QUANTUM EFFICIENCY OPTIMIZATION OF InP-BASED In$_{0.53}$Ga$_{0.47}$As PHOTODETECTORS

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Abstract: A modified physical model on the optical response of InP-based In$_{0.53}$Ga$_{0.47}$As P N photodetectors was presented. By introducing a collecting factor, the optical response and quantum efficiency were simulated. The influences of device parameters on quantum efficiency of typical In$_{0.53}$Ga$_{0.47}$As/InP P N photodetectors under both front and backside illuminated conditions were investigated by using our model. Furthermore, two modified InGaAs/InP PD structures for back-illumination were proposed, and the optimal structural parameters were discussed.

Key words: shortwave-infrared; photovoltaic detectors; InGaAs; quantum efficiency

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In this paper, a modified physical model used for QE optimization of InP-based In$_{0.53}$Ga$_{0.47}$As PDs is demonstrated. In this model, a collecting factor is introduced and proper parameters of the materials are adopted. Based on this model, the QE of typical In$_{0.53}$Ga$_{0.47}$As/InP P N PDs under front and backside illuminated conditions with different doping levels and the thicknesses of absorbing layer are investigated in detail. Furthermore, two modified structures for back-illumination are proposed, and the relationships of their structural parameters with QE are simulated.

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1 Physical model and parameters

In P N PDs, photo-carriers induced by incident photons (\( \nu > E_g \)) are separated by the electric field to the opposite side of the junction, and consequently photo-current is generated. The photo-current consists of two parts: photo-carriers generated in the depletion layer, and photo-carriers generated outside the depletion region that diffused into the depletion layer\(^{[7]}\).

For typical In\(_{0.53}\)Ga\(_{0.47}\)As/InP PDs as schematically shown in Fig 1, the generation rate \( g_i (x) \) of electron-hole pairs in In\(_{0.53}\)Ga\(_{0.47}\)As absorbing layer is given by\(^{[7]}\)
\[
g_i (x) = P(x) \cdot \alpha_1 = P_0 \cdot e^{-\alpha x} \cdot e^{-\alpha_1 x} \cdot \alpha_1 \left[ \right],
\]
where \( P_0 \) is the incident light power, \( \alpha_1 \) and \( \alpha_2 \) are the absorption coefficient of In\(_{0.53}\)Ga\(_{0.47}\)As and InP, respectively.

Since electrons and holes in the depletion layer are moving very fast in the electric field, recombination in the depletion region is negligible\(^{[8]}\). And the influence of band discontinuity on carrier transport at the junction is also neglected in our model\(^{[7]}\). Therefore the collecting factor \( \eta_1 (x) \) in the depletion region is close to unity. Assuming the collecting factor outside the depletion layer decreases exponentially with the minority carrier diffusion length \( L_{d1} \), \( \eta_1 (x) \) in the In\(_{0.53}\)Ga\(_{0.47}\)As layer can be written as
\[
\eta_1 (x) = \begin{cases} 1, & x \geq 0 \\ 1 - e^{-x/d_1}, & d_1 \geq x \geq l_1 \end{cases}.
\]

The photocurrent contributed from the n\(^-\) - In\(_{0.53}\)Ga\(_{0.47}\)As absorber layer is
\[
J_{s1} = \int_0^d \eta_1 (x) \cdot J (x) \, dx \left[ \right],
\]
Similarly, the photocurrent contributed from P' - InP cap layer can be deduced. Thus the total photocurrent could be calculated.

Careful choice of the material parameters is of great importance in acquiring accurate modeling predictions\(^{[7,8]}\), especially the key electrical and optical parameters, such as minority-carrier lifetime, mobility, absorption coefficient, etc. Some widely investigated II-VI material parameters are available in related papers\(^{[9,12]}\) and handbooks\(^{[13,14]}\), yet others still lack of reliable data. Among these key parameters, the minority carrier lifetime (\( \tau \)) and absorption coefficient (\( \alpha \)) have direct effects on modeling accuracy.

The minority-carrier lifetime of In\(_{0.53}\)Ga\(_{0.47}\)As as a function of carrier concentration used in our simulation is plotted in Fig 2, where the quasi-empirical model proposed by R. K. Ahrenkalt\(^{[15]}\) is adopted in combination with the consideration of photon recycling effect\(^{[16]}\) of double heterostructures by introducing a recycling factor of 10\(^{[17,18]}\). The values of some key parameters used in our simulation are summarized in Table 1.

2 QE optimization

InGaAs PDs for optical communication applications emphasize particularly on the frequency characteristic, then the QE and dark current. While for remote sensing applications, the QE and dark-current are the primary concern. In array applications the total noise
Some key parameters of InGaAs and InP used in our calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (cm$^{-1}$)</td>
<td>$5 \times 10^3$</td>
</tr>
<tr>
<td>$E_g$ (eV)</td>
<td>1.331</td>
</tr>
<tr>
<td>$N_c$ (cm$^{-3}$)</td>
<td>$2 \times 10^{17}$</td>
</tr>
<tr>
<td>$N_v$ (cm$^{-3}$)</td>
<td>$7.5 \times 10^{19}$</td>
</tr>
<tr>
<td>$D_0$ (cm$^2$/s)</td>
<td>130</td>
</tr>
<tr>
<td>$D_1$ (cm$^2$/s)</td>
<td>5</td>
</tr>
<tr>
<td>$\tau$ (ns)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A: band-gap narrowing due to heavily doping is considered.
B: $\tau$ of n-doped InP is $2 \times 10^3$. 1 ns is adopted in our simulation.

arises from both the PDs and the read-out circuit (ROC). In lattice matched case, the total noise is usually dominated by ROC rather than PDs, therefore the optimization of QE becomes the main concern.

Since the optical response of PDs mainly comes from InGaAs absorbing layer, which is directly proportional to QE, the influence of i-layer parameters (i.e. i-layer thickness and doping concentration) on the internal QE of these InGaAs/InP PDs around peak wavelength is mainly investigated in this paper.

Front-illuminated InGaAs PD

The influence of i-layer thickness and doping concentration on internal QE of front illuminated InGaAs/InP PDs is shown in Fig 3. The QE decreases slowly as the doping concentration increases, and increases monotonously with i-layer thickness until saturation occurs. It could be deduced that, under front illuminated condition, i-layer thickness of 1.5 μm is thick enough to reach higher QE, whereas the optimal doping concentration should be a trade-off between QE and dark current. When the PD with n-InGaAs/InP PDs under backside illumination, optimal QE requires a relatively thin n-InGaAs absorbing layer. But a thinner absorbing layer is not sufficient for collecting all incident photons. Hence, it is not suitable for the required high-sensitivity applications.

Back-illuminated InGaAs PD

As shown in Fig 4, as for typical InGaAs/InP PD under back-illumination, the internal QE firstly increases with the augment of i-InGaAs layer thickness $d_i$ and then decreases as $d_i$ gets thicker. The higher the i-layer doping concentration is, the faster the QE decreases as i-layer becomes thicker. Simulation results indicate that the internal QE around 80% could be achieved when the back-illuminated InGaAs/InP PD with n-InGaAs thickness around 0.8 μm and doping concentration below 5E16 cm$^{-3}$.

Two other structures for back illumination

It is noticed from above analysis that for typical InGaAs/InP PDs under backside illumination, optimal QE requires a relatively thin n-InGaAs absorbing layer. But a thinner absorbing layer is not sufficient for collecting all incident photons. Hence, it is not suitable for the required high-sensitivity applications.

In order to further improve the internal QE of InGaAs/InP PDs for back illumination, homojunction or multi-layer heterostructures can be used. However, PDs with homojunctions suffer from soft reverse IV characteristics which results in a higher dark current. Here a modified structure with a thin InP barrier layer is adopted. The InP barrier would slightly reduce the optical response from the upper InGaAs layer (when the lower InGaAs layer thickness > 1 μm, the QE comes...
from the upper-InGaAs (<2%), but it would effectively block the photo-carriers to diffuse towards the surface, thus the surface recombination would be greatly suppressed. The QE of two modified structures for back illumination based upon above analysis is calculated. The influence of structural parameters on internal QE is also investigated.

The structure 1 is a $n$-$p$-$n$ stack as shown in Fig. 5. The doping concentration of $P^+$-$InP$ cap layer is set as $2E18cm^{-3}$. The influence of $n^-$-InGaAs absorbing layer thickness at various doping concentrations on QE is calculated. As plotted in Fig. 5, the total QE increases logarithmically with $n^-$-InGaAs thickness, and the contribution of $N^+$-InGaAs cap layer becomes negligible when the absorbing layer is thicker than about 1 $\mu$m. Considering the trade-off between the QE and dark current, an internal QE above 95% can be achieved in the back-illuminated PD1 with $n^-$-InGaAs layer thicker than 1 $\mu$m and doping concentration around $2E18cm^{-3}$.

The structure 2 with a $p$-$n$-$n$ configuration for back-illumination is schematically shown in Fig. 6. The 0.5 $\mu$m $p$-$InP$ barrier layer doped to $1E18cm^{-3}$ is kept constant in our simulation. The total thickness of $n^-$-InGaAs and $P^+$-InGaAs layer is assumed to be 1 $\mu$m.

As shown in Fig. 6, with the increase of $d_t$, the total QEs firstly increase and then decreases slowly. The contribution from $P^+$-InGaAs layer decreases with the increase of $n^-$-InGaAs layer thickness. The internal QE of 90% could be achieved with the thickness of $n^-$-InGaAs layer around 0.5 $\mu$m and the doping concentration around $2E16cm^{-3}$, and moderate dark light is focused on the surface. The extra light can be absorbed in the $P^+$-$InGaAs$ cap layer.
current characteristic could also be expected. The p-InP barrier layer concentration also has a slight influence on internal QE, which is found to be appropriate at higher doping levels. However, considering the inter-diffusion effect during the growth, the concentration of p-InP barrier layer around 5E17 cm⁻³ is preferable.

3 Conclusions

In conclusion, a physical model of PN PDs for optical response optimization is established. The optical response properties of several lattice-matched InGaAs/InP PD structures under front and backside illuminated configurations are investigated in detail, and the optimal parameters for higher QE are also discussed. Combining this model with dark current analysis, further optimization on SNR and detectivity of InGaAs/InP PN PDs and arrays could be realized.

REFERENCES


