Analysis and Optimization of PIN photodetectors for optical communication
Claúdio Miguel Caramona Fernandes

Abstract — The analysis and optimization of photodetectors and their topologies are essential in optical communications. A photodetector is mainly characterized by its bandwidth, quantum yield and noise. In this study the main emphasis will be given to the bandwidth and the quantum yield of a PIN photodetector. All these features are determined by materials and structures used. The determination of the bandwidth is based on a relatively simple, yet very general method, which can be applied to multi-layer structures in situations of non-uniform illumination and an arbitrary electric field profile in the absorption region. After a detailed analysis of the frequency response in a conventional PIN structure, the frequency response will be investigated for a PIN photodiode with drift region. The results suggest that the introduction of the drift region improves the frequency response of the device.

I. INTRODUCTION

Photodetectors are devices that, under the action of electromagnetic radiation, may change their electrical properties, e.g., the value of their resistance or the current / voltage in an external circuit. The importance of fiber optic communications and the need to achieve higher transmission rates are responsible for the effort made in researching and studying new materials and structures for the photodetectors. The performance of photodetectors is primarily determined in terms of its frequency response, sensitivity and noise [1]. One of the photodetectors, which ensures appropriate values for these parameters, is the PIN photodiode. The PIN structure, which consists of an "I" region lightly doped, between the P and N regions, has advantages over the PN junction and is the basis of more complex photodiode structures used in fiber optic telecommunications.

In fiber optic communications the wavelengths are 1 μm < λ < 1.6 μm and the most appropriate materials for these wavelengths consist in the system InP/In0.53Ga0.47As in which the ternary is used in the intrinsic absorption region and the binary is used in the P and N regions. This structure ensures that the light is absorbed entirely in the intrinsic region "I" since the band gap height of the binary InP is larger than that for the ternary In0.53Ga0.47As [2,3].

In optical communications photodiodes are used to detect the information therefore it is important to characterize and optimize its frequency response since it is associated with the transmission rate. In order to be able to simulate the device’s bandwidth it will be used a methodology that consists in the decomposition of the device in several layers and solves the equations of continuity for each one of them. Thus it is possible to simulate the frequency response of the photodiode even when the electric field is not uniform in the absorption region.

The photodiodes have an associated capacitance which affects their frequency response. It is important to understand the way the capacitance contributes to the system’s response and therefore its effect is included in the model.

II. TERMINOLOGY USED IN OPTICAL DETECTION

In photodiodes when the light is absorbed the electrons may transit from a lower energy level to a higher energy level. These electrons are then detected in an external circuit before returning to their initial energy state. For each semiconductor, the absorption of light is characterized by the absorption coefficient. The absorption coefficient is related to the loss of intensity of the optical beam as it propagates within a given material. In general, high values of the absorption coefficient are desirable. However, a very high absorption coefficient causes the light to be absorbed close to the semiconductor surface, where the recombination rates are high.

An important parameter for measuring the performance of photodetectors is the quantum yield. The quantum yield is defined as the ratio between the number of generated electrons and the number of incident photons (not considering the photogain) [4].

\[ \eta = (1 - r) \eta_i \times (1 - e^{-\alpha l}) \]  

(1)

r is the reflectivity associated with the interface semiconductor-air, \( \eta_i \) is the internal quantum yield, \( \alpha \) is the absorption coefficient and \( l_d \) is the length of the absorption region of the photodiode. In direct band semiconductors the internal quantum yield is practically 1. The frequency response is the most important characteristic of a photodetector. It is analyzed in terms of its 3dB cutoff frequency. The cutoff frequency is the frequency for which the detected electrical power output is reduced to half of its value for low frequencies. The frequency response depends mainly on the carriers’ transit time in the absorption region and on the capacitance introduced by the device and the external circuit.
III. MODELING THE FREQUENCY RESPONSE

The structure of the PIN photodiode under investigation is shown in Figure 1 [2,5]. The radiation may be incident on the N or P side. The device must be reverse biased so that the absorption region is depleted. Thus, one can neglect the recombination of electron-hole pairs. The electron-hole pairs generated by the illumination are separated by the electric field and may cause an electric current in the external circuit.

![Photodiode PIN structure.](image)

Figure 1 – Photodiode PIN structure.

A. Transit time effects

The frequency response of these devices can be obtained by combining the coefficients derived from a matrix formulation, as a result of the analytical solution of the continuity equations. However, it is necessary that the electric field is constant, i.e., in the absorption region the carriers’ velocity is constant. Therefore the absorption region will be divided in several layers, each layer with a constant electric field [4]. Thus, it is possible to obtain analytical solutions for each of these layers by combining the coefficients of every layer it is possible to calculate the frequency response of the photodiode. The accuracy of the results is dependent on the number and size of the layers.

The continuity equations can be written in the frequency domain as [2,4,5]:

\[
\begin{align*}
\frac{i_0}{v_{in}} J_{in}(x, \omega) &= \frac{d}{dx} J_{in}(x, \omega) + G_i(x, \omega) \\
\frac{i_0}{v_{ip}} J_{ip}(x, \omega) &= -\frac{d}{dx} J_{ip}(x, \omega) + G_i(x, \omega)
\end{align*}
\]  

(2)

\( J_{in}(\omega) \) and \( J_{ip}(\omega) \) are the electron and hole current densities respectively, \( v_{in} \) and \( v_{ip} \) are the electron and hole drift respectively and \( G_i(x, \omega) \) refers to the generation rate of electron-hole pairs due to optical absorption in layer \( i \).

The electron-hole pairs generation rate depends on the direction of the incident radiation [5]:

\[
\begin{align*}
G_i(x, \omega) &= q \alpha \phi_1 e^{-ax}, \quad (x_{i-1} \leq x \leq x_i) \\
G_i(x, \omega) &= q \alpha \phi_1 e^{-a(l_a-x)}, \quad (x_{i-1} \leq x \leq x_i)
\end{align*}
\]  

(3)

\( \alpha \) is the absorption coefficient, \( q \) is the magnitude of electron charge and \( \phi_1 \) is the amplitude of the sinusoidal component of the incident radiation flux.

Assuming that the velocity of the carriers in each layer is constant one can write the relation between input and output currents in a given layer as [2]:

\[
\tilde{J}(x, \omega) = T_i \tilde{J}(x_{i-1}, \omega) + \tilde{S}_i
\]

(4)

\( T_i \) is the transfer current matrix and \( \tilde{S}_i \) is a column vector containing the effects associated with light absorption. If the incidence of the light is on the N side of the photodiode, the coefficients are the following [5]:

\[
\begin{align*}
T_i &= \begin{bmatrix} e^{-i\alpha \tau_{ip}} & 0 \\ 0 & e^{i\alpha \tau_{in}} \end{bmatrix} \\
\tilde{S}_i &= q \alpha \phi_1 l_i e^{-a \tau_{ip}} \begin{bmatrix} f(i\omega \tau_{ip} - \alpha l_i) \\ -f(-i\omega \tau_{in} - \alpha l_i) \end{bmatrix}
\end{align*}
\]

(5)

\[
\begin{align*}
\tau_{ip} &= l_i / v_{ip} \\
\tau_{in} &= l_i / v_{in} \\
f(\theta) &= (1 - e^{-\theta}) / \theta
\end{align*}
\]

(6)

Thus, the current density is defined as:

\[
p_i(\omega) = \int [J_{in}(x, \omega) + J_{ip}(x, \omega)] dx
\]

(7)

The coefficients \( \tilde{R}_i \) and \( D_i \) are obtained from:

\[
p_i(\omega) = \tilde{R}_i^* \tilde{J}(x_{i-1}, \omega) + D_i
\]

(8)

\( D_i \) is a scalar that contains the contributions of the optical sources.

\[
\begin{align*}
\tilde{R}_i &= l_i \begin{bmatrix} f(i\omega \tau_{ip}) \\ f(-i\omega \tau_{in}) \end{bmatrix} \\
D_i &= q \alpha \phi_1 l_i^2 e^{-a(l_a-x)} \begin{bmatrix} f(\alpha l_i) - f(-i\omega \tau_{in}) \\ \alpha l_i + i\omega \tau_{in} \\
\alpha l_i - f(i\omega \tau_{ip}) \\ \alpha l_i - i\omega \tau_{in} \end{bmatrix}
\end{align*}
\]

(9)

If the incident light is on the P side of the photodiode the coefficients are given by [2,5]:

\[
\begin{align*}
T_i &= \begin{bmatrix} e^{-i\alpha \tau_{ip}} & 0 \\ 0 & e^{i\alpha \tau_{in}} \end{bmatrix} \\
\tilde{S}_i &= q \alpha \phi_1 l_i e^{-a(l_a-x)} \begin{bmatrix} f(i\omega \tau_{ip} + \alpha l_i) \\ -f(-i\omega \tau_{in} + \alpha l_i) \end{bmatrix} \\
\tilde{R}_i &= l_i \begin{bmatrix} f(i\omega \tau_{ip}) \\ f(-i\omega \tau_{in}) \end{bmatrix} \\
D_i &= q \alpha \phi_1 l_i^2 e^{-a(l_a-x)} \begin{bmatrix} f(-\alpha l_i) - f(-i\omega \tau_{in}) \\ -\alpha l_i + i\omega \tau_{in} \\
f(-\alpha l_i) - f(i\omega \tau_{ip}) \\ \alpha l_i + i\omega \tau_{in} \end{bmatrix}
\end{align*}
\]

(10)

These four coefficients characterize a given layer of the absorption region. To obtain the coefficients for the whole region the following relations will be used [2,5,6]:
\[ T_{i+1,l} = T_{i+1}T_l \\
S_{i+1,l} = S_{i+1} + T_{i+1}S_l \\
\bar{R}_{i+1,l} = \bar{R}_{i+1}T_l + \bar{R}_l \\
D_{i+1,l} = \bar{R}_{i+1}^T S_l + D_{i+1} + D_l \] (11)

The indices \((i), (i+1)\) represent adjacent layers and \((i, l)\) their respective union. Once you know the four coefficients for the absorption region it is possible to determine the frequency response of the device:

\[
\begin{align*}
J(\omega) &= \delta(\omega)/I_a \\
\delta(\omega) &= D - R_nS_n/T_{nn}
\end{align*}
\] (12)

\(R_n, S_n\) refer to the element (2,1) of the coefficients \(R\) and \(S\) and \(T_{nn}\) refers to the element (2,2) of the coefficient \(T\).

The drift velocity depends on the electric field [2,5,7,8] and can be expressed by:

\[
\begin{align*}
v_n(E) &= \mu_n E + \beta v_{sat} E^\gamma \\
v_p(E) &= v_{pl} \tanh \left( \frac{\mu_p E}{v_{pl}} \right)
\end{align*}
\] (13)

\(\mu_n\) and \(\mu_p\) are the electron and hole mobilities respectively, \(v_{sat}\) and \(v_{pl}\) are the electron and hole saturation velocities respectively, \(\beta = 7.4 \times 10^{-15} (m/V)^{2.5}\) and \(\gamma = 2.5\).

The bias voltage affects the electric field [2,5,7,8]:

\[ E(x) = \frac{2U_d}{l_a x} + \frac{U - U_d}{l_a} \] (14)

\(U\) is the bias voltage and \(U_d\) is the minimum voltage that guarantees that the absorption region is depleted:

\[ U_d = \frac{qNL^2}{2\varepsilon_n} \] (15)

\(N\) is the impurity density and \(\varepsilon_n\) is the electric permittivity of InGaAs.

\section*{B. Capacitive Effects}

In addition to the carriers’ transit time in the absorption region, the capacitive effects must also be included, which as we will see, can be very important especially, when the devices are short.

The transit time of a device is directly proportional to the thickness and inversely proportional to the carriers’ drift velocity \(v\) [9]:

\[ \tau_{TR} = \frac{l_a}{v} \] (16)

The time constant associated with the capacitance of a PIN photodiode is proportional to area \(A\), to the electric permittivity \(\varepsilon_n\) and to the load resistance \(R_L\) and inversely proportional to the thickness [9]:

\[ \tau_{RC} = \frac{\varepsilon_n A R_L}{l_a} \] (17)

Thus, it appears that for shorter devices, the carriers’ transit time decrease and consequently, the frequency response will be better. However, shorter devices have larger capacitance, which leads to a deterioration in the frequency response.

The frequency response of the device can be obtained in the frequency domain by performing the product between the frequency response due to transit time and the frequency response associated with capacitive effects [9,10]. The transfer function associated with the capacitive effects can be expressed in its simplest form as:

\[
\begin{align*}
H_{RC} &= \frac{1}{1 + j\omega R_L C} \\
C &= C_{parasitic} + C_{absorption} \\
C_{absorption} &= \frac{\varepsilon_n A}{l_a}
\end{align*}
\] (18)

The transfer function (17) does not consider the internal resistance of the PIN device \(R_S\) associated with the absorption region which can be obtained by:

\[ R_S = \frac{l_a}{qN\mu_n A} \] (19)

The equivalent circuit of the PIN photodiode including the series resistance \(R_S\) and leakage resistance \(R_d\) is shown in Figure 2:

\[ \text{Figure 2 – Equivalent model circuit of the PIN photodiode considering the internal resistance.} \]

The transfer function associated with the capacitive effects not including the leakage current is [11]:

\[ H_{RC} = \frac{1}{-\omega^2 R_L R_S C_p C_J + j\omega (C_J (R_L + R_S) + R_L C_p) + 1} \] (20)

\section*{C. PIN structure with drift region}

In order to minimize the tradeoff between the transit time and the capacitance associated with the device one may use different materials or another type of structure.

In Figure 3, it is shown a PIN structure with an InP drift region in contact with the absorption region InGaAs [6,9]:

\[ \text{Figure 3 – PIN structure with an InP drift region.} \]
The structure of the photodiode with the drift region is based on a PIN structure. This structure should provide a better frequency response than the basic PIN structure because the capacitance is smaller. In the drift region, carriers’ saturation velocity is high and there is no light absorption. Since this structure is just an evolution of the basic PIN structure, the numerical model implemented is also applied to the PIN photodiode with drift region.

In the PIN photodiode with drift region, the drift region can be placed next to the N or P side. For each case the direction of the incident light affects the carriers as shown in Figures 4-7.

Considering the capacitance, the transfer function associated with the capacitive effects for the PIN photodiode with drift region is given by (18).

\[
C = C_{\text{absorption}} + C_{\text{drift}} + C_{\text{parasite}}
\]

(21)

The influence of the capacitance in these structures is identical to the conventional PIN photodiode, and it is given by:

\[
C_{\text{drift}} = \frac{\varepsilon_n A}{l_d}
\]

\[
C_{\text{absorption}} = \frac{\varepsilon_n A}{l_g}
\]

Considering the capacitance (21), the transfer function associated with the capacitive effects for the PIN photodiode with drift region is given by (18).

### IV. PIN PHOTODIODE - SIMULATION AND ANALYSIS

The following simulations will use the parameters in TABLE 1.

The electric field varies spatially along the absorption region, therefore the carriers’ velocity varies as well. Figure 8 shows the carriers’ drift velocities in the In_{0.53}Ga_{0.47}As at 300K as a function of electric field.

<table>
<thead>
<tr>
<th>Parameters (T = 300K)</th>
<th>Units</th>
<th>In_{0.53}Ga_{0.47}As [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption Coefficient ((\alpha)) ((d = 1.3 , \mu m))</td>
<td>(m^{-1})</td>
<td>(1.15 \times 10^6)</td>
</tr>
<tr>
<td>Electron saturation velocity ((v_{ei}))</td>
<td>(m/s)</td>
<td>(6 \times 10^4)</td>
</tr>
<tr>
<td>Hole saturation velocity ((v_{pi}))</td>
<td>(m/s)</td>
<td>(4.8 \times 10^4)</td>
</tr>
<tr>
<td>Electron mobility ((\mu_e))</td>
<td>(m^2/V\cdot s)</td>
<td>1.05</td>
</tr>
<tr>
<td>Hole mobility ((\mu_h))</td>
<td>(m^2/V\cdot s)</td>
<td>0.042</td>
</tr>
<tr>
<td>Electric permittivity ((\varepsilon_n))</td>
<td>(F/m)</td>
<td>(14.1 \varepsilon_0)</td>
</tr>
</tbody>
</table>
In the following simulations the absorption region is divided into 10 layers and in each one, the electric field is constant and equals the value at the midpoint of the layer. All the simulations take into account a variable electric field and the capacitive effects. Since the side of the incident light is not a parameter that influences the capacitive effects, when not mentioned in the figures it is assumed that the light is incident on the P side. The capacitive effects may be important and responsible for the fall of the bandwidth of very short devices.

A. Influence of the absorption region width

The simulation assumed a bias voltage: \( U = 11V \), an impurity density: \( N = 10^{21} m^{-3} \), a load resistance: \( R = 60 \Omega \), a diameter of the device: \( d = 25 \mu m \) and a parasitic capacitance: \( C_{\text{parasitic}} = 0.02 pF \).

Analyzing Figure 9, it appears that the capacitive effects may be neglected only for devices with incident radiation on the N side when their length is greater than 3 \( \mu m \). For incident radiation on the P side the capacitive effects do not seem to affect the frequency response for devices longer than 4 \( \mu m \). Table 2 shows the length values which maximize the bandwidth of the device when the radiation is incident on the N or P sides.

<table>
<thead>
<tr>
<th>Incident radiation</th>
<th>Length (( \mu m ))</th>
<th>Maximum bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N side</td>
<td>0.85</td>
<td>20.59</td>
</tr>
<tr>
<td>P side</td>
<td>0.9</td>
<td>21.52</td>
</tr>
</tbody>
</table>

B. Influence of the area

The bandwidth of PIN photodiodes as a function of the length considering several device areas was investigated. In these simulations we used the values given in subsection A.

Analyzing Figure 10, it appears that the capacitive effects may be neglected only for devices with incident radiation on the N side when their length is greater than 3 \( \mu m \). For incident radiation on the P side the capacitive effects do not seem to affect the frequency response for devices longer than 4 \( \mu m \). Table 3 shows the length that maximizes the device’s bandwidth for each of the diameters under investigation.

<table>
<thead>
<tr>
<th>Diameter (( \mu m ))</th>
<th>Length (( \mu m ))</th>
<th>Maximum bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0.55</td>
<td>32.67</td>
</tr>
<tr>
<td>25</td>
<td>0.9</td>
<td>21.52</td>
</tr>
<tr>
<td>35</td>
<td>1.3</td>
<td>16.18</td>
</tr>
</tbody>
</table>

C. Influence of the series resistance

Let’s now study the influence of the series resistance on the bandwidth of PIN photodiodes. The values used are the same as those given in subsection A.
Figure 11 – Bandwidth as function of the length of the PIN photodiode considering the 1st and 2nd order capacitive effects.

Figure 11 shows that with the inclusion of the series resistance (19), the transfer function associated with the capacitive effects, is a 2nd order function (20), and is responsible for a decrease of the bandwidth.

TABLE 4

Length of the PIN photodiode which maximizes the bandwidth when considering the influence the 1st and 2nd order capacitive effects.

<table>
<thead>
<tr>
<th>Capacitive effects</th>
<th>Length (µm)</th>
<th>Maximum bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1º ordem</td>
<td>0.9</td>
<td>21.52</td>
</tr>
<tr>
<td>2º ordem</td>
<td>0.95</td>
<td>20.26</td>
</tr>
</tbody>
</table>

The calculation of the series resistance is dependent on the length of the device (19), which does not include the resistance associated with InP regions. Figure 12 shows the response of the system when considering several values of the series resistance.

Figure 12 – Simulation of the bandwidth as a function of the length of the PIN photodiode when several values of series resistance are considered.

Figure 12 shows that if the value of the series resistance increases, the influence of capacitive effects on the response of the system also increases, Table 5.

TABLE 5

Length of the PIN photodiode which maximizes the bandwidth when several values of series resistance are considered.

<table>
<thead>
<tr>
<th>Series resistance (Ω)</th>
<th>Length (µm)</th>
<th>Maximum bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.9</td>
<td>21.52</td>
</tr>
<tr>
<td>25</td>
<td>1.1</td>
<td>19.06</td>
</tr>
<tr>
<td>50</td>
<td>1.25</td>
<td>17.27</td>
</tr>
<tr>
<td>75</td>
<td>1.35</td>
<td>15.91</td>
</tr>
<tr>
<td>100</td>
<td>1.5</td>
<td>14.84</td>
</tr>
</tbody>
</table>

V. PIN PHOTODIODE WITH DRIFT REGION – SIMULATION AND ANALYSIS

It is intended to investigate if the frequency response of a PIN photodiode with drift region is better than that obtained for a conventional PIN photodiode. Since the objective of these simulations is to compare the two photodiode topologies, the simulations will only take into account the most relevant parameters, such as the absorption and drift region lengths. The following simulations will use the parameters in Table 6.

TABLE 6

Parameters used in the simulation of the frequency response of a PIN photodiode with drift region.

<table>
<thead>
<tr>
<th>Parameters (T = 300K)</th>
<th>Units</th>
<th>InGaAs [2]</th>
<th>InP [12,13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption Coefficient (α)</td>
<td>m⁻¹</td>
<td>1.15 × 10⁶</td>
<td>—</td>
</tr>
<tr>
<td>(λ = 1.3 µm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron saturation velocity (vₑ)</td>
<td>m/s</td>
<td>6 × 10⁴</td>
<td>8.11 × 10⁴</td>
</tr>
<tr>
<td>Hole saturation velocity (vₒ)</td>
<td>m/s</td>
<td>4.8 × 10⁴</td>
<td>8.11 × 10⁴</td>
</tr>
<tr>
<td>Electron mobility (µₑ)</td>
<td>m²V⁻¹s⁻¹</td>
<td>1.05</td>
<td>—</td>
</tr>
<tr>
<td>Hole mobility (µₒ)</td>
<td>m²V⁻¹s⁻¹</td>
<td>0.042</td>
<td>—</td>
</tr>
<tr>
<td>Electric permittivity (εₑ)</td>
<td>F/m</td>
<td>14.1ε₀</td>
<td>12.56ε₀</td>
</tr>
</tbody>
</table>

In the drift region there is no light absorption, however, the carriers’ saturation velocity is higher than that in the absorption region. Therefore, there is a relationship between the lengths of the two regions that maximizes the frequency response of the device.

For a given photodiode total length, it is important to determine what is the percentage of the absorption region length and the percentage of the drift region length that maximize its bandwidth.
A. Drift region in the N side

The bandwidth simulation as function of the length of the drift and absorption regions will consider a photodiode 2$\mu$m long. The model first assumes a constant electric field and no capacitive effects. The results are presented in Figure 13.

Figure 13 shows that the maximum bandwidth of a 2$\mu$m photodiode with the drift region on the N side, will be obtained when the light is incident on the N side. Looking at Figure 6 and Figure 7 it is clear that the response of the device will always be slower when the light is incident on the P side because the electrons will have to cross both the absorption and the drift regions. When the light is incident on the N side, the response of the device is either conditioned by the time taken by the electrons to cross the drift region or by the time taken by the holes to cross the absorption region.

Table 7 shows the length of the absorption and drift regions of a PIN photodiode with drift region in the N side that maximizes the bandwidth.

<table>
<thead>
<tr>
<th>2 $\mu$m PIN photodiode with drift region in the N side</th>
<th>$l_a$ ((\mu)m)</th>
<th>$l_d$ ((\mu)m)</th>
<th>$B$ (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident light on N side</td>
<td>1</td>
<td>1</td>
<td>20.82</td>
</tr>
<tr>
<td>Incident light on P side</td>
<td>0.64</td>
<td>1.36</td>
<td>18.35</td>
</tr>
</tbody>
</table>

Table 7 shows the length of the absorption and drift regions of a PIN photodiode with drift region in the N side that maximizes the bandwidth.

A 2$\mu$m PIN photodiode will always have better bandwidth results when considering the topology of a photodiode with the drift region in the N side instead of the conventional PIN photodiode, regardless of the side where the radiation is incident.

In the following simulations a more complete photodiode model will be used. This model takes into account a variable electric field in the absorption region and the capacitive effects. In the drift region it will still be used the carriers’ saturation velocity.

Let’s now investigate from all possible lengths of PIN photodiodes with drift region in the N side which length maximizes their bandwidth. The simulation carried out considers a length variation of 0.2$\mu$m to 4$\mu$m, the absorption region voltage: $U_{\text{absorption region}} = 11V$, a device with impurity density: $N = 10^{22} m^{-3}$, a load resistance: $R = 60 \Omega$, the diameter of the device: $d = 25 \mu m$ and a parasitic capacitance: $C_{\text{parasitic}} = 0.02 \mu F$. The results are presented in Figure 14 and Figure 15.

Figure 14 and Figure 15 show that for devices above 2.75$\mu$m long and also light incident on the P side the capacitive effects are negligible and since the carriers’ drift velocity in the absorption region is faster than the carriers’ drift velocity in the drift region, in order to maximize the bandwidth the device should not have a drift region.

It is possible with these data to determine the absorption and drift regions length that maximize the bandwidth for a given length of the device. Table 8 shows the maximum possible bandwidth of a PIN photodiode with the drift region in the N side along with the total length, and the absorption and drift regions length.
Analyzing the Figure 16 and Figure 17 and comparing them with Table 8, it appears that the results are consistent. The maximum bandwidth is indicated in both figures.

Table 9 shows the length that maximizes the bandwidth for photodiodes with drift region in the N side for several values of the bias voltage and impurity densities.

The results in Table 9 show that the maximum bandwidth is always greater when the light is incidence on the N side than when the light is incidence on the P side no matter what are the values of the bias voltage or the density of impurities. It also appears that with increasing bias voltage, the maximum bandwidth decreases regardless of the side on which the light is incident.

**B. Drift region in the P side**

The simulations from the previous section were repeated under the same conditions but this time considering the drift region in the P side, Figure 18 and Figure 19.

### Table 8

<table>
<thead>
<tr>
<th>Incident radiation</th>
<th>Total length (µm)</th>
<th>l_a (µm)</th>
<th>l_d (µm)</th>
<th>B (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N side</td>
<td>1</td>
<td>0.42</td>
<td>0.58</td>
<td>24.96</td>
</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.247</td>
<td>0.703</td>
<td>24.42</td>
</tr>
</tbody>
</table>

One can still trace the contours of constant bandwidth for PIN photodiodes with drift region in the N side. Each contour line delimits the area where the bandwidth remains above a certain value, as shown in Figure 16 and Figure 17. Between each contour there is a 2 GHz bandwidth difference and the inner contour is assigned 24 GHz.

![Figure 16](image)

**Figure 16** – Contours of the PIN Photodiode with drift region in the N side, with the incident radiation on the N side, considering the capacitive effects and a variable electric field.

![Figure 17](image)

**Figure 17** – Contours of the PIN Photodiode with drift region in the N side, with the incident radiation on the P side, considering the capacitive effects and a variable electric field.

Analyzing the Figure 16 and Figure 17 and comparing them with Table 8, it appears that the results are consistent. The maximum bandwidth is indicated in both figures.

### Table 9

<table>
<thead>
<tr>
<th>N (m^{-3})</th>
<th>U_{la} (V)</th>
<th>Incident radiation</th>
<th>Total length (µm)</th>
<th>l_a (µm)</th>
<th>l_d (µm)</th>
<th>B (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.10</td>
<td>N side</td>
<td>0.561</td>
<td>0.539</td>
<td>25.71</td>
<td></td>
</tr>
<tr>
<td>P side</td>
<td>1.00</td>
<td>0.520</td>
<td>0.480</td>
<td>24.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
<td>N side</td>
<td>0.525</td>
<td>0.525</td>
<td>25.41</td>
<td></td>
</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.409</td>
<td>0.541</td>
<td>24.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.05</td>
<td>N side</td>
<td>0.494</td>
<td>0.556</td>
<td>25.23</td>
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</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.361</td>
<td>0.589</td>
<td>24.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.00</td>
<td>N side</td>
<td>0.420</td>
<td>0.580</td>
<td>24.96</td>
<td></td>
</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.257</td>
<td>0.693</td>
<td>24.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.00</td>
<td>N side</td>
<td>0.420</td>
<td>0.580</td>
<td>24.93</td>
<td></td>
</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.276</td>
<td>0.674</td>
<td>24.42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.00</td>
<td>N side</td>
<td>0.410</td>
<td>0.590</td>
<td>24.90</td>
<td></td>
</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.219</td>
<td>0.731</td>
<td>24.39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 18](image)

**Figure 18** – Maximum bandwidth simulation as function of the length of a PIN photodiode with drift region in the P side considering the capacitive effects and the variable electric field.
Figure 19 – Graph showing the percentage of the absorption region that maximizes the bandwidth for each length of the PIN photodiode with the drift region on P side considering the capacitive effects and variable electric field model.

When the light is incident on the N side, in order to maximize the bandwidth the drift region must be bigger than the absorption region of the device since the holes’ drift velocity in the absorption region is lower than their saturation velocity in the drift region. However for light incident on the P side, in order to maximize the bandwidth it is necessary that the absorption region is bigger than the drift region since the electrons’ drift velocity in the absorption region is higher than their saturation velocity in the drift region if the length of the device is bigger than \( \frac{1}{G_372/G_1e4/G_372/G_749} \)

It is possible, with these data, to determine the absorption and drift region lengths that maximize the bandwidth for a given length of the device. Table 10 shows the maximum possible bandwidth of a PIN photodiode with the drift region in the P side and also the total length and the absorption and drift region lengths.

**TABLE 10**

<table>
<thead>
<tr>
<th>Incident radiation</th>
<th>Total length (( \mu m ))</th>
<th>( l_a ) (( \mu m ))</th>
<th>( l_d ) (( \mu m ))</th>
<th>B (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N side</td>
<td>0.9</td>
<td>0.009</td>
<td>0.891</td>
<td>24.33</td>
</tr>
<tr>
<td>P side</td>
<td>0.9</td>
<td>0.009</td>
<td>0.891</td>
<td>24.33</td>
</tr>
</tbody>
</table>

In order to maximize the bandwidth of the device it is necessary to minimize the length of the absorption region. Due to the fact that in the drift region the carriers’ saturation velocity is used the results for the maximum bandwidth are independent of the direction of the incident light.

One can still trace the contours of constant bandwidth for PIN photodiodes with drift region in the P side. Each contour line delimits an area where the bandwidth remains above a certain value, as shown in Figure 20 and Figure 21. Between each contour there is a 2 GHz bandwidth difference and the inner contour is assigned 24 GHz.

Figure 20 – Contours of the PIN Photodiode with drift region in the P side, with the incident radiation on the N side, considering the capacitive effects and variable electric field.

Figure 21 – Contours of the PIN Photodiode with drift region in the P side, with the incident radiation on the P side, considering the capacitive effects and variable electric field.

Analyzing both the Figure 20 and Figure 21 and comparing them with Table 10, it appears that the results are consistent. The maximum bandwidth is indicated in the figures.

Table 10 shows that the absorption region length that maximizes the bandwidth is only \( \frac{1}{G_372/G_1e4/G_372/G_749} \) no matter what is the direction of the incident light. This causes the quantum yield to be very small. For this reason, let’s see what happens to the bandwidth of the PIN photodiode with the drift region in the P side when it is used the optimal configuration of the PIN photodiode with drift region in the N side, Table 8. The results can be seen in Table 11.

**TABLE 11**

<table>
<thead>
<tr>
<th>Incident radiation</th>
<th>Total length (( \mu m ))</th>
<th>( l_a ) (( \mu m ))</th>
<th>( l_d ) (( \mu m ))</th>
<th>B (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N side</td>
<td>1</td>
<td>0.42</td>
<td>0.58</td>
<td>22.66</td>
</tr>
<tr>
<td>P side</td>
<td>0.95</td>
<td>0.247</td>
<td>0.703</td>
<td>23.82</td>
</tr>
</tbody>
</table>
The bandwidth results in this configuration are naturally inferior to the optimal setting. However, the absorption region length is increased and consequently the quantum yield is also higher. However, it is important to note that there are other possible configurations that lead to different values of quantum yield and bandwidth.

VI. CONCLUSIONS

The frequency response of PIN photodiodes depends on several factors such as the side of the incident light, the length, the bias voltage, the density of impurities, the area and the location of the drift region, if it exists. The numerical model can simulate the behavior of the device with an accuracy as high as desired and several simulations under different conditions were implemented. The results of the simulations enable us to get some insight about the settings that optimize the frequency response of PIN photodiode with various topologies. For the conventional PIN photodiode topology, when the light is incident on the P side, the frequency response is enhanced due to the high electron drift velocity. The simulations that test the bias voltage effect on the frequency response of the device show that, for lower bias voltages, the PIN photodiode has a higher bandwidth. This happens because the electrons’ drift velocity is maximum for low values of the electric field, decreasing as the electric field increases. The impurity density does not affect significantly the frequency response. Decreasing the impurity density can however contribute to lower the bias voltage, and this is important since the bias voltage is related to the electric field and the carriers’ velocity.

The area of the device is important because it affects the capacitance of the device. If the area of the device is smaller the associated capacitance will also be smaller, thus increasing the bandwidth. The length that maximizes the bandwidth of a conventional PIN photodiode, assuming that the light is incident on the P side, 1.3 μm wavelength, 300K temperature, 10^{21} m^{-3} impurity density, 11 V bias voltage and 25 μm device’s diameter, is 0.9 μm which results in a 21.52 GHz bandwidth. The PIN photodiode with drift region is an evolution of the conventional PIN photodiode topology. The inclusion of a drift region may increase the frequency response of the system since the carriers’ saturation velocity is higher in this region and also because the device capacitance is reduced. The results from all the simulations indicate that the PIN photodiode with the drift region topology always presents better bandwidth results that the conventional PIN photodiode topology. The lengths that maximize the bandwidth of the PIN photodiode with drift region in the N side, assuming that the light is incident on the N side, 1.3 μm wavelength, 300K temperature, 10^{21} m^{-3} impurity density, 11 V bias voltage and 25 μm device’s diameter, are 0.42 μm for the absorption region and 0.58 μm for the drift region (1 μm total device length) which results in a 24.96 GHz bandwidth.

REFERENCES