Evanescently coupled photodiode (ECPD)

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High Performance Photodiode with Partially P-Doped Photo-absorption Layer for 40Gbit/sec Fiber Communication System

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Solid-state & Microwave Laboratory
Super Photonic & Electronic Device Group (SPED Group)
I. Motivation

II. Design Principle & Simulation

IV. Measurement System

V. Measurement Results

VII. Conclusion
Multiple sets data are combined / separated through TDM & WDM

**High speed TDM system is necessary (Superior bandwidth usage than WDM system)**!!

Fiber optic components provides the channel linking (From transmitter port to receiver port)
Multiple sets data are combined / separated through TDM & WDM

*High speed TDM system is necessary (Superior bandwidth usage than WDM system)!!*

Fiber optic components provides the channel linking (From transmitter port to receiver port)

*High Speed Photodetector serve as a key component in the front-end of receiver*
Three Major Requirement in Photodetectors

- High Power
- No preamplifier
Three Major Requirement in Photodetectors

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  - No preamplifier
- High Speed
  - Large transmission capacity
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  - Enhance S/N ratio

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ECPD
Outline

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How We Design the Structure?

**Epi-Layer structure**

*Epi-layer structure: Partially p-doped photo-absorption layer*
How We Design the Structure?

- Epi-Layer structure
- Geometric structure

- Epi-layer structure: Partially p-doped photo-absorption layer
- Geometric structure: Evanescently coupled waveguide
How We Design the Structure?

- **Epi-Layer structure**: Partially p-doped photo-absorption layer
- **Geometric structure**: Evanescently coupled waveguide
- **ECPD**: Three major targets can be achieved simultaneously
Why ECPD Have High Saturation Power?

Thin intrinsic absorption layer

Thick intrinsic absorption layer

Anode

Cathode

Absorption layer (intrinsic)

CB

VB

Why ECPD Have High Saturation Power?

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Thick intrinsic absorption layer

Absorption layer (intrinsic)

**Why ECPD Have High Saturation Power?**

Thin intrinsic absorption layer

Thick intrinsic absorption layer

\[ J_{\text{max}} \approx (V_{\text{bias}} + \theta) \varepsilon V_{\text{hole}} / D^2 \]

Why ECPD Have High Saturation Power?

Thin intrinsic absorption layer

Thick intrinsic absorption layer

$J_{\text{max}} \approx (V_{\text{bias}} + \vartheta) \varepsilon V_{\text{hole}} / D^2$

$D_1 < D_2 \quad J_{\text{max}1} >> J_{\text{max}2}$

Why ECPD Have High Saturation Power?

Thin intrinsic absorption layer

- High Saturation Current
- Low Responsivity
- Low Speed

\[ J_{\text{max}} \approx (V_{\text{bias}} + \phi) \varepsilon V_{\text{hole}} / D^2 \]

\[ D_1 < D_2 \quad \Rightarrow \quad J_{\text{max}1} >> J_{\text{max}2} \]

Why ECPD Have High Saturation Power?

Partially P-doped absorption layer

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Why ECPD Have High Saturation Power?

Partially P-doped absorption layer

Absorption layer (P-doping)
Absorption layer (intrinsic)

Anode
Cathode

Diffusion block

CB
VB

\[ J_{\text{max}} \approx (V_{\text{bias}} + \theta) \varepsilon V_{\text{hole}} / D^2 \]

\[ D_1 < D_2 \quad \Rightarrow \quad J_{\text{max}1} \gg J_{\text{max}2} \]

Why ECPD Have High Saturation Power?

Without sacrificing the absorption thickness

High Saturation Current !!
High Responsivity !!
High Speed !!

Three Limitations are Concerned in Electric Simulation

- RC Limitation
- Drift Time Limitation

\[ F_\text{3dB} \]
Three Limitations are Concerned in Electric Simulation

- High Current Saturation Limitation
- Drift Time Limitation
- RC Limitation

\[ F_{3dB} \]
The Degradation of Hole Velocity under High Power Operation

\[ \Delta E_{\text{space}} = \frac{J \cdot D}{V_{\text{hole}}} \varepsilon \]

\[ E_{\text{eff}} = E_{\text{DC}} - \Delta E_{\text{space}} \]

\[ E_{\text{DC}} = \frac{V_{\text{eff}}}{D} \]

\[ V_{\text{eff}} = V_{\text{apply}} - 50 \cdot I + V_{\text{bi}} \]

- \( \Delta E_{\text{space}} \): Hole carriers induce electrical field
- \( E_{\text{DC}} \): Effective voltage induces electrical field
The Degradation of Hole Velocity under High Power Operation

As the photo-current increase, the effective electrical field decrease.

Accumulated Hole Carrier

\[ \Delta E_{\text{space}} \uparrow \rightarrow E_{\text{eff}} \downarrow \]

\[ V_{\text{hole}} \downarrow \downarrow \rightarrow \Delta E_{\text{space}} \uparrow \uparrow \]

\[ \Delta E_{\text{space}} = \frac{J \times D}{V_{\text{hole}}} \]

\[ E_{\text{eff}} = E_{\text{DC}} - \Delta E_{\text{space}} \]
The Bandwidth Simulation Model

- **RL** = Load resistor
- **RC Bandwidth Limitation** ($RC(\omega)$)

$$RL = \text{Load resistor}$$

$$RC\text{ Bandwidth Limitation} = \left(\frac{1}{1 + j\omega (R_{\text{total}} + R_L)C_{\text{total}}}\right)$$

- **Bandwidth Limitation of Drift Time** ($Id(\omega)$)

$$Id = Q\left\{Sa\left(\frac{\omega \tau_d}{2}\right) + j\frac{2}{\omega \tau_d}\left[Sa(\omega \tau_d) - 1\right]\right\}$$

$V_{\text{out}}$, $R_{\text{total}}$, $R_L$, $I_{\text{pc}}$, $C_j$, $Q$
The Bandwidth Simulation Model

- **RL** = Load resistor
- **RC Bandwidth Limitation** \( RC(\omega) \)
  
  \[
  = \left( \frac{1}{1 + j\omega(R_{\text{total}} + R_L)C_{\text{total}}} \right)
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- **Bandwidth Limitation of Drift Time** \( \text{Id}(\omega) \)
  
  \[
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  \]

- **Net 3dB Bandwidth Limitation**
  
  \[
  = | RC(\omega) | \times | \text{Id}(\omega) |
  \]
The Optimum Thickness of P-doped Photo-Absorption Layer

- The ratio of p doped layer thickness to undoped layer thickness ($W_N/W_D$)

- Design Window
- Absorption layer (P-doping)
- Absorption layer (intrinsic)
- Anode
- Cathode
- CB
- VB

Graph showing frequency (GHz) vs. design window with different bias voltages (5mA, 10mA, 20mA) and ratio $W_N/W_D$.
Why We Adopted Evanescently Coupled Waveguide Structure?

Vertical illuminated Photodiode:

*Poor Bandwidth-Responsivity Product*
Why We Adopted Evanescently Coupled Waveguide Structure?

Vertical illuminated Photodiode:
- Poor Bandwidth-Responsivity
- Product

Waveguide Type Photodiode:
- Low Saturation Power due to Input-end Saturation!!

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Why We Adopted Evanescently Coupled Waveguide Structure?

Power Reflected

$P_{\text{in}} \times (1-R) \exp(-\alpha_{ab}X)$

Absorption Length ($X$)

Why We Adopted Evanescently Coupled Waveguide Structure?

Uniform Power Distribution

Power Reflected:
\[ P_{\text{in}} \times (1-R) \exp(-\alpha_{ab}X) \]

Absorption Length (X)


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STFOC Introduction of ECPD
Why We Adopted Evanescently Coupled Waveguide Structure?

Uniform Power Distribution

Power Reflected

$P_{in} \times (1-R) \exp(-\alpha_{ab}X)$

Optical Power

Absorption Length (X)

Coupling Power

$C \times P_{in} \times (1-R) \exp(-\alpha_{ab}X)$

Optical Power

Absorption Length (X)


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Optical Simulation Results

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InGaAsP
(High Reflect index)
with gradual change thickness

InGaAsP
(Low Reflect index)

InP (Low Reflect index)

InP (Low Reflect index)

InP (Low Reflect index)

InP (Low Reflect index)

Absorption layer

Coupling guide

Fiber guide

Waveguide length (um)

Power ratio

Total power

Fiber guide power

Absorption layer power

Coupling guide power
Our Structure!!

Evanescently coupled Structure with partially p-doped photo-absorption layer
Photodiode (ECPD)

20μm<<700μm of ATW!!

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How Do We calibrate the Heterodyne-Beating Measurement System

\[ S_{F11} = \Gamma_{ML} \]

\[ S_{F22} = \frac{\Gamma_S (\Gamma_{ML} - \Gamma_{MO}) + \Gamma_O (\Gamma_{MS} - \Gamma_{MO})}{\Gamma_S \Gamma_O (\Gamma_{MS} - \Gamma_{MO})} \]

\[ S_{F2} S_{F12} = \frac{(\Gamma_S - \Gamma_O) \Gamma_{MS} \Gamma_{MO} (\Gamma_{MO} - \Gamma_{ML})}{\Gamma_S \Gamma_O (\Gamma_{MS} - \Gamma_{MO})} \]
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The Reference Structure

Both device A & B have the same absorption thickness (0.5 μm)

Device A

Partially P-Doped

Device B

Fully Un-Doped
Responsivity

The measured photocurrent vs. optical pumping power. The partially p-doped doesn’t degrade the responsivity at all.

Device A: Responsivity (1.01 A/W)
The measured frequency responses of device A and B under high output current (5.5mA) operation.

Bias Voltage: -1V
Photocurrent: 5.5mA
Active Area: 150μm²

-3dB
The measured frequency responses of ECPD under three different output photocurrent. The dc bias voltage is fixed at -5V.

**Active area:** 200 μm²  
**Bias:** -5 V  

- **Photocurrent:** 2mA  
- **Photocurrent:** 4mA  
- **Photocurrent:** 8mA
The measured frequency responses of device A under three different dc bias voltages.

Photocurrent: 2mA
Active area: 200μm^2
High Power Performance

RF power versus dc photocurrent of device A and device B under different reverse bias voltages

- A (-1V)
- B (-5V)
- A (-5V)

f = 40GHz
Active area: 150μm²

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High Power Performance

RF power versus dc photocurrent of ECPD for different reverse at 40GHz.

- f= 40GHz
- Bias voltage: -5V

(23mA, 6.5dBm)

- 100μm²
- 150μm²
- 200μm²

40 GHz Output RF Power (dBm)

DC photocurrent (mA)
The comparison of Measured and Simulated Frequency Response

The simulated frequency responses is very consistence with the measured traces.

- Device A
  - Bias Voltage: -5V
  - Active Area: 200 μm²
  - Symbols:
    - S: 2 mA
    - S: 5 mA
    - M: 2 mA
    - M: 5 mA

- Device B
  - Bias Voltage: -5V
  - Active Area: 200 μm²
  - Symbols:
    - S: 0.05 mA
    - S: 5 mA
    - M: 0.05 mA
    - M: 5 mA

- Frequency (GHz) Range:
  - Device A: 0 to 50 GHz
  - Device B: 10 to 30 GHz
The Benchmark of Photodetector State of The Art Performance

Bandwidth-Efficiency Product

- NTT
- AUSTIN
- NCU

Efficiency (%)

Bandwidth (GHz)

- WGPD
- VPD
- ALACTAL
- Sumitomo

State of the art result

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Super Photonic & Electronic Device Group (SPED Group)
The Benchmark of Photodetector
State of The Art Performance

<table>
<thead>
<tr>
<th></th>
<th>Responsivity (A/W)</th>
<th>Bandwidth (GHz)</th>
<th>RF power $P_{1dB}$ (dBm)</th>
<th>Saturation current &amp; Bandwidth Product (mA*GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTT</td>
<td>0.27</td>
<td>50</td>
<td>9dBm@40GHz</td>
<td>1400 (35mA@40GHz)</td>
</tr>
<tr>
<td>ALACT</td>
<td>0.76</td>
<td>40</td>
<td>-1dBm@50GHz</td>
<td>1100 (22mA@50GHz)</td>
</tr>
<tr>
<td>AUSTIN</td>
<td>1.02</td>
<td>48</td>
<td>-1dBm@48GHz</td>
<td>440 (11mA@40GHz)</td>
</tr>
<tr>
<td>U²t</td>
<td>0.5~0.75</td>
<td>32~45</td>
<td>-8 dBm@50GHz</td>
<td>475 (9.5mA@50GHz)</td>
</tr>
<tr>
<td>NCU</td>
<td>1.01</td>
<td>50</td>
<td>&gt;6.5dBm@40GHz</td>
<td>920 (23mA@40GHz)</td>
</tr>
</tbody>
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Conclusions

• By incorporating the evanescent-coupling optical waveguide structure and partially p-doped photo-absorption layer, state of the art performance of photodiode has been achieved
  – **Bandwidth:** >50GHz
  – **Responsivity:** 1.01A/W
  – **RF power & Saturation Current:** 6.5 dBm at 40GHz & 23mA