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Design of High Speed InGaAs/InP One-Sided Junction Photodiodes with Low Junction Capacitance

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Abstract

A high speed InGaAs/InP one-sided junction photodiode (OSJ-PD) with low junction capacitance is presented and investigated for the first time. Compared with the well known uni-traveling carrier photodiode (UTC-PD), the OSJ-PD has the advantages of simpler epitaxial layer structure and lower junction capacitance, while maintaining the characteristics of high speed and high output power. The OSJ-PD is studied by simulation. The performance characteristics of OSJ-PD including internal electric field distribution, energy band diagram, frequency response, photocurrent and junction capacitance, are carefully studied.

Keywords: InGaAs, InP, photodetector, one-sided junction photodiode, uni-traveling carrier photodiode.

1. Introduction

Photodiode is the key component for many applications, such as high speed fibre-optic communication systems [1], radio-over-fibre wireless communication systems [2-4], terahertz (THz) and millimetre-wave (MMW) generation schemes [5], etc. Thanks to the development of Erbium Doped Fibre Amplifier (EDFA), by combining high speed photodiode and powerful EDFA, THz and MMW signals can be generated directly from photonics links. Compared with other THz and MMW signal generation techniques [6], this approach can eliminate the need of bulky and expensive electrical post-amplifiers. Thus, the overall bandwidth can be very broad, and the overall system complexity can be reduced. Moreover, photodiode can be integrated with photonic integrate circuit (PIC) components and even with a planar antenna for many applications [2,3,7,8].

Since photodiode is the main limitation for the overall performance of the aforementioned systems, there is an urgent need for high speed and high output power photodiodes. Before the invention of uni-traveling carrier photodiode (UTC-PD), PIN photodiode (PIN-PD) [9-14] has been used for fibre-optic communications, since it has a broad bandwidth of 67 GHz [9] and over 100 GHz [10,11]. However, for conventional PIN-PD, both holes and electrons are active carriers. Since the holes drift at a lower velocity, the performance of PIN-PD, such as bandwidth, is limited by holes. And thus, there is an inevitable tradeoff between output power and other characteristics [11].

To overcome the inherent drawbacks of PIN-PD, UTC-PD was first developed in 1997 [15]. Since UTC-PD utilizes fast carrier electrons as the only active carriers, the speed and output power is improved significantly compared to PIN-PD. In UTC-PD, the absorption layer and depletion layer are separated, which decouples the bandwidths determined by transit time and resistance-capacitance (RC) charging time. With the increasing demand of wireless communications, the MMW frequency range from 40 GHz to 300 GHz has attracted more and more attention [2,3]. MMW-over-fibre (MoF) technique is a promising solution for such wireless communication systems [2,3]. Nowadays, UTC-PD has been widely used for MoF links. It has been demonstrated that the UTC-PD at C-band wavelength range can have a bandwidth from 20 GHz to 315 GHz [16-24]. All UTC-PD structures, such as stepped doping [16,20,22] or linear-graded doping [17-19,21] in the absorption layer, modified UTC-PD (MUTC-PD) [16], triple transition region photodiode (TTR-PD) [24], and near-ballistic UTC-PD (NBUTC-PD) [17-19,21] have been proposed from the basic UTC-PD structure [15].

To simplify the epitaxial layer structure and improve the performance of photodiodes, we propose a high speed one-sided junction photodiode (OSJ-PD) with low junction capacitance, which can be an excellent photodiode for MoF links. The OSJ-PD is proposed based on the concept of the InGaAs Schottky barrier photodiode (SB-PD) [25-29] and UTC-PD [15]. However, since the Schottky barrier height of InGaAs is very low (about 0.2 to 0.3 eV), the dark current of InGaAs SBD is high [27]. This drawback has dramatically limited the applications of InGaAs SB-PD, and there are very few reports on it. Extensive studies have been conducted to overcome this drawback and different approaches have been adopted to increase the InGaAs Schottky barrier height. These approaches include cryogenic processing of metal deposition [30,31], chemical passivation [32], employing a thin cap layer of InAlAs, InP, Al\(_2\)O\(_3\), GaAs or InGaP to increase barrier height [33-37].
adding a thin counter-doped p'-InGaAs layer on n-InGaAs [37-39], etc. However, cryogenic processing and chemical passivation require additional fabrication steps and employing a thin cap layer will result in energy band discontinuity. Thus, a OSJ-PD structure has been adopted without complicating fabrication process and causing energy band discontinuity.

In this paper, the OSJ-PD is proposed and studied by theoretical analysis and Technology Computer-Aided Design (TCAD) simulation. The performance characteristics of UTC-PD and OSJ-PD are compared carefully. First, the epitaxial layer structures and the energy band diagrams of UTC-PD and OSJ-PD are illustrated.

Then, the theory used for TCAD simulation is explained briefly. Finally, the simulated characteristics of UTC-PD and OSJ-PD including internal electric field distribution, energy band diagram, electron and hole concentration, electron and hole current, frequency response, photocurrent, and junction capacitance are presented and compared.

Fig. 1. Space charge density of a one-sided p' n' junction.

Fig. 2. Energy band diagram of OSJ-PD.

2. Device design and operation

An asymmetrical pn junction is called a one-sided junction, either a p'n junction or a n'p junction, where p' and n' indicate heavily doped semiconductor. The schematic diagram of a p'n junction is given in Fig. 1. For the p'n junction, \( x_p \ll x_n \) and \( W \approx x_n \), where \( x_p \) is the depletion width in p' region, \( x_n \) is the depletion width in n region, and \( W \) is the total depletion width. The heavily doped semiconductor is similar to metal and there is no depletion in metal [40]. The OSJ-PD structure is similar to SB-PD structure [25-29], since the heavily doped p contact layer is similar to metal. The epitaxial layer structure of the designed OSJ-PD is given in Table 1. In order to make a comparison, the epitaxial layer structure of the conventional UTC-PD is given in Table 2. The detailed numerical modelling study of the conventional UTC-PD is given in [41]. Obviously, the OSJ-PD has a much simpler structure, which can lower the cost for epitaxial layer material growth.

The designed OSJ-PD is a backside illuminated photodiode, operating at around 1550 nm light wavelength.
From top to bottom, the OSJ-PD epitaxial layer structure consists of a heavily doped p-type InGaAs contact layer, a lightly doped n-type InGaAs absorption layer, two lightly doped n-type InGaAsP spacer layers, a lightly doped n-type InP collector layer and a heavily doped n-type InP contact layer. This simple structure can be grown by Metal-organic Chemical Vapor Deposition (MOCVD) or Molecular beam epitaxy (MBE).

Table 1
Epitaxial layer structure of the OSJ-PD.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Band gap (eV)</th>
<th>Thickness (nm)</th>
<th>Doping level (cm⁻³)</th>
<th>Dopant type</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Contact</td>
<td>InGaAs</td>
<td>0.734</td>
<td>50</td>
<td>1×10¹⁸</td>
<td>P</td>
</tr>
<tr>
<td>Absorption</td>
<td>InGaAs</td>
<td>0.734</td>
<td>300</td>
<td>5×10¹⁷</td>
<td>N</td>
</tr>
<tr>
<td>Spacer</td>
<td>InGaAsP</td>
<td>0.882</td>
<td>20</td>
<td>3×10¹⁸</td>
<td>N</td>
</tr>
<tr>
<td>Spacer</td>
<td>InGaAsP</td>
<td>1.105</td>
<td>20</td>
<td>5×10¹⁷</td>
<td>N</td>
</tr>
<tr>
<td>Collector</td>
<td>InP</td>
<td>1.35</td>
<td>300</td>
<td>2×10¹⁸</td>
<td>N</td>
</tr>
<tr>
<td>N Contact</td>
<td>InP</td>
<td>1.35</td>
<td>800</td>
<td>8×10¹⁸</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 2
Epitaxial layer structure of the UTC-PD.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Band gap (eV)</th>
<th>Thickness (nm)</th>
<th>Doping level (cm⁻³)</th>
<th>Dopant type</th>
</tr>
</thead>
<tbody>
<tr>
<td>P Contact</td>
<td>InGaAs</td>
<td>0.73</td>
<td>50</td>
<td>3×10¹⁹</td>
<td>P</td>
</tr>
<tr>
<td>Block</td>
<td>InGaAsP</td>
<td>0.85</td>
<td>20</td>
<td>2×10¹⁹</td>
<td>P</td>
</tr>
<tr>
<td>Absorption</td>
<td>InGaAs</td>
<td>0.73</td>
<td>220</td>
<td>1×10¹⁹</td>
<td>P</td>
</tr>
<tr>
<td>Spacer</td>
<td>InGaAs</td>
<td>0.73</td>
<td>8</td>
<td>1×10¹⁹</td>
<td>Undoped</td>
</tr>
<tr>
<td>Spacer</td>
<td>InGaAsP</td>
<td>1.00</td>
<td>16</td>
<td>1×10¹⁹</td>
<td>Undoped</td>
</tr>
<tr>
<td>Spacer</td>
<td>InP</td>
<td>1.35</td>
<td>6</td>
<td>1×10¹⁹</td>
<td>Undoped</td>
</tr>
<tr>
<td>Cliff</td>
<td>InP</td>
<td>1.35</td>
<td>7</td>
<td>1×10¹⁹</td>
<td>N</td>
</tr>
<tr>
<td>Collector</td>
<td>InP</td>
<td>1.35</td>
<td>263</td>
<td>1×10¹⁹</td>
<td>N</td>
</tr>
<tr>
<td>Subcollector</td>
<td>InP</td>
<td>1.35</td>
<td>12</td>
<td>5×10¹⁹</td>
<td>N</td>
</tr>
<tr>
<td>N Contact (Etch Stop)</td>
<td>InGaAs</td>
<td>0.73</td>
<td>0.2</td>
<td>1×10¹⁹</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 3
Material parameters used in the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter description</th>
<th>InP</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron mobility, μₑ</td>
<td>2×10²⁰ cm²/Vs</td>
<td>12000 cm²/Vs</td>
<td></td>
</tr>
<tr>
<td>Hole mobility, μₕ</td>
<td>200 cm²/Vs</td>
<td>300 cm²/Vs</td>
<td></td>
</tr>
<tr>
<td>Conduction band density of states, Nₖ</td>
<td>5.7×10¹⁷ cm⁻³</td>
<td>2.1×10¹⁷ cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Valence band density of states, Nᵥ</td>
<td>1×10⁴⁹ cm⁻³</td>
<td>7.7×10⁴⁹ cm⁻³</td>
<td></td>
</tr>
<tr>
<td>Electron saturation velocity</td>
<td>6.6×10⁶ cm/s</td>
<td>2.5×10⁶ cm/s</td>
<td></td>
</tr>
<tr>
<td>Hole saturation velocity</td>
<td>5×10⁰ cm/s</td>
<td>5×10⁰ cm/s</td>
<td></td>
</tr>
<tr>
<td>Electron and hole life time (UTC-PD)</td>
<td>1×10⁻⁷ s</td>
<td>1×10⁻⁷ s</td>
<td></td>
</tr>
<tr>
<td>Electron and hole life time (OSJ-PD)</td>
<td>2×10⁻⁸ s</td>
<td>1×10⁻⁷ s</td>
<td></td>
</tr>
<tr>
<td>Electron Auger coefficient</td>
<td>3.7×10⁻³⁰ cm³/s</td>
<td>3.2×10⁻²⁹ cm³/s</td>
<td></td>
</tr>
<tr>
<td>Hole Auger coefficient</td>
<td>8.7×10⁻³⁰ cm³/s</td>
<td>3.2×10⁻²⁸ cm³/s</td>
<td></td>
</tr>
<tr>
<td>Real refractive index (1550 nm)</td>
<td>3.165</td>
<td>3.595</td>
<td></td>
</tr>
<tr>
<td>Imaginary refractive index (1550 nm)</td>
<td>0</td>
<td>0.075</td>
<td></td>
</tr>
</tbody>
</table>

Table 4
Mobility model parameters used in the simulation.

<table>
<thead>
<tr>
<th>Mobility parameter</th>
<th>Parameter description</th>
<th>InP</th>
<th>InGaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU1N.CAUGH</td>
<td>Minimum mobility at high doping</td>
<td>300 cm²/Vs</td>
<td>3372 cm²/Vs</td>
</tr>
<tr>
<td>MU2N.CAUGH</td>
<td>Maximum mobility at low doping</td>
<td>4917 cm²/Vs</td>
<td>11599 cm²/Vs</td>
</tr>
<tr>
<td>MU1P.CAUGH</td>
<td>Minimum mobility at high doping</td>
<td>20 cm²/Vs</td>
<td>75 cm²/Vs</td>
</tr>
<tr>
<td>MU2P.CAUGH</td>
<td>Maximum mobility at low doping</td>
<td>151 cm²/Vs</td>
<td>331 cm²/Vs</td>
</tr>
<tr>
<td>ALPHAN.CAUGH</td>
<td>Fitting parameter</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>ALPHAP.CAUGH</td>
<td>Fitting parameter</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BETAN.CAUGH</td>
<td>Fitting parameter</td>
<td>-2.3</td>
<td>-2.3</td>
</tr>
<tr>
<td>BETAP.CAUGH</td>
<td>Fitting parameter</td>
<td>-2.2</td>
<td>-2.2</td>
</tr>
<tr>
<td>GAMMAN.CAUGH</td>
<td>Fitting parameter</td>
<td>-3.8</td>
<td>-3.8</td>
</tr>
<tr>
<td>GAMMAP.CAUGH</td>
<td>Fitting parameter</td>
<td>-3.7</td>
<td>-3.7</td>
</tr>
<tr>
<td>DELTAN.CAUGH</td>
<td>Fitting parameter</td>
<td>0.46</td>
<td>0.76</td>
</tr>
<tr>
<td>DELTAP.CAUGH</td>
<td>Fitting parameter</td>
<td>0.96</td>
<td>1.37</td>
</tr>
<tr>
<td>NCRITN.CAUGH</td>
<td>Critical doping above which mobility degrades</td>
<td>6.4×10⁷ cm⁻³</td>
<td>8.9×10⁸ cm⁻³</td>
</tr>
<tr>
<td>NCRITP.CAUGH</td>
<td>Critical doping above which mobility degrades</td>
<td>7.4×10⁷ cm⁻³</td>
<td>1×10⁸ cm⁻³</td>
</tr>
</tbody>
</table>
To better understand the operating mechanism and the advantages of the OSJ-PD, the energy band diagram of the OSJ-PD is given in Fig. 2. The energy band diagrams of the PIN-PD and UTC-PD are also given in Figs. 3 and 4 for comparison. Light is injected into the bottom N contact layer and passes through the collector layer, which is composed of wide energy gap material InP, and then absorbed in the absorption layer, which is composed of narrow energy gap material InGaAs. The electron and hole pairs are generated in the absorption layer and then separated and swept away quickly by the strong electric field in the absorption layer. This phenomenon differs significantly from the conventional UTC-PD [41], which utilizes electrons as the only active carriers. In the UTC-PD, electron and hole pairs are generated in the absorption layer, and minority carrier electrons will diffuse/drift to the collector layer. Since electrons’ diffusive velocity in the absorption layer is usually lower than the drift velocity in the collector layer, the bandwidth of UTC-PD is mainly dominated and limited by electrons’ traveling time in the absorption layer [42].

In the OSJ-PD, since all the active layers are depleted, the slow diffusion process can be eliminated. Both electrons and holes travel at saturation velocity or faster. The saturation velocities of electrons and holes in InGaAs are 2.5×10^7 cm/s and 5×10^6 cm/s respectively, and the saturation velocities of electrons and holes in InP are 2.6×10^7 cm/s and 6.6×10^6 cm/s respectively [42-45]. As shown in Fig. 2, the traveling distance of holes is much shorter than that of electrons. Even though the saturation velocity of holes is slower than that of electrons, the traveling time of electrons and holes can be tuned by carefully designing the thickness of an absorption layer and a collector layer. Generally speaking, the speed of a photodiode, i.e., 3-dB bandwidth, is mainly determined by:

\[
f_{MB} = \frac{1}{\sqrt{\tau_r^2 + \tau_{RC}^2}}
\]

where \(\tau_r\) is carrier transition time and \(\tau_{RC}\) is RC charging time. The output power of a photodiode is mainly determined by space charge effects and thermal management. In OSJ-PD, since the absorption layer and collector layer are separated, the carrier transition time and RC charging time can be adjusted independently. Thus, the OSJ-PD can be designed with a comparable bandwidth to UTC-PD. Because the OSJ-PD is reversely biased at high voltage and the internal electric field is high, the space charge effect can be reduced as well, and thus high output power is achievable.

\[\nabla^2 \psi = -\frac{\rho}{\varepsilon}
\]

(2)

\[
\tilde{J}_n = q\mu_n \vec{E} + qD_n \vec{\nabla}n
\]

(3)

\[
\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q} \nabla \cdot \vec{J}_n
\]

(4)

\[
\frac{\partial p}{\partial t} = G_p - R_p + \frac{1}{q} \nabla \cdot \vec{J}_p
\]

(4)

\(\psi\) is the electrostatic potential, \(\varepsilon\) is the permittivity, \(\rho\) is the space charge density, \(\tilde{J}_n\) and \(\tilde{J}_p\) are the electron and hole current densities, \(\mu_n\) and \(\mu_p\) are electron and hole mobilities, \(D_n\) and \(D_p\) are electron and hole diffusion coefficients, \(q\) is electron charge, \(G_n\) and \(G_p\) are electron and hole generation rates and \(R_n\) and \(R_p\) are electron and hole recombination rates.

The electrical and optical properties of InGaAs and InP materials are taken from [43-45,47-51] and the parameters used in our simulation are given in Tables 3 and 4. Basic models included in TCAD simulation are: concentration-dependent lifetime model CONSRLH, concentration-dependent mobility model ANALYTIC, parallel electric field dependent mobility model FLDMOB, Shockley-Read-Hall recombination minority carrier lifetime model SRH, and Auger recombination model AUGER. In order to verify the accuracy of our simulation models and configurations, we have compared our simulation results with [41,47] and similar results can be reproduced. To make the simulated results comparable, all devices’ area is set to 20 mm² and load resistance is set to 50 Ω. Excluding contact layers, the UTC-PD has a thickness of 590 nm and the OSJ-PD has a comparable thickness of 640 nm.

4. Device characteristics

4.1 Reverse bias voltage and internal electric field

Photodiode serves as an O/E converter. In order to get high output, reverse bias voltage should always be applied. However, a high reverse bias voltage could result in device breakdown. The breakdown electric fields of InGaAs and InP are around 2×10^7 V/cm and 5×10^7 V/cm respectively [50]. In conventional UTC-PD given in Table 2, the depletion region is the spacer layers, cliff layer, and collector layer. The total depletion width is around 300 nm. As shown in Fig. 5, at bias voltages of -2 V and -4 V, the
electric fields in spacer and cliff layers are around 200 kV/cm and 250 kV/cm respectively, and the electric fields in collector layer are around 100 kV/cm and 150 kV/cm respectively.

This feature differs significantly from the conventional UTC-PD and greatly simplifies the epitaxial growth process. Thus OSJ-PD is suitable for applications which require high RF output power.

4.2 Energy band diagram

The energy band diagrams of UTC-PD (Table 2) and OSJ-PD (Table 1) with and without reverse bias voltage are given in Figs. 7 and 8. Obviously, the operation mechanisms of UTC-PD and OSJ-PD are different. In UTC-PD, the electric field in absorption layer is almost zero and a block layer is used to prevent the photogenerated electrons from diffusing towards contact layer. In OSJ-PD, the electric field in absorption layer is strong enough and photogenerated electron and hole pairs will be swept out of the depletion region quickly. Thus, there is no need for a block layer, which is necessary for conventional UTC-PD. Electrons and holes will drift towards n and p contact layers respectively. This feature differs significantly from the conventional UTC-PD and greatly simplifies the epitaxial growth process.
Layer structure. In UTC-PD, a cliff layer is used to increase the electric field and facilitate the traveling of electrons at the interface between absorption layer and collector layer. In OSJ-PD, the electric field is too high so that electrons can travel through spacer layers easily even without a cliff layer.

4.3 Electron and hole concentration

![Graph 9](image1.png)

**Fig. 9.** Electron concentration profiles of UTC-PD with 4 V reverse bias voltage at different light intensities.

![Graph 10](image2.png)

**Fig. 10.** Hole concentration profiles of UTC-PD with 4 V reverse bias voltage at different light intensities.

For UTC-PD, the electron and hole concentration profiles across the device are given in Figs. 9 and 10. Light is absorbed in the absorption layer and electron and hole pairs are generated in this layer. Photogenerated electrons diffuse towards spacer layers and then drift through spacer and collector layers under high electric field. As shown in Fig. 9, electron concentration across the device increases with injected light intensity. However, the electron concentration in collector layer stops to increase when light intensity goes beyond 5×10⁵ W/cm². Large amount of electrons begin to accumulate in absorption layer and saturation occurs. Since holes are majority carriers in heavily doped p-type absorption layer, photogenerated holes respond very fast within the dielectric relaxation time and excess holes will return to equilibrium by conduction process. As shown in Fig. 10, the hole concentration across the device is almost constant at different light intensities. The variation of hole concentration in the collector layer is mainly due to light absorbed in the 10 nm InGaAs contact (etch stop) layer. Therefore, the photoresponse of a UTC-PD is mainly determined by electron transportation.

![Graph 11](image3.png)

**Fig. 11.** Electron concentration profiles of OSJ-PD with 10 V reverse bias voltage at different light intensities.

![Graph 12](image4.png)

**Fig. 12.** Hole concentration profiles of OSJ-PD with 10 V reverse bias voltage at different light intensities.

For OSJ-PD, the electron and hole concentration profiles across the device are given in Figs. 11 and 12. The absorption layer is totally depleted. Photogenerated electron and hole pairs are separated by internal electric field and electrons and holes drift towards n-type and p-type contact layers respectively. The photoresponse of an OSJ-PD is determined by both electrons and holes, which is significantly different from a UTC-PD. Thanks to the shorter traveling distance of holes, though holes travel at a
relatively low saturation velocity of $5 \times 10^6$ cm/s, they won’t slow down the overall speed. As shown in Fig. 11, the electron concentration increases with injected light intensity. However, electrons in the absorption layer start to accumulate when light intensity reaches $6 \times 10^5$ W/cm$^2$ and electron concentration in the collector layer stops to increase. As shown in Fig. 12, the hole concentration across the device is almost constant at different light intensities, except in the absorption layer. In the absorption layer, hole concentration increases with injected light intensity. Obviously, hole accumulation doesn’t occur from a low light intensity of $1 \times 10^4$ W/cm$^2$ to a high light intensity of $6 \times 10^5$ W/cm$^2$. Holes start to accumulate near the interface between absorption layer and spacer layer at a light intensity of $7 \times 10^5$ W/cm$^2$. At high light intensity, not only holes but also electrons accumulate. The electrons accumulation is mainly caused by conduction band discontinuity between InGaAs and InP. When large amount of electrons accumulate, the internal electric field starts to drop. Once internal electric field drops to below 40 kV/cm, the traveling velocity of holes starts to decrease and holes accumulation occurs. Since there isn’t any valence band discontinuity between p contact layer and absorption layer, holes can travel easily from absorption layer to p contact layer and holes accumulation is not prominent.

### 4.4 Electron and hole current

![Graph showing electron, hole, and total current density inside the UTC-PD with 4 V reverse bias voltage at light intensity of $1 \times 10^4$ W/cm$^2$.](image)

Fig. 13 shows the electron, hole and total current density inside the UTC-PD. In the absorption layer, both electrons and holes contribute to the photocurrent. Electrons diffuse towards the collector layer, and holes drift to the p contact layer. The electron current increases from zero at the block layer interface to maximum at the spacer layer interface. The hole current increases from zero at the spacer layer interface to maximum at the block layer interface. In the collector layer, the photocurrent is carried totally by electrons drifting towards n contact layer. The total current across the device is constant since the photodiode is a two-terminal device. Note that light might be absorbed in the p contact layer also. In the p contact layer, since light intensity reaches $5 \times 10^5$ W/cm$^2$, the electric field at the interface of absorption layer and spacer layers drops to zero and electrons start to

### 4.5 Internal electric field at different light intensities

![Graph showing internal electric field of UTC-PD with 4 V reverse bias voltage at different light intensities.](image)

The internal electric field of UTC-PD with 4 V reverse bias voltage versus different injected light intensities is given in Fig. 15. When light intensity reaches $5 \times 10^5$ W/cm$^2$, the electric field at the interface of absorption layer and spacer layers drops to zero and electrons start to
accumulate. It agrees well with the phenomenon in Fig. 9 that electron concentration in collector layer doesn’t increase with injected light intensity when it goes beyond 5x10^5 W/cm^2.

The internal electric field of OSJ-PD with 10 V reverse bias voltage versus different injected light intensities is given in Fig. 16. When light intensity reaches 6x10^5 W/cm^2, the electric field at the interface of absorption layer and spacer layers drops to below 40 kV/cm and both electrons and holes start to accumulate. It agrees well with the phenomenon in Fig. 11 that electron concentration in collector layer doesn’t increase with injected light intensity when it goes beyond 6x10^5 W/cm^2.

4.6 Frequency response

![Graph showing internal electric field of OSJ-PD with 10 V reverse bias voltage at different light intensities.](image)

The frequency responses of UTC-PD and OSJ-PD are obtained by small signal analysis in TCAD simulation and are given in Figs. 17 and 18. For both UTC-PD and OSJ-PD, because of the space charge effect the 3-dB bandwidth drops when injected light intensity increases. However, their mechanisms for bandwidth degradation are different. For UTC-PD, electrons are driven by concentration gradient in the absorption layer. As shown in Fig. 9, electron concentration gradient is prominent when light intensity is below 4x10^5 W/cm^2 and the gradient vanishes at light intensities above 5x10^5 W/cm^2. The variation of electron concentration gradient in Fig. 9 agrees well with the change of 3-dB bandwidth in Fig. 17. For OSJ-PD, both electrons and holes are driven by internal electric field. As shown in Fig. 16, the internal electric field drops to zero at light intensity of 7x10^5 W/cm^2. The variation of internal electric field in Fig. 16 corresponds well with the change of 3-dB bandwidth in Fig. 17.

As shown in Figs. 17 and 18, the UTC-PD with 220 nm absorption layer and 263 nm collector layer has a bandwidth of 33.5 GHz at low light intensity, while the OSJ-PD with 300 nm absorption layer and 300 nm collector layer has a bandwidth of 64 GHz at low light intensity.

![Graph showing 3-dB bandwidth of UTC-PD versus light intensity.](image)

4.7 Photocurrent

The simulated DC photocurrent densities of the UTC-PD and OSJ-PD versus injected light intensity with different bias voltage are given in Figs. 19 and 20. The UTC-PD can achieve a photocurrent density of more than 1.1x10^6 A/cm^2 with a bias voltage of 4 V. The OSJ-PD can achieve a photocurrent density of more than 2.4x10^5 A/cm^2 with a bias voltage of 10 V. In reality, the maximum current density can be improved by thermal management, i.e., flip-chip bonding the photodiode onto high thermal conductive substrate such as AlN or Diamond [17-19,21,23]. Obviously, the reverse bias voltage has a great influence on the photocurrent and photocurrent density usually increases with bias voltage. However, the bias voltage should be lower than the breakdown voltage of the device. Mainly due to the much higher bias voltage, the saturation photocurrent of OSJ-PD is much higher than UTC-PD. It’s worth mentioning that the space charge effect...
in UTC-PD and OSJ-PD can be relaxed by modified unidirectional carrier photodiode (MUTC-PD) structure and modified one-sided junction photodiode (OSJ-PD) structure respectively. The detailed discussion can be found in [16, 52].

![Graph of DC photocurrent density versus light intensity with different reverse bias voltage (UTC-PD).](image1)

![Graph of DC photocurrent density versus light intensity with different reverse bias voltage (OSJ-PD).](image2)

4.8 Junction capacitance

Since the overall speed of the photodiode is determined by transit time and RC charging time (1), another effective way to improve speed is to reduce the RC charging time. The RC charging time can be expressed as,

\[ \tau_{RC} = 2\pi (R_s + R_i) (C_j + C_p) \]  

where \( R_s \), \( R_i \), \( C_j \), and \( C_p \) are series resistance, load resistance, junction capacitance and parasitic capacitance respectively. Photodiode with a lower junction capacitance can relax the bandwidth degradation caused by RC charging time. The photodiode junction capacitance is similar to parallel plate capacitance, which is given by

\[ C = \frac{\varepsilon_c A}{d} \]  

where \( \varepsilon_c \), \( A \), and \( d \) are relative permittivity, permittivity of free space, area of the junction and depletion width, respectively. Since the photodiode has multilayer dielectric, the equivalent permittivity \( \varepsilon_{req} \) is given by [53],

\[ \varepsilon_{req} = \left[ \sum_{m=1}^{n} d_m \varepsilon_m \right]^{-1} \]  

(7)

\[ d_p = d_1 + d_2 + \cdots + d_n \]  

(8)

where \( d_m \) is the thickness of the \( m \)-th layer dielectric, and \( d_p \) is the total thickness. In UTC-PD, the depleted region is the spacer layers, cliff layer, and collector layer. In OSJ-PD, the depleted region is the absorber layer, spacer layers, and collector layer. Since the depletion width of OSJ-PD is usually larger than UTC-PD, for device with the same area, the junction capacitance of OSJ-PD can be lower than UTC-PD.

5. Conclusion

We have proposed a novel concept, one-sided junction photodiode, for InGaAs/InP photodiode design. The concept of OSJ-PD is different from the UTC-PD in the epitaxial layer structure, internal electric field distribution, energy band diagram and operation mechanism. It has been demonstrated that the OSJ-PD has the characteristics of the simple epitaxial layer structure, high speed, high output power, and low junction capacitance. The OSJ-PD with 300 nm absorption layer thickness has achieved a bandwidth of 64 GHz and a photocurrent density of 2.4x10^4 A/cm^2 under a 10 V bias voltage. The OSJ-PD can become an attractive choice for high speed fibre-optic communication systems, radio-over-fibre wireless communication systems, and THz and MMW generation schemes in the future.

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References


