Theory Study of SAGCM
InGaAs/InP Single Photon Avalanche Diode

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Outline

- Application
- Avalanche photodiode theory
- InGaAs/InP SAGCM APD
- Experimental results of basic structure
- Theory study of SAGCM APD
- **Application**

- Avalanche photodiode theory
- **InGaAs/InP SAGCM APD**
- Experimental results of basic structure
- Theory study of SAGCM APD
Optical fiber communication systems

1. High bit-rate and long distance;
2. Three fiber communication windows: 0.85µm, 1.31µm and 1.55µm;

Photon counting

1. Quantum cryptography;
2. Optical time-domain reflectometry;
3. Time-of-flight ranging;
4. Time-resolved photoluminescence.
Application

- Avalanche photodiode theory
- InGaAs/InP SAGCM APD
- Experimental results of basic structure
- Theory study of SAGCM APD
Avalanche Gain Mechanism

When the photogenerated or other primary free carriers gain sufficient energy from the electric field, additional (secondary) free carriers are generated by impact ionization of the valence electrons into the conduction band, leaving free holes in the valence band.

Secondary carriers that are generated in this way can in turn be accelerated by the electric field and generate more secondary carriers when they impact-ionize other valence electrons.
Impact-ionization coefficients

Definition: the reciprocal of the mean free path between ionizing collisions

Assumption:

\[ \alpha(E) = A \exp(-b/E) \]
\[ \beta(E) = A' \exp(-b'/E) \]

Experimental ionization coefficients for InP at room temperature:
(From Cook’s results)

<table>
<thead>
<tr>
<th>Doping level (cm$^{-3}$)</th>
<th>Field range (10$^5$ V/cm)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$\beta$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 $\times$ 10$^{15}$</td>
<td>2.4–3.8</td>
<td>1.12 $\times$ 10$^7$ exp ($-3.11 \times 10^9/E$)</td>
<td>4.79 $\times$ 10$^8$ exp ($-2.55 \times 10^9/E$)</td>
</tr>
<tr>
<td>3.0 $\times$ 10$^{16}$</td>
<td>3.6–5.6</td>
<td>2.93 $\times$ 10$^6$ exp ($-2.64 \times 10^8/E$)</td>
<td>1.62 $\times$ 10$^8$ exp ($-2.11 \times 10^8/E$)</td>
</tr>
<tr>
<td>1.2 $\times$ 10$^{17}$</td>
<td>5.3–7.7</td>
<td>2.32 $\times$ 10$^5$ exp ($-7.16 \times 10^{11}/E^2$)</td>
<td>2.48 $\times$ 10$^5$ exp ($-6.23 \times 10^{11}/E^2$)</td>
</tr>
</tbody>
</table>
Basic parameters:
1. **Dark current**
2. **Punch-through voltage**: Absorption region begins to be depleted.
3. **Break down voltage**: Avalanche gain is infinite.

Working mode:
1. **Linear**
2. **Geiger**
   An APD is usually dc biased a few volts below its breakdown voltage, and is periodically pulse biased above its breakdown voltage for a short time.
Dark currents

- Generation-recombination
- Diffusion
- Thermionic emission
- Tunneling
  - Band-to-band tunneling (BBT)
  - Trap-assisted tunneling (TAT)
Basic parameters:
1. Dark current
2. Punch-through voltage: Absorption region begins to be depleted.
3. Break down voltage: Avalanche gain is infinite.

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2. Geiger

An APD is usually dc biased a few volts below its breakdown voltage, and is periodically pulse biased above its breakdown voltage for a short time.
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- Avalanche photodiode theory
- InGaAs/InP SAGCM APD
- Experimental results of basic structure
- Theory study of SAGCM APD
Material characteristics

1. Band gap (at room temperature)

\[ E_{\text{InGaAs}} = 0.77\, eV \quad E_{\text{InP}} = 1.34\, eV \]

2. Absorption coefficients (at 1.55\, \mu\text{m})

\[ \alpha_{\text{InGaAs}} \gg \alpha_{\text{InP}} \]

3. Ionization coefficients

\[ \alpha(e)_{\text{InGaAs}} > \beta(h)_{\text{InGaAs}} \quad \alpha(e)_{\text{InP}} < \beta(h)_{\text{InP}} \]
Device structure
SAGCM APD
(Separate absorption, grading, charge, and multiplication avalanche photodiode):

Characteristics:

1. Separate absorption and multiplication layers:
   
   Prohibit tunneling in the low bandgap absorbing InGaAs ternary layer

2. Charge layer:
   
   Control the electric field more easily, the electric field is sufficiently high within the InP to support avalanche multiplication, yet low enough in the small bandgap InGaAs to prevent interband tunneling and impact ionization.

3. InGaAsP grading region:
   
   Avoid hole trapping at the interface
- Application
- Avalanche photodiode theory
- InGaAs/InP SAGCM APD
- *Experimental results of basic structure*
- Theory study of SAGCM APD
Basic structure

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Carrier Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25µm</td>
<td>n⁻ InP</td>
<td>1e15 cm⁻³</td>
</tr>
<tr>
<td>0.17µm</td>
<td>n⁺ InP charge</td>
<td>1e17 cm⁻³</td>
</tr>
<tr>
<td>0.08µm</td>
<td>n InGaAsP grade</td>
<td>2e16 cm⁻³</td>
</tr>
<tr>
<td>2.8µm</td>
<td>n⁻ InGaAs</td>
<td>1e15 cm⁻³</td>
</tr>
<tr>
<td>0.5µm</td>
<td>n⁻ InP buffer</td>
<td>1e15 cm⁻³</td>
</tr>
<tr>
<td></td>
<td>n⁺ InP substrate</td>
<td>1e18 cm⁻³</td>
</tr>
</tbody>
</table>
Planform of our SPADs
Single photon experimental results of our basic structure (at room temperature)

We can see from the I-V curve that the breakdown voltage is 63V, and the dark current is 3nA at 95% of the breakdown voltage.

In the gated mode, a dark-count probability of \(6.5 \times 10^{-5}\) per pulse at room temperature at 1310nm was measured with a fixed detection efficiency of 10%.
Application

Avalanche photodiode theory

InGaAs/InP SAGCM APD

Experimental results of basic structure

Theory study of SAGCM APD
The basic equations of numerical simulation

Continuity equations:

\[
-\frac{1}{q} \nabla \cdot J_n + R + \frac{\partial n}{\partial t} = 0 \quad \frac{1}{q} \nabla \cdot J_p + R + \frac{\partial p}{\partial t} = 0
\]

Poisson equation:

\[
\nabla \psi = -q(p - n + N_D - N_A) / \varepsilon
\]

Current densities equations:

\[
J_n = -q \mu_n n \nabla \phi_n \quad J_p = -q \mu_p p \nabla \phi_p
\]

The simulation was performed using Sentaurus Device, a commercial package by Synopsys.
Numerical simulation models:

1. Transport model: drift-diffusion model

2. Mobility models: doping dependent, highfield saturation;

3. Generation–recombination models: Shockley–Read–Hall, Auger, Band to band tunneling, Trap-assisted tunneling, Radiative;

4. Avalanche model: van Overstraeten–de Man model;

5. Termionic emission model
For a SPAD, the dark count probability, which is dependent on the number of dark carriers and the avalanche probability, is an important parameter. Therefore, it is significant to make a detailed study of the dark current on the influence of the variation of the structure.

Theory study dark current and other parameters from these aspects:

- **Basic structure**
- Changing the thickness of the charge layer
- Changing the thickness of the multiplication layer
- Changing the number of the grating layers
Band gap structure
Electric field

- Multiplication layer
- Charge layer
- Absorption layer

Parameters:
- Voltage: 0V, 14V, 28V, 42V, 56V, 70V
- Electric field (V/cm) range: 0 to 400,000
- X-axis (μm) range: 0 to 6
I-V plot (numerical results vs. experimental results)
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- **Basic structure**
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- **Changing the thickness of the multiplication layer**
- **Changing the number of the grating layers**
Electric field (63V)

As the increasing of charge layer thickness, the electric field of multiplication layer increases, but the electric field of absorption layer decreases.
The avalanche happens before punch through, when the thickness of the charge layer is 0.40 μm
Breakdown voltages and dark currents at 95% of the breakdown voltages

There is a minimal dark current when the charge layer thickness is 0.14 μm. We may conclude that when the charge layer is thicker than 0.14 μm, the dominant part of the dark current is the tunneling and generation current in high field region, else, is the tunneling and generation current in absorption layer.
For a SPAD, the dark count probability, which is dependent on the number of dark carriers and the avalanche probability, is an important parameter. Therefore, it is significant to make a detailed study of the dark current on the influence of the variation of the structure.

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- Basic structure
- Changing the thickness of the charge layer
- Changing the thickness of the multiplication layer
- Changing the number of the grating layers
Electric field (at the breakdown voltage)

As the increasing of multiplication layer thickness, both electric fields of multiplication layer and absorption layer decrease at the breakdown voltage.
I-V plot

- Total Current (A)
- Voltage (V)

- Multiplication layer thickness (μm)
  - 0.1
  - 0.25
  - 0.35
  - 0.6
  - 0.8
  - 1.0
  - 1.4
  - 1.8
  - 2.0
  - 2.1
Breakdown voltages and dark currents at 95% of the breakdown voltages

As the increasing of multiplication thickness, there is a maximal dark current, and there are maximal and minimal breakdown voltages, which are due to the influence of both the electric field profile and the effective multiplication length.
For a SPAD, the dark count probability, which is dependent on the number of dark carriers and the avalanche probability, is an important parameter. Therefore, it is significant to make a detailed study of the dark current on the influence of the variation of the structure.

Theory study dark current and other parameters from these aspects:

- **Basic structure**
- **Changing the thickness of the charge layer**
- **Changing the thickness of the multiplication layer**
- **Changing the number of the grating layers**
Dark currents at 95% of breakdown voltages

For a SPAD which is operated at the Geiger mode, there is no hole trap at the InGaAs/InP interface when it is worked at a high reverse bias voltage. Therefore, to reduce the dark current, it may be no need for so many InGaAsP grading layers.
Conclusion

Theoretical study of the SAGCM SPAD

- The thickness of the charge layer
- The thickness of the multiplication layer
- The number of the grading layers

How alterations in the device geometry can affect its performance
The way to reduce the dark currents
Thank you!