Numerical Modeling of the Transient Response of Metal-Semiconductor-Metal Photodetector Using Discrete Fourier Transform Method

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Abstract: A one dimensional (1-D) simulation program based on the drift-diffusion model and Discrete Fourier Transform method (DFT) is developed. This program numerically solves the time-dependent continuity equations for electrons and holes in a semiconductor device. This model simulates carrier concentrations and the impulse response of a GaAs metal-semiconductor-metal (MSM) photodetector at a constant bias voltage. From this simulation, we found that for a smaller value of carrier lifetime, the response fall time decreases without significantly reducing the responsivity of the device. The simulation results are well in agreement with the experimental finding and our results match the work of other people who have done the same simulation but with different approach.

Key Words: Simulation; Discrete Fourier Transform (DFT) Method; Impulse Response; Metal-Semiconductor-Metal (MSM) Photodetector.

1. Introduction
The planar Metal-Semiconductor-Metal (MSM) photodetector has become very attractive for application in optoelectronic communication systems [1]. This device consists of a semiconductor absorbing layer on which two electrodes have been deposited to form back-to-back Schottky diodes. The two top electrodes can be as simple as two parallel electrodes or designed in an interdigitated [2] or circular pattern [3]. It has several advantages over traditional p-i-n photodiodes. MSM photodetectors have a lower intrinsic capacitance than p-i-n photodetectors, which results in higher speeds for high bit rate, high sensitivity optoelectronic integrated receivers [4]. In addition, since MSM structures have a lateral design, they have, for the same absorbing layer thickness, a larger surface area than vertical p-i-n photodetectors for similar capacitance and bandwidth [5]. This larger area results in higher alignment tolerance, and thus, reduced packaging cost. Also MSM structure has process compatibility with field effect transistor (FET). In fact, the monolithic integration of MSM structure with a FET is very simple. This is because the electrodes of the MSM photodetector and the gate fingers of a FET can be defined with the same photolithographic step and then deposited with the same metallization [6].

The impulse response of the MSM photodetector often exhibits two different components, a fast rise time, and a long fall time. In high speed digital communications, the long fall time results in intersymbol interference. This is typically caused by the holes since they have much lower mobility than the electrons [7]. One of the reported approaches for reducing the fall time of the transient response of the GaAs MSM photodetector is to use intermediate temperature grown GaAs (ITG-GaAs) for which the growth...
temperature of the semiconductor composite is intermediate between the standard growth temperature of GaAs and that for low temperature grown (LTG) GaAs. The outcome is that the carrier lifetime in the light absorption region is only slightly longer than the transit-time between the electrodes. Thus, the speed of the photodetector is improved without significantly reducing the responsivity [8].

In this paper, we use the Discrete Fourier Transform (DFT) method to simulate the transient response of the GaAs MSM photodetector and to investigate the effect of the lifetime parameter value on the device impulse response. The simulation is based on a one-dimensional (1-D) numerical solution of the time–dependent continuity equations for electrons and holes.

2. Modeling and Simulation

The basic planar MSM photodetector is schematically shown in Fig. 1. It consists of interdigitated metal fingers formed on the top surface of a semiconductor layer. These electrodes are made to form Schottky contacts with the semiconductor. A voltage is applied to the metal fingers to create sufficient electrical field within the semiconductor layer. Light incident on the top surface of the photodetector is absorbed to generate electron-hole pairs. The electric field sweeps the photogenerated carriers out of the device to produce a photocurrent. This photocurrent can be modeled in a one-dimensional regime [9-13].

\[ \frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_n}{\partial x} - R + G_{opt} \quad (1) \]

\[ \frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} - R + G_{opt} \quad (2) \]

\[ J_n = q \mu_n n E + q D_n \frac{\partial n}{\partial x} \quad (3) \]

\[ J_p = q \mu_p p E - q D_p \frac{\partial p}{\partial x} \quad (4) \]

\[ n = n_0 + \delta n \quad (5) \]

\[ p = p_0 + \delta p \quad (6) \]

Where \( J_{n,p} \) are the electron and hole currents, \( R \) is the net carrier recombination rate and \( G_{opt} \) is the generation rate due to illumination, \( \mu_{n,p} \) and \( D_{n,p} \) are the electron/hole mobilities and diffusivities, \( E \) and \( q \) are the electric field and the elementary charge, respectively. A constant electric field is assumed across the device in accordance with ref. [13]. \( n_0 \) and \( p_0 \) are the thermal equilibrium electron and hole concentrations and are independent from the time and space coordinate (assuming a homogeneous active region), \( \delta n \) and \( \delta p \) are photogenerated (excess) electron and hole concentrations. The recombination rates are chosen to be \( n/\tau_n \) and \( p/\tau_p \), where \( \tau_{n,p} \) are the carriers lifetime.

We use the field-dependent expression for the carriers’ mobilities \( \mu_n \) and \( \mu_p \) as follows [14]

\[ \mu_{n,p} = \frac{\mu_{0n,0p}}{1 + \left( \frac{\mu_{0n,0p} E}{v_{0n,sp}} \right)} \quad (7) \]
Where $\mu_{0n,0p}$ are the low field electron and hole mobilities, and $v_{sn,sp}$ are the electron and hole saturation velocities, respectively. The parameters which have been used for the GaAs MSM photodetector are $\mu_{0n} = 8500 \text{ cm}^2/\text{V.s}$, $\mu_{0p} = 400 \text{ cm}^2/\text{V.s}$, $E_0 = 4 \times 10^4 \text{V.cm}^{-1}$, $v_{sn} = 8.5 \times 10^6 \text{cm.s}^{-1}$ and $v_{sp} = 1.5 \times 10^7 \text{cm.s}^{-1}$.

The carriers' diffusion constants are determined by use of the Einstein relation [15-16] as follows

$$D_{n,p} = \frac{kT}{e} \mu_{n,p}$$  \hspace{1cm} (8)

Where $k$ is Boltzmann's constant and $T$ is the carrier temperature (room temperature).

From the symmetrical geometry of the interdigitated electrodes, it is sufficient to treat only a single unit cell whose boundaries are at two adjacent electrical metal fingers. We take the fingers to be located at $x=0$ and $x=L$. With the assumption of ideal Ohmic contacts with an infinite surface recombination velocity, the densities of electrons and holes at the fingers are taken to be at thermal equilibrium, i.e., their excess densities are zero [12].

The DFT method is used to numerically solve continuity equations for excess electrons and holes. Once the carrier concentrations have been calculated, the photocurrents can be found afterwards.

3. **Simulation Method**

In this simulation, the illumination is assumed to be uniform over the entire active region with an arbitrary band-to-band generation rate of $1 \times 10^{19}$ (electron-hole).m$^{-3}$ at $t=0$. It has been assumed that no generation of carriers happens in latter time steps.

We have numerically solved the continuity equations for electrons and holes by the use of Fourier transform technique. By substituting equations (3-6) into the equations (1) and (2), we obtain:

$$\frac{\partial (\delta n(x,t))}{\partial t} = D_n \frac{\partial^2 (\delta n(x,t))}{\partial x^2} + \mu_n E \frac{\partial (\delta n(x,t))}{\partial x} - \frac{\delta n(x,t)}{\tau_n}$$  \hspace{1cm} (9)

$$\frac{\partial (\delta p(x,t))}{\partial t} = D_p \frac{\partial^2 (\delta p(x,t))}{\partial x^2} - \mu_p E \frac{\partial (\delta p(x,t))}{\partial x} - \frac{\delta p(x,t)}{\tau_p}$$  \hspace{1cm} (10)

The Fourier transforms of the entire equations (9) and (10) are as follows [17]

$$F[\frac{\partial (\delta n(x,t))}{\partial t}] = D_n F[\frac{\partial^2 (\delta n(x,t))}{\partial x^2}] + \mu_n E F[\frac{\partial (\delta n(x,t))}{\partial x}] - \frac{1}{\tau_n} F[\delta n(x,t)]$$  \hspace{1cm} (11)

$$F[\frac{\partial (\delta p(x,t))}{\partial t}] = D_p F[\frac{\partial^2 (\delta p(x,t))}{\partial x^2}] - \mu_p E F[\frac{\partial (\delta p(x,t))}{\partial x}] - \frac{1}{\tau_p} F[\delta p(x,t)]$$  \hspace{1cm} (12)

To solve the above two equations, we have used the Fourier transform properties [17]. The Fourier transform of the first and second-order spatial derivatives and the Fourier transform of the time derivative of the photogenerated electron density, respectively, are equal to

$$F[\frac{\partial (\delta n(x,t))}{\partial x}] = ikF[\delta n(x,t)]$$  \hspace{1cm} (13)

$$F[\frac{\partial^2 (\delta n(x,t))}{\partial x^2}] = (ik)^2 F[\delta n(x,t)]$$  \hspace{1cm} (14)

$$F[\frac{\partial (\delta n(x,t))}{\partial t}] = \frac{\partial}{\partial t} F[n(x,t)]$$  \hspace{1cm} (15)

The same expressions can be found for the photogenerated hole density. Substituting these expressions into equations (11) and (12) results in

$$(-k^2 D_n + \frac{1}{\tau_n}) F[\delta n(x,t)] = \frac{\partial}{\partial t} F[\delta n(x,t)]$$  \hspace{1cm} (16)
Equations (16) and (17) are first-order constant coefficient differential equations. Their solutions are as follows

\[ F[\delta n(x,t)] = F[\delta n(x,0)] \exp((-k^2 D_n + i k E \mu_n - \frac{1}{\tau_n})t) \]  

(18)

\[ F[\delta p(x,t)] = F[\delta p(x,0)] \exp((-k^2 D_p - i k E \mu_p - \frac{1}{\tau_p})t) \]  

(19)

Where \( \delta n(x,0) \) and \( \delta p(x,0) \) are the initial photogenerated electrons' and holes' densities in x-space. Equations (18) and (19) give the electron and hole densities at any time in k-space, respectively. We have used DFT method to numerically solve these two equations [18-21]. We have arbitrary chosen \( 2N=512 \) sample points in x and k-space. The values of x and k satisfy the following formulas

\[ x_k = \frac{kL}{2N}, \quad 0 \leq k \leq (2N - 1) \]  

(20)

\[ k_j = \frac{2\pi j}{L}, \quad 0 \leq j \leq (2N - 1) \]  

(21)

The Discrete Fourier Transforms of the excess electron and hole concentrations at any time have the following formulas

\[ F[\delta n(x_k,t)] = \delta N(k_j,t) = \frac{1}{2N} \sum_{k=0}^{2N-1} \delta n(x_k,t) e^{-ik_jx_k}, \quad 0 \leq j \leq (2N - 1) \]  

(22)

\[ F[\delta p(x_k,t)] = \delta P(k_j,t) = \frac{1}{2N} \sum_{k=0}^{2N-1} \delta p(x_k,t) e^{-ik_jx_k}, \quad 0 \leq j \leq (2N - 1) \]  

(23)

To obtain the carriers' concentrations, in the first step, we take Discrete Fourier Transform of the excess electron and hole concentrations at \( t=0 \) by using equations (22) and (23). In the second step, equations (18) and (19) are numerically solved at any time step to obtain the excess carrier's concentrations in k-space, \( \delta N(k,t) \) and \( \delta P(k,t) \). Finally, we take the Inverse Discrete Fourier Transform of \( \delta N(k,t) \) and \( \delta P(k,t) \) to obtain the excess carrier's concentrations in x-space, \( \delta n(x,t) \) and \( \delta p(x,t) \), using the following formulas

\[ \delta n(x_k,t) = \sum_{j=0}^{2N-1} \delta N(k_j,t) e^{ik_jx_k}, \quad 0 \leq k \leq (2N - 1) \]  

(24)

\[ \delta p(x_k,t) = \sum_{j=0}^{2N-1} \delta P(k_j,t) e^{ik_jx_k}, \quad 0 \leq k \leq (2N - 1) \]  

(25)

After calculating the excess carriers' concentrations, the electron and hole currents are calculated by using the following formulas, respectively

\[ I_e(t) = \frac{qE}{L} \sum_{k=0}^{2N-1} \delta n(x_k,t) \mu_e \Delta x \]  

(26)

\[ I_p(t) = \frac{qE}{L} \sum_{k=0}^{2N-1} \delta p(x_k,t) \mu_p \Delta x \]  

(27)

The total current passing through the device is the summation of the electron and hole currents given in equations (26) and (27).
4. Simulation Results

Plots of the electron, hole and the total photocurrents are shown in Fig. 3 at 10 volts bias voltage and 6 µm fingers spacing. In each subplot, the upper curve is for electrons and the lower one is for holes. Since electrons have a greater mobility than the holes, they are swept out of the device much more quickly than the holes and this results in a strong increase in the total photocurrent. As can be seen from Fig. 3(a), the electron and hole carriers with the same lifetime have the same FWHM and fall time in their response currents. In Fig. 3(b) holes have a larger lifetime than the electrons and this results in a long tail in the total photocurrent.

![Figure 2: The electron, hole and the total photocurrent in an MSM photodetector versus time for the cases (a) carriers with the same lifetime (τ_n and τ_p equal to 50 ps), (b) carriers with different lifetime (τ_n=50 ps and τ_p=100 ps). The fingers spacing is 6 µm and the applied voltage is 10 V.](image1)

A plot of the hole response current for various lifetimes is shown in Fig. 3.

![Figure 3: The hole current of an MSM photodetector for various values of lifetime parameter of 50, 60, 70, 80 and 90 ps at 10 volts applied voltage and 6 µm finger spacing.](image2)

As can be seen from Fig. 2 and Fig. 3, hole carriers with shorter lifetime give a faster response time or shorter tail in the response pulse without significantly reducing the device responsivity. These results show good correspondence to the experimental finding of Fig. 4 in ref. [8] and are in agreement with simulation results of the effect of lifetime parameter on the hole impulse response of Fig. 4 and Fig. 5 in ref. [22].

Conclusion

In this paper, by using DFT method, we have numerically solved the continuity equations for the electron and hole carriers with the inclusion of drift, diffusion and bulk recombination terms in one-dimension. Transient photocarrier concentrations and photocurrents are numerically calculated in a low applied field regime. Also the effect of variation of carriers’ lifetime on the impulse response of the photodetector is investigated. The simulation results are comparable with the reported experimental finding and published simulation results.
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