Terahertz Response of MSM Photodiodes: Monte Carlo Simulation

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Ultra–high–frequency response of interdigitated metal-semiconductor-metal photodiodes with GaAs absorbing layer is studied using an ensemble Monte Carlo particle method.

1. Introduction

Interdigitated metal–semiconductor–metal (MSM) photodiodes have received increasing interest in optical fiber communication systems, optical heterodyne conversion and other applications. Despite a considerable amount of papers on MSM photodiodes have been reported (see Refs. [1-7]), some aspects of their operation need further study. This paper deals with a two–dimensional ensemble Monte Carlo (MC) particle simulation of the MSM photodiode operation in the terahertz range of signal frequencies. Terahertz response of MSM photodiodes is associated with ultrafast carrier dynamic (transit time and velocity overshoot effects). We consider planar MSM photodiodes consisting of a GaAs absorbing region with a system of Schottky contacts made "back-to-back" on the above layer. High–frequency response of MSM photodiodes is determined by the electron (hole) transit time between the contacts τ_{tr} and the characteristic time of the velocity overshoot effect τ_0, which are much shorter than the carrier lifetime τ_l: $\tau_0 \ll \tau_{tr} \ll \tau_l$.

2. Model

MSM photodiodes made of a GaAs/AlGaAs heterostructure with an interdigitated system of Schottky contacts are considered. A schematic view of the MSM photodiode (a) and the geometry of the simulated structure (b) are shown in Fig. 1. The MC model takes into account the band structure and scattering mechanisms for GaAs and $Al_{0.3}Ga_{0.7}As$. It uses sets of parameters published previously [8,9]. The Dirichlet boundary conditions are used at the metalic contacts while the Neuman boundary conditions with zeroth normal derivatives of the potential are assumed at the other boundaries of the simulated region. We assume that the contacts absorb incident electrons and holes. Thermionic injection

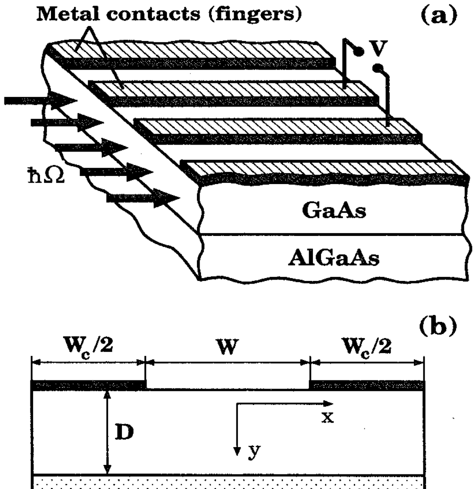

Figure 1: Structure of MSM photodiode (a) and the geometry of the simulated region (b).

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from contacts is neglected. The two–dimensional Poisson equation is solved at each time step. A time step of 5-10 ps and 100,000 particles are used. The capacitance matrix technique is utilized to calculate the electric field fluxes via the contacts. The displacement current is calculated using the values of the electric field flux at each time step.

We consider the intrinsic transient response of the device under the influence of a probing ultra–short δ-like light pulse, hence the input power is given by

$$P(t) = P_0 + Q \cdot \delta(t).$$

Here P_0 is the stationary power, Q is the pulse energy, and $\delta(t)$ is the Dirac δ-function. Possible nonuniformity of spatial distribution (in (x,y)-plane, see Fig. 1) of the photogenerated electrons and holes is neglected. It is assumed that photoelectrons and photoholes are monoenergetic immediately after the pulse. To calculate the MSM photodiode frequency response the obtained temporal dependences of the photocurrent triggered by the pulse are subjected to the Fourier transform.

The MSM photodiodes with the absorbing layer thickness $D = 0.2$ μm and different contact spacing W and width W_c are studied and compared ($W = W_c = 0.025 - 1.0$ μm). The energy of incident photons is given in the range $\hbar\Omega = 1.45 - 2.0$ eV, so that the initial energy of the photogenerated electrons $\varepsilon_0 \simeq 30 - 580$ meV. It is assumed that the temperature $T = 300$ K. The bias voltage V is chosen to provide the average electric field between the contacts $E = V/W = 50$ kV/cm.

3. Results

The normalized frequency response of the MSM photodiode with $W = 0.2$ μm for different ε_0 is shown in Fig. 2. The inset in Fig. 2 shows the transient photocurrent corresponding to different ε_0. The normalized frequency response for different contact spacings is shown in Fig. 3. Figures 2 and 3 demonstrate that if the photon energies are close to the absorbing layer energy gap, i. e., in the case of relatively low initial energy of photoelectrons, the MSM photodiode frequency response reveals rather long tail in terahertz range where the response is relatively strong. It takes place even for the devices with large enough contact spacing. This is due to velocity overshoot exhibited by photoelectrons in perfect absorbing region (see Ref. [4]). The importance of the velocity overshoot effect exhibited by photoelectrons was confirmed experimentally [10].

Figure 4 shows the normalized response at fixed frequencies as a function of the contact spacing revealing marked maxima at $W = 0.2$ μm. The response–frequency product as a function of signal frequency for the MSM photodiodes is presented in Fig. 5. It is seen that these characteristics reveal sharp maxima at terahertz frequencies. The shift of the maxima to higher frequencies in the range $W < 0.2$ μm can be explained by a considerable shortening of the transit time of photoelectrons with

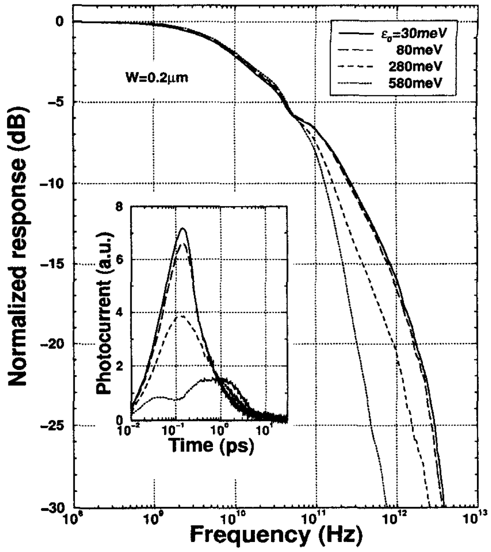

Figure 2: Normalized response vs signal frequency and photocurrent vs time (inset) for MSM photodiode with $W = 0.2$ μm and different initial energies of photoelectrons ($\varepsilon_0 = 30 - 580$ meV).

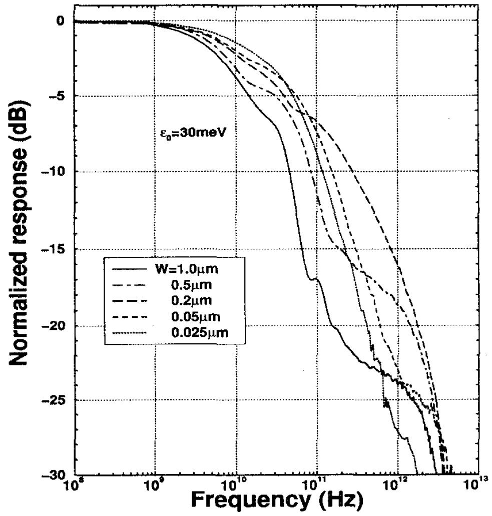

Figure 3: Normalized response vs signal frequency for different contact spacings ($W = 0.025 - 1.0$ μm) and $\varepsilon_0 =$ 30 meV.

reducing contact spacing. This shift appears when the transit time becomes comparable or less than the duration of the photoelectron velocity overshoot. More details will be reported later [11].

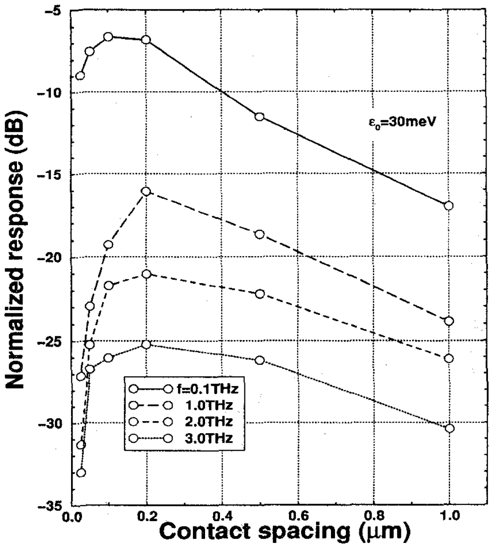

Figure 4: Normalized response at different frequencies ($f = 0.1 - 3.0$ THz) as a function of contact spacings.

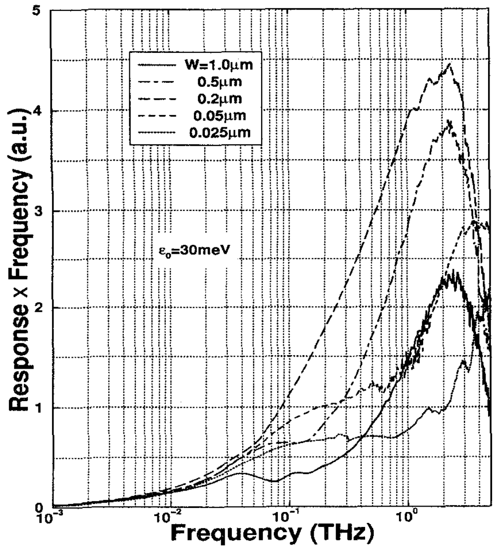

Figure 5: Response–frequency product vs signal frequency for different contact spacings ($W = 0.025 - 1.0$ μm) and $\varepsilon_0 = 30$ meV.

4. Conclusion

Calculations by ensemble MC particle method on ultra-high-frequency response of MSM photodiodes were reported. It was shown that MSM photodiodes with relatively large contact spacing exhibit a marked response at signal frequencies in the terahertz range. The frequency response is a nonmonotonic function of the contact spacing with a maximum at a certain value of the latter. The response-frequency product shows a pronounced peak at a frequency in the terahertz range. The features in question of the MSM photodiode operation are attributed to the velocity overshoot effect revealed by the photoelectrons shortly after their generation in the conduction band of the absorbing layer.

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