optical fibers etc. [14]-[15]. The proposed technique can be generalized for the successful demonstration of the experimental THz spectroscopy of the others group IV, III-V and II-VI semiconductors.

The Monte Carlo (MC) technique is used for the solution of the coupled BTE with the various types of non-linear scattering mechanisms [16] – [18]. The acoustic & intervalley [10]-[11], carrier-carrier [17], known as intrinsic scatterings and impact ionization [19] – [21] (extrinsic) scattering mechanisms are used for the complex conductivity computations. The proposed technique does not use any priori assumptions regarding specific nonlinear scattering rates which are used as the fitting parameters in the relaxation time approximation (RTA) methods [6], [12–13]. The peak THz field strengths 1 MV/m, 5 MV/m 15 MV/m are used in present analysis which are comparable to the nonlinear semiconductor devices e.g. Gunn and tunnel diodes. Due to the interaction of the THz field energy with the electrons, the electrons dynamics have been extracted on the three non-parabolic valleys i.e. Γ , L and X respectively. The contribution of various types of scattering mechanisms provides valuable information associated with the hot carrier dynamics. As per the author's knowledge, the technique with the advances in the theoretical treatments to explain the ultrafast spectroscopy has been reported first time without using any initial assumptions and fitting parameters [16] – [18].

II. Technique

The solution of the coupled Boltzmann transport equation (BTE) with the various types of scattering mechanisms are carried out through in-house developed Monte Carlo (MC) technique under the non-equilibrium conditions as described in reference [18]. The technique is used to predict the ultrafast carrier's dynamics at three valleys on the full electronic band structure [22] – [23]. The full electronic band structure has been simulated for the extraction of various fundamental properties of the Ge material as refers to TNL-FB simulator [18], [22]. The material parameters are tabulated in the **Table 1**. The equal number of electrons is initially distributed on the non-parabolic Γ , L and X valleys. In the absence of the THz field i.e. under the steady state conditions, the carriers attain equilibrium for the suppression of the possibility of any kind of the intrinsic noise presence. Most of the high energy, X-valley electrons transfer

itself spontaneously to lower energy valleys while under steady state electrons are also thermally populated (known as Boltzman thermal population) in the Γ valley.

The single-cycle THz pulses are designed in such a way that these are generated with the time delay of $3/4T$, where T is the time period of each pulse. These single-cycle pulses interact with the free carriers and the carriers absorb THz energies. Due to the change in the carrier energies, the valley transition process initiated. The changes are observed in the carriers mobility due to the increase in occurring probabilities of the scattering mechanisms [17]-[18].

The time dependent single-cycle THz pulse is taken as [16];

$$E(t) = E_0 \cos(2\pi f p dt)$$

1

Here, E_0 is the peak amplitude of the driving THz pulse, f is the THz frequency, p is the number of total time steps and dt is the time step (the duration of the carrier interaction). The interaction time 'dt' is chosen in such a way that only a single pulse of the applied continuous THz pulse interact with the carriers in the thin film sample during one complete iteration. The successive various THz mono-frequency pulses interact with the carriers. The product $p*dt$ is the total interaction time of the field with the electrons. The total time scale for the simulation for each THz field is considered 20ps which ensures the at least one complete period of the driving frequency pulse must interact with the electrons during the time span [16].

The hot carrier dynamics on three valleys in TNL-TS simulator are studied by the solution of the Boltzmann transport equation (BTE) under non-equilibrium conditions under influence of the applied THz field including rate change of distribution function due to various scattering probabilities. The details of the Monte Carlo program implemented in TNL-TS simulator for simulation of the hot carrier dynamics is well documented in the reference [18]. The electron-lattice, electron-electron and electron-applied field coupling strengths are important physical quantities dictating the interactions of the electrons with the lattice. These interactions are responsible for relaxing momentum and the energy of the electrons, and are included in terms of different scattering probabilities in the simulation program. Scattering rates are strongly dependent on the electronic band structure [18], [22]. Density of states in particular valley at particular time instant plays important role in deciding the probability of the particular scattering events which follow the energy conservation principle i.e. Fermi Golden rule. The details of method are given in the reference [18].

The electrons free flight duration is chosen with a probability distribution function which is decided by the various types of non-linear scattering probabilities. The change in carrier's momentum as a function of THz frequencies is computed as [16];

$$\mathbf{k}(dt) = \mathbf{k}_i - \frac{q\mathbf{E}(t)dt}{\hbar} \quad (2)$$

Here, k_i is denoting the initial wave vector associated with previous time step, $\hbar$ is Planck's constant, q is the electronic charge and E is the time dependent THz pulse field strength [16].

Hot carrier excitation process is dependent on the pulse width of the single-cycle THz pulse which is applied along the thickness of Ge thin film. The velocity of each particle is recorded at each time step, where y-component of carrier drift velocity at the p^{th} time step is computed as [16];

$$v_{y,p} = v_{y,p-1} + \frac{eE_0 dt}{m^*} \cos(2\pi f p dt)$$

3

Here, $v_{y,p-1}$ is the y-component of the velocity at the previous time-step. The proposed model has flexibility for application of THz pulses coupling in any direction i.e. x, y, z with the thin films. The drift velocity of the carriers under the transient conditions is estimated by the ensemble average of the velocity component at the p^{th} time step and is given as [16];

$$v_d(t) = \frac{1}{N} \sum_{j=1}^N v_y^j(pdt)$$

4

Here, p is the number of total time steps, dt is the time step, N is the number of simulated particles and j labels the number of particles in the ensemble.

The time domain current density $J(t)$ is calculated using the drift velocity at every time step and is given by [16]

$$J(t) = N e v_d(t) \alpha_n(E) L_{eff}$$

5

Here, N is the total number of electrons, e is electronic charge and α_n is the impact ionization coefficient expressed as a function of peak strength of the THz field. L_{eff} is the characteristic length of the high field region [19] – [20].

The frequency dependent complex conductivity is computed through Fourier transformation method and is given as [16],

$$\sigma(\omega) = \frac{\sum J(t) (\cos \omega t + i \sin \omega t)}{\sum E(t) (\cos \omega t + i \sin \omega t)}$$

6

The absorption coefficient is dependent on conductivity and computed as,

$$\alpha(\omega) = \frac{4\pi\sigma_R(\omega)}{n_r c}$$

7

Here, $\sigma_R(\omega)$ is real part of conductivity, n_r [12] is the real refractive index and c is the velocity of light.

iii. Results & Discussion

An innovative atomistic technique for the successful demonstration of the real time time-dependent THz spectroscopy experiment through the simulation with inclusion of the non-linear scattering mechanisms is presented. The in-house developed algorithms are capable to extract various physical parameters associated with the ultrafast nonlinear carrier dynamics under influence of time-dependent THz pulses. The reliability of proposed technique (in form of TNL-TS simulator) is verified against the various experimental studies reported for the different semiconductor materials. In present manuscript, the free carrier absorption experimental findings reported by *János Hebling et. al.* [1] has been compared with the results obtained by the proposed technique at different applied THz field strengths. The material parameters used in present study are listed in Table 1.

The peak THz field strengths, 1, 5 and 15 MV/m are used [1] in current study to study the hot carrier's dynamical behavior. The THz pulses interact strongly with the electrons, enabling them to undergo intra- and inter-valley transitions. The various fundamental physical scattering mechanisms applicable for most of the semiconductor materials are considered in the present study [23] – [25]. The acoustic [10 - 11], intervalley [23–25], Coulomb i.e. electron-electron [26- 27] and impact ionization [19]-[21] scattering mechanisms are included in the present work and found to play a deciding role in free carrier absorption mechanism.

Figure 1 shows the THz absorption spectra of n-type Ge thin film at room temperature (294K). The experimental absorption spectra taken from reference [1] are shown by symbols whereas absorption spectra obtained through the proposed technique are shown by solid lines at various THz field strengths i.e. 1, 5 and 15 MV/m respectively. The theoretical absorption spectra are in the good agreement with the experimental results at different applied THz field strengths. The appropriate conditions mentioned in ref. [1] are chosen as the initial conditions in the simulation studies for the verification of the experimental results. It is clearly reflected from Figure 1 that at high THz field strength i.e. 15MV/m with varying frequencies (0.1 - 2 THz), the computed absorption spectrum is accurately matching with the experimental absorption spectrum. The nature of the absorption spectrum curve at moderate peak field strength i.e. 5MV/m in the frequency range of 0.2- 0.8 THz is following the experimental curve. A slight mismatch in the theoretical curve is observed in the frequency range of 0.8 THz < f_{THz} < 1.2, whereas it is again well matched with the experimental curve in the frequency range of 1.2 THz < f_{THz} < 2 THz. At lower peak field strength i.e. 1MV/m and low to moderate THz frequency range (0.1- 1 THz) the room temperature absorption curve accurately matches with the experimental result, however, the slight mismatch is observed beyond the frequency range increases from 1THz.

The slight mismatch at field strengths 5MV/m (0.8 THz - 1.2 THz) and 1MV/m ($1.6 \text{ THz} < f_{\text{THz}} < 2.0 \text{ THz}$) respectively can be explained on the basis of the THz-induced Kerr effect (TKE), where change in refractive index exhibits quadratic dependence on an externally applied electric field [29]-[30]. The experimental single-cycle THz pulses with μJ energies is generated in a LiNbO₃ (LN) crystal by optical rectification of 100 fs pulses at 800 nm with the tilted-pulse-front method without explaining the scope of THz-induced Kerr effect which is dominant at low peak field strengths [1]. The slight mismatches are observed at low (1MV/m) and moderate field (5MV/m) strengths in experimental and theoretical absorption spectra which are actually attributed due to difference in refractive index values. It may have quadratic dependence and change in refractive index occur in experimental results, whereas in the theoretical study only frequency dependent refractive index is considered as given in ref. [15]. At high peak THz strength, no such effects are observed hence the theoretical method generate well matched absorption spectrum with the experimental result.

The free carrier absorption phenomenon prompts the carriers intervalley transitions. It is extracted here in the terms of the valley population or carrier occupancy denoted by Γ -valley (Red), L-valley (Blue) and X-valley (Green) carrier population respectively as shown in Fig. 2. The single cycle THz pulse is shown by black solid curve with the pulse frequency at the 0.25 THz frequency at peak field strength 15 MV/m ramping from minimum amplitude to maximum amplitude and its vice-versa. In the positive half cycle, the hot electrons excited from L- and Γ -valley to X-valley as clearly reflected from Fig. 2 the red, blue and green curves are showing valley population i.e. electrons distribution in Γ -, L- and X-valleys respectively with the time step 'dt' i.e. the time in which single cycle THz pulse passes through the Ge thin film. It is also evident from the Fig. 2 that during delay time of pulse ($3/4T$, T is the time period of pulse), most of the electrons attained equilibrium i.e. X- and Γ -valley electrons itself spontaneously transfer to L-valley which is lowest lying energy level in case of Ge semiconductor material. Also Boltzmann thermal population is observed in the Γ -valley. There are intervalley carrier transitions probabilities are observed zero during the pulse delay time whereas the contribution of intra-valley scattering mechanism is observed in term of acoustic mechanism. As the positive half cycle of the single cycle THz pulse interacts with the electrons, the free carriers absorb THz energy and transfer itself to highest energy level i.e. from L-valley and Γ -valley to X-valley, The absorption spectra shown in Fig. 1 depict strong saturation over the frequency range between 1.0 - 2.0 THz. However, in 0.25-1.0 THz frequency range and peak field strength $\sim 1 \text{ MV/m}$ (7%), the absorption curve is following the Drude type nature. At high peak THz field strengths i.e. ~ 5 (33%) and 15 (100%) MV/m, strong saturation of absorption curve over the entire THz frequency range (0.25 - 2.0) have been observed. The absorption spectrum curve for 7%, 33% and 100% are well matched with the experimental results [1] in low, medium and high frequency ranges at appropriate THz fields. The free-carrier absorption is found to be mainly dictated by carrier-phonon (acoustic), carrier lattice (impact ionization) and carrier-carrier (Coulomb) interaction mechanisms. Fig. 3-a, 3-b, 3-c elaborate more details about the microscopic valleys transition behavior of electrons with interaction of different THz frequency pulses. In low frequency range and low peak THz field intensity, the acoustic scattering mechanism is found to dictate the intravalley carrier transfer. With the increase in peak THz field strength, the impact ionization scattering mechanism becomes dominant scattering mechanism.

The significance of impact ionization scattering mechanism can be understood in term of free carriers generation, hence more absorption probabilities with increased number of free carriers, Fig. 5. The strong saturation absorption curve observed in Fig. 1 at high THz fields i.e. at ~5 and 15 MV/m can be successfully demonstrated through electrons impact ionization mechanisms. The increased number of electrons tends to enhance the probability of free carrier absorption mechanism at higher peak field strength depending upon the pulse width. On the other hand, the increased number of electrons also increases the probability of the carrier scattering mechanisms especially Coulomb scattering. Hence, carrier generation due to impact ionization process and Coulomb scattering process compete with each other. Once the equilibrium attain between these two processes, the saturated behavior of absorption curve is observed under application of moderate and higher peak field strengths. On other hand at low THz field strength, free carrier absorption mechanism is only limited to the free carriers available due to doping of Ge thin film. The steep fall in absorption curve is observed at higher frequency region i.e. (1.0-2.0 THz) at 1 MV/m peak field strengths.

The detailed ultrafast carrier intervalley transitions on the time scale are shown in the Fig. 3-a, 3-b, 3-c respectively. Fig. 3a shows the interaction of single cycle THz pulses of the frequencies 0.25, 0.75, 1.25 and 1.75 THz respectively with the electrons in Ge material at peak THz field strength 15MV/m. Similarly, Fig. 3b and Fig. 3c show carrier transitions at single cycle THz pulses interaction with electrons at the peak THz field strength of 5MV/m and 1MV/m respectively. It is evident from the curve that at lower frequency i.e. the pulse width is large, the carriers have enough time to strongly interact with the incident THz photons. Hence the probability of intervalley carrier transitions is large. However, with the increase in THz frequencies, the pulse width decreases, the interaction time of THz photons with free carriers is less, hence maximum intervalley transitions are observed at low frequency range for each peak field strengths, Fig. 3-a, b, c. The increase in the THz frequency and the THz pulse width is in order of pico-second (ps), the interaction time of the THz photons with the electrons decrease. It prompts to the decrease in the intervalley transition rate. The carriers get less time to interact with the THz field at higher frequencies range as compared to lower frequency ranges which is clearly reflected from Fig. 3-a, b, c. The absorption spectra shown in Fig. 1 also reflect the saturated behavior in higher frequency ranges due to low probability of free carrier absorption. These results also explain the hot carrier transitions behavior. The low THz frequencies are responsible for more intervalley transitions mechanisms justified the results observed here. The free carrier generation due to impact ionization mechanism is responsible for maintaining the constant free carrier absorption rate with the increase in the carrier-carrier (Coulomb) scattering rate at higher peak field strength.

The impact of the acoustic and coulomb scattering mechanisms with energies are shown in Fig. 4 and Fig. 5. The acoustic scattering rates increase with the increase in carrier energies in the Γ - (brown), L- (red) and X- (green) valleys. It is evident from the figure that X-valley acoustic rate is higher as compared to L- valley and Γ -valley acoustic rate depending on the THz energy absorbed. The maximum acoustic rate $\sim 10^{13} \text{ s}^{-1}$ is exhibit by X-valley electrons. At the start of carrier free flight i.e. in absence of th THz pulses, the coulomb scattering initiated whereas acoustic vibrations are observed with low scattering rates. The

free carrier absorption causes to increase the carrier's vibrational energy hence the intervalley transitions rates increase. The Coulomb scattering rates are only dependent on intrinsic carrier density, which is almost saturated with increase in the carrier energy. The impact ionization scattering rate as shown in Fig. 6 with respect to THz field strength is initiated under the influence of THz field strength. It is clearly reflected from the curve that the threshold field value for impact ionization process is ~ 0.12 MV/m. The free electrons generation due to impact ionization process start contributing for the free carrier generation process. In present case the contribution of holes scattering is neglected. The increased carrier density due to the impact ionization process increases the Coulomb scattering rate. It causes the degradation in the conductivity of the Ge thin film at higher THz field strengths. The overall impact of acoustic, intervalley and impact ionization scattering mechanism is accounted in term of carrier drift velocity, current density (not shown here).

Figure 7 shows the complex conductivities extracted through the proposed technique at peak THz field intensities i.e. at the 1 (blue line), 5 (red line) and 15 MV/m (black line) respectively with variation in THz frequencies. It is clearly reflected from the curves that at the low peak THz field strength (~ 1 MV/m), the conductivity decreases linearly as the frequency increases from 0.2 – 2.0 THz. At moderate peak THz field intensity (~ 5 MV/m), the conductivity is linearly decreases first in frequency range $0.2 \text{ THz} < f_{\text{THz}} < 1.0 \text{ THz}$ and in frequency range 1.0-2.0 THz, the conductivity curve attained the saturation. At higher peak THz field strength (~ 15 MV/m), the conductivity curve shows the strong saturation over entire frequency range i.e. 0.2-2.0 THz range. The conductivities at different peak THz field strengths are extracted and with the help of proposed method with inclusion of the different scattering mechanisms described as above which explain the saturation behavior itself. At low THz field intensity, the acoustic (electron-phonon), intervalley and Coulomb scattering mechanisms are responsible for degrading the hot carriers drift velocity, as the free carrier absorption is limited to only available intrinsic carrier density in Ge crystal. Hence passing the low peak field strength single cycle THz pulse generates hot carriers, so initially the higher value of conductivity is observed. However, continued scattering mechanisms cause the degradation in the conductivities values and linear behavior is observed. It is well known that at ≥ 0.12 MV/m, the impact ionization process initiated in Ge semiconductor and carrier generation started. The Coulomb (carrier-carrier) scattering mechanism is found to be dominant mechanism in moderate to higher peak THz field strength. On the other hand increase number of free carrier generated due to impact ionization process at peak THz field strength is ≥ 0.12 MV/m. The probability of free carrier absorption is increased. As the peak THz field strength increases above from threshold value, the impact ionization process started depending on the applied field strengths. The carriers generated due to impact ionization process take part in free carrier absorption mechanism and Coulomb i.e. carrier-carrier scattering probabilities also increases. Coulomb scattering is found to be dominating scattering mechanism over other scattering mechanisms at higher peak field strengths. The nature of conductivity curves as shown in Figure 7 also justifies the competitiveness between Coulomb and impact ionization scattering mechanisms i.e. at higher frequencies the saturated complex conductivity curves are observed for both peak THz field strengths of 5 MV/m and 15 MV/m. The saturated conductivity is observed for 15 MV/m case for entire frequency range (0.25-2.0 THz), Fig. 3.

IV. Conclusion

In present manuscript, the authors have successfully demonstrated the real time THz spectroscopy experiments through in-house developed innovative technique at atomistic scale without using any fitting parameters and any prior assumptions regarding scattering mechanisms. The proper understanding of ultrafast nonlinear carriers dynamics on the basis of solid physical foundation is carried out. The significant contributions of the various types of scattering mechanisms on complex conductivity of Ge crystal have been observed. The experimental complex conductivity and free carrier absorption spectra are successfully demonstrated theoretically with the help of proposed atomistic technique. The Monte Carlo method is used for the solution of Boltzmann Transport Equation (BTE). The proposed technique is converted into form of TNL-TS simulator which can be used to demonstrate the real time THz spectroscopy experiments for most of the semiconductor materials with capability to extract various physical parameters at atomistic scale. The low-frequency conductivities for nonlinear ultrafast carriers dynamics including various types of scattering mechanisms are presented first time.

Declarations

AVAILABILITY OF DATA: The data that support the findings of this study are available. All the results are produced from the TNL-TS simulator and are reproducible. Upon reasonable request to the corresponding author, he will provide the access of the data associated with the each result shown in the manuscript. The readers may directly download the TNL-TS simulator from www.technextlab.com to reproduce the data as **an alternative option** for the reproduction of the results reported here.

Competing Interests: The authors declare no competing interests. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions: P.K.S., F.K.G., A.S., P.S. and A.S. develop idea, theory and P.K.S. supervised the whole work. A.S., A.S., F.K.G., P.S., run the simulations and did the data collection. P.K.S., F.K.G, P.S. edited the manuscript. All authors discussed the results and commented on the manuscripts

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Table

Table 1 is available in the Supplemental Files section

Figures

Figure 1

Absorption spectra at peak THz strengths 1 MV/m (7%), 5 MV/m (33%), 15 MV/m (100%) with varying THz frequency. Absorption spectra data obtained from present work are displayed as solid lines whereas experimental results taken from reference [1] are depicted by symbols (circles, triangles and squares at THz field strengths 1 MV/m, 5 MV/m, 15 MV/m respectively).

Figure 2

Variation in various valleys population i.e. number of electrons of Γ (Red), L(Blue) and X (Green) valleys with single cycle THz pulse (Black) with peak strength of 15 MV/m at 0.25 THz frequency with respect Time

a

b

c

Figure 3

a. Variation in Valley Population at various THz Frequencies at peak field intensity 15 MV/m with respect time

b. Variation in Valley Population at various THz Frequencies at peak field intensity 5 MV/m with respect time

c. Variation in Valley Population at various THz Frequencies at peak field intensity 1 MV/m with respect time

Figure 4

Acoustic (electron-phonon) scattering rate at Γ -valley (Brown), L-valley (Red) and X-valley (Green) with respect to Energy (eV).

Figure 5

Coulomb (carrier-carrier) scattering rate at Γ -valley (Black), L-valley (Red) and X-valley (Blue) with respect to Energy (eV).

Figure 6

Variation of impact ionization coefficient with respect to varying THZ field intensity.

Figure 7

Variation of complex THz conductivities at peak field strengths 1, 5, 15 MV/m with varying frequency

Supplementary Files

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- [Table1.docx](#)