Monte Carlo simulation of THz radiation detection in GaAs $n^+nn^+$ diodes with inhomogeneously doped $n$-region

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Abstract. A proper profile of nonuniform doping of GaAs $n^+nn^+$ structure to reach the maximum detection sensitivity is proposed. It is shown that the main role in formation of longitudinal transport asymmetry and THz radiation detection is played by optical phonon emission process. It is found that the detection current depends on frequency in spectral range 0.02 - 1 THz, reaches maximum near 2.2 THz (10 and 80 K) or 3 THz (300 K) and then becomes to decrease due to the inertia of optical phonon emission process.

1. Introduction
To detect the microwave power semiconductor diodes with asymmetric current-voltage relation (CVR) are widely used. Usually, such an asymmetry is obtained by forming various barriers ($pin$, Schottky, heterojunction, etc.) in the active region. Unfortunately, in going to terahertz (THz) region the sensitivity of barrier-structures rapidly decreases due to time-delay related with large values of the barrier capacitance and its resistance. In contrast, as it was experimentally demonstrated recently [1], these restrictions can be overcome in asymmetricaly narrowed $nn^+$ GaAs structure. Due to the resistance gradient along the axis of narrowing active region there appears nonuniform electric field with a peak placed in the narrowest place. The height and width of the peak depend on the flowing current direction, thus leading to asymmetric CVR.

The novel idea proposed in this report is to form the longitudinal gradient of resistance necessary for the CVR asymmetry by using nonuniform doping of the active region and keeping the constant cross-section area along the structure. In the framework of such an approach, a proper choise of $n$-region doping profile will allow one to obtain asymmetric CVR and microwave-THz power detection by using more simple geometry than previous one. Therefore, the aim of this work is to investigate an electron transport and THz radiation detection in GaAs $n^+nn^+$ diodes with inhomogeneously doped $n$-region by using Monte Carlo particle method.

2. Simulation method and detector model
The simulations are performed using Monte Carlo particle (MCP) technique [2]. Electron motion in GaAs is simulated with account of scatterings by acoustic, optical and intervalley phonons and scatterings by ionized impurities as well. Three valley ($\Gamma$, L and X) GaAs model is used [3].

The investigated detector consists of two 0.3 $\mu$m $n^+$-layers with 0.5 $\mu$m $n$-layer between them. The $n^+$-layers are uniformly doped by donors up to $N^+ = 10^{18}$ cm$^{-3}$. The $n$-layer consists of
20 \delta x = 0.025 \mu m thick minilayers. The doping of each minilayer is given by formula \( N = N^+ \exp[-(21-n)/b]^2 \), where \( n = 1, 2, ..., 20 \) is minilayer number (the number is increasing with increased coordinate \( x \)) and \( b = 0.19024 \mu m \). So formed doping profile is shown in Fig. 1. The number of simulated particles depending on case is from 60,000 to 150,000 and time step in all cases is of \( 10^{-15} \) s.

![Figure 1. Doping profile of GaAs \( n^+nn^+ \) structure.](image)

![Figure 2. Static CVR of GaAs structure for positive (1) and negative (2) current direction.](image)

3. Static characteristics

![Figure 3. Electron velocity and concentration profiles in GaAs structure at 80 K (a) and 300 K (b), when \( |U_0| = 0.1 \) V. 1 - positive current direction, 2 - negative current direction.](image)

The current-voltage relation (CVR) is calculated by simulation of time dependent current at given constant bias. The current value is calculated by averaging in time the stationary part of current trajectory. So calculated CVR for 80 and 300 K are presented in Fig. 2. To show the CVR asymmetry the absolute current values \( |j| \) are plotted versus absolute voltage \( |U_0| \). The solid lines 1 in Figs. 2-4 correspond to the positive current direction i.e. current flows in direction of increased coordinate \( x \). Also it should be stressed that due to the negative electron charge the electrons flow in the direction opposite to the current. For CVR asymmetry analysis the profiles of various physical quantities inside the detector at \( |U_0| = 0.1 \) V and 80 and 300 K are presented below. Fig. 3(a,b) shows the electron velocity absolute value and concentration profiles. One can see that higher velocity in high concentration regions gives higher current in positive direction. The CVR asymmetry can be explained by analysis of electron dynamics in the detector. In this case the electrons are scattered by impurities and acoustics and optical phonons. The electron dynamics is mostly affected by optical phonon scattering because this scattering changes electron velocity and energy at the same time. Electrons entering the \( n \)-region from the left immediately enter the high field region and are near ballistically accelerated to higher
velocity and energy, than electrons entering from the right side where electric field gradient is much smaller due to lower concentration gradient and electrons are accelerated slowly with high scattering by impurities and acoustic phonons. Electrons moving from left to right have to experience more scattering events by optical phonon emission than ones moving in opposite direction. This is illustrated in Fig. 4(a,b) where local optical phonon emission $\nu_L$ profiles are shown.

![Figure 4](image.png)

**Figure 4.** Local optical phonon emission $\nu_L$ profiles in GaAs structure at 80 K (a) and 300 K (b), when $|U_0| = 0.1$ V. 1 - positive current direction, 2 - negative current direction.

It is easy to see that electrons moving from left to right experience more optical phonon emission events (Fig. 4(a), compare lines 1 and 2), which results in higher resistivity than in the electron opposite movement case. At 300 K the asymmetry is much lower due to the increased scattering by acoustic phonons and optical phonon absorption. Thus, we have shown that major influence to the CVR asymmetry in the $n^+nn^+$ GaAs detector with the doping gradient in $n$-region gives the optical phonon emission. Below we will investigate the characteristics of the detector in high frequency electric field.

### 4. THz radiation detection

![Figure 5](image.png)

**Figure 5.** Detector current $j_d$ dependence on $U_1^2$ at 300 K and $f = 1$ THz (a) and $j_d$ spectra at $U_1 = 0.1$ V and 10, 80 and 300 K (b). The straight line in (a) shows the linear part of $j_d$.

The detector current $j_d$ response to the radiation is simulated applying to the structure an alternative bias $U(t) = U_1 \cos(2\pi ft)$, where $U_1$ is voltage induced in structure by radiation and $f$ is the radiation frequency. As in the case of static characteristics the long current response trajectories are simulated. The $j_d$ value is obtained by averaging in time the stationary part of trajectory. The wide band detectors are used in radiation power measurements. Therefore the detected signal should be the linear function of radiation power, which is proportional to the $U_1^2$. To find the $U_1$ range where $j_d$ is linear function of power the $j_d$ dependence on $U_1^2$ is calculated at $f = 1$ THz and 300 K (Fig. 5(a)). It is found that linear dependence of $j_d$ on
radiation power takes place when $U_1$ is in the range from 0 to 0.15 V (see Fig. 5(a)). This range weekly depends on temperature and is approximately the same for 10 and 80 K. Choosing $U_1 = 0.1$ V the $j_d$ dependence on frequency $f$ (from 0.02 to 10 THz) is simulated at 10, 80 and 300 K (Fig. 5(b)). At lower temperatures (10 and 80 K) $j_d$ is higher due to the reduced scattering rates by acoustics phonons and optical phonon absorption as compared with that at 300 K (Fig. 5(b)). In the frequency range 0.02 - 1 THz the $j_d$ spectra are flat for all temperatures. At frequencies over 1 THz the $j_d$ is increased with frequency increase and after reaching the maximum becomes to decrease. At low temperatures (10 and 80 K) the $j_d$ maximum is at 2.2 THz, while at 300 K the maximum is at 3.0 THz (Fig. 5(b)). Such a behavior of $j_d$ spectrum can be explained using optical phonon emission rate $\nu$ dependencies on electron energy (Fig. 6(a)). At low temperatures (10 and 80 K) the $\nu$ dependencies on energy are practically the same while at 300 K the optical phonon emission rate is significantly higher: at energy 0.1 eV and low temperature $\nu \approx 4.8$ THz, while at 300 K $\nu \approx 6.5$ THz. It should be noted that the ratio of these frequencies is practically the same as the frequency ratio of low temperature and 300 K $j_d$ spectra maxima (Fig. 5(b)). The $j_d$ decrease at high frequencies can be explained by optical phonon emission inertia: electron gains the energy from the field over optical phonon energy during one half of period and looses it during another half of period with no optical phonon emission. So the radiation frequency increase should result in decrease of local optical emission rate $\nu_L$ inside the detector. It is demonstrated in Fig. 6(b) where the $\nu_L$ profiles in detector are simulated at 0.5, 1.0, 2.0, 3.0, 6.0 and 10 THz frequencies. One can see from Fig. 6(b) that local optical phonon emission rate in n-region of detector is decreased at increased radiation frequency. Also it is seen from this figure that $\nu_L$ maximum is approaching the higher electron concentrations (compare Fig. 1 and Fig. 6(b)) at frequency increased. It means that more electrons experience the maximum optical emission rate. So it is the reason for $j_d$ maxima formation in $j_d$ spectra (see Fig. 5(b)).

Finally, the upper analysis shows that optical phonon emission plays the main role in wide band THz radiation detection by GaAs $n^+nn^+$ diodes with inhomogeneously doped n-region.

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5. References
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