Characterization of silicon n^+-p-p^+ detectors with Al_2O_3 passivating layers grown by Atomic Layer Deposition method

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Al_2O_3 layers processed by ALD

Atomic Layer Deposition (ALD) Al_2O_3 layers – suggested for surface passivation in devices on p-Si with low and high Si resistivity

1. B. Hoex, et al., Appl. Phys. Lett., 91, 112107 (2007)
2. F. Werner, et al., J. Appl. Phys. 109, 113701 (2011)
3. M. Christophersen and B. F. Philips, 2011 IEEE Nucl. Sci. Symp. Conf. Rec., p. 113
4. J. Härkönen, et al., Nucl. Instrum. Meth. A 828 (2016) 46
5. J. Härkönen, et al., Nucl. Instrum. Meth. A 831 (2016) 2

ALD method of Al_2O_3 processing:

Low temperatures (200-300°C)
After standard planar technology process
Thin films (tens of nm)
Negative charge, $Q_f = -(10^{11}\text{-}10^{13})$ cm^{-2} (referred data)
– allows to isolate n^+ segments and simplify design and processing of n-on-p detectors

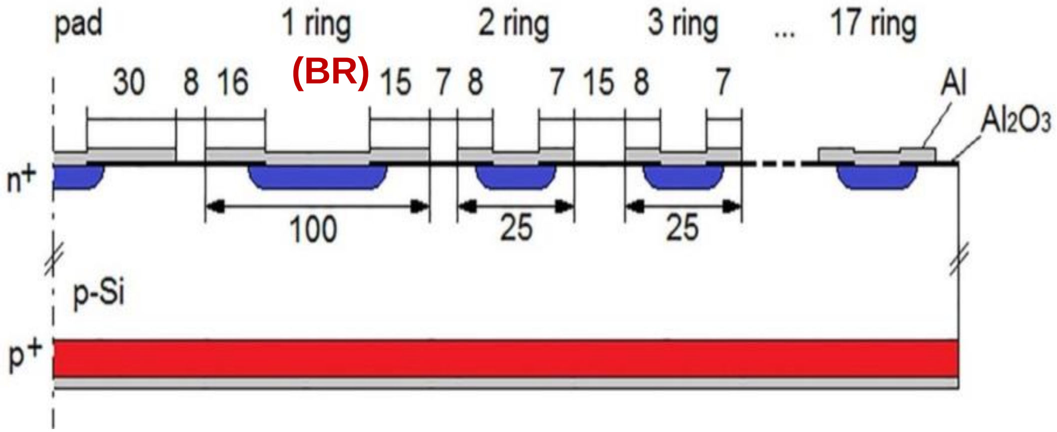
Goals of the study

Approach: to combine experimental data and TCAD simulations for characterizing n-on-p Si detectors with alumina isolating layers

- Measure the characteristics of n^+-p-p^+ silicon detectors with Al_2O_3 isolation films designed for high voltage operation
- Simulate the potentials and electric field in the n-on-p detector with multiple n^+ rings
- Extract the fixed charge density Q_f in Al_2O_3 in the detector under study
- Estimate the impact of the charge density Q_f in Al_2O_3 on the electric field
- Define the parameters of the detector design allowing to maintain high voltage operation

The results are published in: V. Eremin, et al., 2018 JINST 13 P11009

Si n^+-p-p^+ detectors with Voltage Termination Structure (VTS)



n-on-p detector with **bias ring (BR) + 16 floating guard rings - Voltage Terminating Structure (VTS)** distributing the bias /potential over the rings

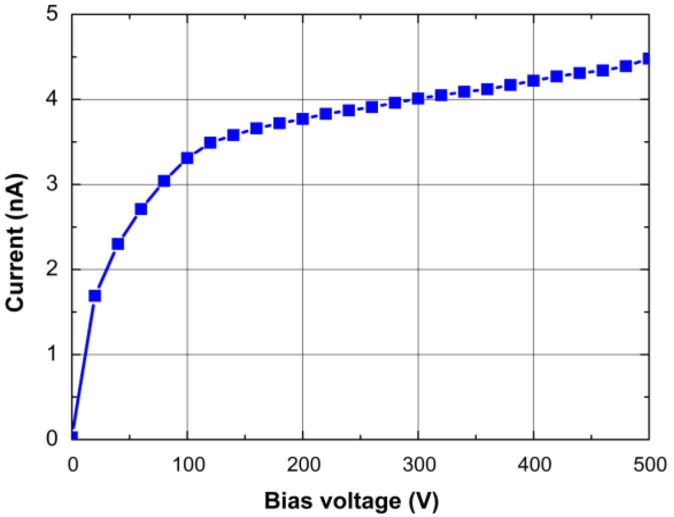
MCz p-type silicon, ρ = 7 kΩcm, (N_{eff} = 1.9×10^{12} cm^{-3}), d = 300 μm V_{fd} = 125 V

active area 5 × 5 mm^2

See presentation of Jennifer Ott

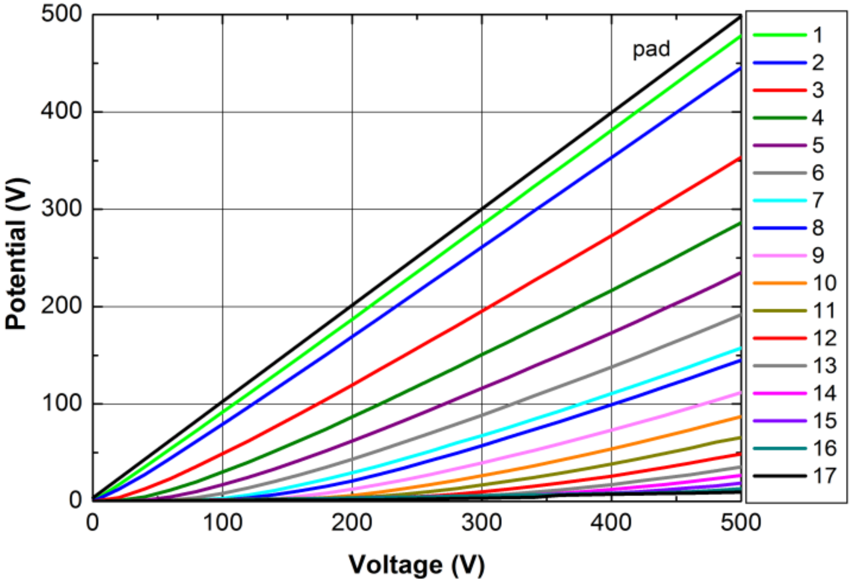
- ALD at 200-300°C after ion implantation and annealing
- mean Al_2O_3 thickness about 50 nm
- Q_f in the range of -(10^{11}-10^{12}) cm^{-2}

I-V characteristic

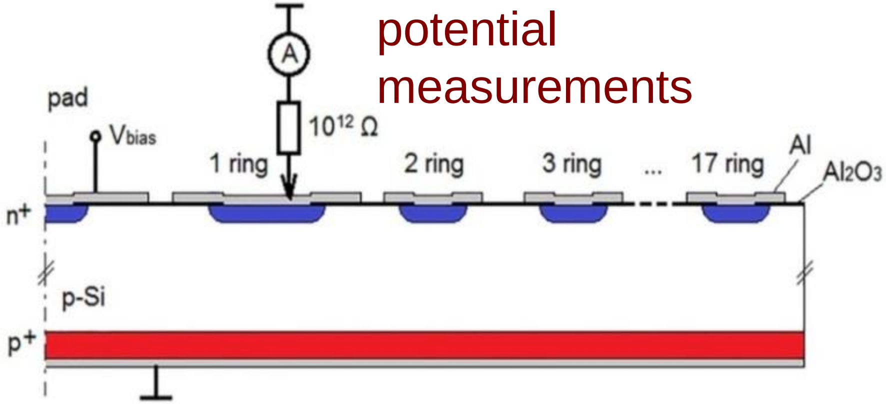


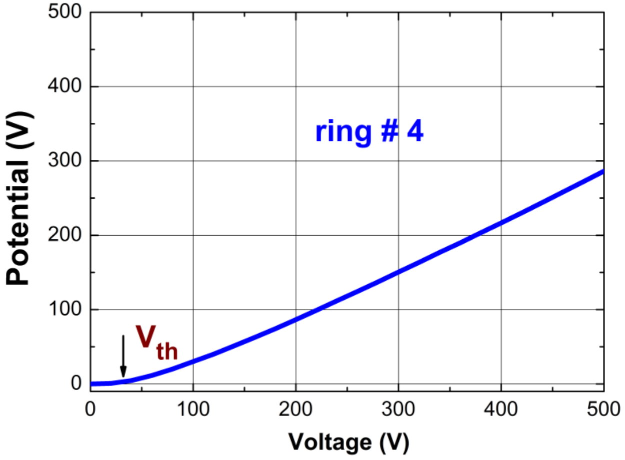
Potential distribution in Si n-on-p detectors with VTS

Distribution of potential φ over the rings vs. applied bias V_b



Schematic of the ring potential measurements





φ vs. V_b curves show two regions:

- the flat region with a zero potential,
- region of the gradual potential rise starting at threshold voltage V_{th}.

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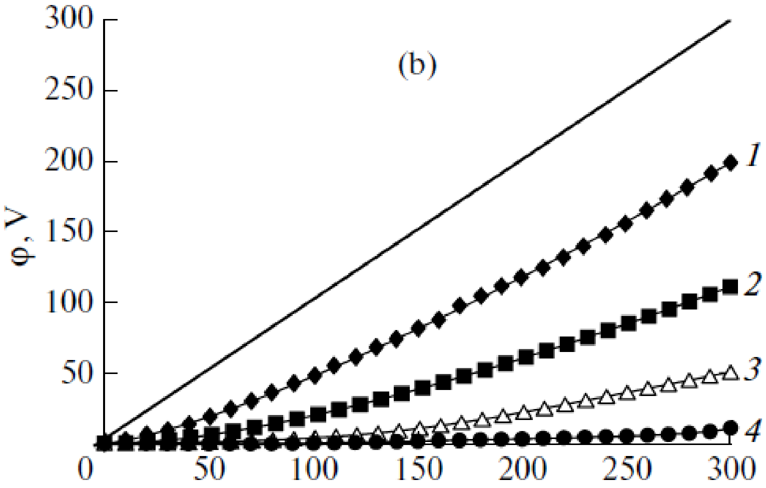
Punch-through mechanism of potential distribution over the rings

φ(Vb) curves in p-on-n detectors with SiO_2 isolation (positive charge in SiO_2)



V. Eremin et al., *Semiconductors* (2011) **45**, No. 4, 536)

Similar shapes of φ(Vb) curves in p-on-n detectors with SiO_2 isolation (positive charge in SiO_2) and in n-on-p detectors with Al_2O_3 isolation (negative charge in alumina) evidences t**he same punch-through mechanism of potential transfer:**

coupling of neighboring rings occurs via carrier injection from inner ring to the outer ring that switches one of the junctions in forward direction

Difference	
p-on-n with SiO_2 – hole injection from p^+	**n-on-p with Al_2O_3 – electron injection from n^+**

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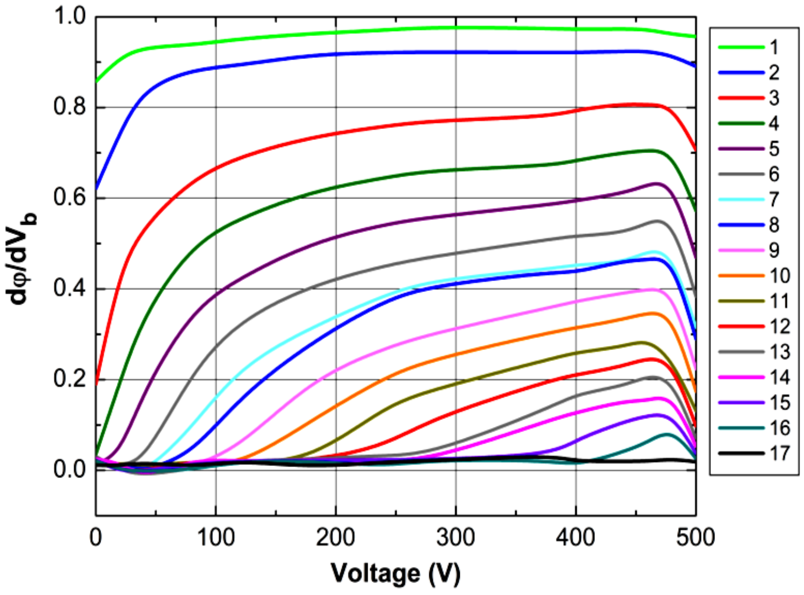
Rate of potential growth

V_{th} is visualized in the dependence of derivative dφ/dV_b vs. V_b → shows the rate of potential growth



V_{th} is about zero for the rings 1-4;

At $V_b > V_{th}$ the rate of potential growth is not constant:
first increases and then is low or close to zero → manifests reaching the steady-state potential value;

At V_b > 450 V the rate of the φ rise drops.

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Simulations of potentials and 2D electric field

2D Athena and Atlas (Silvaco) TCAD tool

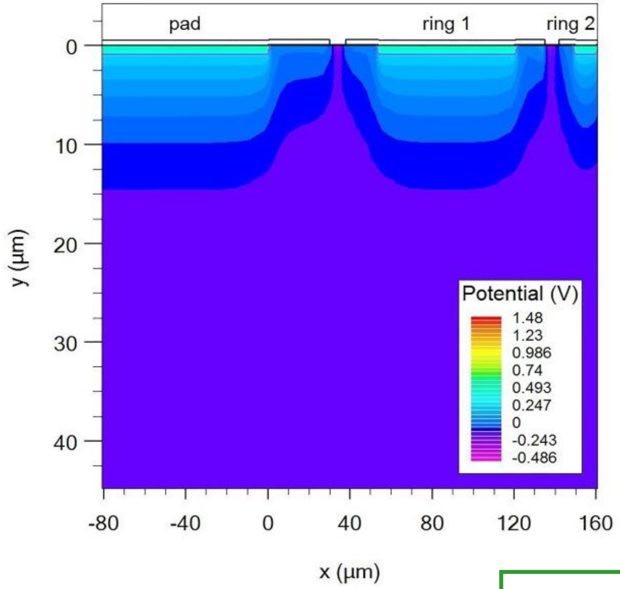
- ♦ basic equations solved via iteration procedure
- ♦ Selberherr model of impact ionization

- ♦ the n^+-p junction depth of 1 μm
- ♦ Al_2O_3 thickness of 52 nm
- ♦ Q_f as a parameter -(1-10)×10^{11} cm^{-2}

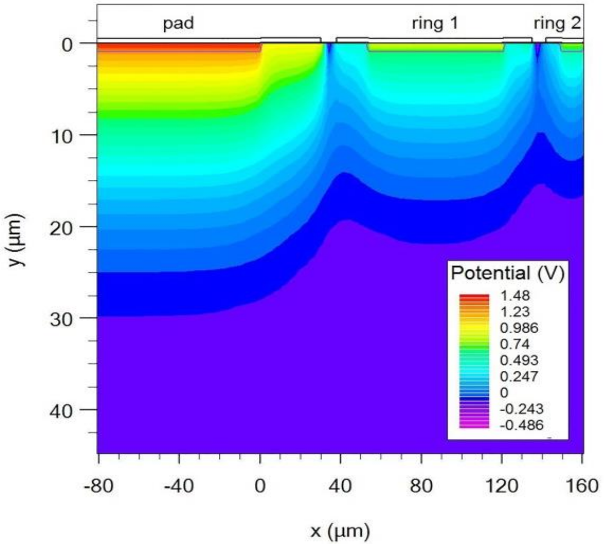
Initial stage of potential (φ) transfer

$Q_f = -4\times10^{11}$ cm^{-2}

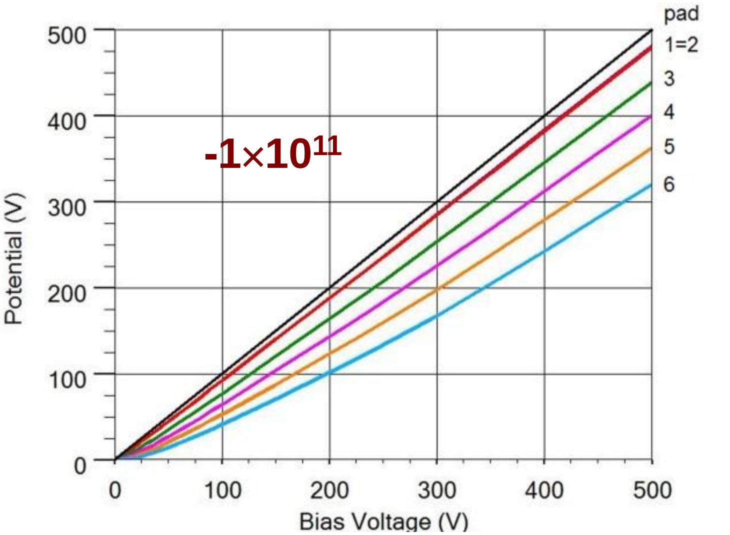
V_b = 0 V, but $V_{cont} \neq 0$

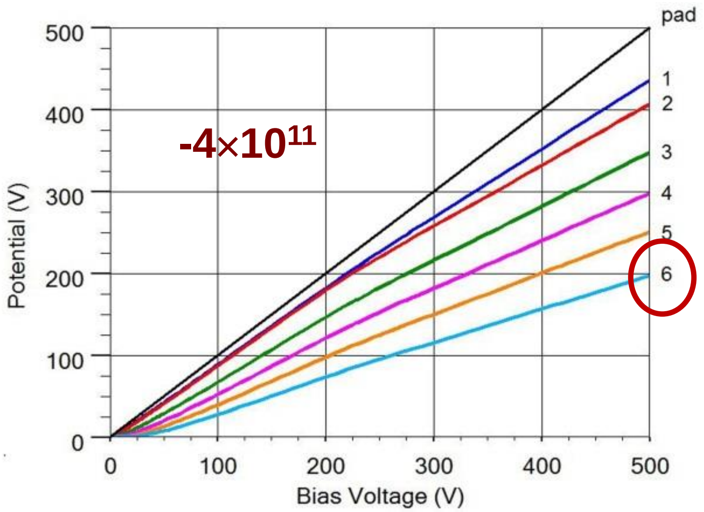


V_b = 1 V



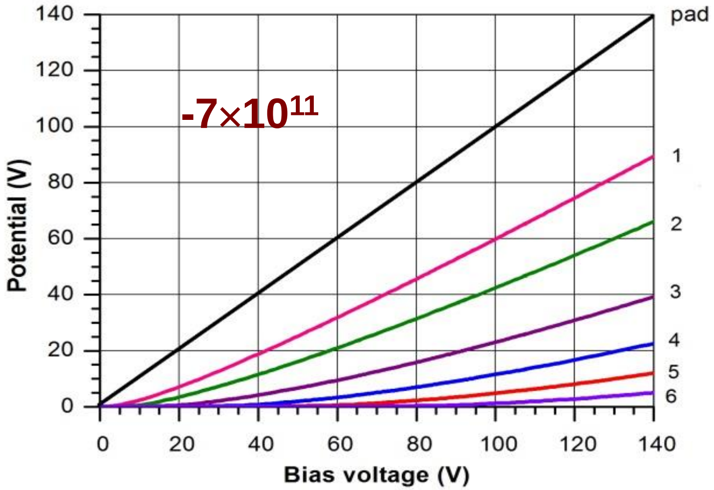
Simulated potentials at various Q_f

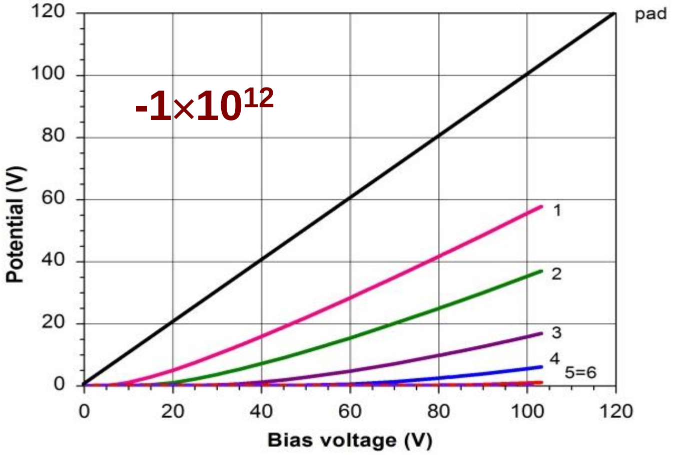




N,B. Scales in fragments differ

The same φ as in the experiment





Potential of any ring goes down with Q_f rise

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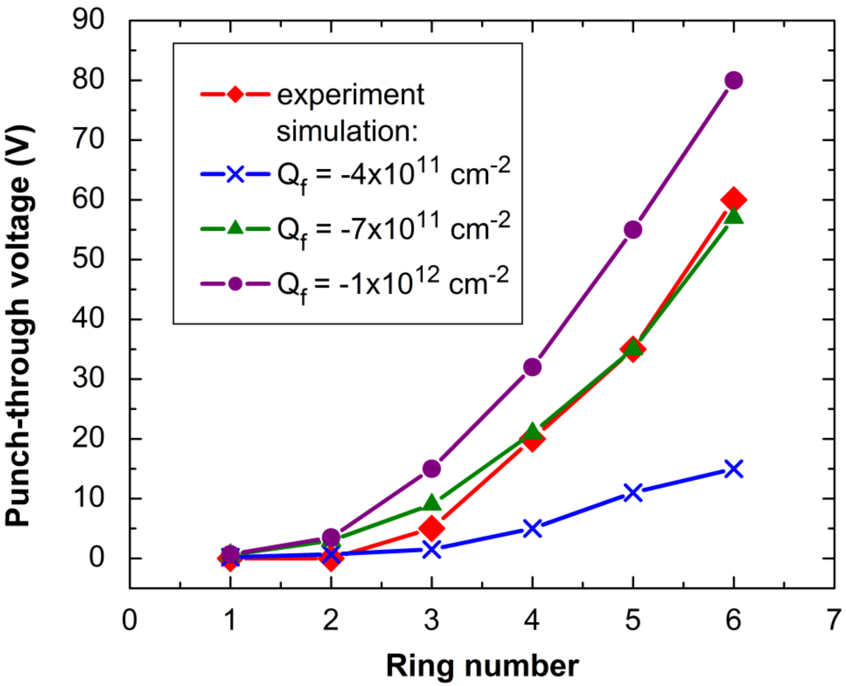
Extraction of Q_f from comparison of experimental and simulated data on V_{th}



- $Q_f = -1\times10^{11}$ cm^{-2} - no agreement
- $Q_f = -4\times10^{11}$ cm^{-2} - V_{th} agree for the 1st and 2nd rings
- $Q_f = -7\times10^{11}$ cm^{-2} - agreement for rings 4-6 better than 10%
- $Q_f = -1\times10^{12}$ cm^{-2} - all simulated V_{th} values exceed the experimental data

In the detector under study (used design and technological process)

Q_f is within the range $-(4\text{-}7)\times10^{11}$ cm^{-2}

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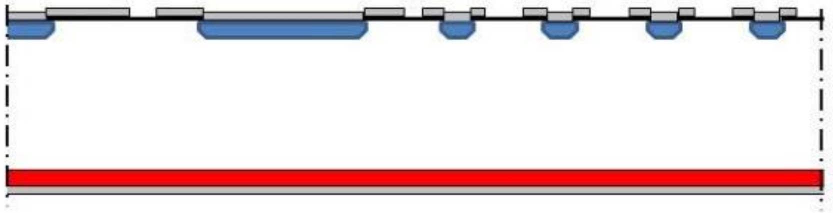
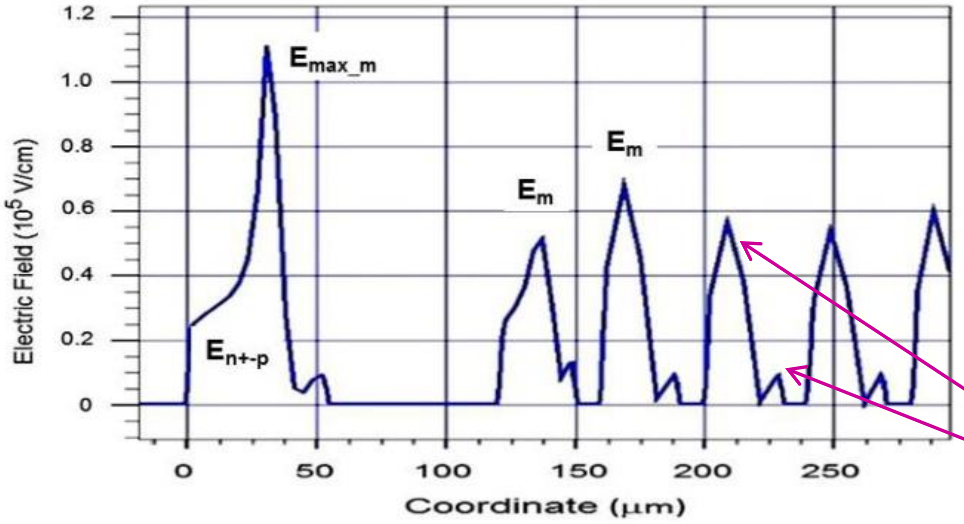
Simulation of electric field distributions





Top: detector schematic topology
Bottom: electric field at the distance of 0.1 μm **beneath Al_2O_3/Si interface** at 500 V and Q_f of -4×10^{11} cm^{-2}; taken from 2D electric field

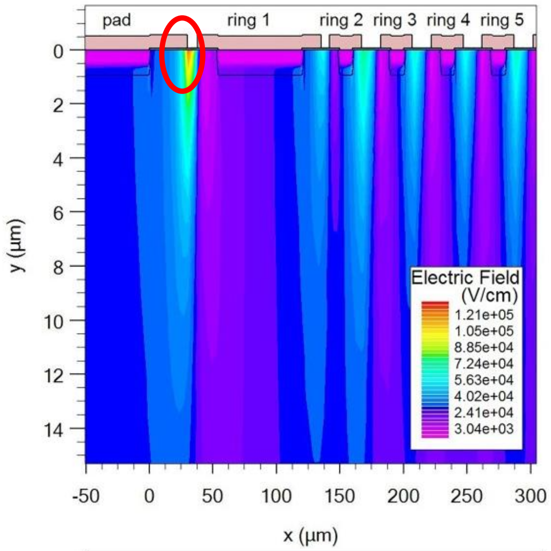
Specific points in E(x)

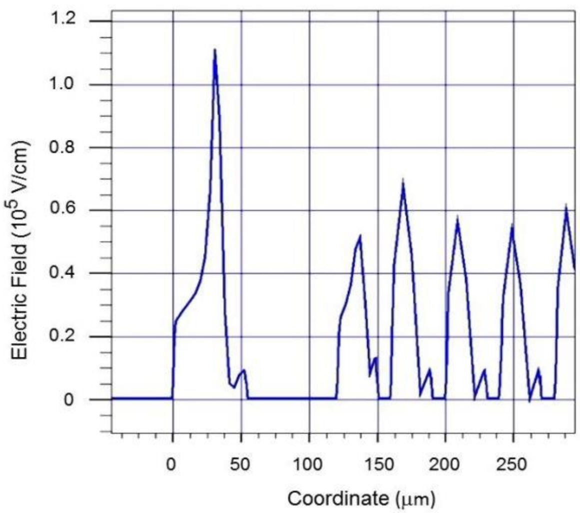
E_{n+-p} - at pad junction edge (x = 0)
E_m - E maxima at outward edges of the n^+ segment field plates
E_{max_m} – absolute E maximum, at the edge of the pad field plate

E around passivated gap - a structure with two separate peaks and a minimum *in between*

Simulated electric field at various Q_f

-4×10^{11} cm^{-2}

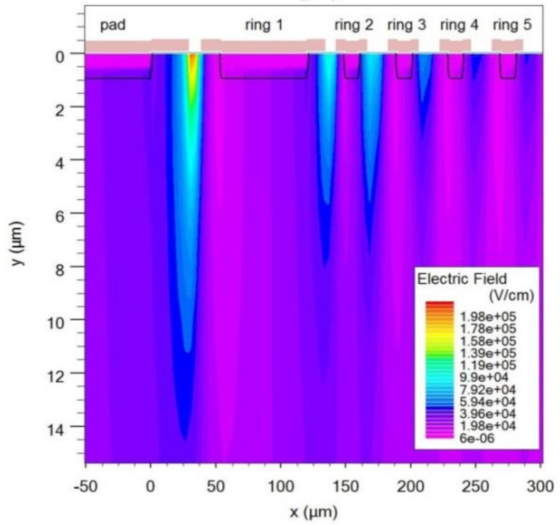


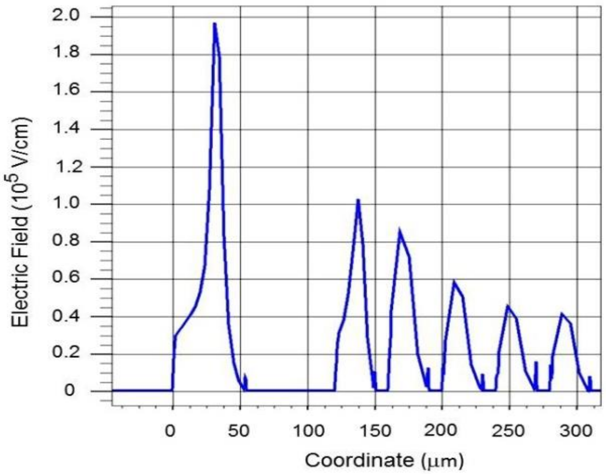


In oval:
regions of E_{max_m} and E_{min} in between

E_{max_m} = 1.1×10^{5} V/cm

-7×10^{11} cm^{-2}





φ and E redistribution, extension of high field region

E_{max_m} = 2×10^{5} V/cm

Critical for carrier avalanche multiplication

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Impact of design parameters on the electric field in the gaps: goal

Goal: reduction of E at the edge of the pad field plate

Two parameters were changed in simulations for n^+-p-p^+ detectors with Al_2O_3 isolation:

- Width of the gap between the edges of the pad field plate and inner metal plate of the bias ring ($w_{pad\text{-}BR}$)
- Silicon resistivity ρ

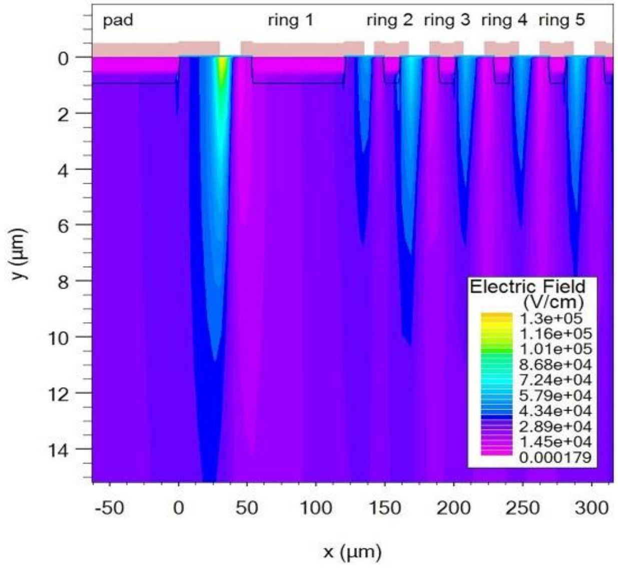
Known for p-on-n detectors:

- $w_{pad\text{-}BR}$ growth increases E at the pad field plate edge; our task is estimating the scale of this increase;
- use of n-type 20 kΩcm silicon (FZ Si) allowed to realize detectors with a thickness of **1 mm**, operating **up to 1000 V** with a current density ≤ 10 nA/cm^2 (see V. Eremin et al., *Semiconductors* (2011) **45**, No. 4, 536)

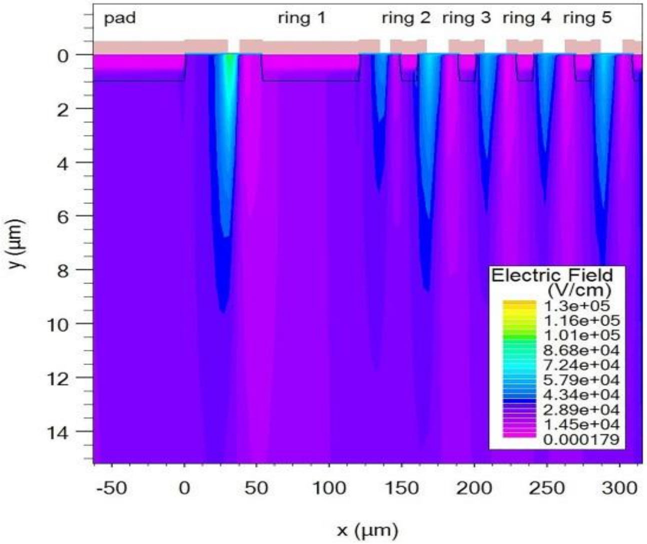
Impact of design parameters on the electric field in the gaps: results

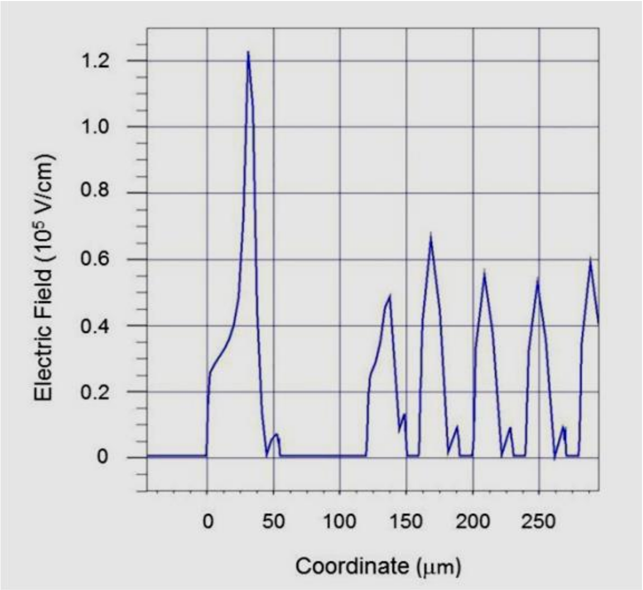
1. Increase of $w_{pad\text{-}BR}$

2. Increase of silicon resistivity to 20 k

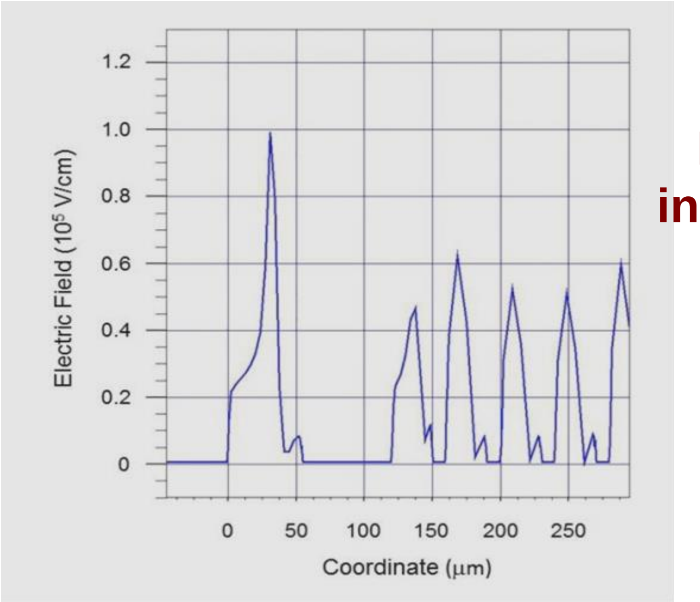


-4×10^{11} cm^{-2}; 500 V





E_{max_m} ↑ 10%



E_{max_m} ↓ in 2 times

Parameters of the detector design and characteristics derived from simulations

$$\alpha_e = A_e exp\left(-\frac{B_e}{E}\right) \qquad j(x) = \int eGdx + \int_0^d \alpha_e(x) j_e(x) dx$$

Si grade	ρ (kΩcm)	width of the pad field-plate (μm)	width of pad-BR gap (μm)	Q_f (cm^{-2})	E_{max_m} at pad field-plate edge (V/cm)	α_e (cm^{-1})
experiment						
MCZ	7	30	8	-(4-7) ×10^{11}		
simulations						
MCZ	7	30	8	-1×10^{11}	5×10^{4}	3.3×10^{-5}
MCZ	7	30	8	-4×10^{11}	1.1×10^{5}	14.7
MCZ	7	30	8	-7×10^{11}	2×10^{5}	2×10^{3}
MCZ	7	30	15*	-4×10^{11}	1.2×10^{5}	36.4
FZ	20	30	8	-4×10^{11}	1×10^{5}	4.93

* the width of the BR field plate is reduced to 9 μm.

With respect to avalanche multiplication:

- Q_f of **-7×10^{11} cm^{-2} is critical**
- **Application of 20 kΩcm p-Si** allows reducing the electric field and α_e

Experiment: see [5] in slide 2, n-on-p detectors operating at V up to 900 V.

Summary

1. The measurements showed efficient VTS operation: gradual potential attenuation to less than 10% of the applied bias on the last n^+ ring.

2. Punch-through model built for the p^+-n-n^+ detectors with SiO_2 passivation is valid for n^+-p-p^+ detectors having Al_2O_3 isolation layer with the opposite oxide charge.

3. Simulations allowed extracting the Q_f charge of $-(4\text{-}7)\times10^{11}$ cm^{-2} in Al_2O_3 in the detector with the used design and technology ($-(10^{11}\text{-}10^{13})$ cm^{-2} is referred to in literature).

4. Q_f is shown to be crucial for VTS operation and detector performance. For the studied detector, an upper limit of Q_f is -7×10^{11} cm^{-2}.

5. A promising approach to reducing the electric field is to use p-type Si with increased resistivity of about 20 kΩcm.

Thank you for attention!