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*

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- Optical fiber communication systems

  1.High bit-rate and long distance;

  2.Three fiber communication windows: 0.85μm、**1.31**μm and **1.55**μm;

- Photon counting

  1.Quantum cryptography**;**

  2.Optical time-domain reflectometry;

  3.Time-of-flight ranging;

  4.Time-resolved photoluminescence.

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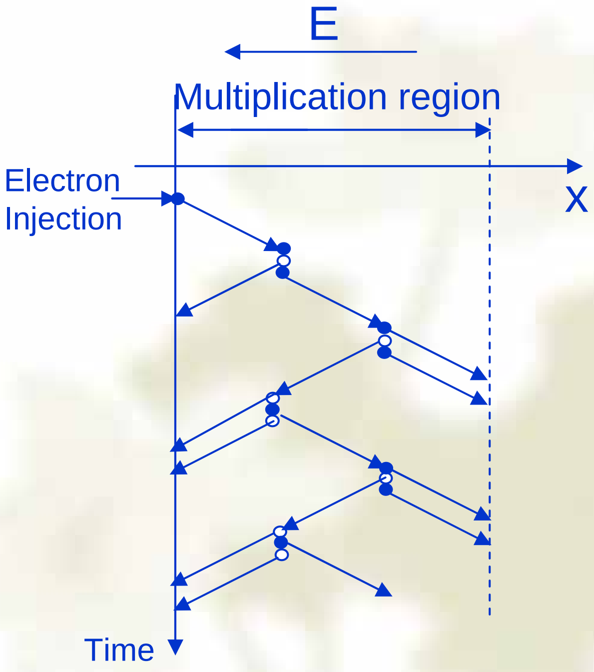
❖ Avalanche Gain Mechanism

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

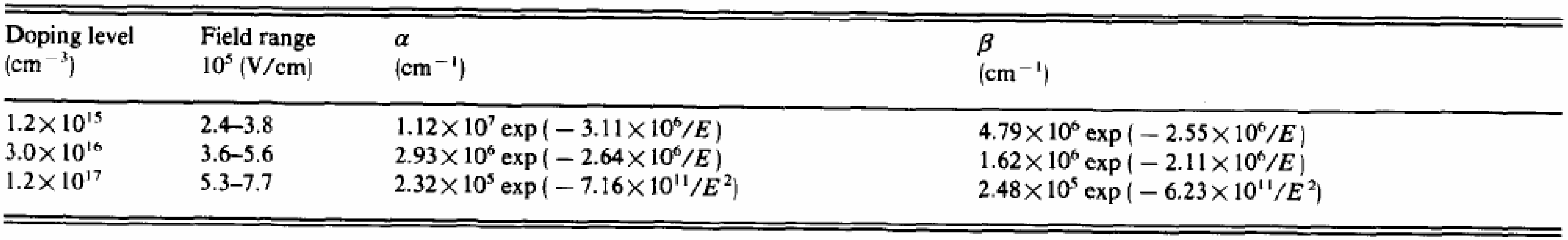
Assumption:

$$\alpha(E) = A\exp(-b/E)$$

$$\beta(E) = A'\exp(-b'/E)$$

Experimental ionization coefficients for InP at room temperature:

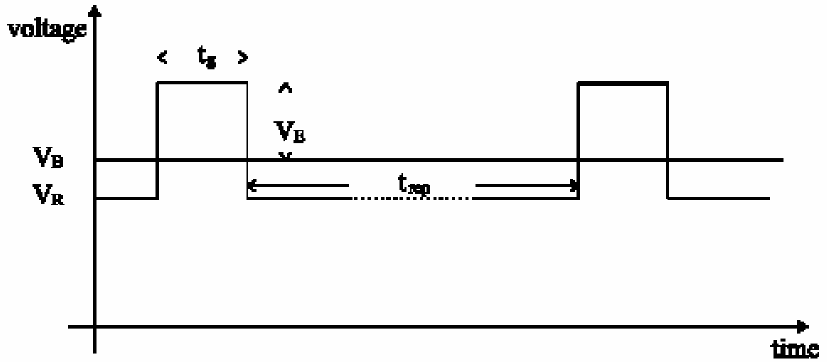
(From Cook's results)



Doping level (cm^{-3})	Field range 10^5 (V/cm)	α (cm^{-1})	β (cm^{-1})
1.2×10^{15}	2.4–3.8	$1.12\times10^{7}\exp(-3.11\times10^{6}/E)$	$4.79\times10^{6}\exp(-2.55\times10^{6}/E)$
3.0×10^{16}	3.6–5.6	$2.93\times10^{6}\exp(-2.64\times10^{6}/E)$	$1.62\times10^{6}\exp(-2.11\times10^{6}/E)$
1.2×10^{17}	5.3–7.7	$2.32\times10^{5}\exp(-7.16\times10^{11}/E^{2})$	$2.48\times10^{5}\exp(-6.23\times10^{11}/E^{2})$

- 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）

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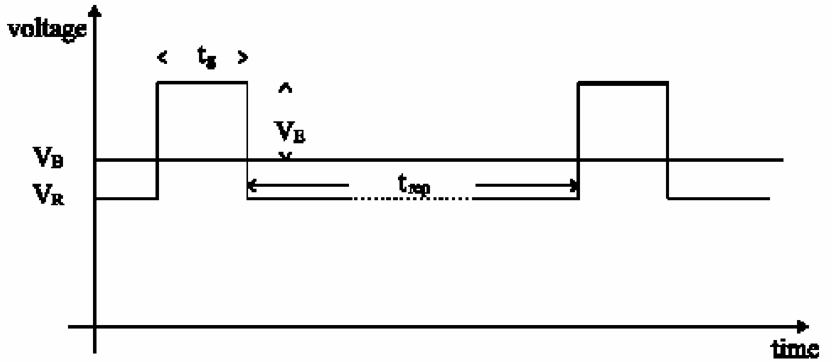

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❖ Material characteristics

1.Band gap (at room temperature)

$$E_{InGaAs} = 0.77eV \qquad E_{InP} = 1.34eV$$

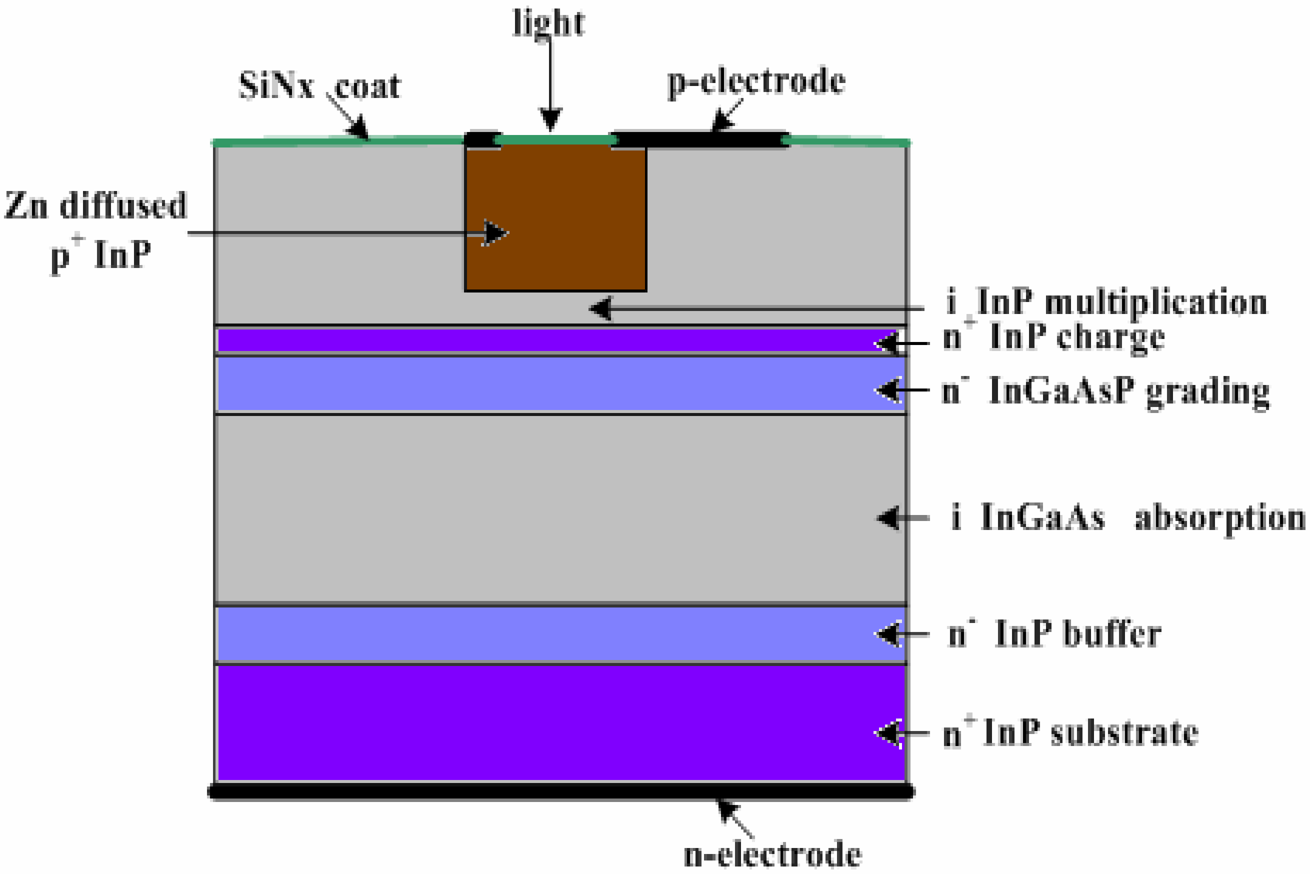
2.Absorption coefficients (at 1.55μm)

$$\alpha_{InGaAs} >> \alpha_{InP}$$

3.Ionization coefficients

$$\alpha(e)_{InGaAs} > \beta(h)_{InGaAs} \qquad \alpha(e)_{InP} < \beta(h)_{InP}$$

❖ Device structure



SAGCM APD

(Separate absorption, grading, charge, and multiplication avalanche photodiode) :

Characteristics:

1.Separate absorption and multiplication layers:

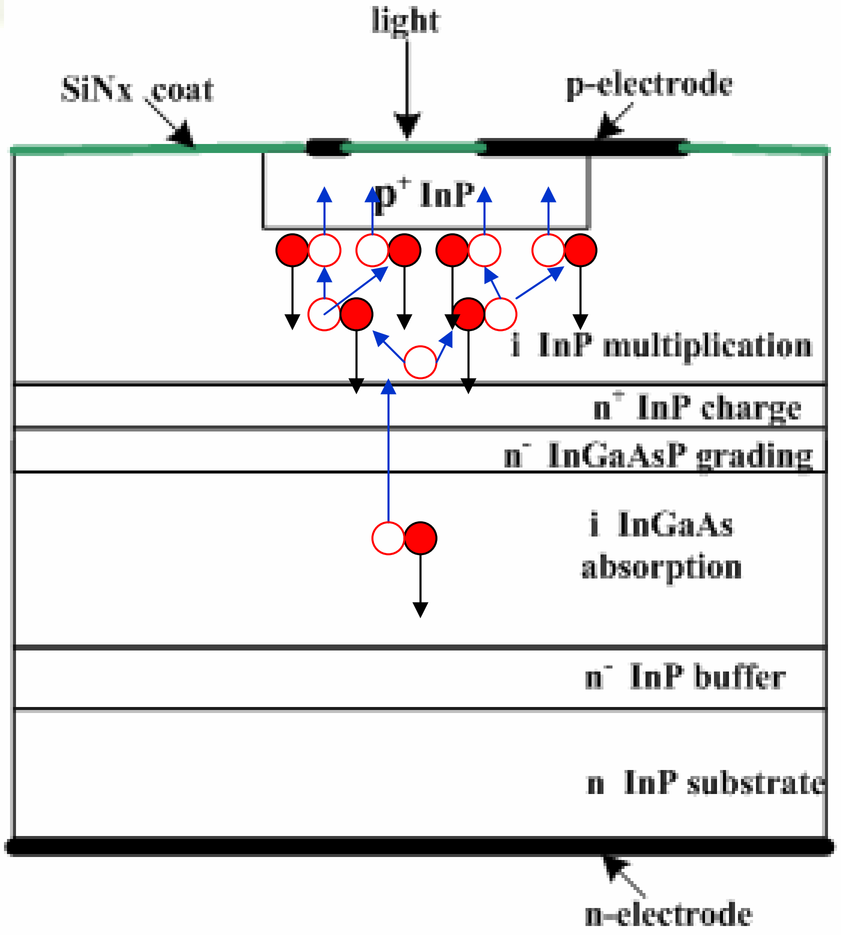
Prohibit tunneling in the low bandgap absorbing InGaAs ternary layer

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


light
SiNx coat
p-electrode
p+ InP
i InP multiplication
n+ InP charge
n- InGaAsP grading
i InGaAs
absorption
n- InP buffer
n InP substrate
n-electrode

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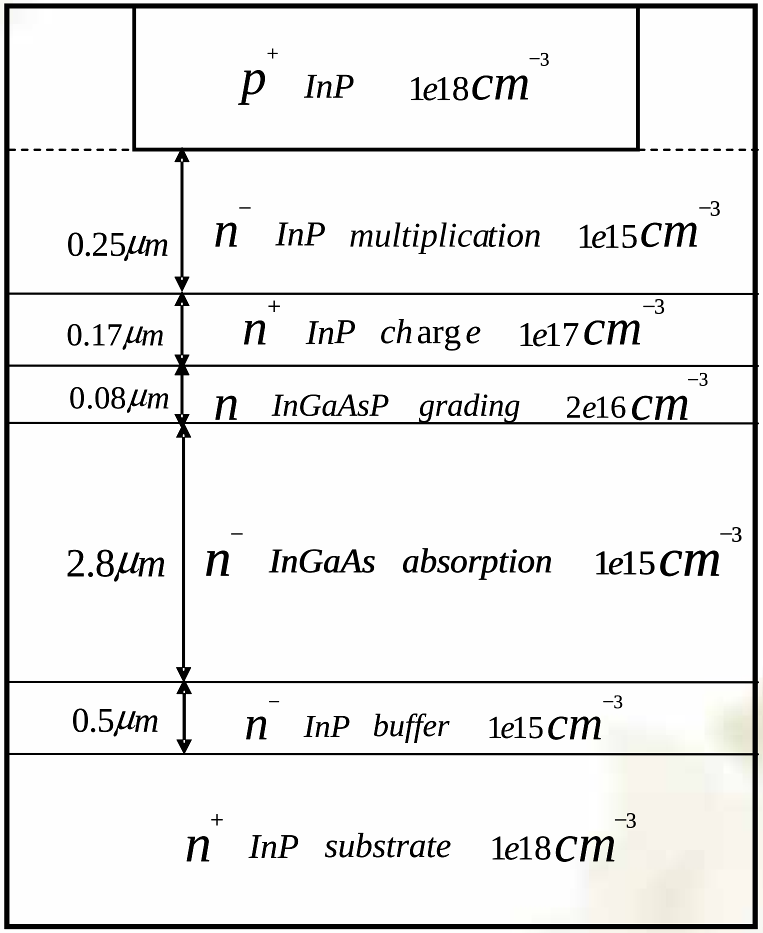

p^{+} InP $1e18\,cm^{-3}$

$0.25\mu m$ n^{-} InP multiplication $1e15\,cm^{-3}$

$0.17\mu m$ n^{+} InP charge $1e17\,cm^{-3}$

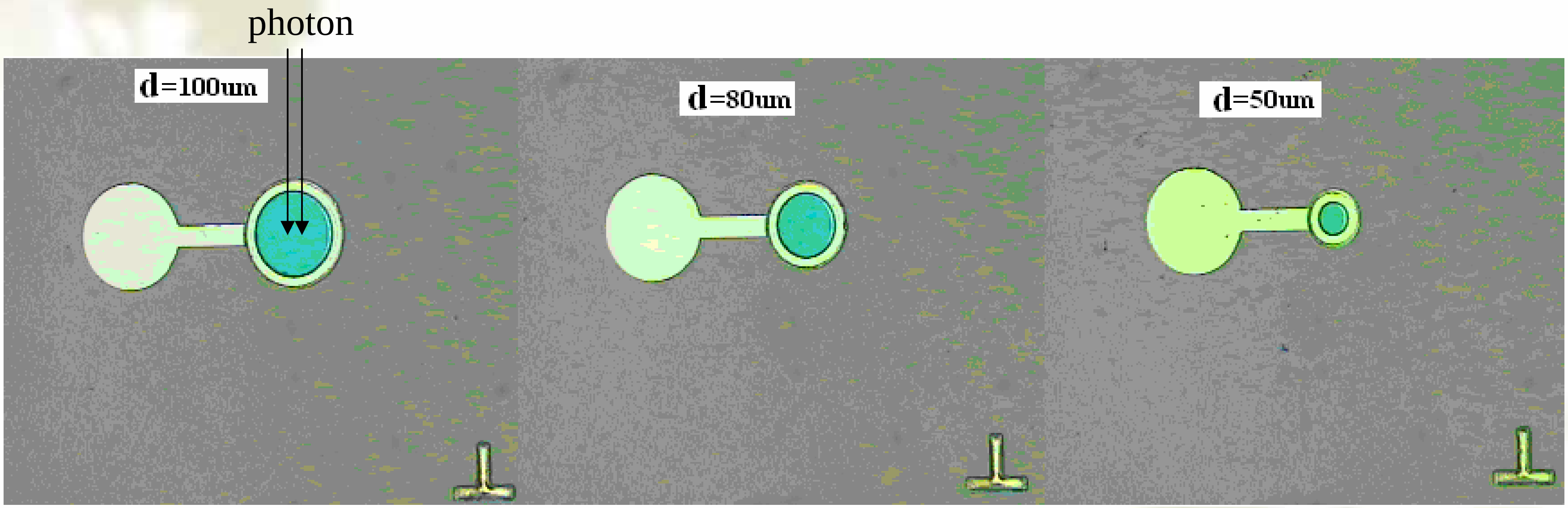
$0.08\mu m$ n InGaAsP grading $2e16\,cm^{-3}$

$2.8\mu m$ n^{-} InGaAs absorption $1e15\,cm^{-3}$

$0.5\mu m$ n^{-} InP buffer $1e15\,cm^{-3}$

n^{+} InP substrate $1e18\,cm^{-3}$

Basic structure

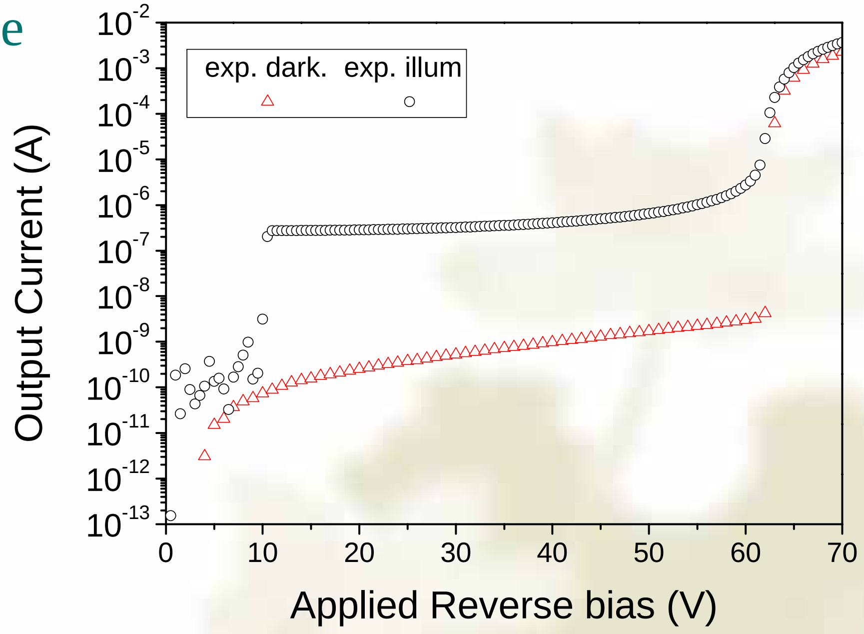


Planform of our SPADs

❖ 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 6.5×10-5 per pulse at room temperature at 1310nm was measured with a fixed detection efficiency of 10%.

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The basic equations of numerical simulation

Continuity equations: $-\frac{1}{q}\nabla \bullet J_n + R + \frac{\partial n}{\partial t} = 0$ $\frac{1}{q}\nabla \bullet J_p + R + \frac{\partial p}{\partial t} = 0$

Poisson equation: $\nabla \psi = -q(p - n + N_D - N_A)/\varepsilon$

Current densities equations: $J_n = -q\mu_n n \nabla \phi_n$ $J_p = -q\mu_p p \nabla \phi_p$

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;*

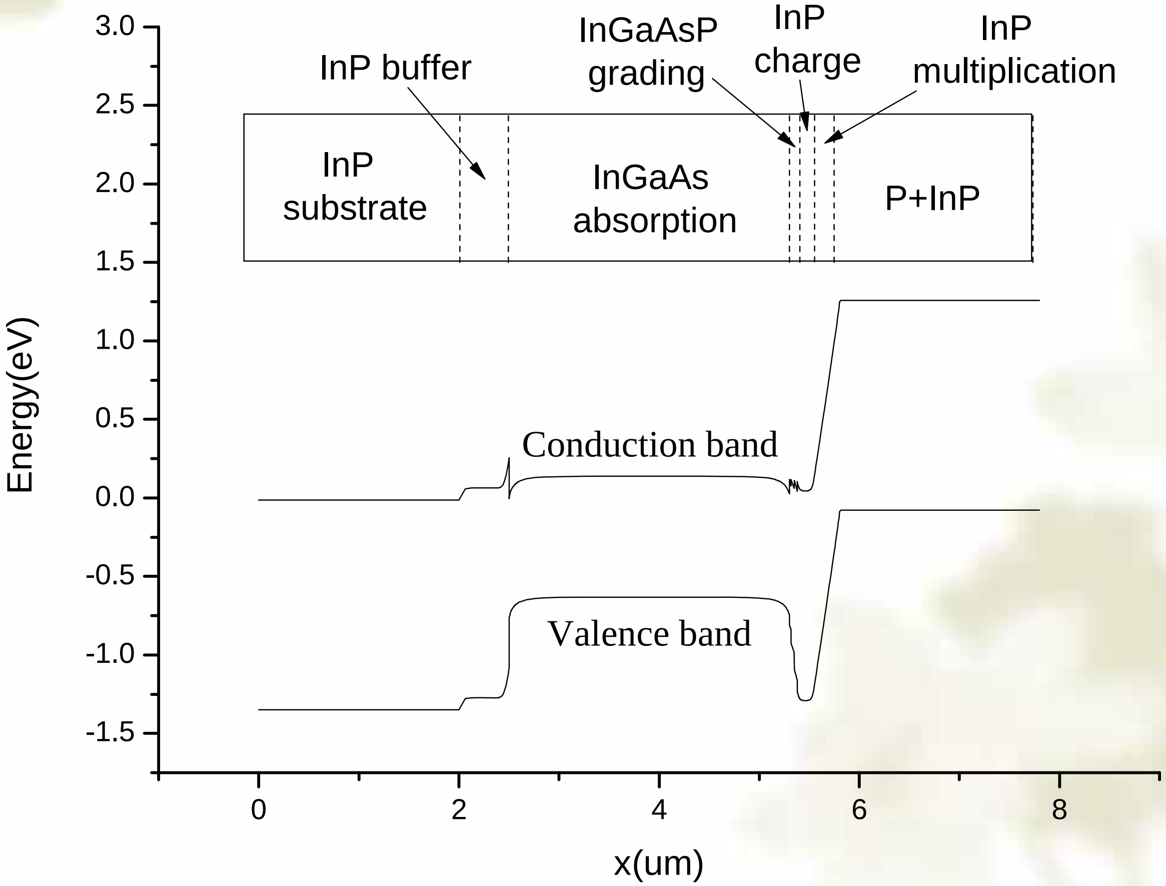
5. Termionic emission model

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.

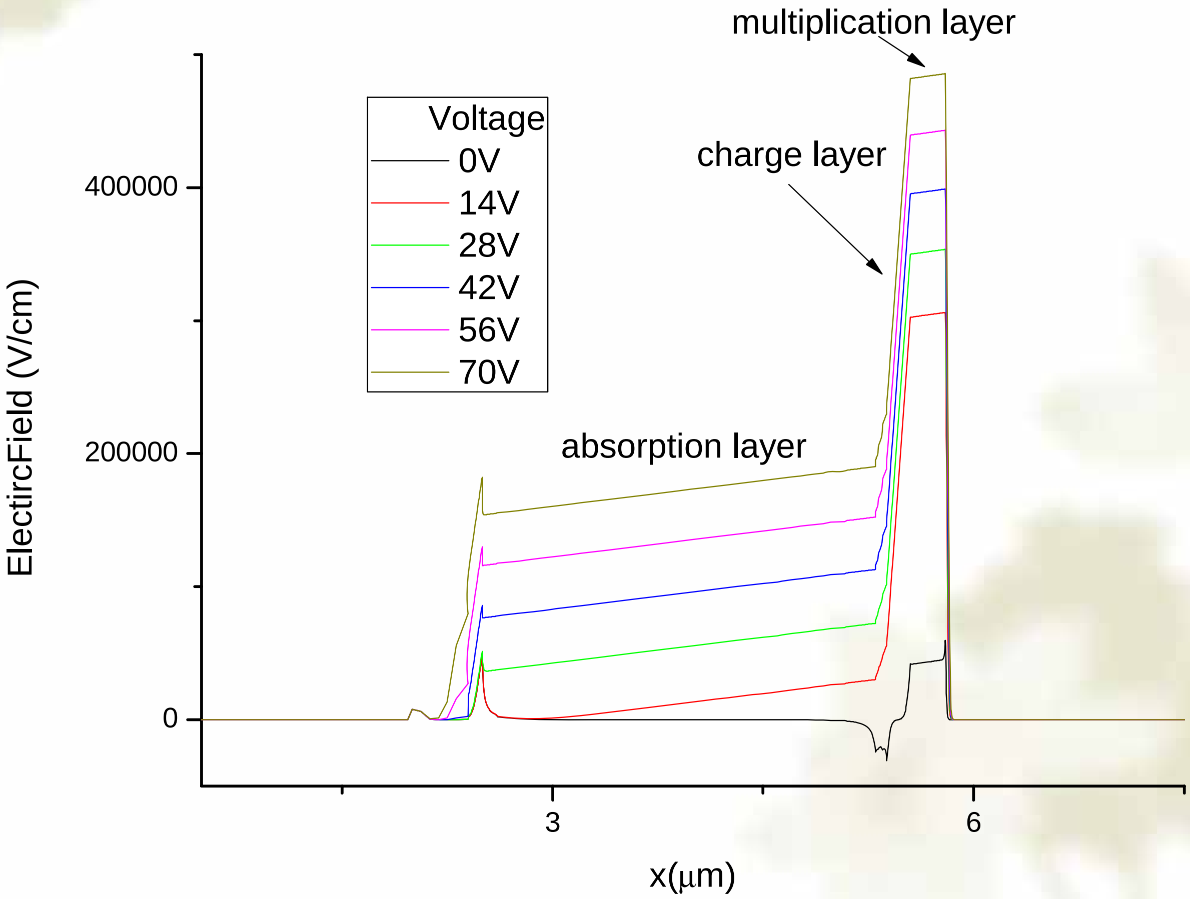
Theory study dark current and other parameters from these aspects:

- Basic structure
- Changing the thickness of the charge layer
- Changing the thickness of the multiplication layer
- Changing the number of the grating layers

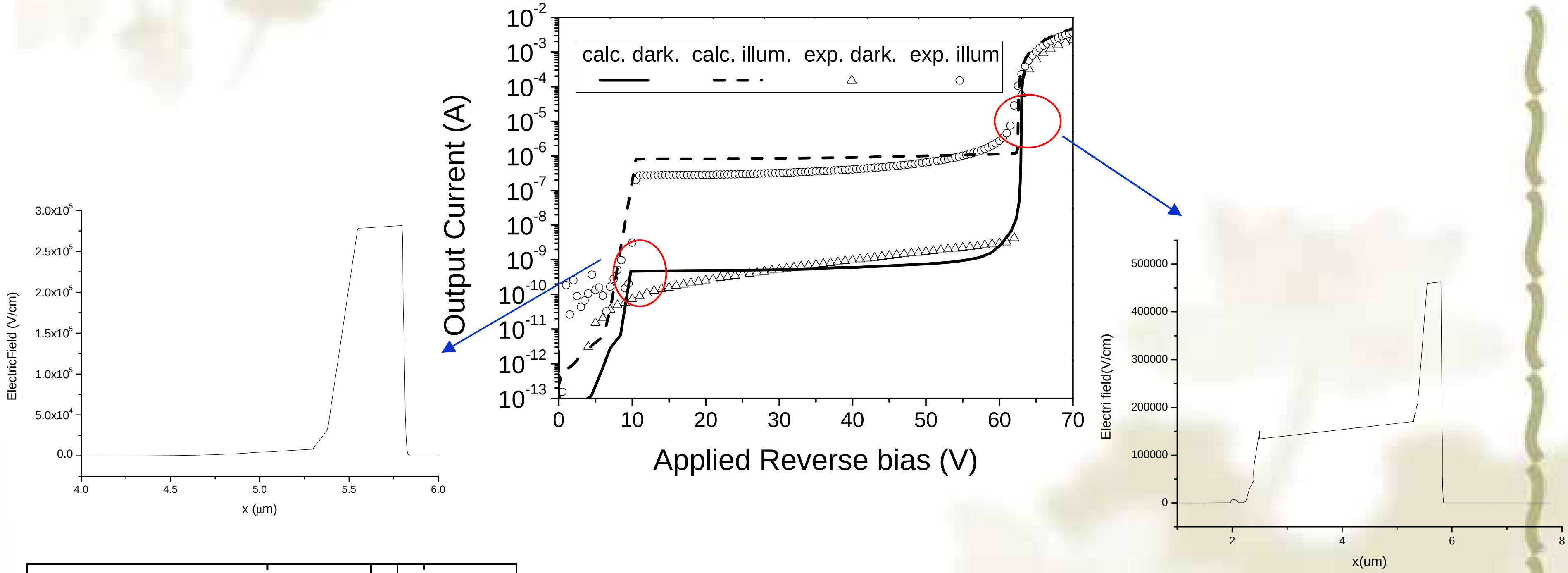
- Band gap structure

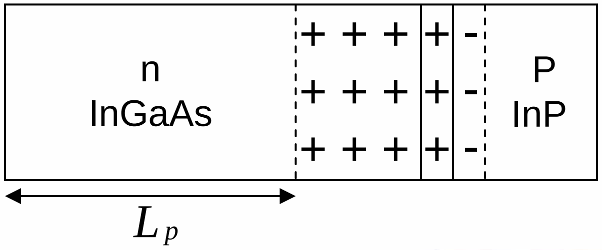


Electric field



- I-V plot (numerical results vs. experimental results)





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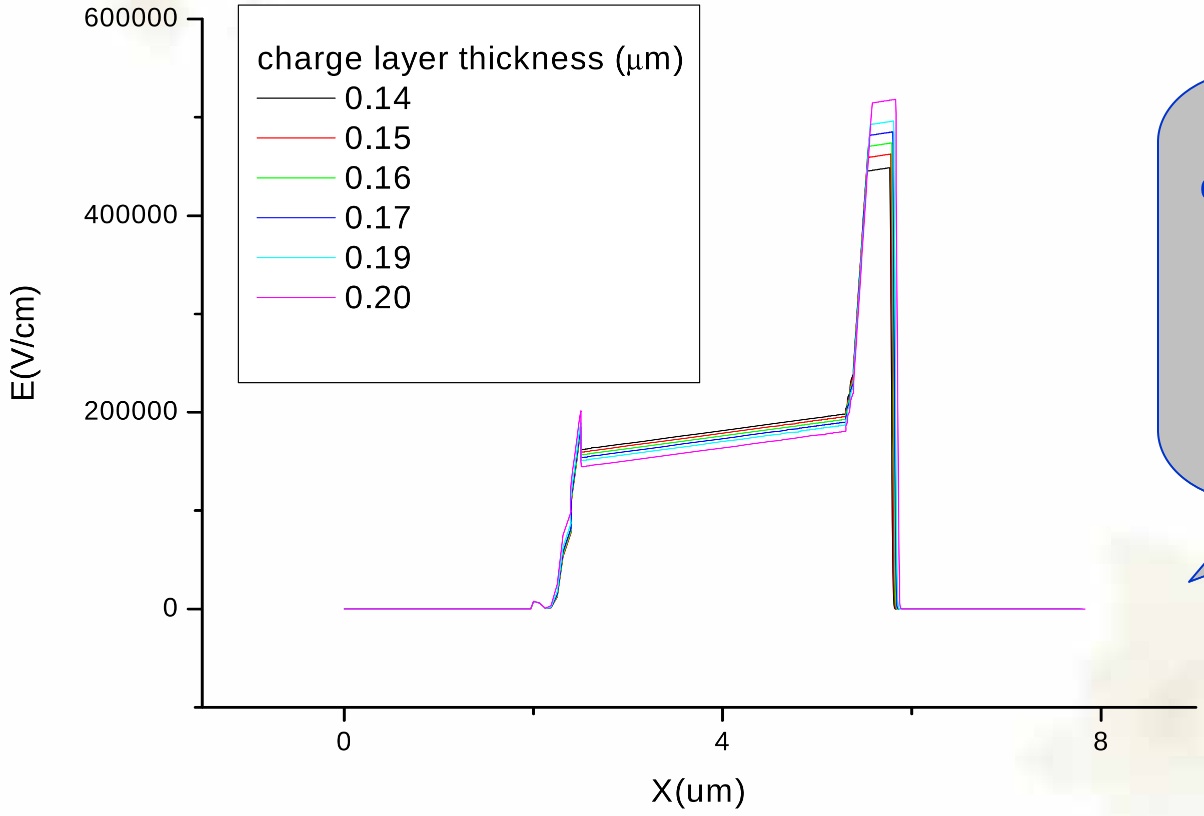
Theory study dark current and other parameters from these aspects:

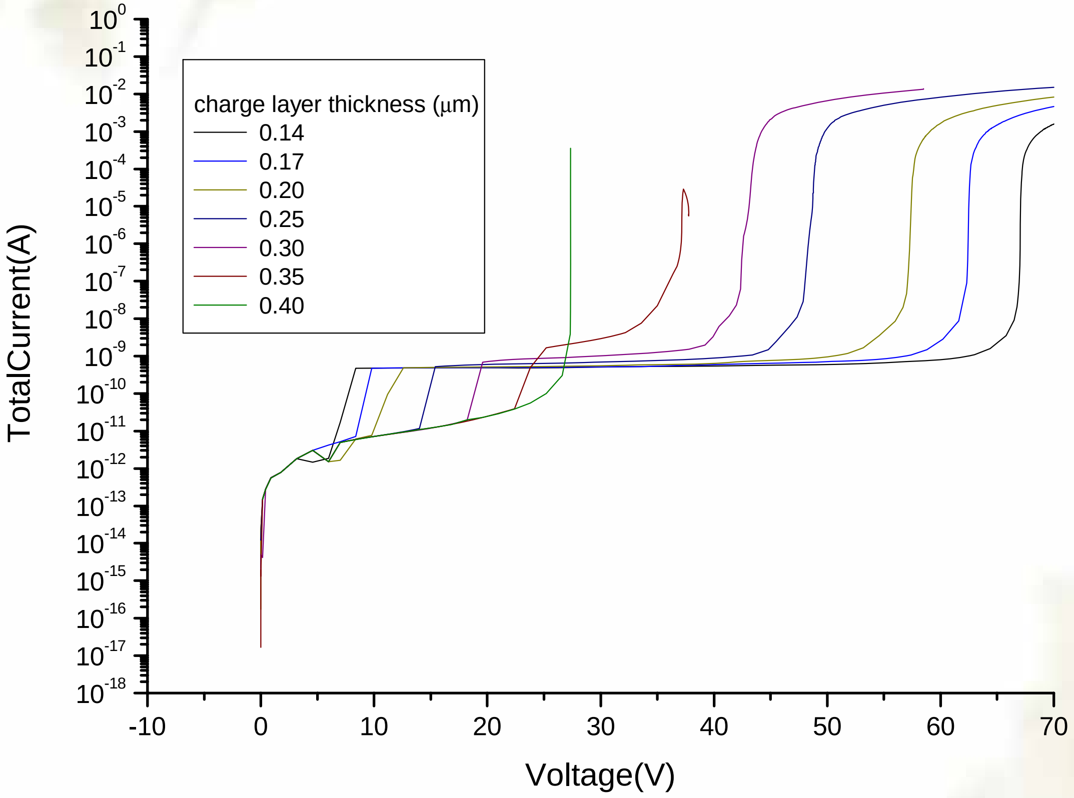
- Basic structure
- <u>Changing the thickness of the charge layer</u>
- Changing the thickness of the multiplication layer
- Changing the number of the grating layers

❖ Electric field (63V)



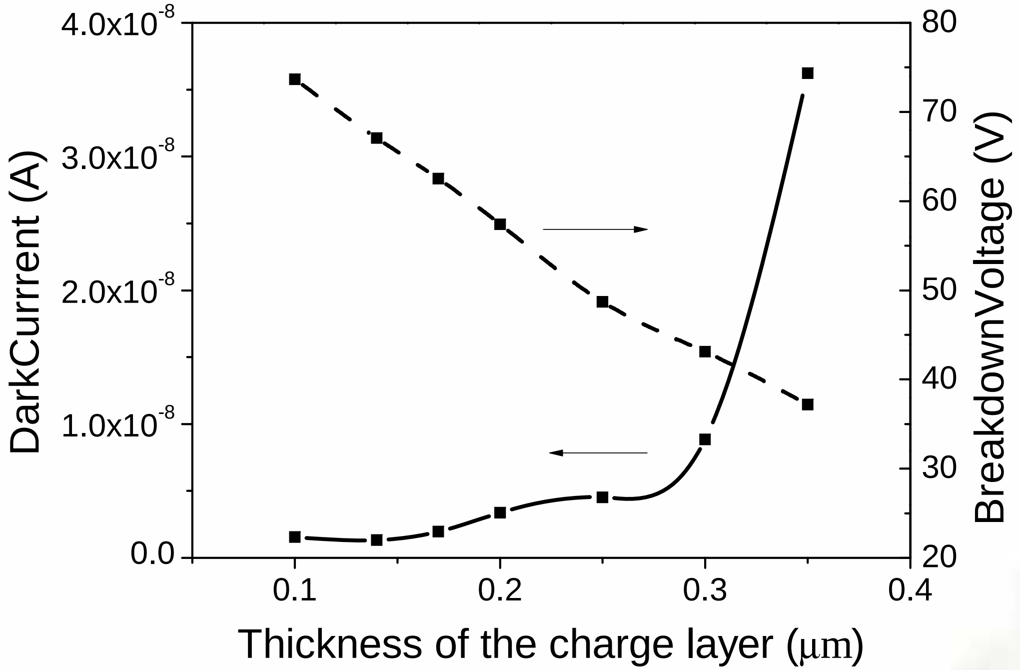
As the increasing of charge layer thickness, the electric field of multiplication layer increases, but the electric field of absorption layer decreases.

❖ I-V plot



The avalanche happens before punch through, when the thickness of the charge layer is 0.40 μ m

- Breakdown voltages and dark currents at 95% of the breakdown voltages



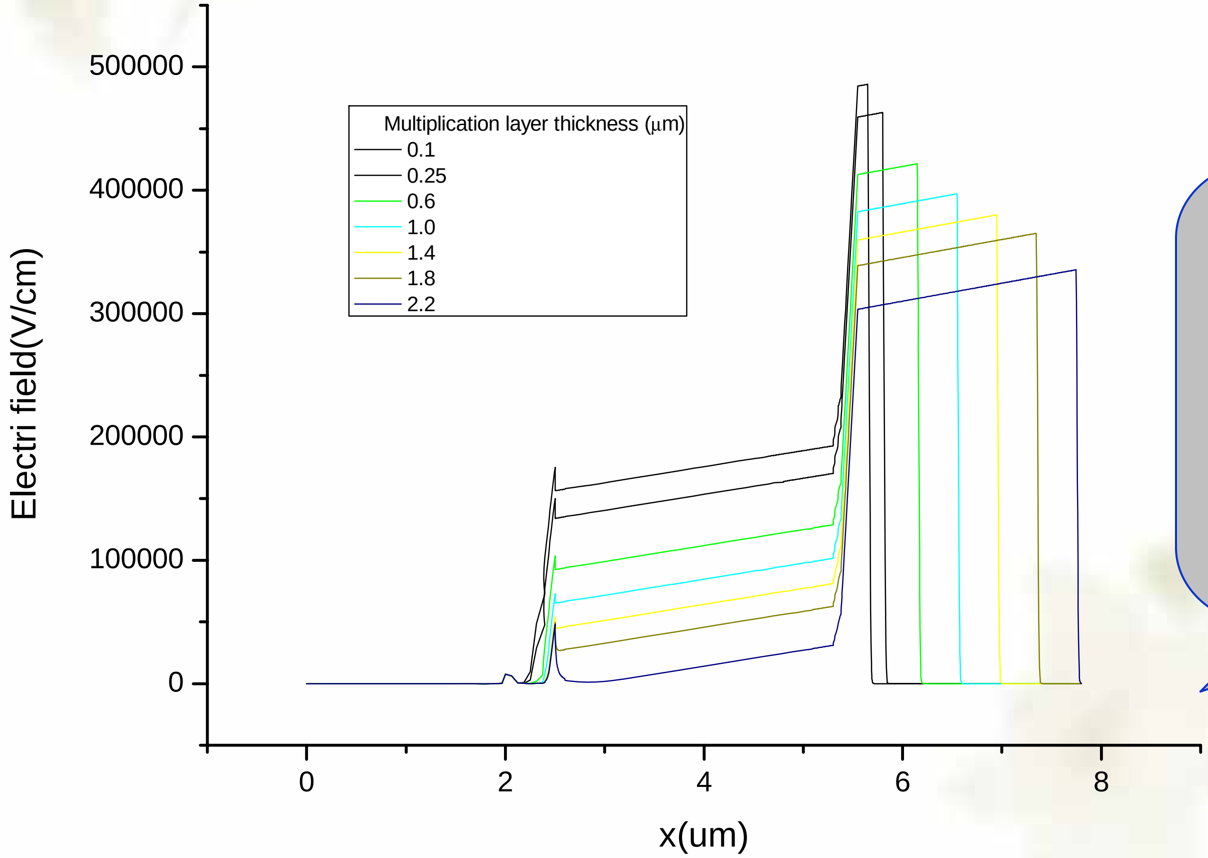
There is a minimal dark current when the charge layer thickness is 0.14 μ m. We may conclude that when the charge layer is thicker than 0.14 μ m, the dominant part of the dark current is the tunneling and generation current in high field region, else, is the tunneling and generation current in absorption 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.

Theory study dark current and other parameters from these aspects:

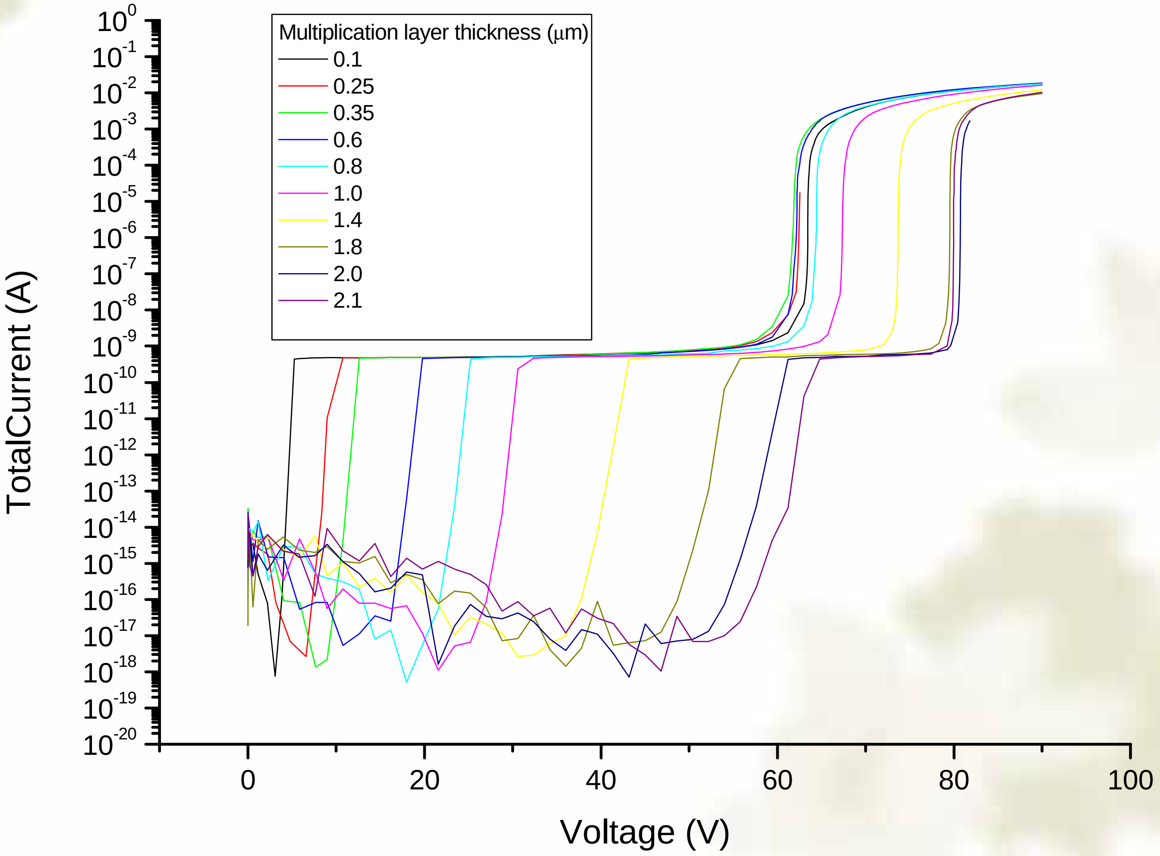
- Basic structure
- Changing the thickness of the charge layer
- Changing the thickness of the multiplication layer
- Changing the number of the grating layers

❖ Electric field (at the breakdown voltage)

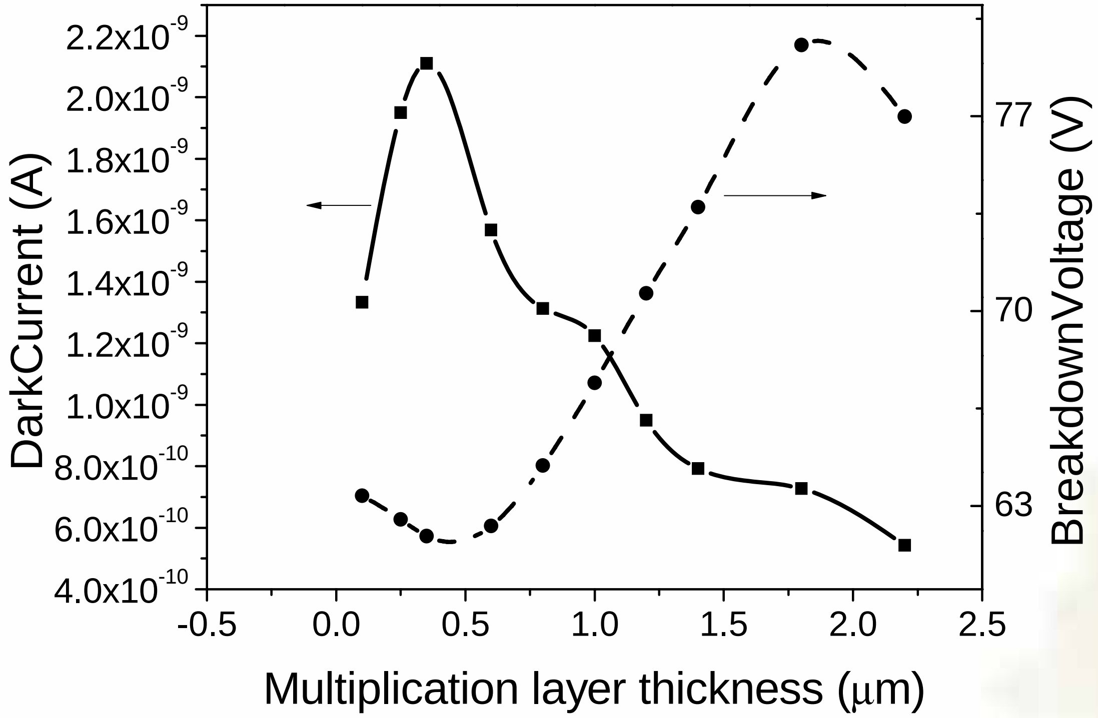


As the increasing of multiplication layer thickness, both electric fields of multiplication layer and absorption layer decrease at the breakdown voltage.

❖ I-V plot


Multiplication layer thickness (μm)
0.1
0.25
0.35
0.6
0.8
1.0
1.4
1.8
2.0
2.1
TotalCurrent (A)
Voltage (V)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10^-19
10^-20
0
20
40
60
80
100

❖ Breakdown voltages and dark currents at 95% of the breakdown voltages



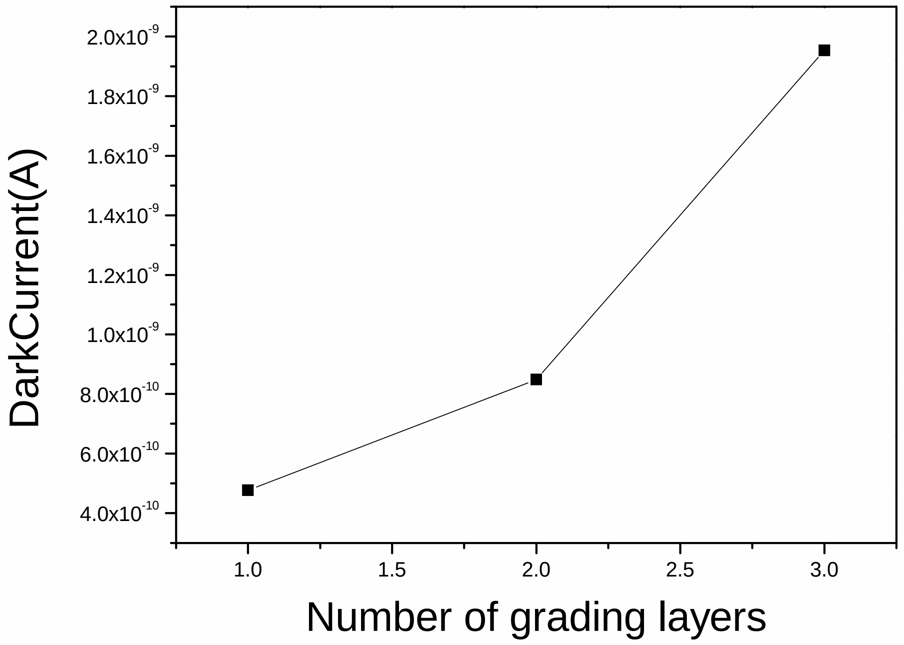
As the increasing of multiplication thickness, there is a maximal dark current, and there are maximal and minimal breakdown voltages, which are due to the influence of both the electric field profile and the effective multiplication length.

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!