Noise Calculation in nano-channel diodes for Terahertz detectors application

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Abstract: An analytical calculations of the intrinsic noise and Noise Equivalent Power (NEP) in the InGaAs nanochannel diode are proposed. The model based on the one dimensional Poisson equation which is derived to obtain the current-potential relation of the diode. This relation allows to calculate the admittance/impedance elements and establish the noise spectral density according to Nyquist expression. From the complex impedance of the diode, we can extract the Responsivity generated from the power signal in proportional to the power absorbed by the nanochannel diode. The analysis combine the noise spectra and the Responsivity to determine the Equivalent Noise Power (NEP) of the diode under a high frequency signal. The discussion includes the geometrical effects, the operating temperature and proporties of the diode to optimize the generated power in terahertz frequency. The Responsivity and the Noise power schow the appearence of resonances peaks in the terahertz domain. The analysis of the resonances improves the behavior of the nanochannel diodes for high sensitive Terahertz detectors. The analytical noise results are compared with the Mont Carlo calculations in Refs. [1], [2].

Key–Words: Nanochannel diodes, Terahertz (THz), resonances, Noise Equivalent Power (NEP), intrinsic noise.

1 Introduction

The nano-diodes have present a great potential applications in the Terahertz frequencies as detectors and emitters at room temperature [3]. In particular, the nanochannel diodes known as self-switching devices (SSDs) have shown experimentally a good Responsivity and noise properties for microwave and Terahertz detection [4], [5]. Many researchs are supported for the realization of an InGaAs nanochannel diodes in Ref. [6] then for the noise equivalent power calculation by a numerical model in Refs. [7], [4] and Mont Carlo model in Refs. [1], [2].

In this article, the noise equivalent power calculation is based on an analytical approach where the equations particularly focus thier dependance to the material parameters (relaxation rate, mobility, masse effective and permittivity), the channel geometry (length, width and carrier concentration) and the diode properties operationg in applied voltage(resistance and rectifie electric current). Moreover, the analytical model can determine all the parameters related to the generated power such as the impedance $Z(\omega)$ and therefore the resistance R, the noise spectrum (S_{ii} and S_{vv}), the signal power in the diode P_{int} and the Resposivity S_{int}. In this case, the analytical resolution is useful to perform the high frequency generated power by discussing some parameters such as the impedance, the noise spectrum, the Responsivity and the noise equivalent power.

The terahertz noise spectrum (current/voltage densities) in nanochannel diodes is based on the determination of the equivalent circuit elements such as the admittance/impedance parameters of their terminals (anode and cathode). The nanochannel diode impedance can be determined by using the 1D Poisson equation in high doped InGaAs semiconductor. Moreover, the analysis of the complex impedance provides an important information about the noise density and the dynamic regime of the diode under applied signal. In adition, the impedance/admittance elements are useful for two main goals calculations:

- the high-frequency noise of the unipolar diodes, especially the current and the voltage spectral densities. For this approach, we use the Nyquist relation which introduces the real part of the admittance/impedance elements.
- the evaluation of the Responsivity and therefore the power generated from signal, which can be used to model the terahertz detectors based on the nanochannel diodes [8].

In Section 2, firs the potential in the nanochannel diode is described by 1D Poissons equation and therefore the total current is determined. In particular, the

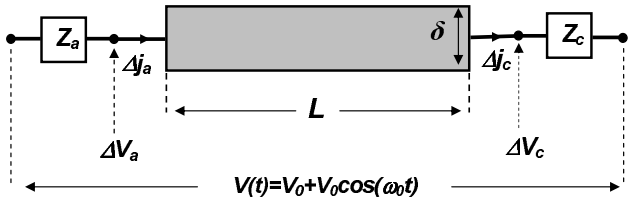

Figure 1: Structure representation of a nanochannel diode of length L and thickness δ. The amplitudes of the anode and cathode are ΔV_a and ΔV_c respectively.

impedance/admittance can be obtained by the relation between the current density and the potential. Second, the complex admittance/impedance elements are useful for the noise densities calculation, the Responsivity to an applied signal and the noise equivalent power of a channel diodes.

In Section 3, the frequency dependent admittance/ impedance matrix is studied and interpreted as a function of the diode geometrical parameters (length and width) and operating temperature.

In Section 4, the noise spectral density is obtained by using the Nyquist relation. Indeed, the diode rectifin properties, the responsivity and the noise equivalent power (NEP), are discussed as a function of different applied voltage (constant and microwave voltage). In the general analysis, the NEP has been considered as an essential factor in the performance of unipolair diode detectors [2].

2 Analytical model of channel diode

We consider a nanochannel diode structure reported schematically in Figure 1 where the L is the length and δ is the thickness of diode.

In extension, the total current density along the diode is obtained by the displacement and drift current components as:

$$\Delta j = -\epsilon_c\epsilon_0 \frac{d}{dt}\frac{d\Delta V}{dx} - e\mu n_0 \frac{d\Delta V}{dx} = \gamma \frac{d\Delta V}{dx} \quad (1)$$

Where the $\mu = \frac{e}{m^*\nu}$ is the material mobility related to the relaxation rate ν and the effective mass m^*, ΔV is the potential along the diode, n_0 is the electron concentration and ϵ_c is the dielectric constants of the nanochannel material. By using the Fourrier transformation, we obtained the term γ of equation (1) as $\gamma = -e^2 n_0/m^*\nu - i\omega\epsilon_c\epsilon_0$.

The potential distribution ΔV is determined through the 1D Poisson equation rewritten as:

$$\frac{d^2\Delta V}{dx^2} = -\frac{e}{\epsilon_c\epsilon_0}\left[n_0 - N(x)\right] \quad (2)$$

Here $N(x)$ is the effective donor concentration. Also the potential conditions at the diode terminals are define as $\Delta V(x=0) = \Delta V_a$ and $\Delta V(x = L) = \Delta V_c$ for solving Eq. (2). After the resolution of equation (2), the equation (1) is accompanied by an aproximated relation between the current and the potential in absence of thermal noise as:

$$\Delta j(\omega) = \frac{G}{L}\Delta V(\omega) \quad (3)$$

Where $G = \epsilon_c\epsilon_0\omega_p^2\alpha^{-1}/(i\omega+\nu)$, $\alpha = \omega_p^2/\left(\omega_p^2 + i\omega(i\omega+\nu)\right)$, $\omega_p = \sqrt{e^2 n_0/\epsilon_c\epsilon_0 m^*}$. The current along the diode is unidemensional and therefore the admittance expression at the cathode, anode and cthode-anode contacts is $|Y_{ij}| = \frac{G}{L}$ (where $ij = a, c$), respectively.
The admittance of equation (3) is similar to that calculated for ungated transistor in Ref. [9]. The equation (3) presents the basis for the calculation of the diode impedance components in terahertz frequency as:

$$Y(\omega) = Z^{-1}(\omega) \quad (4)$$

where $Y(\omega)$ and $Z(\omega)$ are the admittance and impedance elements, respectively. According to equation (4), the linear response descriptions based on the admittance $Y(\omega)$ or impedance $Z(\omega)$ matrixes are equivalent. This condition means that the current/voltage spectral density related to Y/Z has a similar discription which leads to present only the current noise spectrum in the discussion section.

The spectral density of current/voltage fluctua tions can be obtained by using the real parts of the admittance/impedance complex components ($Y(\omega)$ or $Z(\omega)$). In the thermal equilibrium and by using the Nyquist relation, the noise calculations take the form [10]:

$$\begin{aligned} S_{ii}(\omega) &= 4kTRe[Y(\omega)] \\ S_{vv}(\omega) &= 4kTRe[Z(\omega)] \end{aligned} \quad (5)$$

It should be emphasized that the voltage spectral density $S_{vv}(\omega)$ is integrated in the noise equivalent power (NEP) calculations under a microwave voltage applied to the diode tarminals. In particular, the NEP is partially studied for AlGaN unipolar diode by Monte Carlo simulations in article [2]. The sinusoidal voltage applied to the diode is proportional to $V = V_{DC} + V_0 cos(\omega t)$ and the current response $j(t)$ is rectifie to the spectral current representation $\Delta j(\omega)$ obtained by using equation (3).

For simplicity, the intrinsic Responsivity is determined by the rectifie current $\Delta j(\omega)$ and the resistance of the diode R as:

$$S_{int}(\omega) = \frac{\Delta j(\omega) \times R(\omega)}{Re[V_0^2/2Z(\omega)]} \quad (6)$$

with $R(\omega) = Re[Z(\omega)]$ resistance corresponds to the real part of the diode complex impedance $Z(\omega)$. Let us note that the impedance $Z(\omega)$ is extracted from the admittance element described by equation (4).

By using Eqs. (5) and (6), we obtain the intrinsic NEP as the ratio between the voltage spectral density $S_{vv}(\omega)$ in the diode and the intrinsic Responsivity $S_{int}(\omega)$:

$$NEP_{int}(\omega) = \frac{\sqrt{S_{vv}(\omega)}}{S_{int}(\omega)} \tag{7}$$

The Nyquist theorem using for the voltage noise calculation $S_{vv}(\omega)$ impose the equilibrium condition obtained by the small value of DC voltage ($V_{DC} \rightarrow 0$). Therefore, we can express the extrinsic NEP as:

$$NEP_{ex}(\omega) = \frac{\sqrt{S_{vv}(\omega)}}{1 - \left|\frac{Z(\omega)-Z_0}{Z(\omega)+Z_0}\right|^2} \tag{8}$$

The term in the denominator of equation (8) presents the extrinsic Responsivity and Z_0 is the experimental constant impedance of the diode.

In Section 3 and 4, we calculate and discuss the admittance/impedance (Y_{ij}/Z_{ij}) and the noise/NEP spectrum of a nanochannel diode, respectively.

3 Nanochannel diodes response

We discuss, in this section, the modulus of the admittance and the real part of the impedance as functions of the diode parameters (L and ν). We consider a InGaAs channel diode with electron concentration $n_0 = 8 \times 10^{17}$ cm^{-3} and a thickness $\delta = 15$ nm.

Let us note that the admittances of the diode terminals take the same expression $|Y_{aa}| = |Y_{cc}| = |G/L|$ according to equation (3) which leads to present an admittance of anode terminal. The figur 2 illustrates the modificatio introduced by the length L and the relaxation rate ν on the anode admittance modulus $|Y_{aa}|$. We present in figur 3 the real part of impedance $Re[Z_{aa}]$ which is widely used for the noise and the intrinsic Responsivity calculations. In the case of Fig. 2, at low frequencies, $|Y_{aa}|$ demonstrates the Lorentzian shape corresponding to the decrease of G term in the admittance function. For the real part of impedance, we observe the appearance of one resonance peak near 10 THz corresponding to the plasma frequency ω_p. Indeed, the resonance frequency of $Re[Z_{aa}]$ (near 10 THz) can be compared and interpreted by the expression [10, 11]:

$$f_p = \omega_p \frac{p}{\sqrt{\left(\frac{\lambda L}{\pi}\right)^2 + p}} \tag{9}$$

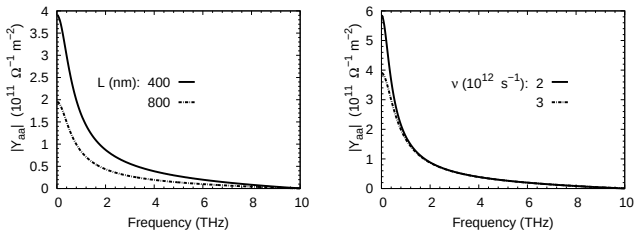

Figure 2: Anode admittance modulus $|Y_{aa}|$ as functions of the frequency for the reported lengths L and relaxation rates ν.

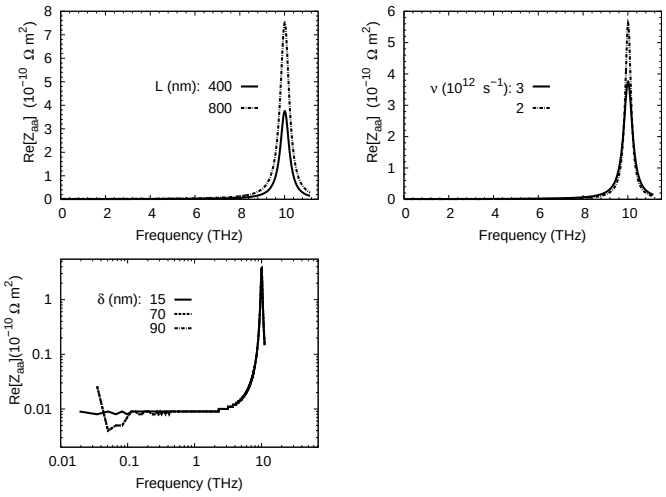

Figure 3: Real part of impedance as functions of the frequency for reported lengths L, relaxations rate ν and thikness δ.

where $p = 1, 2, 3, 4..$ number of excitation and $\lambda = \sqrt{1/d\delta}$. The resonace peak of diode impedance spectrum is obtained according to equation (9) when $\lambda \rightarrow 0$ (for $d \rightarrow \infty$ ungated transistor corresponding to channel diode structure):

$$f_{res} = \omega_p = const \tag{10}$$

Compared to the plasma resonances of the transistor admittance f_p (equation (9)), the impedance spectrum exhibits one plasma resonance f_{res} (equation (10)) explaining the absence of oscillations along the diode channel. It can also be noticed that the amplitude of the resonance peak in figur 3 decreases when the diode length decreases. In low frequency, we observe that the decrease of the length L tends to increase the amplitude of the admittance modulus. Moreover, for the relaxation rate effect, the value 3×10^{12} corresponding to 300 K can decrease bowth the resonance peak of $Re[Z_{aa}]$ and the amplitude of $|Y_{aa}|$. The resonance plasma f_{res} (or ω_p) is related to the relaxation rate through the relation $\nu = \frac{e}{m^*\mu}$.

We can remark that the thikness δ introduces a

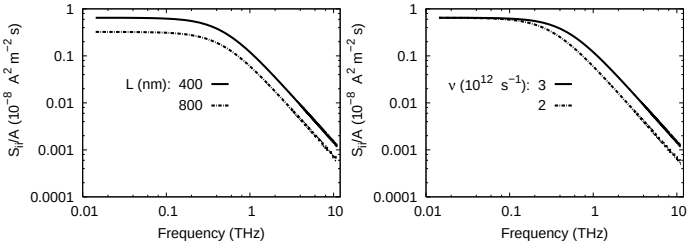

Figure 4: Spectral density of current fluctuation $S_{ii}(\omega)$ as functions of the frequency for the reported lengths L and relaxation rate ν.

modificatio on the diode resistance ($Re[Z_{aa}]$) in low frequency range, where the low thiskness $\delta = 15$ nm stabilize the resistance R.

4 Noise and responsivity of channel diodes

In this section we investigate the Noise, the Responsivity and the noise equivalent power of an InGaAs channel diode.

4.1 Current noise

The noise spectral densities of current/voltage fluc tuations are calculated according to equation (5), in particular, we discuss the current spectral density S_{ii} which is widely used in the literature. Figure 4 reports the frequency dependence of the spectral current density $S_{ii}(\omega)$, proportional to the real part of admittance and obtained through Eq. (5). The spectral density exhibits the usual Lorentzian behavior obtains to diode structures at thermal equilibrium. The results of spectral density are compared to the Lorentz spectrum obtained for the homogenous diode in Ref. [12]. It can be seen that the decreasing of the length L increases the spectral density due to the increases of the admittance modulus. With the decrease of the relaxation rate ν, the noise spectrum decreases in the high-frequency region due to their strongly dependence to the temperature T compared to the relaxation rate ν in real part of admittance according to equation (5).

4.2 Responsivity

The Responsivity of channel diodes to a sinusoidal signal $V(t) = V_{DC} + V_0 cos(\omega t)$ determined in accordance with equation (6) under equilibrium condition achieved by a small values of V_{DC} and V_0. Moreover, we suppose that the dc and ac voltages are equals $V_{DC} = V_0$ at the frequency ω_0, this implies that the applied voltage V is proportional to

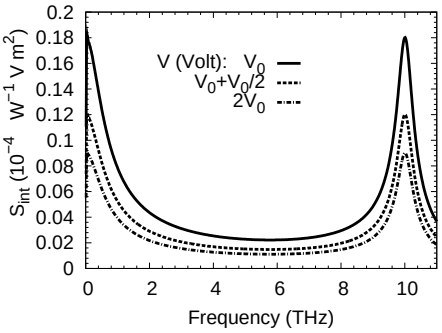

Figure 5: Intrinsic Responsivity S_{int} for different fi ed values of the voltage V corresponding to different phases of the ac component $V(t) = V_0 + V_0 cos(\omega_0 t)$ ($\omega_0 t = 0, \pi/3, \pi/2$). With $V_0 = 0.25$ V, $L = 400$ nm, $\nu = 3\times10^{12}$ s^{-1} and electron concentration $n_0 = 8\times10^{17}$ cm^{-3}.

$V(t) = V_0 + V_0 cos(\omega_0 t)$. The calculations of the Responsivity will be carried out in two steps. In the firs step, the Responsivity is determined for different fi ed values of the voltage $V(t)$ corresponding to different phases of the ac component $\omega_0 t = 0, \pi/3, \pi/2$ ($V = 2V_0, V_0 + \frac{V_0}{2}, V_0$). Such a choice of voltage values ($V = 2V_0, V_0 + \frac{V_0}{2}, V_0$) includes in equation (3) to extracted the rectifie current $\Delta j(\omega)$ at a certain voltage V. In the second step, we assume that the voltage takes an adiabatic variation in time $V(t) = V_0 + V_0 cos(\omega_0 t)$ where ω_0 has a finit value 10 GHz. In the case considered here, the variation $V(t)$ produces the dependence of the Responsivity on the harmonic contribution of the ac signal applied to the diode.

Figure 5 illustrates a frequency behaviour of the Responsivity at absence of harmonics contribution in applied voltage $V = const$ ($\omega_0 t = const$). The results of figur 5 consist the firs step of the Responsivity calculation where $V_0 = 0.25$ V. The Responsivity in figur 5 is permormed under a constant voltage operation V, when the current fl wing through the diode terminals changes its values by a certain time moment $\omega_0 t =$ constant. We remark that the Responsivity, at low frequencies, demonstrates the Lorentzian shape corresponding to the behavior of the admittance $Y(\omega)$ (see figur 2), and a peak at frequency 10 THz corresponding to the presence of a resonance peak in real part of impedance (see figur 3). According to equation (6), the Responsivity behavior at low frequencies (lorentzian form) and near 10 THz (resonance peak) depends to the two parts of ratio $\frac{V_0^2}{2} Y(\omega)$ and $R(\omega) = Re[Z(\omega)]$, respectively. In addition, the decreasing of the voltage V increases the amplitude of the Responsivity according to equation (6). The diode

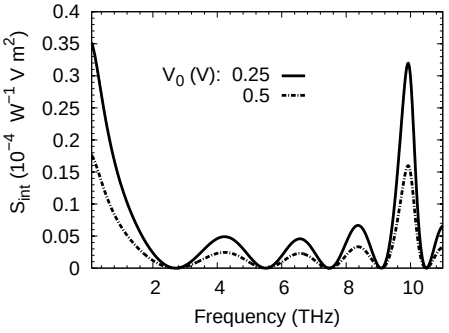

Figure 6: Intrinsic responsivity S_{int} as functions of ac voltage component V_0. With $\omega_0 = 10$ GHz, $L = 400$ nm, $\nu = 3\times10^{12}$ s^{-1} and carrier concentration $n_0 = 8\times10^{17}$ cm^{-3}.

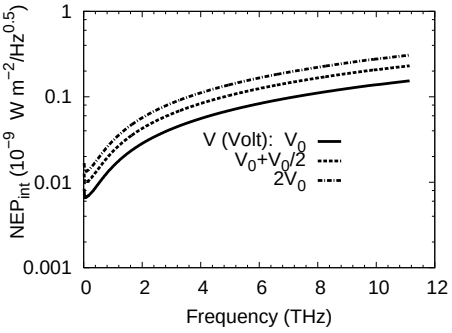

Figure 7: Intrinsic noise equivalent power NEP_{int} as a function of frequency evaluated for different fi ed values V. With $V_0 = 0.25$ V, $L = 400$ nm, 3×10^{12} s^{-1} and $n_0 = 8\times10^{17}$ cm^{-3}.

response behavior under a constant voltage effect has been extensively discussed and explained in Ref. [10].

Figure 6 shows the variation of the Responsivity $S_{int}(\omega)$ as a function of the ac voltage V_0 under a microwave voltage $V(t)$ in accordance with Eq. (6).

In the case of Fig. 6, a short series of peaks caused by the microwave excitation along to the diode is placed between the lorentzian behavior and the resonance peak of 10 THz (see figur 5). Moreover, the small value of voltage V_0 leads to increase the amplitude of resonance peaks. As discussed above in Fig. 5, the most important resonance in the series of peaks (see figur 6) is at the frequency 10 THz where the impedance real part effect is dominant.

4.3 Intrinsic noise equivalent power

In this section, we represent the frequency dependence of the intrinsic noise equivalent power NEP_{int} obtained through Eq. (7). The intrinsic NEP is determined for two case of excitation, under a costant and

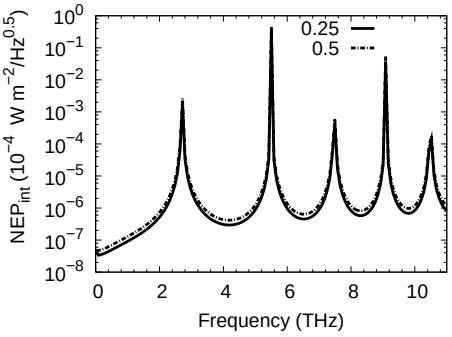

Figure 8: Intrinsic noise equivalent power NEP_{int} as a function of frequency evaluated for different voltage V_0. With $L = 400$ nm, $\nu = 3\times10^{12}$ s^{-1} and $n_0 = 8\times10^{17}$ cm^{-3}.

microwave voltage V applied between the diode terminals, described above in the section of Responsivity. For the firs calculations, the intrinsic Responsivity in equation (7) corresponds to the results of figur 5. Figure 7 presents the modificatio introduced to the intrinsic NEP by different fi ed values of the voltage V corresponding to $2V_0$, $\frac{3V_0}{2}$, V_0. In figur 7, the quality of the intrinsic NEP increases when the voltage V increase to $2V_0$. According to equation (7) the behavior of the intrinsic NEP is inversely proportional to the voltage V_0 dependence as discussed in figur 5.

Figure 8 shows the frequency-dependent of the intrinsic NEP to the microwave signal $V(t)$ for different V_0. The harmonics excitation applied to the diode appears as resonance peaks in the intrinsic NEP spectrum. Originally, resonances that appeared on the intrinsic NEP due to the responsivity behavior in figur 6. Indeed, increasing the voltage V_0 induces an increasing of NEP amplitude without shifts of the resonance frequencies. This fina discussion shows that the variation of the intrinsic noise equivalent power depends to the voltage drop on the diode terminals.

4.4 Extrinsic noise equivalent power

Let remark equation (8), the extrinsic NEP depends strongly to the parameters (length, thikness and relaxation rate) and the response of diode. According to the voltage spectral density approximation S_{vv} in equation (8), the extrinsic NEP reflect the diode behavior such as the impedance response. The extrinsic NEP schows in figure 9 for InGaAs channel diodes. The results reported for different lengths and relaxation rate values. The noise power spectrum exhibits a resonance peak near 10 THz corresponding to the high value of diode resistance (see figur 3). Moreover, the decrease of the diode length decrease the res-

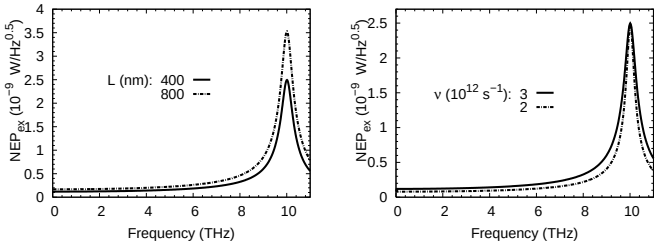

Figure 9: Extrinsic NEP as functions of the frequency for reported length L and relaxation rate ν. With δ =15 nm, $n_0 = 8{\times}10^{17}$ cm^{-3}.

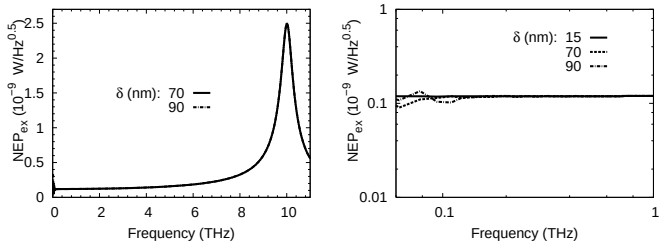

Figure 10: Extrinsic NEP as functions of the frequency for different thikness δ. With L =400 nm, ν =3$\times$10^{12} s^{-1} and $n_0 = 8{\times}10^{17}$ cm^{-3}.

onance quality of the extrinsic NEP amplitude, that is by the decrease of impedance real part (see figur 3). In low frequency, the extrinsic NEP decrease by the decreasing of the relaxation rate. This effect is due to the decrease of the temperature which decreases the voltage spectral density S_{vv} for a small perturbation associated to low frequency.

Figure 10 illustrates the frequency dependence of extrinsic NEP of InGaAs channel diode calculated by using Eq. (8), for the thikness 15, 70 and 90 nm. The diode thikness takes effect in low frequency according to figur 10 when the resonance peak appears near 10 THz for the nano-diode with length 400 nm and high electron concentration $8{\times}10^{17}$ cm^{-3}. Compred with figur 11, the appearence of the resonance peak is near 1.8 THz for the AlGaN micrometer diode with low electron concentration 10^{17} cm^{-3}. Therefore, the diode electron surface density effect is considered on the plasma frequency term ω_p when the electron concentration produces the correct behavoir of the diode in high frequency. In figur 10, the width δ =15 nm gives a constant NEP up to 1 THz when the high width value 90 nm increses the NEP in gigahert frequency. The surface ($L \times \delta$) introduces an increasing on the diode resistance ($Re[Z(\omega)]$) and leads to obtained a poorer high frequency behavior.

For figur 11, we use the analytical model for extrinsic NEP calculation of the AlGaN diode studied in Ref [2]. The analytical simulations in figur 11 is

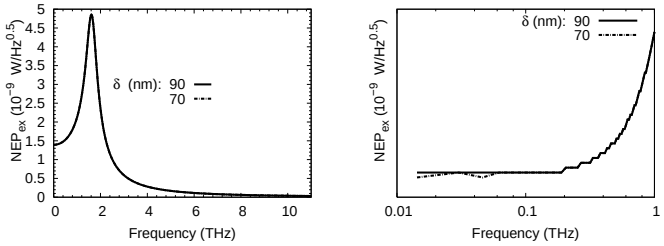

Figure 11: Extrinsic NEP of an AlGaN unipolar diode calculated for different thikness δ, with L = 1 μm, μ = 1200 cm^2/V.s, ν = 5$\times$10^{12} s^{-1} and $n_0 = 10^{17}$ cm^{-3}

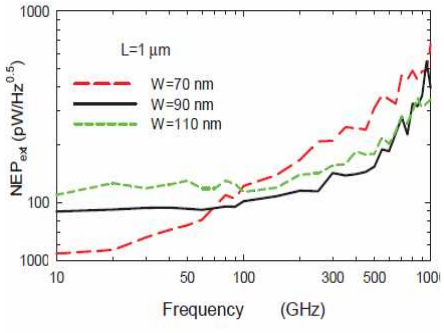

Figure 12: Extrinsic NEP by Mont Carlo calculations of 16 AlGaN nanochannel in parallel. The results are for different thikness δ with length is fi ed to 1 μm. The mobility μ = 1200 cm^2/V.s, ν = 5$\times$10^{12} s^{-1} and $n_0 = 10^{17}$ cm^{-3}

for the AlGaN unipolar diode with 1 μm length and 10^{17} cm^{-3} electron concentration.

It should be emphasized that the good agreement found between analytical and MCP results obtained in Ref. [2], in the gigahertz frequency range. Indeed, the figur 11 presents a resonance peak near 1.8 THz obtained by the micrometer diode with low electron concentration.

The following discussions can extract:

- The high electron mobility of semiconductor as InGaAs gives a high frequency response of detector compared to AlGaN semiconductor.
- The high electron concentration can increase the frequency resonance peak in the NEP since $\omega_p \propto \sqrt{n_0}$, which increases the frequency range of detectors.
- The diode geometry introduces an optimization of the noise equivalent power amplitude, since the diode surface (length and thikness) gives a significan increasing of the diode response (admittance modulus) and resistance ($Re[Z(\omega)]$).

- The contribution of the applied voltages is accounted for the intrinsic detector parameters: responsivity and the noise equivalent power where the microwave voltage leads to appear a suplimentary harmonics resonances.

5 Conclusion

An Extention of analytical calculations based on the transitor model with the condideration distance channel-gate tends to infinit , is useful in this article to determine the response and the noise equivalent power of the nanochannel diodes.

The calculation of the admittance elements can determine the complex impedance where thier real part presents the diode resistance. The impedance spectrum exhibits a peak near 10 THz corresponding to frequency plasma resonance. The diode response explains the behavior of terahertz detector, since the impedance factor is integrated in the voltage spectral density S_{vv}, the intrinsic Responsivity S_{int} and the noise equivalent power NEP expressions.

The discussion of the length and the relaxation rate effects on the diode response and the voltage noise leads to perform the diode geometry for a special frequency range detection. An increase of the diode length increases the extrinsic noise power NEP amplitude and keep the frequency resonance peak while the diode thikness effect takes place in the low frequency and introduces an increasing of the NEP_{ext}. The resistance of the diode ($Re[Z(\omega)]$) decreases when the relaxation rate increase and therefore increases the extrinsic NEP in gigahetz frequency. We let not that has no effect of the diode geometry and the relaxation rate on the resonance plasma frequency ω_p which depends only to the electron concentration.

The intrinsic Responsivity S_{int} and noise power NEP_{int} show a significan dependence on the applied voltage according to their analytical expression. The Responsivity spectrum exhibits a lorentzian form in low frequency and a resonance peak near 10 THz for a constant voltage condition applied between the diode terminals. A sinusoidal voltage applied to the diode introduces a suplimentary resonances due to the harmonic contribution of the signal and leads to obtain a series of peaks in the NEP_{int} pectrum. These peaks explain the frequencies detected by the nanochannel diodes.

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