Hydrodynamic study of terahertz three-dimensional plasma resonances in InGaAs diodes

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Abstract. We investigate the presence of plasma resonances in InGaAs diodes under different optical excitation conditions. In particular, we study the case of diodes submitted to an optical photoexcitation presenting a beating in the terahertz frequency domain. The responses of the diodes are calculated using a hydrodynamic approach coupled to a one-dimensional Poisson solver. The results show clearly the presence of three-dimensional plasma resonances in the terahertz frequency domain. We also show that the resonances frequency and amplitude can be tuned by modifying the diode geometry and doping profile.

1. Introduction
Recent experiments have shown the possibility to use field effect transistors (III-V and Si FETs) as devices able to emit and/or detect terahertz radiations [1, 2, 3]. In all cases, the physical mechanism at the basis of the terahertz working operation is a two-dimensional electron gas plasma wave excited in the transistor channel. On the other hand, the possibility to use three-dimensional plasma waves has received much less attention in the literature even if a terahertz radiations detector based on the excitation of 3D plasma in bulk GaAs was recently proposed [4].

By means of hydrodynamic equations coupled to a one-dimensional Poisson solver, we have performed a systematic study of InGaAs $n^+ - n - n^+$ diodes submitted to an optical photoexcitation presenting a beating in the terahertz frequency domain, according to the experimental technique detailed in [3].

The numerical analysis has been performed by calculating the instantaneous response of carrier velocity, concentration, electric field and current density. In particular, we have studied the effect of the diode geometry and doping profile on the resonance frequency and its amplitude.
2. Numerical model
We couple the one-dimensional hydrodynamic equations relative to the electron density $n(x, t)$, the mean velocity $v(x, t)$, and the mean energy $\epsilon(x, t)$, with the one-dimensional Poisson equation:

\[
\begin{align*}
\frac{\partial n_{3D}}{\partial t} &= \frac{\partial (n_{3D} v)}{\partial x} + G \\
\frac{\partial v}{\partial t} &= -v \frac{\partial v}{\partial x} - \frac{eE}{m(\epsilon)} - \frac{1}{n_{3D}} \frac{\partial (\delta v^2(\epsilon) n_{3D})}{\partial x} - \nu_v(\epsilon) \\
\frac{\partial \epsilon}{\partial t} &= -v \frac{\partial \epsilon}{\partial x} - eEv - \frac{1}{n_{3D}} \frac{\partial (\delta v \delta \epsilon(\epsilon) n_{3D})}{\partial x} - (\epsilon - \epsilon_{equ}) \nu_\epsilon(\epsilon) \\
\frac{\partial \epsilon}{\partial x} &= -e (n_{3D} - N_D)
\end{align*}
\]

where $e$ is the elementary charge, $E$ the electric field, $N_D$ the density of donors, $\epsilon$ the dielectric constant of InGaAs, and $\epsilon_{equ}$ the equilibrium mean energy. The velocity and energy relaxation rates $\nu_v$, $\nu_\epsilon$, the electron effective mass $m$, the velocity variance $\delta v^2$ and the energy-velocity covariance $\delta v \delta \epsilon$ depend on the local mean energy and are calculated by a Monte Carlo simulation of InGaAs bulk material at room temperature. A beating optical excitation can be included in the equations through the term $G = G_0[1 + \cos(2\pi ft)]$ [3].

3. Study of the plasma resonances in a $n^+ - n - n^+$ diode

3.1. Frequency responses in $n$ and $n^+$ regions of the diode
The calculation is made for $n^+ - n - n^+$ diodes submitted to a constant voltage of 0.5 V, and to an optical beating of amplitude $G_0 = 10^{26} \text{ cm}^{-3} \text{s}^{-1}$. We consider a $n^+ - n - n^+$ diode with $n = 10^{16} \text{ cm}^{-3}$ and $n^+ = 10^{17} \text{ cm}^{-3}$ and where the lengths of the different regions are identical, equal to 500 nm. We calculate, through a Fourier transform, the frequency response of the local electric field taken at the center of both $n$ and $n^+$ regions, in order to characterize the resonances. The modulus of the electric field response is represented in Figure 1 which shows that the responses in both $n$ and $n^+$ regions of the diode have a resonance at a frequency within the terahertz domain, that is at 3 and 3.6 THz respectively.

![Figure 1. Normalized modulus of the electric field response as a function of frequency calculated at the center of the $n^+$ and $n$ regions.](image-url)
3.2. Effect of the doping profile on 3D plasma resonance frequencies

The previous calculations are performed for different doping profiles, and the results are compared with the theoretical 3D plasma frequency relative to the corresponding concentration which verifies the theoretical expression [1]:

\[ f_{3D} = \frac{1}{2\pi} \sqrt{\frac{e^2 N_D}{m\varepsilon}} \] (2)

We report in Figure 2 the obtained results as functions of the n region electron density for \( n^+/n = 10 \) (a) and as functions of the \( n^+/n \) ratio for \( n = 10^{16} \) cm\(^{-3}\) (b). We observe in all the considered cases an excellent agreement between the calculated resonance frequencies for the region \( n^+ \) and the corresponding analytical 3D plasma frequencies. On the other hand, we observe a discrepancy of the hydrodynamic results for the resonance frequency and the 3D analytical model in the \( n \) region of the diode. In fact, the resonance of the diode corresponding to the concentration \( n \) is situated between the 3D plasma frequencies corresponding to the concentrations \( n \) and \( n^+ \), so that the resonance \( n \) of the diode is shifted towards the 3D plasma resonance corresponding to the concentration \( n^+ \). This result shows that the main 3D plasma resonance of the diode is that corresponding to the concentration \( n^+ \).

![Figure 2](image_url)

**Figure 2.** Resonance frequencies of the electric field response to an optical beating excitation calculated in the middle of the \( n \) and \( n^+ \) regions of a \( n^+ - n - n^+ \) diode, as functions of \( n \) for \( n^+/n = 10 \) (a) and as functions of the \( n^+/n \) ratio for \( n = 10^{16} \) cm\(^{-3}\) (b). Symbols refer to the hydrodynamic calculations and lines to the analytical formula (2).

3.3. Effect of the diode geometry on 3D plasma resonance frequencies

We have calculated the resonance frequencies for different values of the regions lengths, in order to evaluate the effect of the diode geometry. We have fixed the doping concentrations to \( n = 10^{16} \) cm\(^{-3}\) and \( n^+/n = 10 \). Results are shown in Figure 3 as functions of the internal \( n \) region length by fixing the \( n^+ \) regions length to 500 nm (a) and as functions of the external \( n^+ \) regions length for \( n \) region length fixed to 500 nm (b). The results show that, while the effect of the variation of the external regions length is negligible, the increase of the internal region length is crucial to put in evidence the 3D plasma frequency corresponding to the concentration \( n \). Indeed, the resonance frequency and amplitude decrease if the length of the internal region increases. In fact, by increasing the length of the \( n \) region, the influence of the \( n^+ \) access region on the dynamic behavior of the internal region decreases. As a result, the resonance frequency calculated in the middle of the \( n \) region of the diode decreases and tends more and more towards the 3D plasma resonance frequency corresponding to the concentration \( n \). In particular, when the internal
region length becomes greater than 2000 nm, the resonance frequency in the region \( n \) tends to 1.1 THz which is rigorously close to the 3D plasma resonance frequency corresponding to the concentration \( n = 10^{16} \text{ cm}^{-3} \) (Figure 3). Then, the resonance frequency corresponding to the concentration \( n \) in the diode \( n^+ - n - n^+ \) is evidenced when the length of the internal \( n \) region is greater than 2000 nm. On the other hand, we observe that the resonance frequency corresponding to the concentration \( n^+ \) is evidenced in all cases. Indeed, whatever the lengths of the diode regions, the resonance frequency of the external \( n^+ \) regions tends to 3.6 THz, that is to the 3D theoretical plasma frequency for the considered doping concentrations (see Figure 3).

![Figure 3](image)

**Figure 3.** Resonance frequency and amplitude in \( n \) and \( n^+ \) regions of the diode as functions of the internal (a) and external (b) region length of the diode.

4. Conclusion
We have performed a numerical investigation of the plasma resonances in InGaAs \( n^+ - n - n^+ \) diodes. We have calculated the frequency and amplitude of the resonance peaks as functions of the doping and the geometry of the devices. In all the considered cases, the presence in the doped access regions of a resonance at the usual 3D plasma frequency of a \( n^+ \)-doped semiconductor has been shown. In the internal \( n \) region, we evidenced another resonance whose frequency is shifted from the \( n \) 3D plasma frequency toward the \( n^+ \) frequency. We showed that this shift towards the \( n^+ \) frequency is reduced and even suppressed for long \( n \) regions. Anyway, the results show clearly that the resonances associated with three-dimensional plasma open new possibilities to exploit not only field effect transistors but also diodes in the field of solid-state terahertz devices operating at room-temperature.

**References**

[1] Knap W, Lusakowski J, Parenty T, Bollaert S, Coppy A, Popov V V and Shur M S 2005 *J. Appl. Phys.* **97** 64307

[2] El Fatimy A, Teppe F, Dyakonova N, Knap W, Seluuta D, Valuis G, Shchepestov A, Roelens Y, Bollaert S, Coppy A and Runyantsev S 2006 *Appl. Phys. Lett.* **89** 131926

[3] Torres J, Marinchio H, Nouvel P, Sabatini G, Palermo C, Varani L, Chusseau L, Shiktorov P, Starikov E and Gruzinskis V 2008 *IEEE J. Sel. Topics Quantum Electron* **14** 491

[4] Kim S, Zimmerman J, Focardi P, Gossard A, Wu D and Sherwin W 2008 *Appl. Phys. Lett.* **92** 253508