An Ensemble Monte Carlo Model to Calculate Photocurrent of MSM Photodetector

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Abstract

In this paper, we present an ensemble Monte Carlo model to calculate the time response for GaAs MSM photodetectors. Our model includes two valleys and two bands for electrons and holes respectively. We simulate optical pulse absorption and trajectory of carriers to calculate electron and hole currents. Also, we calculate the effect of different voltages and optical pulses on photocurrent. To validate, we compare the results obtained from Monte Carlo simulation with another simulation.

Keywords: *MSM photodetector, Monte Carlo simulation, Photocurrent.*

1. Introduction

Metal-semiconductor-metal (MSM) photodetectors have been known as main candidates for high performance photodetections. They have been widely used in optical communication links, high speed sampling and optoelectronic integrated circuits [1-2].

The development of optical fiber transmission links has increased the demands for high speed photodetection. MSMs have important advantages such as higher sensitivity and bandwidth, lower dark current and more compatibility with large scale planar integrated circuit technology than avalanche photodiodes (APDs), phototransistors, and p-i-n photodetectors [3].

It was experimentally found that the photocurrent intensity is depending on the position of the incident light in MSMs [4]. It has been shown that a delta doped layer can improve the time response of MSM photodetectors [5]. This layer changes the distribution of electric field in depth of the device and reduces the tailing of photoholes response.

Different mechanisms are occurred in MSM photodetectors such as absorption, drift, recombination and scattering. Interference and overlap of them causes the simulation of the device be complex. Although the macroscopic models such as circuit models and drift-diffusion models have been presented, they are not able to describe the details of carriers such as trajectory, distribution of energy and momentum in time and space domains [6].

From last two decades, a microscopic view to simulate the carrier transport in optoelectronic devices has become an applicant and interest issue. Presenting of an efficient model which shows the microscopic behavior of carriers can be an important object. This model along with new fabrication techniques result in high performance devices.

Monte Carlo (MC) model is a robust means to simulate phenomena which have random nature. As an example, a numerical analysis has been presented to evaluate GRIN lenses using the Monte Carlo method [7]. Also, a parallel implementation has been carried out for MC simulation of light propagation in heterogeneous tissues whose surfaces are constructed by different number of triangle meshes [8]. Using a direct MC technique, a new scheme has been reported to calculate adsorption and scattering for a gas-surface system in thermal scattering regime [9].

Besides, a sequential MC model has been employed to simulate impact of distributed generation to distribution system reliability [10]. A two dimensional Particle in Cell - MC Collision (PIC-MCC) model has been developed in order to simulate partial discharges inside a narrow micro-channel encapsulated within the volume of a dielectric material [11]. A two dimensional kinetic model has been used to investigate the filamentary distribution of spark-type partial discharges (PD’s) inside a micro-cavity. The model is based on Particle-in-Cell methods with Monte Carlo Collision techniques for modeling of collision processes (PIC-MCC) [12]. Carrier transport in optoelectronic devices is complex issue that includes different mechanisms with random nature. Using MC models, one can see the motion of each super particle (or carrier) in time and space. A two-dimensional time-dependent simulation has been used to calculate the electron-hole transport at different energy of optical pulses [13].

In this paper, we present a MC model to simulate the carrier transport in MSM devices. The model is capable of calculating voltage and electric field distribution, photocurrent as well as time response for optical pulses. The presented model involves two valleys and two bands for electrons and holes respectively. We assume acoustic and polar optical phonons and ionized impurity scattering mechanisms as the results of collisions.

We simulate GaAs MSMs where are used in short distance links such as networks, including processors, circuit boards [14], and plastic fiber optical network[15,16]. We calculate the photohole and photoelectron currents separately. To validate, we compare the simulation results with another simulation results obtained from [13] for different optical energies, finger spaces and bias voltages.

In next section, we briefly illustrate the structure of MSM photodetector and its performance. We present an ensemble Monte Carlo (EMC) model and describe its algorithm to calculate photocurrent in section 3. Finally, we calculate the photocurrent for different parameters such as bias voltage, optical energies of pulse and distances between neighbor fingers.

2. MSM Photodetector

A MSM photodetector consists of a semiconductor absorbing layer sandwiched between two metal contacts. As a result, a Schottky barrier is formed at each metal semiconductor interface, which prevents the flow of electrons from the metal to the semiconductor. Light is absorbed at the gap between the two metal contacts. Electron-hole pairs are generated due to absorption of light. They flow towards the metal contacts, resulting in a photocurrent that is related to the incident optical power. Figure 1 shows a view of MSM where W, L, V and hυ are finger width, finger spacing, bias voltage and the photon energy respectively [16].

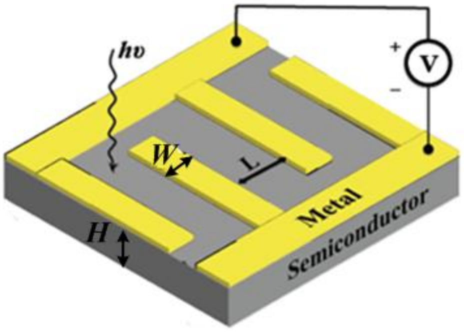


Fig.1 Physical schematic of MSM photodetector [16].

3. Monte Carlo Model

The Monte Carlo provides a useful tool for the development, analysis, and understanding of semiconductor devices. The MC method can precisely solve the Boltzmann transport equation (BTE) and calculate the distribution of carriers in time and space domains [17].

The EMC method consists of the drift and scattering processes which are frequently repeated. Due to applied electric field, carriers move inside the device and obtain the kinetic energy. Although, the effect of external forces is deterministic, the collision processes affect the motion in a probabilistic manner [18]. The important carrier scattering mechanisms considered in simulation are polar optical phonon, ionized impurity, and acoustic phonon scatterings.

Our model includes two valleys (Γ and L) and two bands (heavy and light) for electrons and holes transport respectively. We assume the non parabolic-spherical bands for both electrons and holes. As an initial condition, electrons and holes moves in Γ valley and heavy hole band respectively.

To calculate the distribution of potential, we combine the semi-classical equations of motion with an ensemble solution of Poisson's equation. We use the cloud-in-cell (CIC) scheme to charge assignment. In this plan, charge of each particle is assigned to a particular mesh point. Since it is not possible to simulate all the carriers present in a real device, we suppose many super particles (SPs) in device. Each SP is defined as a group of same carriers.

The incident optical pulse illuminates the surface of MSM in certain duration. The photons are equally absorbed in the same surfaces, whereas are exponentially absorbed in depth of the device. To simulate this subject, we employ the rejection technique and use two random numbers independently [19].

The number of absorbed photon in each time step is related to optical energy, duration of illumination and light wavelength [17,19]. Difference energy between the photon energy and band-gap is divided two equal sections for generated electron and hole.

After illumination, we follow the trajectory of all carriers in device until they are outgoing from contacts. This issue is known as time response of the device. Figure 2 shows the flowchart of EMC simulation.

4. Results and Discussion

According to mentioned MC model in section 3, we calculate the photocurrent of a MSM photodetector whose parameters are given in Table I for a 70fs optical pulse.

Figure 3 compares the photocurrent obtained from MC simulation with it obtained from another simulation [13]. In this case, applied voltage is 3v and L and W are equal to 3μm. photodetector is illuminated with a 2pJ optical pulse. Total photocurrent consists of electrons flowing out of the positive contact and holes out of the negative contact. This figure demonstrates that both components of current are agree with obtained results from [13].

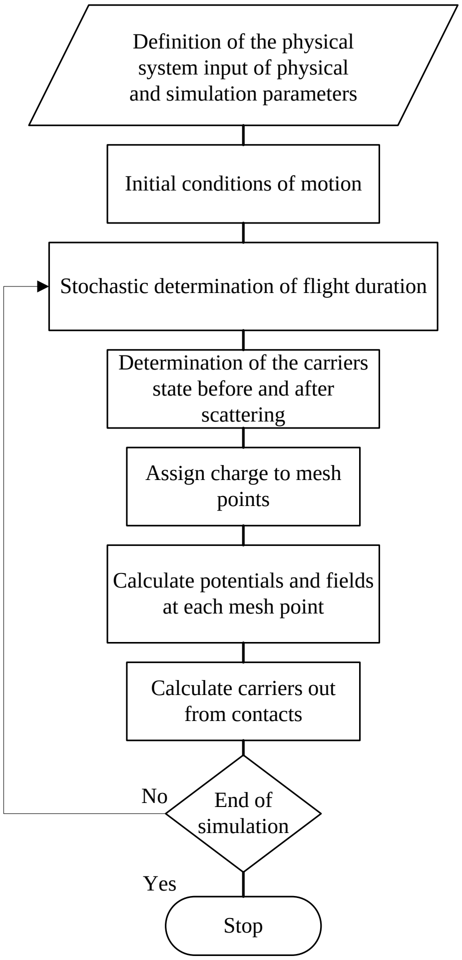


Fig. 2 Flow chart of an ensemble Monte Carlo (EMC) simulation.

Table I: Parameters for a sample device

Parameters	Value (unit)
Finger width (W)	3 and 10 (μm)
Finger spacing (L)	3 and 10 (μm)
Depth (H)	10 (μm)
Wavelength (λ)	850 (nm)
Bias voltage (V)	3, 20, and 50 (v)
Optical energy (E)	2 and 200 (pJ)

Figure 3 shows that the time response initially is due to photoelectron current while the photohole current results in tailing of response. Lower effective mass and higher velocity of electrons than holes can describe this issue. The response time is found that consists of three components: 1) a fast initial peak due to velocity overshoot for electrons at Γ valley, 2) after peak section due to slow electrons at L valley, and 3) tailing section due to holes. Figure 4 presents the electron velocity in conjunction with hole velocity versus the electric field for GaAs [20]. This calculation has demonstrated the maximum value of electron velocity is related to Γ valley.

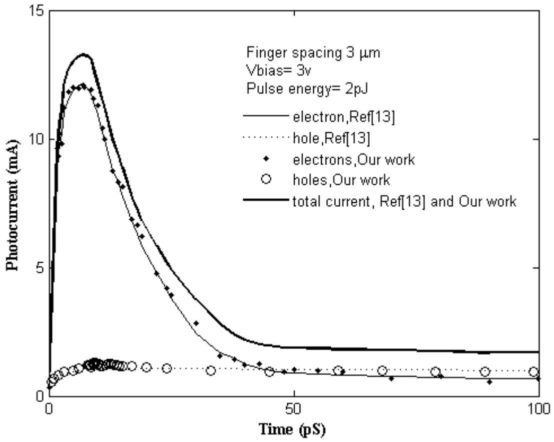


Fig. 3 Comparison between the photoelectron and photohole currents obtained with MC simulation with another simulation [13].

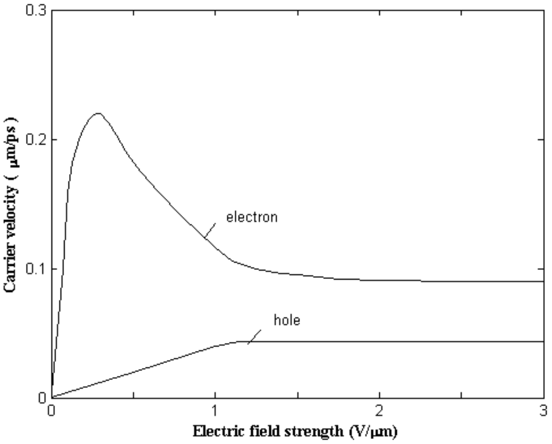
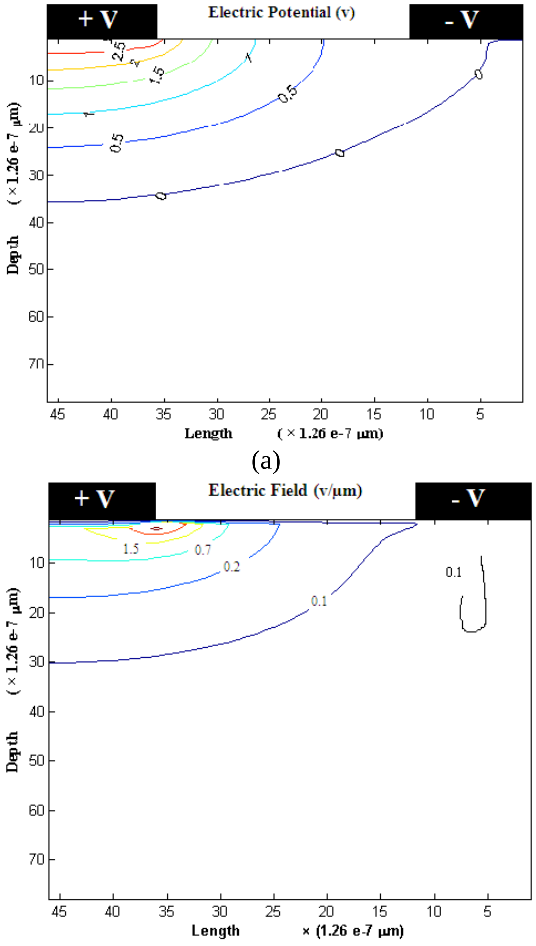


Fig. 4 Field-dependent drift velocity of electrons and holes in GaAs [20].

Our simulations can show the distribution of electric potential and electric filed throughout of the mentioned device (see figure 5). It can be seen that the electric field at below the surface is higher than depth of the device. Besides, a high electric field distribution is dominated around the left contact. This issue drifts photo-generated electrons at below the surface toward the contacts. Photo-generated holes at depth gain low energy via the electric field and move slowly to right contact. Consequently, these carriers results in tailing for time response of the device.

To demonstrate the capability of the model, we simulate the effect of optical energy on photocurrent for MSM photodetectors. We assume L, W and V are equal to 10µm, 10µm and 50v respectively. In figure 6, the device is illuminated with a 70fs optical pulse whose energy is 2pJ and 200pJ.

It can be seen with 2pJ optical energy, photocurrent of the device becomes negligible after 310ps, while the photocurrent response is calculated more than 500ps for 200pJ illumination. As the optical energy is higher, the density of the photo-generated carriers in the surface layer is much higher. Now, electrons and particularly holes are no longer removed from the active region of the device and decrease the quantum efficiency (QE) 0.87. Quantum efficiency of the device is defined as the rate of photo-electron-hole pairs divided by the rate of photons absorption. As a result, our simulations show high intensity of light increases the photocurrent level of MSM while degrades the tailing at time response.

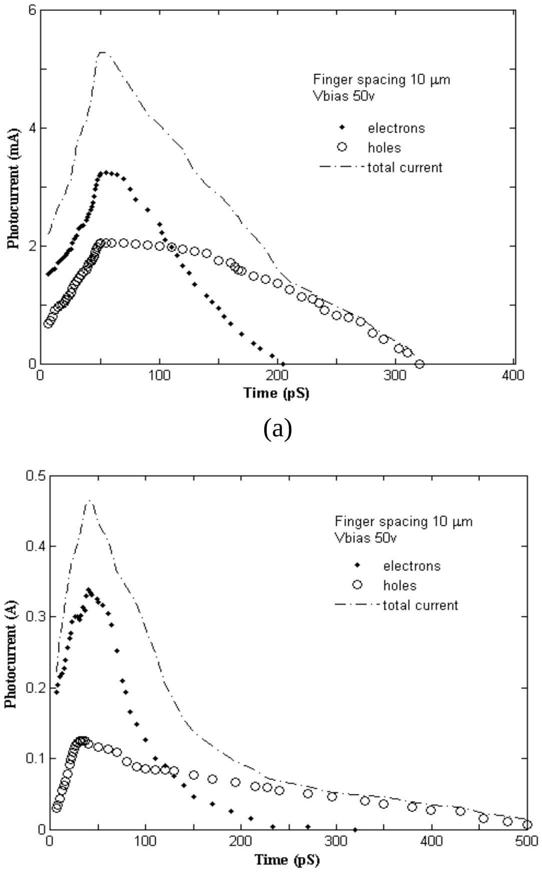


(a)

(b)

Fig. 5 (a) Electric potential and (b) electric field contours for a GaAs-MSM photodetector with W=L=3µm, V=3v and E=2pJ.

Our simulation demonstrated high energy illumination generates many carriers at below the surface of device which changes the distribution of carrier density. Solving the Poisson equation in conjunction with transport equations showed the slope of electric potential toward the contacts is increased due to the high illumination. This slope is known as electric field distribution. Therefore, higher electric field at near contacts assists to carriers which are rapidly absorbed via contacts. Figure 6 shows the peak of photocurrent occurs at 50fs with 2 pJ illumination while this time is 39fs with 200pJ. Table II shows full width at half maximum (FWHM) for photocurrent with different optical energies.



(a)

(b)

Fig. 6 Photocurrent response to a 70fs optical pulse with energy (a) 2pJ and (b) 200pJ. W, L and V are equal to 10µm, 10µm and 50v respectively.

Table II: FWHM for photocurrent with different optical energies

Optical Energy (ev)	2	50	100	150	200
FWHM (ps)	111	97	93	91	90
QE (%)	0.98	0.90	0.885	0.875	0.87

The presented model can calculate the effect of applied bias voltage on photocurrent response of MSM. Figure 7 shows photoelectron and photohole current for applied bias 20v. One can compares this figure with figure 6(a) to understand the bias effect on photocurrent of device. Our simulations shows peak of response is shifted to left for higher voltage, because the high voltage increases mean velocity of carriers. Besides, the tailing is decreasing when applied voltage is increased. This issue is related to drift mechanism for photoholes. Higher electric field can assist to holes to gain more energy and move rapidly toward the negative contact.

Our simulations demonstrated that the presented model can calculate photocurrent of MSM photodetectors. It is capable of calculating the components of photocurrent virtually. Besides, the model can demonstrate the effect of optical energy of light incident, bias voltage on photocurrent of device as well as finger space. The presented model solves Poisson equation in conjunction with Boltzmann transport equation and obtains electric field and potential distributions through of MSM.

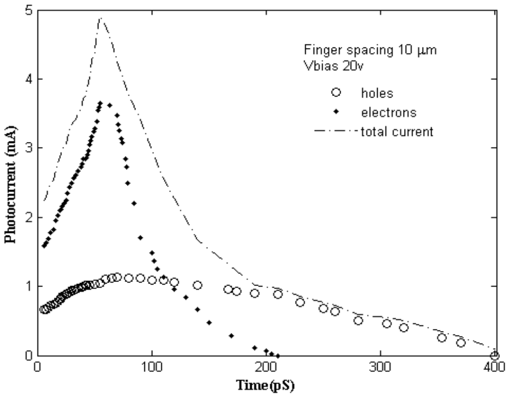


Fig. 7 Photocurrent of a MSM for applied voltage 20v. Other parameters are same as figure 6 (a).

Although a disadvantage of the model is that it takes long time for simulation, authors believe the MC model can present a microscopic view to MSM photodetectors. Accuracy and calculation of trajectories for carriers are main motivations for widely employing MC models in optoelectronic devices.

5. Conclusions

Using Monte Carlo method, we solved Boltzmann transport conjunction with Poisson equations throughout GaAs MSM photodetectors.

The presented model included drift and scattering processes serially. We calculated temporal response of a MSM photodetector to optical pulse excitation. One can see the presented model is capable of simulating photocurrent for different parameters such as optical power, bias voltage and finger spicing.

References

[1] J. Harari, J. p. Violet, and D. Decoster, Metal Semiconductor Metal Photodetectors, New York: Wiley, 1999.

[2] H. S. Nalwa, Photodetectors and Fiber Optics, London: Academic Press, 2001.

[3] K. Nakajima, T. Iida, K. I. Sugimoto, H. Kan, and Y. Mizushima, “Properties and Design Theory of Ultrafast GaAs Metal-Semiconductor-Metal Photodetector with Symmetrical Schottky Contacts”, IEEE Transaction on. Electron Devices, Vol. 37, 1990, pp. 31-37.

[4] S. Yuan, J. Wang, Y. Zhang, and J. Krasinski, “Position Dependent Photocurrent Intensity of MSM Photodetectors”, in 5th International Conference on Electronic and Photonic materials, 2006, pp. 208-210.

[5] M. Soroosh, M. K. Moravvej-Farshi, and K. Saghafi, “Reduction of Photo-hole Transit Time in GaAs of Metal-Semiconductor-Metal Photodetectors”, International Conference on Optical Communications and Networks, 2007, pp. 53-55.

[6] M.Soroosh and M. A. Mansouri-Birjandi, “Monte Carlo Simulation of Multiplication Factor in PIN In0.52Al0.48As Avalanche Photodiodes”, International Journal of Communication and Information Technology, Vol. 1, 2001, pp. 21-24.

[7] S. Yoshida, S. Horiuchi, Z. Ushiyama and M. Yamamoto, “A Numerical Analysis Method for Evaluating Rod Lenses Using the Monte Carlo Method”, Optics Express, Vol. 18, 2010, pp. 2716-2727.

[8] N. Ren, J. Ling, X. Qu, J. Li, B. Lu and J. Tiam, “GPU-Based Monte Carlo Simulation for Light Propagation in Complex Heterogeneous Tissues”, Optics Express, Vol. 18, 2010, pp. 6811- 6823.

[9] N. Bentley and I. Brook, “New Method of Calculation Adsorption and Scattering for Xe-Pt (111) Using Direct Simulation Monte Carlo techniques”, Journal of Vacuum Science and Technology, Vol. 30, 2012, pp. 61401-61408.

[10] F. Li and N. Sabir, “Evaluation of Distribution Reliability Improvement with Distributed Generators using Monte Carlo Simulation”, International Review on Modeling and Simulations, Vol. 2, 2012, pp. 356-361.

[11] J. Bowers and C. Burrus, “Degradation of Surrounding Dielectrics of a Micro-Channel Due to Partical Discharges, Part: 1: The Model”, International Review on Modeling and Simulations, Vol. 5, 2012, pp. 187-192.

[12] N. Ganjovi and G. Rastpour, “Modeling of Distribution of PD Pulses within Micro-Cavities”, International Review on Modeling and Simulations, Vol. 4, 2011, pp. 674-682.

[13] S. V. Averine and R. Sachot, “Effect of Optical Excitation Signal Intensity on the Impulse Response of a Metal-Semiconductor-Metal Photodiode,”, Technical physics, Vol. 54, 2009, pp. 1490-1495.

[14] J. Lu, R. Surridge, G. Pakulski, H.-V. Driel and J.-M. Xu, “Studies of High-Speed Metal-Semiconductor-Metal Photodetector with a GaAs/AlGaAs/GaAs Heterostructure”,

IEEE Transactions on Electron Devices, Vol. 40, 1993, pp. 1087-1092.

[15] V. Krishnamurthy and M.C. Hargis, “A 4-GHZ Large-Area MSM-PD on ITG-GaAs”, IEEE Photonics Technology letter, Vol. 12, 2000, pp. 71-73.

[16] Z. Marks and B. V. Zeghbroeck, “High-Speed Nanoscale Metal-Semiconductor-Metal Photodetectors with Terahertz Bandwidth”, in 10th International Conference on Numerical Simulation of Optoelectronic Devices, 2010, pp. 11-12.

[17] M. Soroosh, M. K. Moravvej-Farshi and K. Saghafi, “A Simple Empirical Model for Calculating Gain and Excess Noise in GaAs/AlGaAs APDs”, Journal of Electronics Express,Vol. 5, 2008, pp. 853-859.

[18] Y. Belhadji and B. Bouazza, “Steady State and Transient Study of The Electron Transport In N-Type GaSb Using Three Valley Monte Carlo Model”, International Journal of Computer Science Issues, Vol. 9, 2012, pp. 160-164.

[19] C. Moglestue, Monte Carlo Simulation of Semiconductor Devices, Delhi: Chapman & Hall, 1993.

[20] J. Bowers and C. Burrus, “Ultra-Wide-Band Long Wavelength PIN Photodetectors”, Journal of Lightwave Technology, Vol. 5, 1987, pp. 1339-1350.

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