Surface Effects and Breakdown Voltage

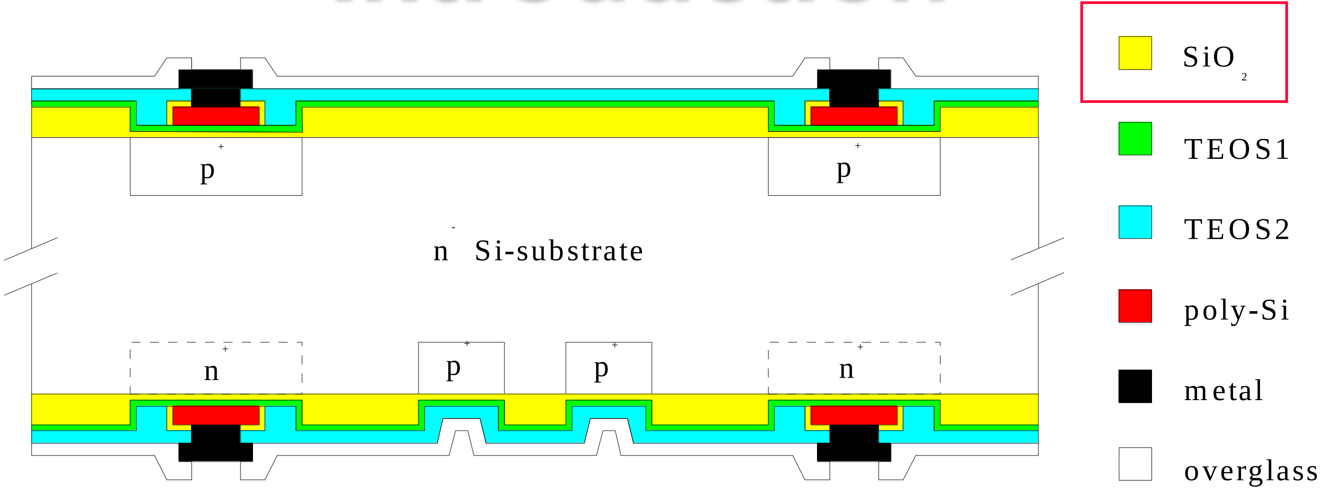
Gian-Franco Dalla Betta

INFN and DISI - University of Trento
Via Sommarive, 14
I-38123 Povo di Trento (TN), Italy
dallabe@disi.unitn.it

Outline

- Introduction
- Basic mechanisms
- Main parameters:
  - how to measure them
  - experimental results
- Consequences for detectors:
  - Main focus on breakdown
- Conclusion

Introduction



- Silicon detectors are mainly “volume” devices, hence particularly sensitive to bulk defects, induced by processing or radiation damage - Non Ionizing Energy Loss (NIEL)
- But Si crystal periodicity ends at the surface, this resulting in a high defect density: surface requires passivation with SiO_2 layer
- Yet some residual defects still remain within the SiO_2 layer and at the Si/SiO_2 interface, and can be enhanced by ionizing radiation (IEL)
- This affects detector properties …

Charges in silicon oxide

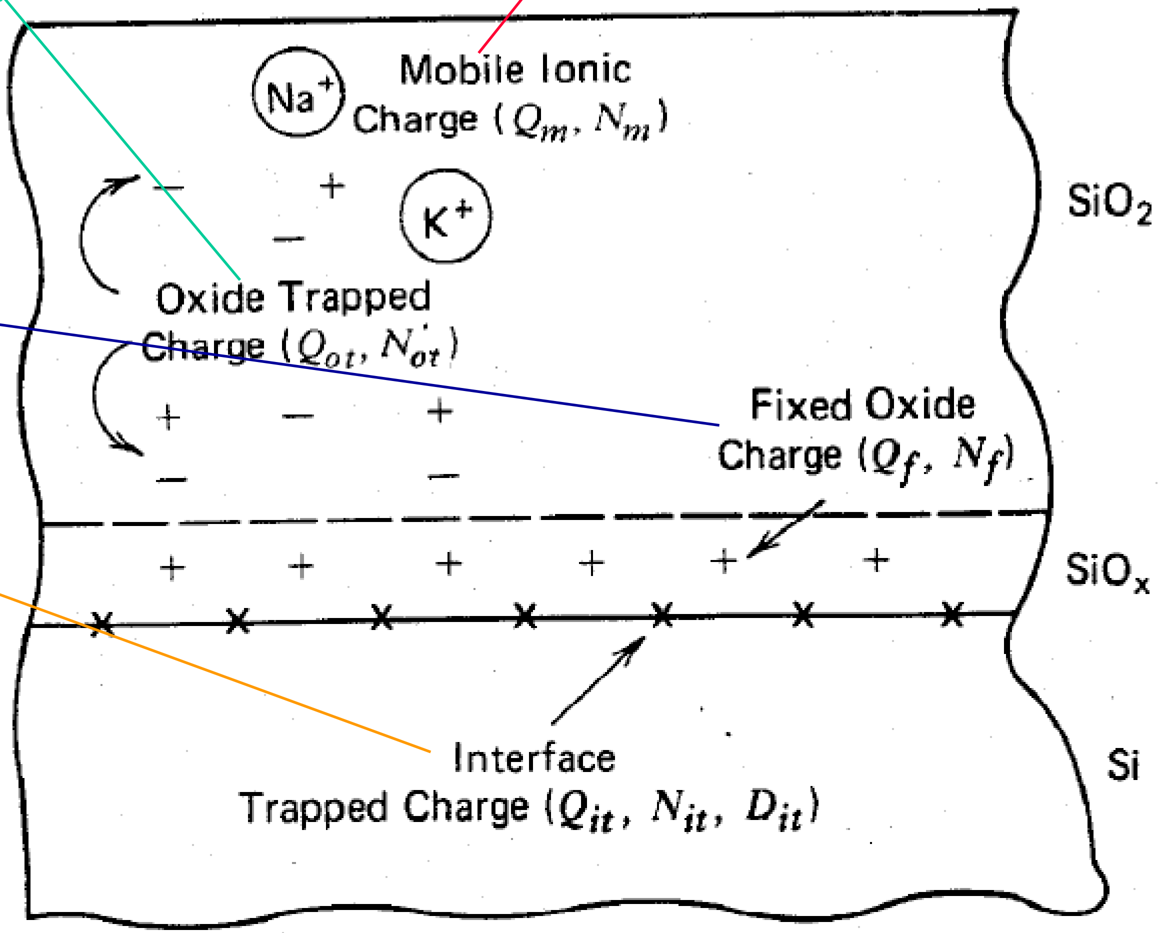
Due to defects in the SiO_2 network, negligible in fresh oxides, but can be degraded by radiation.

Affected early stage MOS structures, today inot an issue

Due to ionic Si and uncompensated Si-Si or Si-O bonds (within 3nm from interface, highly desordered region).

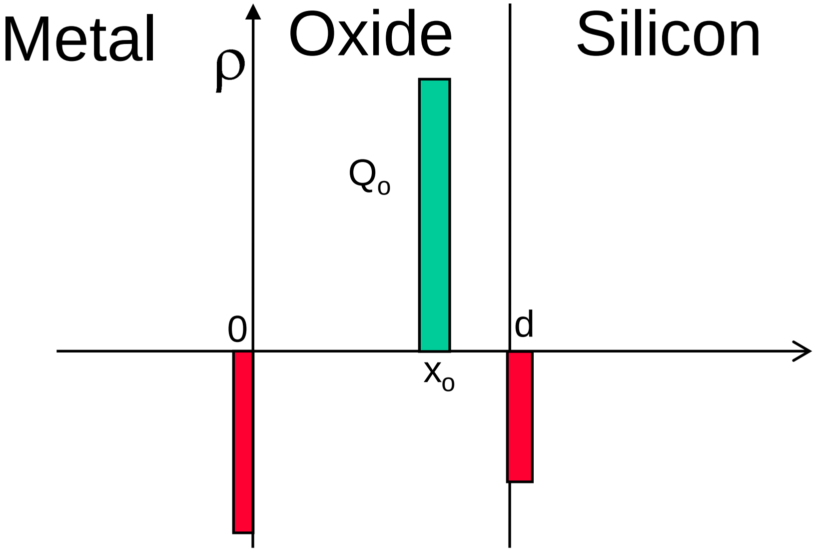
Due to traps at the interface (unterminated Si bonds) with energy states in the forbidded bandgap; also act as G-R centers (s_0)

Both N_f and N_{it} are strongly dependent on crystal orientation and processing



S.M. Sze, Semiconductor Devices: Physics and Technology, Wiley, 1985

Effect of oxide charge sheet



- Positive oxide charge induces negative charge in silicon, this effect is weighted by the charge position
- Shift in flat band voltage (V_{FB}) can be expressed as:

$$\Delta V_{FB} = -\frac{1}{C_{ox}} \cdot \left[\frac{1}{d} \cdot \int_0^d x \cdot \rho(x) \cdot dx \right]$$

- Charge close to interface is the most effective
- For Q_f, the distance from the Si-SiO$_2$ interface is much smaller than typical passivation oxide thickness:

$$\Delta V_{FB}(Q_f) \cong -\frac{Q_f}{C_{ox}}$$

- Similar equation for Q_{it} (but voltage dependent, so C-V curves are streched):

$$\Delta V_{FB}(Q_{it}) \cong -\frac{Q_{it}}{C_{ox}}$$

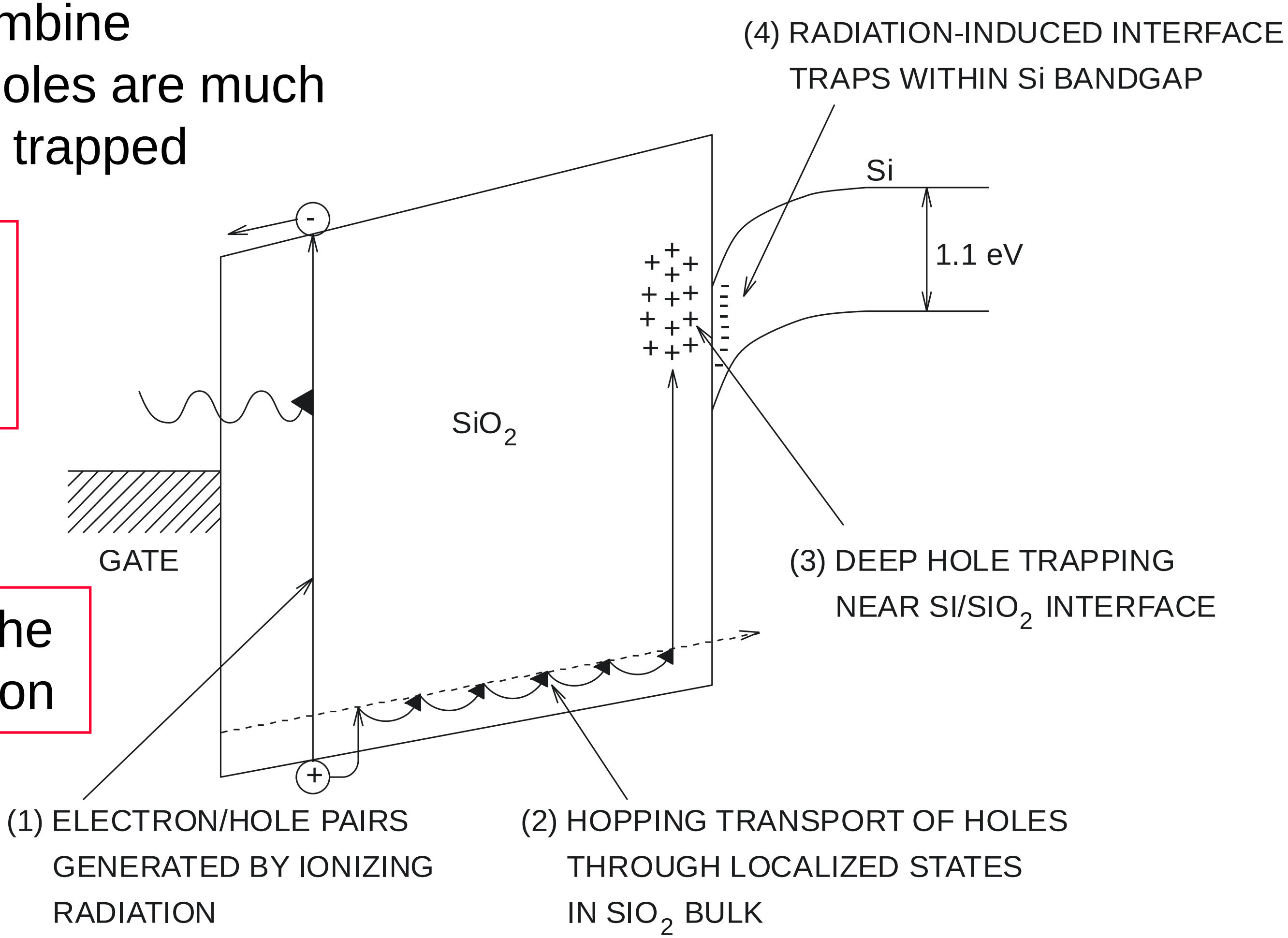
S.M. Sze, Semiconductor Devices: Physics and Technology, Wiley, 1985

Surface radiation damage

- Most e-h pairs recombine
- Electrons escape, holes are much slower and finally get trapped

SiO_2:
μ_n~20cm^2/(Vs),
μ_p~2x10^{-5} cm^2/(Vs)

- Strong effects of the bias during irradiation



T.R. Oldham, Ionizing radiation effects in MOS oxides, World Scientific, 1999

Some facts

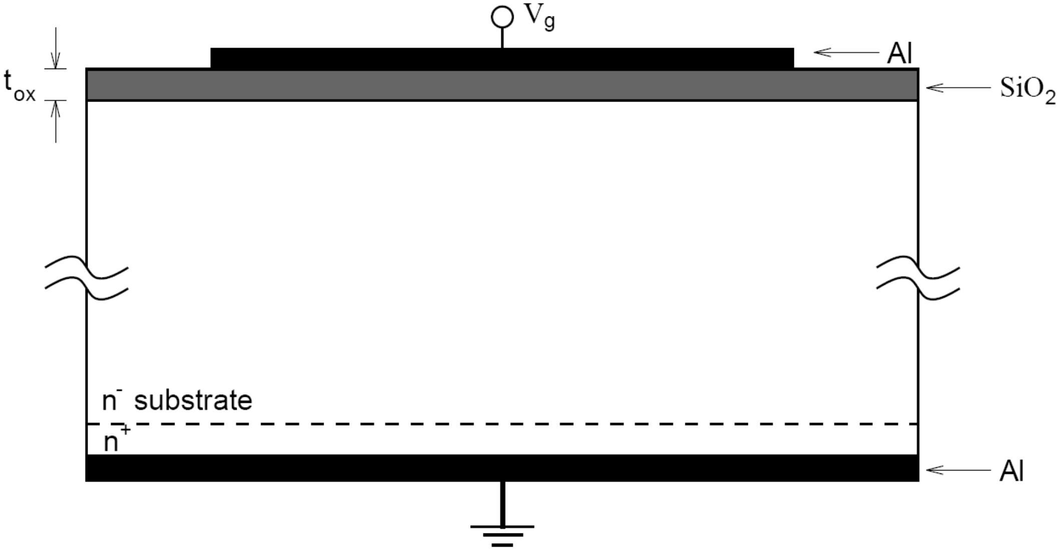
- Surface damage is due to Ionizing Energy Loss, normally expressed as a “Dose”:
  - a) 1 rad: 100erg per gram
  - b) 1 gray (Gy): 1 joule per kilogram

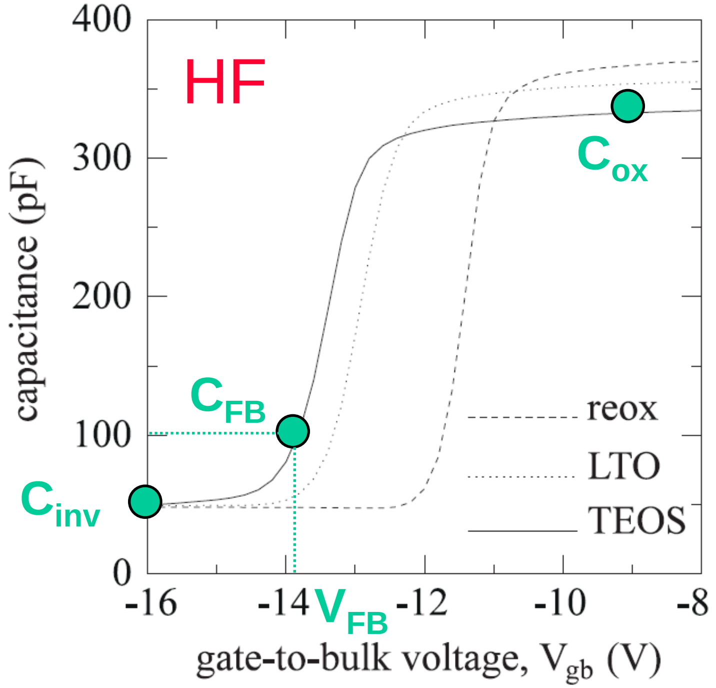
1erg=10^{-7} J
1 Gy=100 rad

A.Holmes-Siedle, L. Adams, Handbook of radiation effects, Oxford Univ. Press, 2002

- Ionizing radiations with energies above threshold ~17eV (e.g., UV light, X and γ-rays, charged particles) can produce surface damage
- Since the number of traps is limited, saturation effects are expected (and observed) for Q_f, Q_{it} and s_0 after irradiation
- Values reported in literature are not very uniform due to strong process dependence

TS1: MOS capacitor





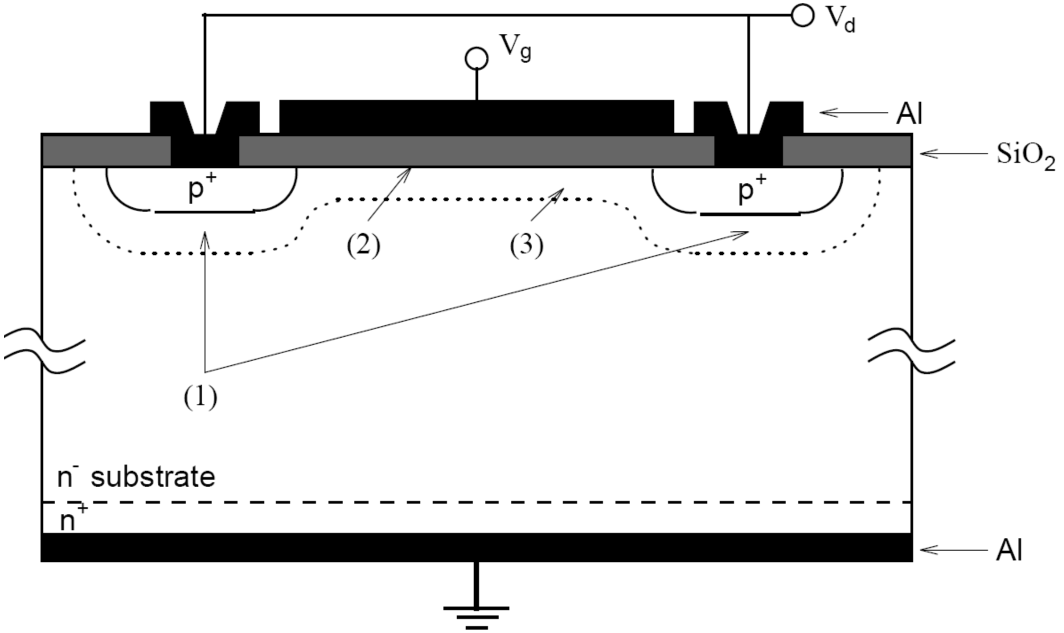
From HF C-V curves

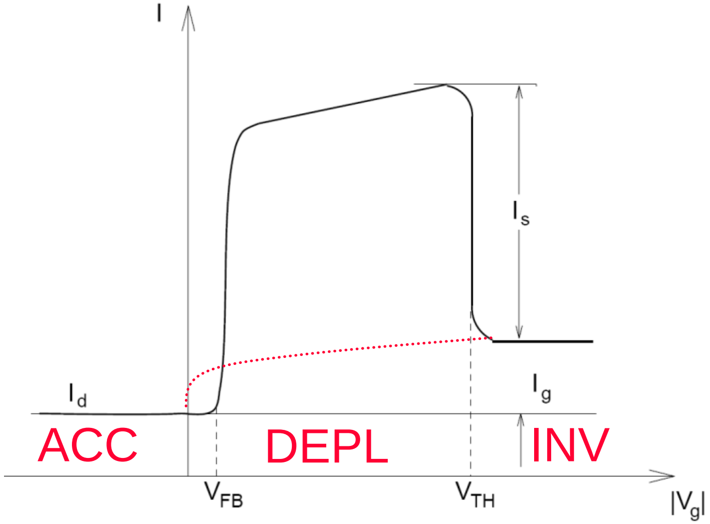
- C_{ox} from C value at accumulation
- N_{sub} from C value at inversion → C_{FB}
- V_{FB} from C_{FB} → Q_f from V_{FB}

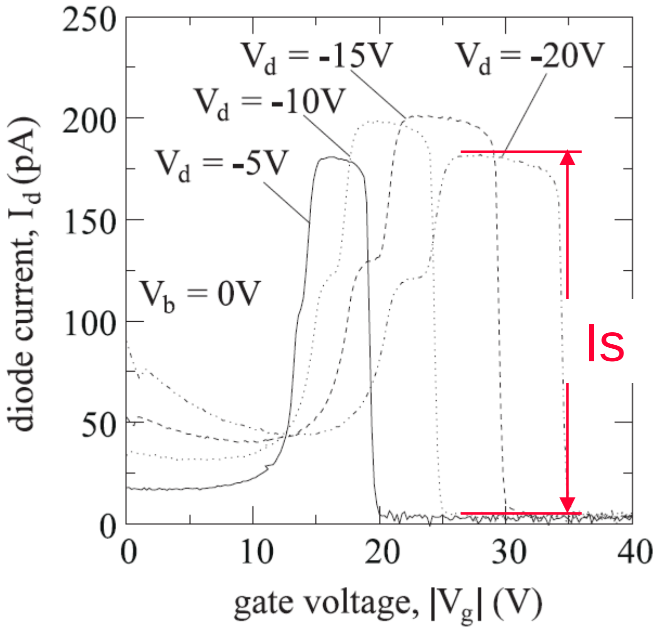
$$\boxed{V_{FB}(Q_f) \cong \phi_{MS} - \frac{Q_f}{C_{ox}}}$$

E.H. Nicollian, J.R. Brews, MOS – Physics and Technology, Wiley, 1982

TS2: gated diode







From I-V curves

$$I_S = I_{depl-\max} - I_{inv}$$

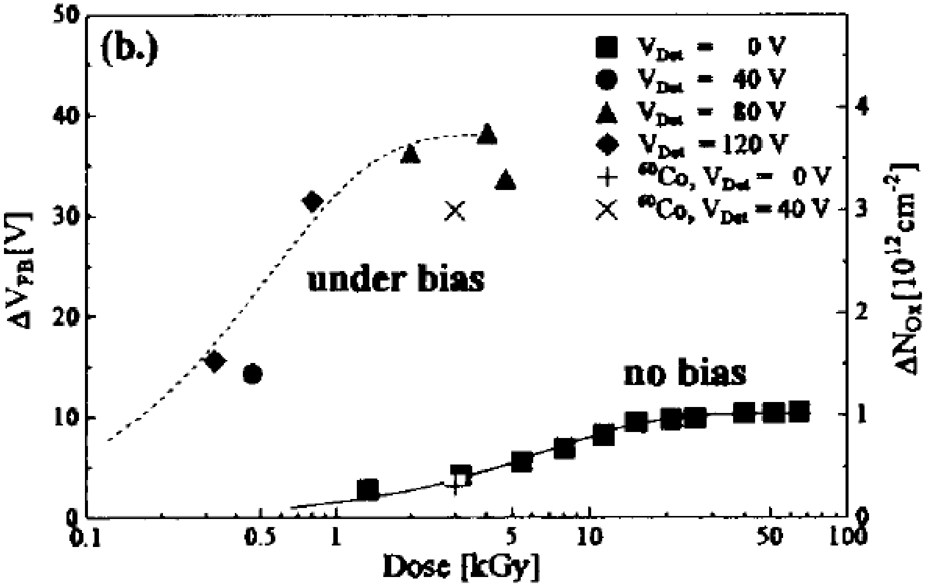
$$s_0 = \frac{I_S}{A_{Gate} \cdot q \cdot n_i}$$

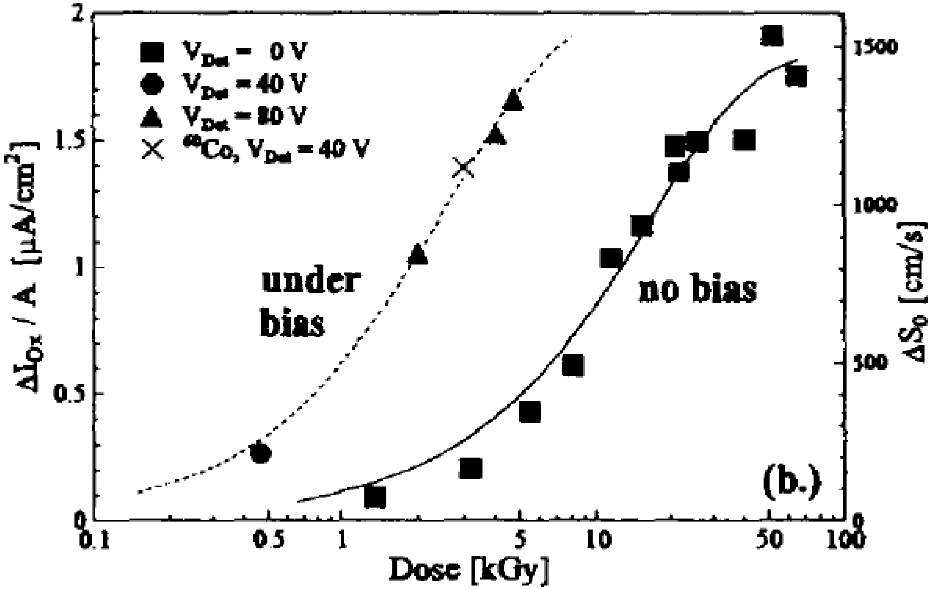
[cm/s]

G. Verzellesi, et al., IEEE TED 46(4) (1999) 817

Experimental data

Irradiations with 20keV SEM electrons and ^{60}Co gammas





- Charge density: can increase up to a few 10^{12} cm^{-2}
- Surface generation velocity: can increase up to a few 10^{3} cm/s
- As expected, strong influence of bias on measured values

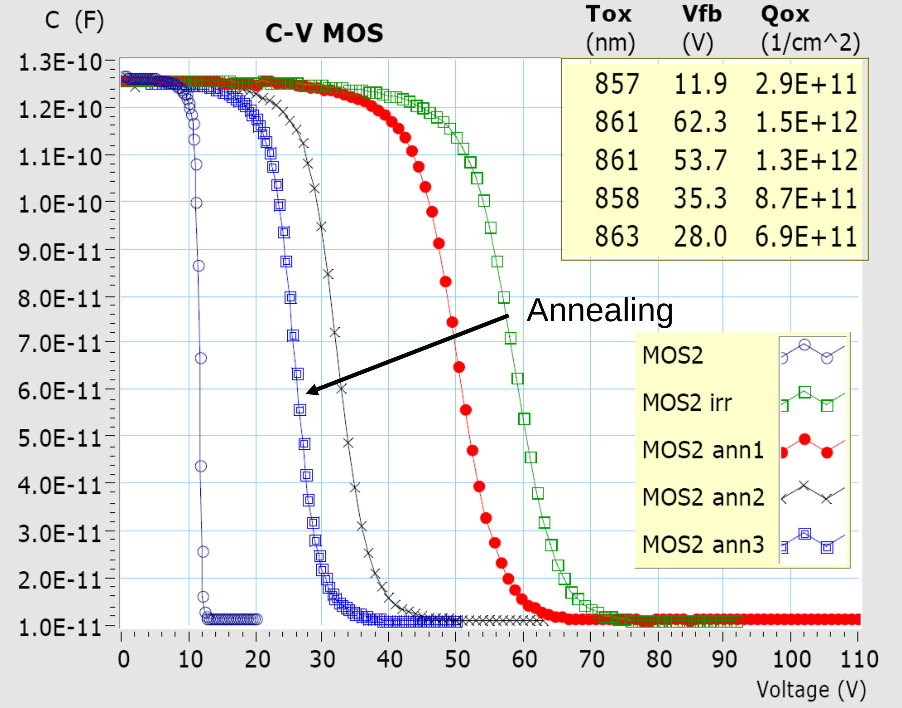
R. Wunstorf et al., NIMA 377 (1996) 296

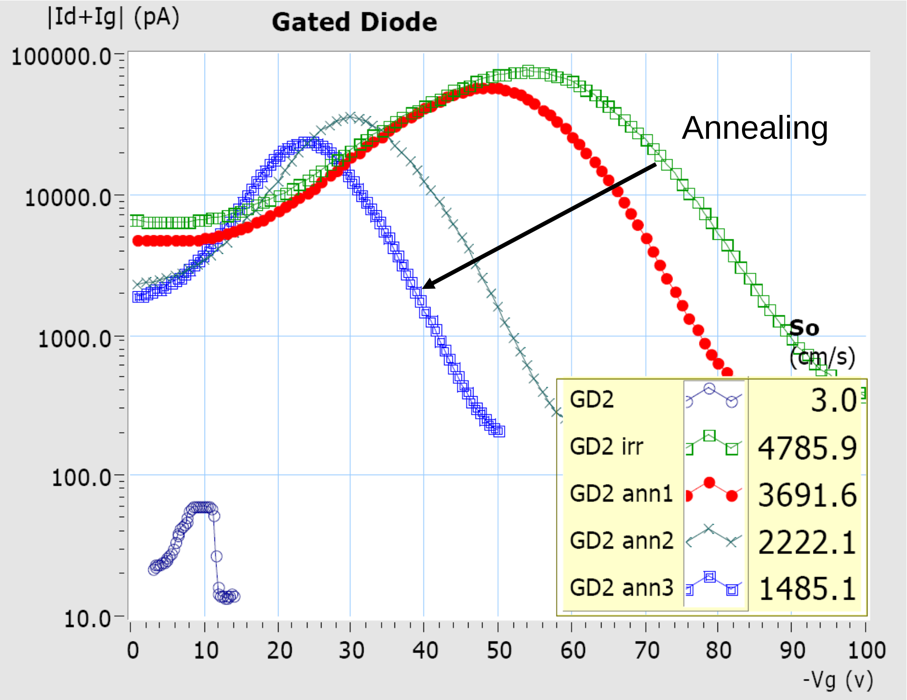
Annealing effects

Surface damage can be partially recovered (annealed), even at RT. Thermal treatments at temperatures ~150 C produce larger annealing effects.

A.Holmes-Siedle, L. Adams, Handbook of radiation effects, Oxford Univ. Press, 2002

Example: 2Mrad(Si) X-ray irradiation and annealing in 3 steps:
1) 13days@RT; 2) +20min@120 C; 3) +30min@120°C





M. Boscardin et al., IEEE TNS 50(4) (2003) 1001

Consequences for detectors

1. Positive fixed oxide charge density induces a negative charge at the Si-SiO_2 interface, which affects:
    a) isolation between n^+ regions;
    b) parasitic capacitance between adjacent regions (→ noise);
    a) electric fields at surface: breakdown;
    b) punch-through voltage between adjacent regions;
    c) to a lower extent, substrate depletion voltage.

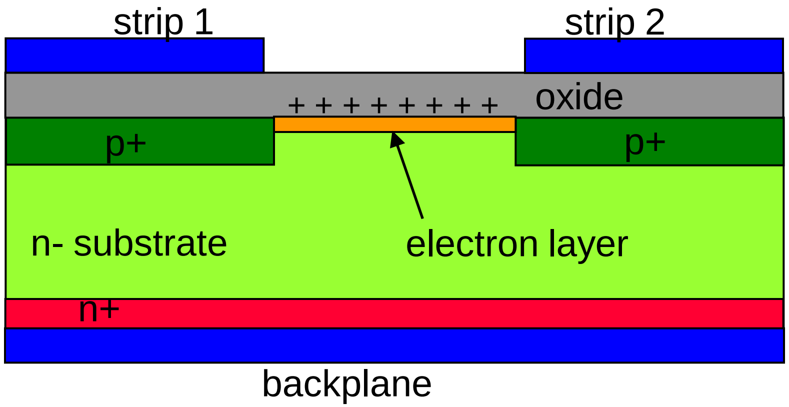
2. Surface generation/recombination leads to:
    a) Increased surface leakage current;
    b) Increased surface charge recombination (can affect charge collection properties in case of radiation absorbed near the surface, e.g., low energy electrons)

Radiation effects may vary with detector structure …

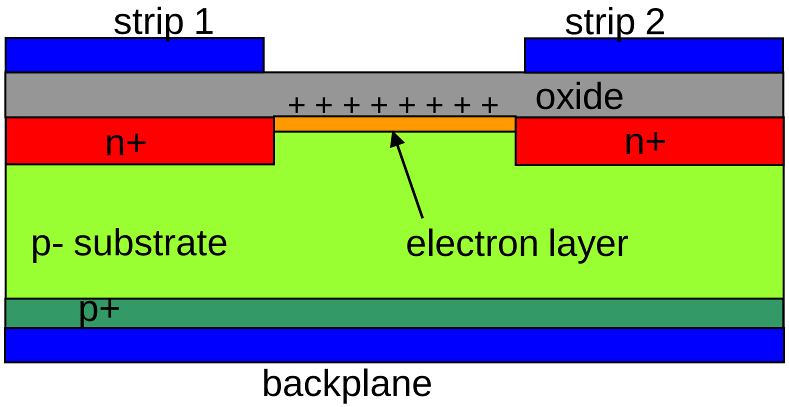
P-on-N vs N-on-P

With reference to strip detectors

P-on-N



N-on-P (N-on-N)

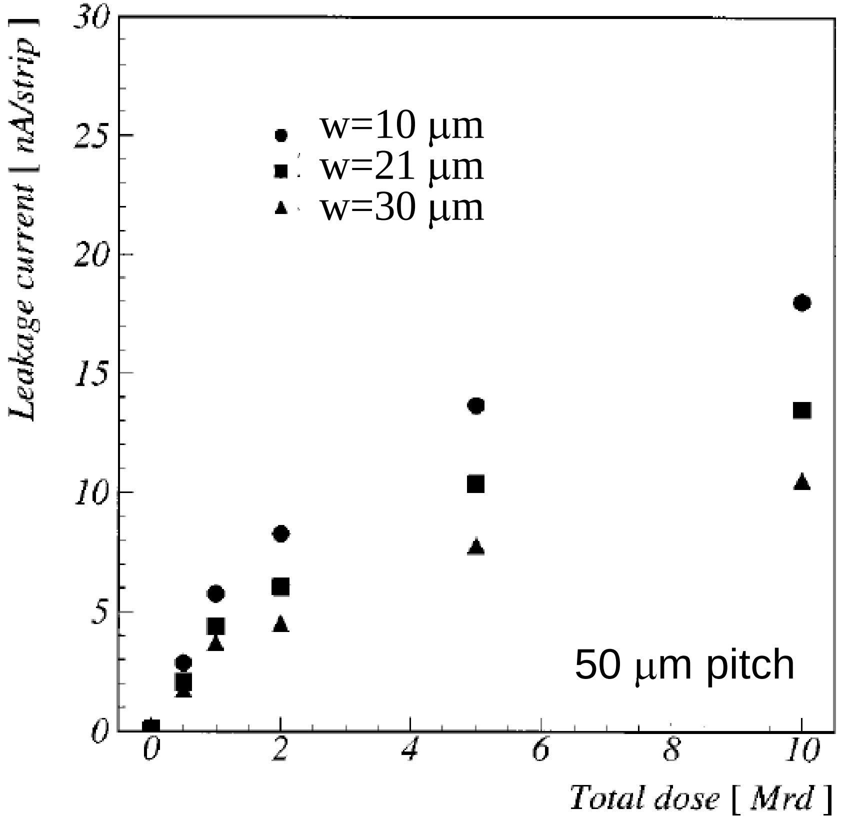


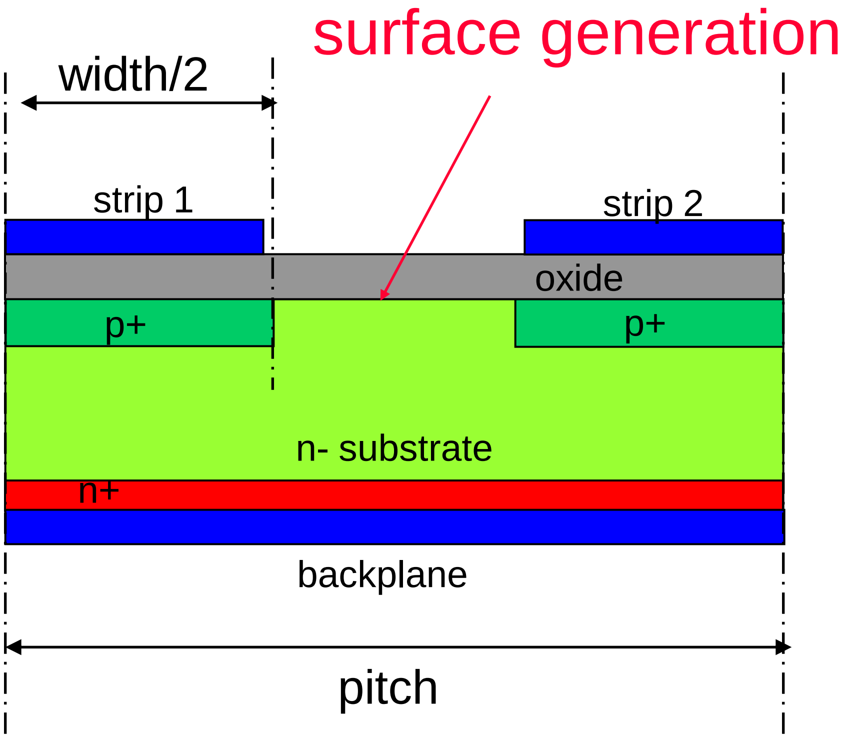
- Strips are “self-isolated”
- Increase of oxide charge density further improves isolation, but:
  - reduces breakdown voltage
  - increases interstrip capacitance

- Strips are connected by electrons
- Need for isolation structures
- Impact of increased oxide charge density on breakdown voltage and interstrip capacitance depends on isolation structures

P-on-N: surface current

Tokio Institute of Technology, 1MeV ^{60}Co gamma irradiation, 100 krad/h



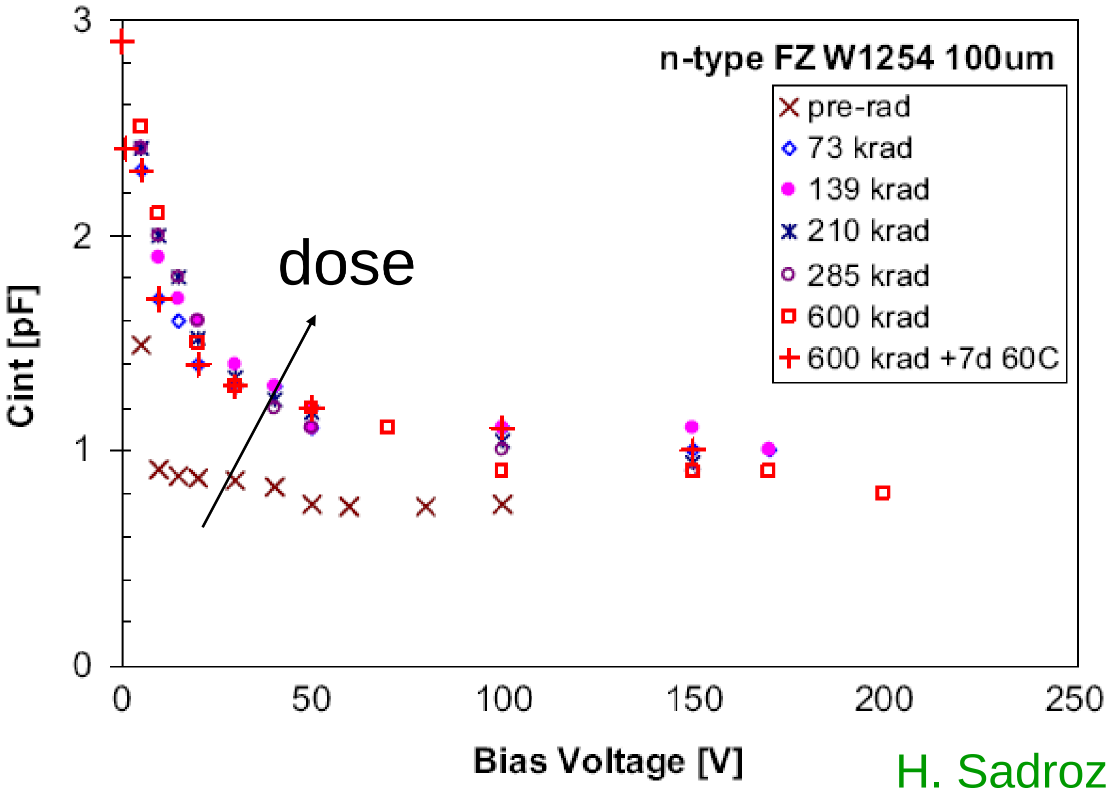


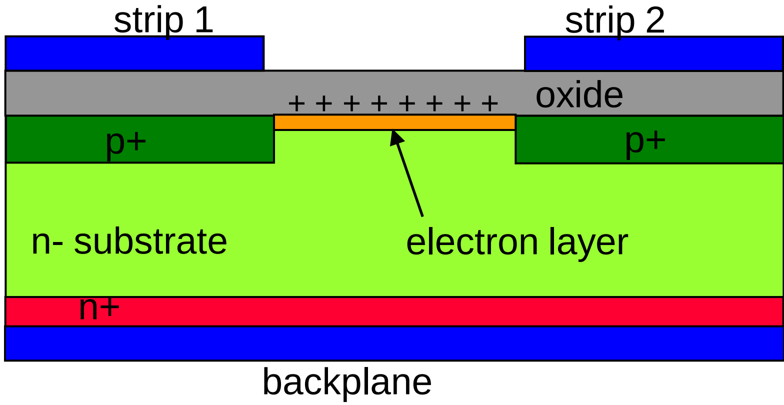
J. Kaneko et al., IEEE TNS 49(4) (2002) 1593

- Leakage current increases with dose
- Effects are more severe for small width (larger surface)

P-on-N: interstrip capacitance

Irradiation at UCSC, ^{60}Co gamma source, 70krad steps



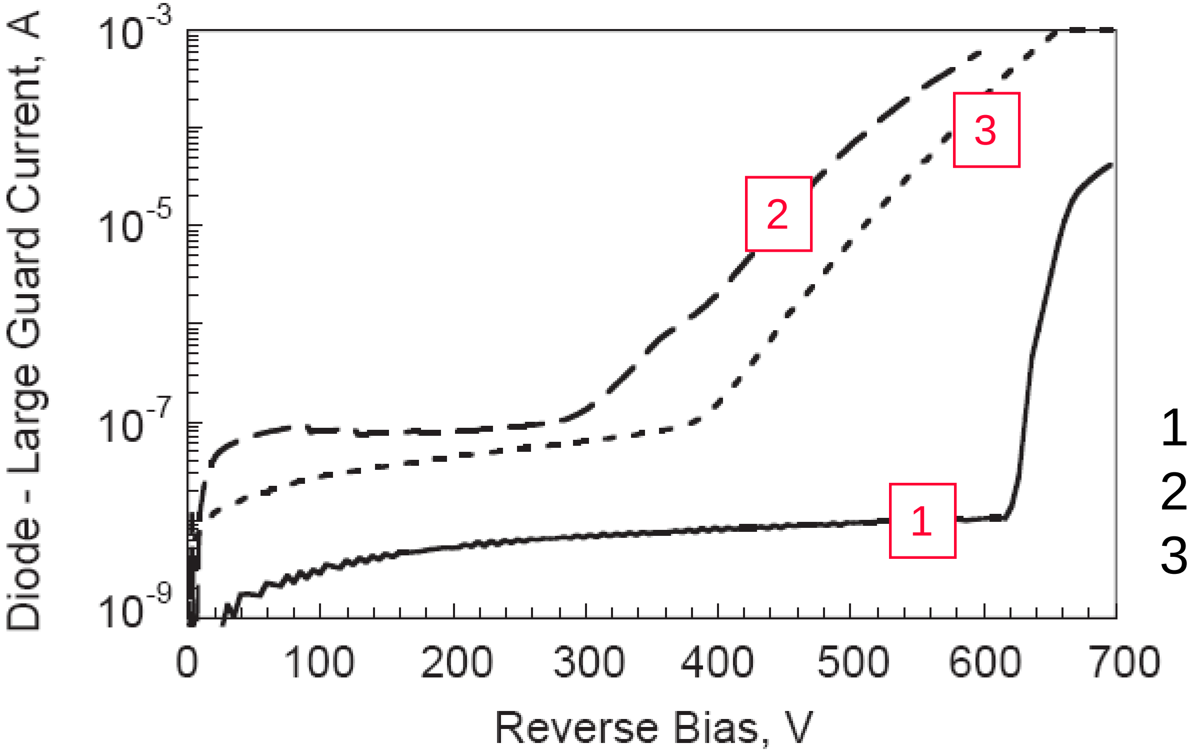


H. Sadrozinski et al., NIMA 579 (2007) 769

- Interstrip capacitance increases after irradiation, due to higher concentration of electrons in the accumulation layer, and is partially recovered with annealing

P-on-N: edge breakdown

Irradiation: CNR Bologna, ^{60}Co gamma source, 200krad(Si)

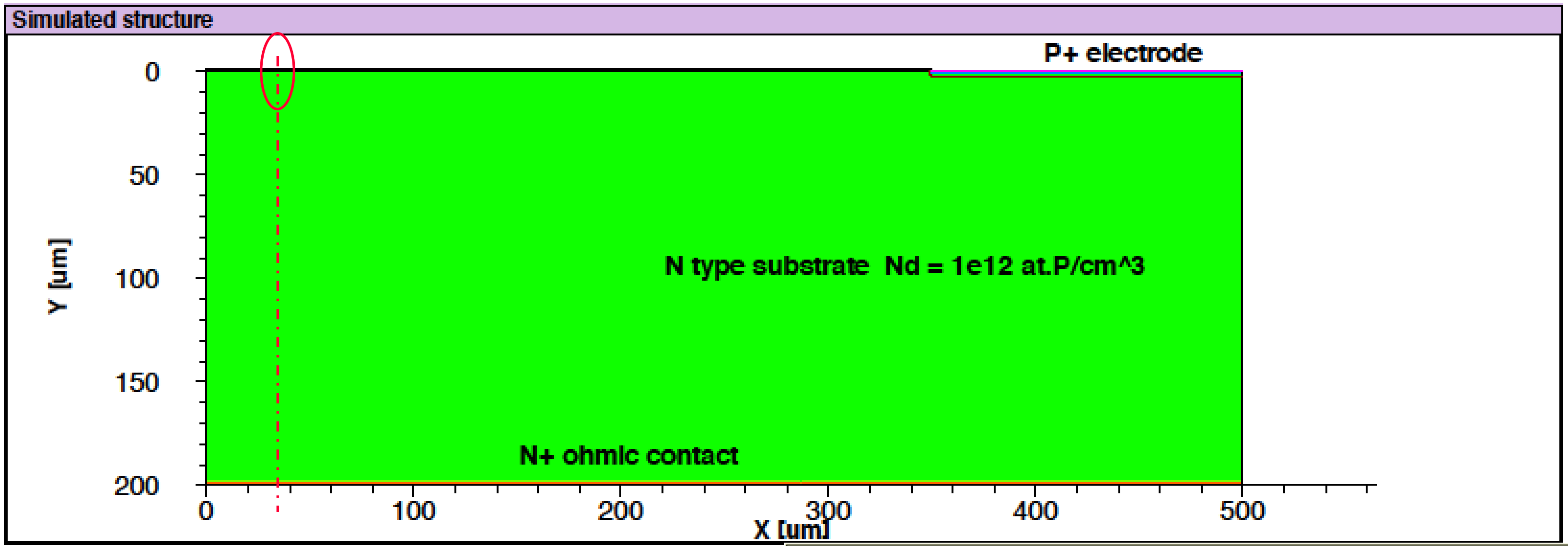


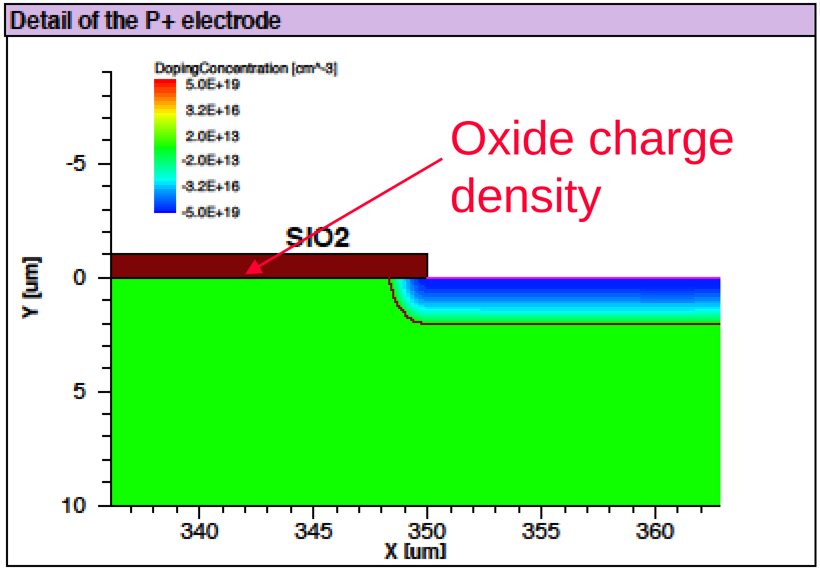
1. pre-irradiation
2. soon after irradiation
3. four days after irradiation

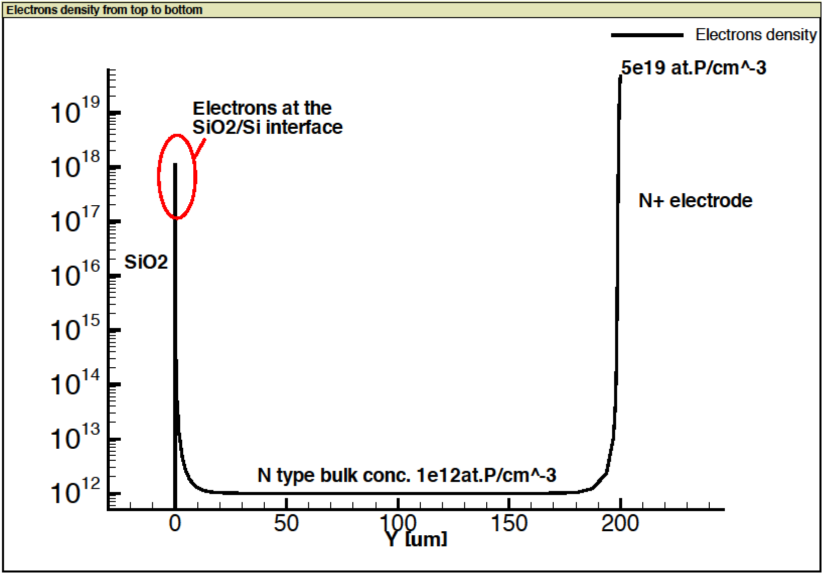
- Breakdown voltage decreases after irradiation, and is slightly recovered with room temperature annealing

M. Da Rold, et al., IEEE TNS 44(3) (1997) 721

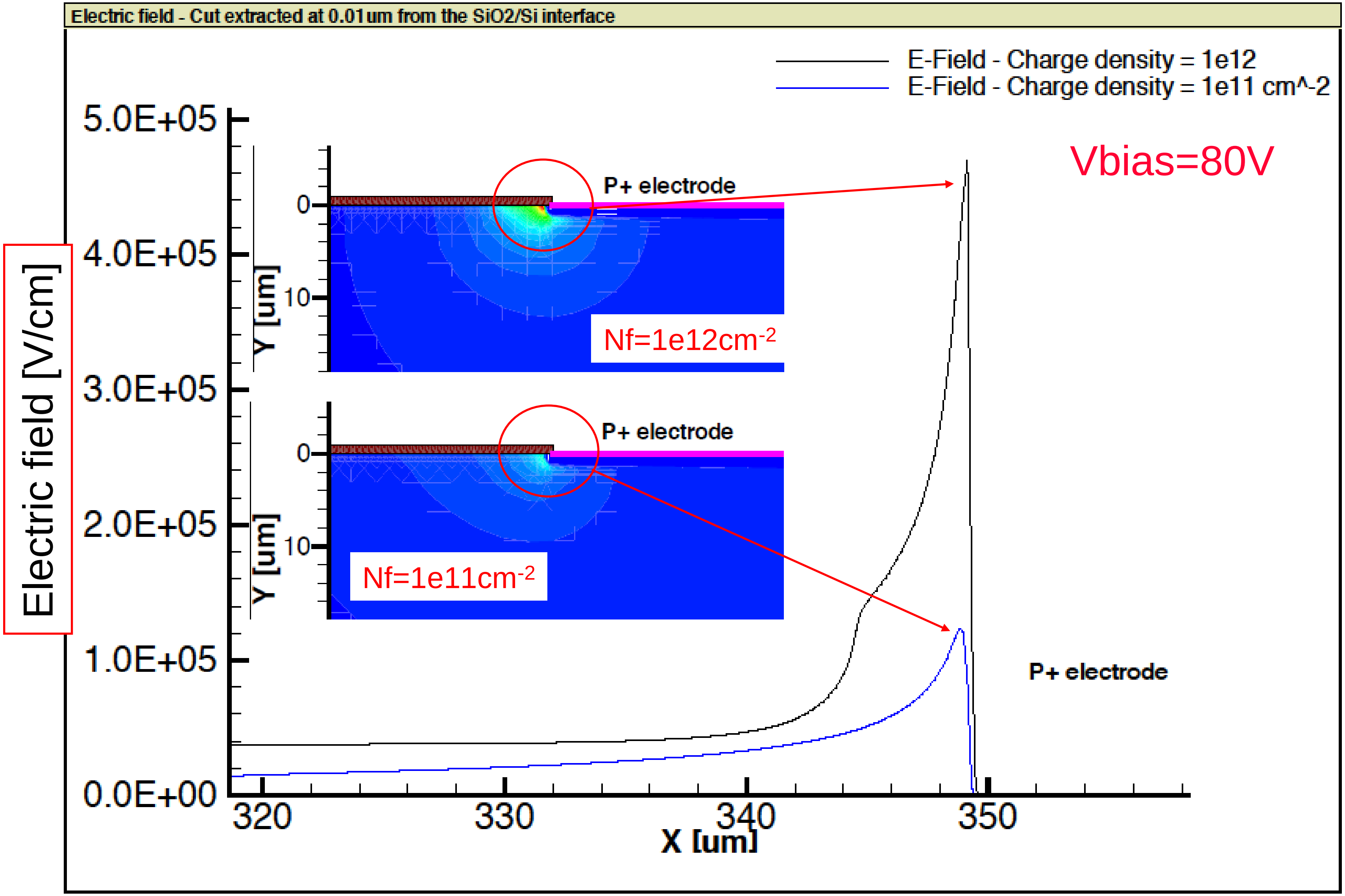
TCAD explanation







Simulated electric field

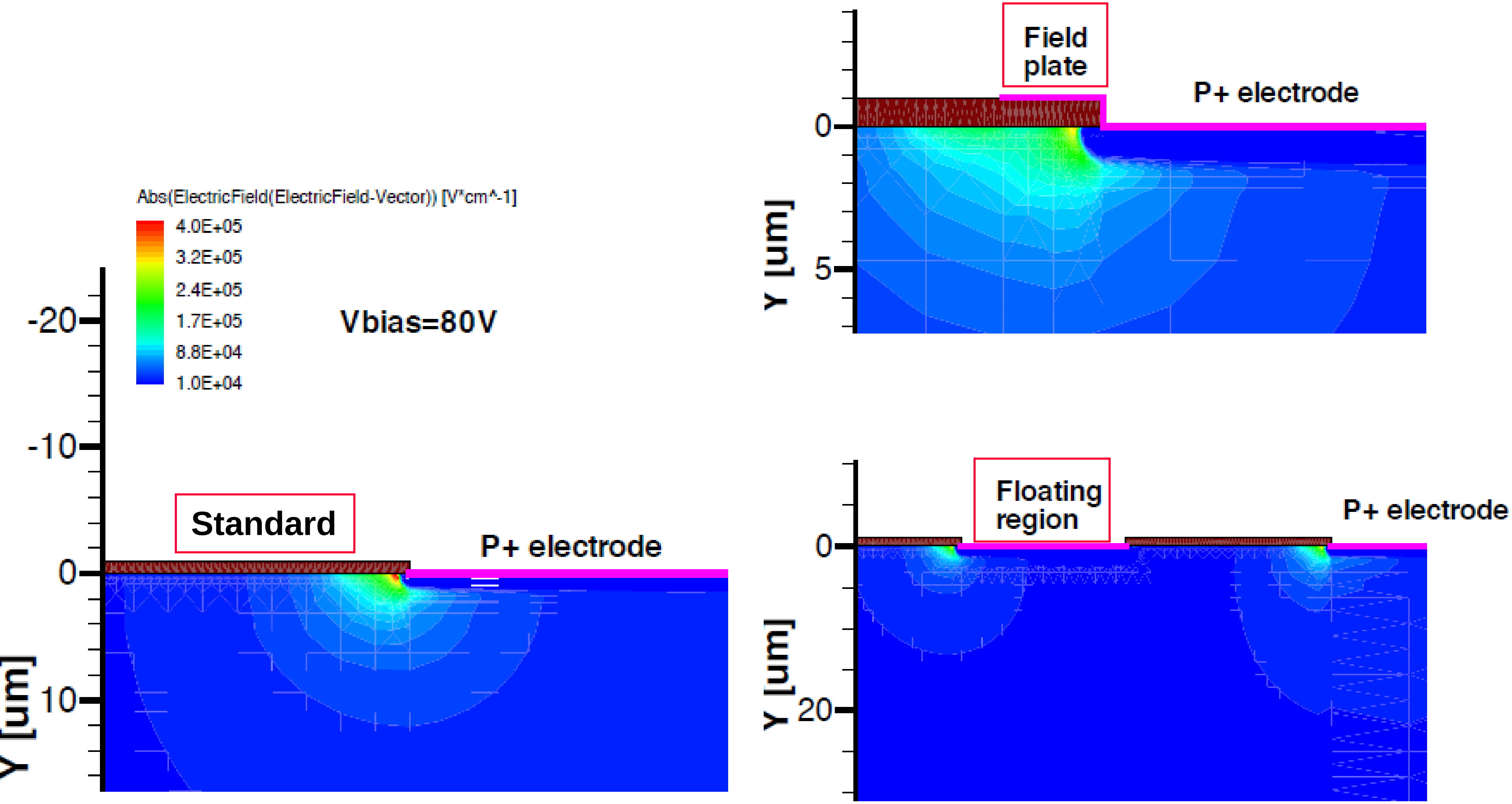


Vbias=80V

Nf=1e12cm^{-2}

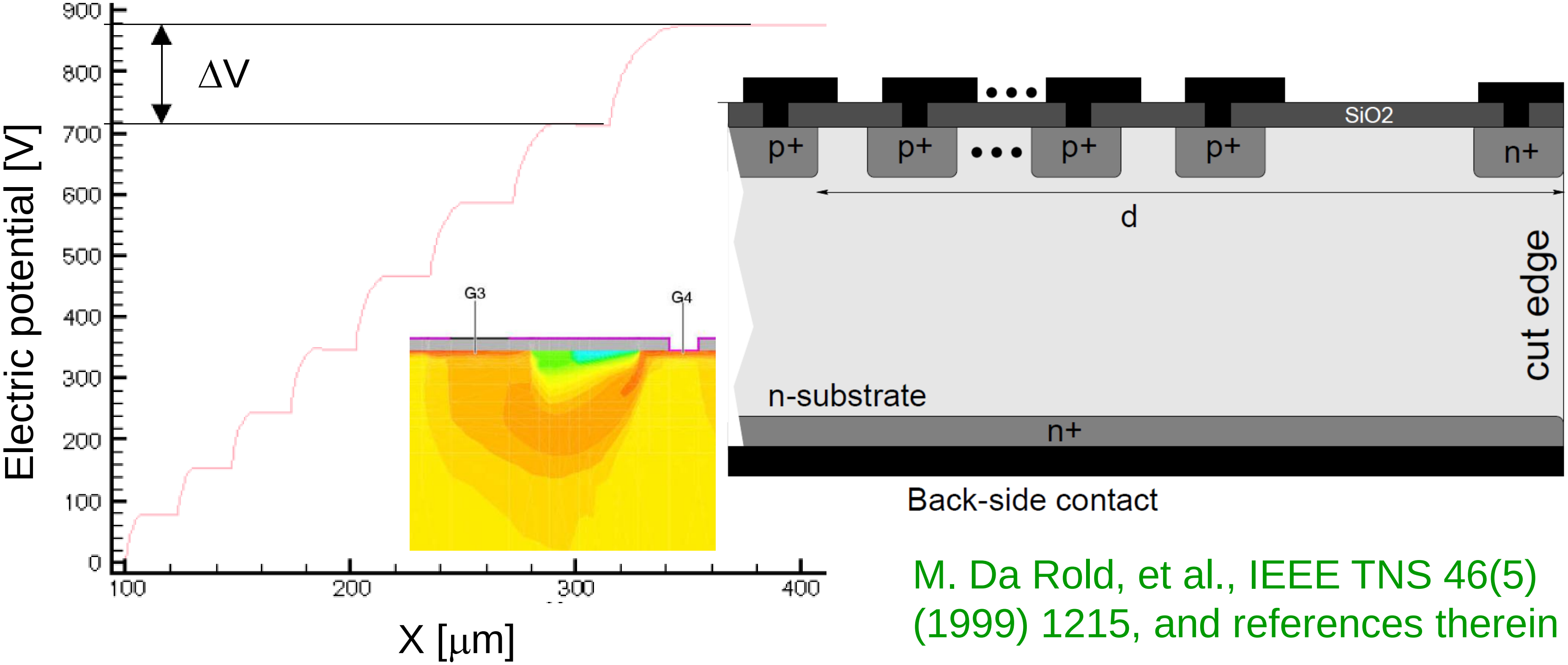
Nf=1e11cm^{-2}

Design improvements



Multiple rings with field plates

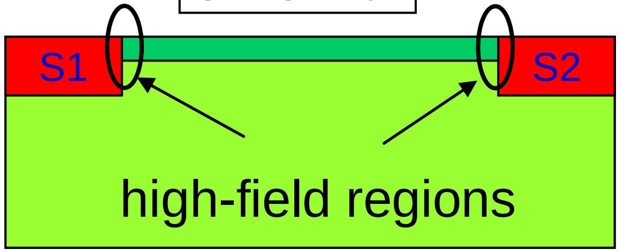
- Guard ring potential scales according to punch-through spreading
- The potential (field) can be evenly distributed enhancing the breakdown voltage, at the expense of dead area at the edges
- Main design parameters: ring spacing, FP size, oxide thickness



M. Da Rold, et al., IEEE TNS 46(5) (1999) 1215, and references therein

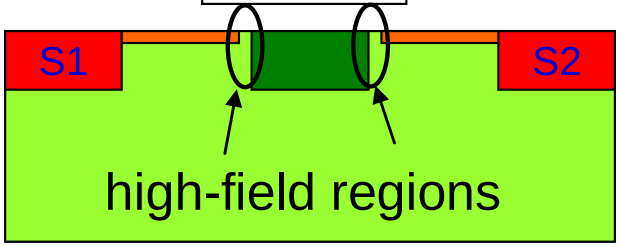
N-side: surface isolation

p-spray



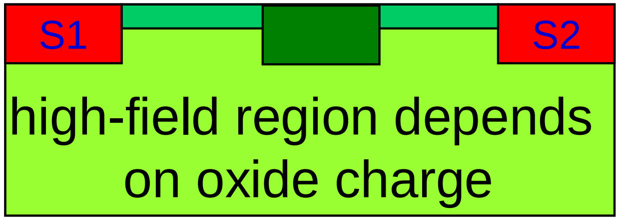
high-field regions

p-stop



high-field regions

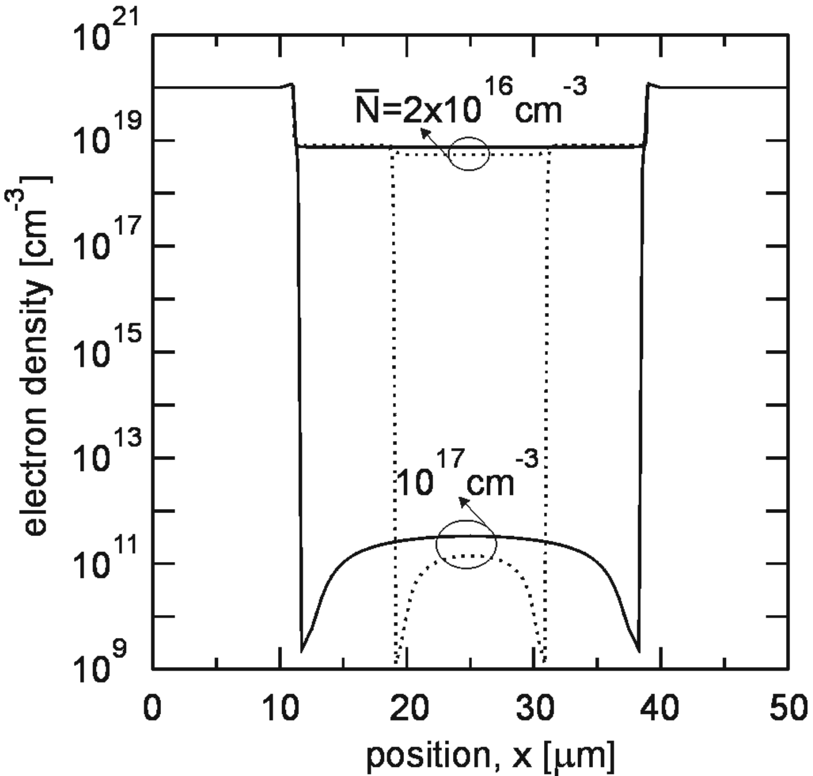
p-spray/p-stop



high-field region depends on oxide charge

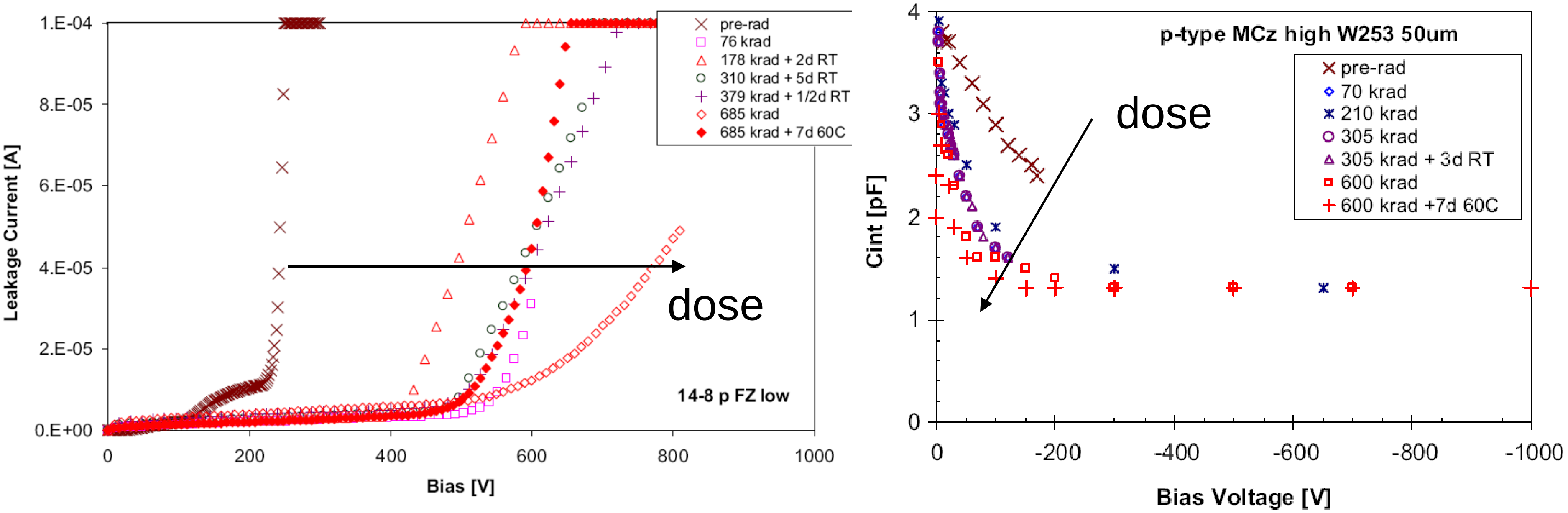
R. Richter et al., NIMA 377 (1996) 412

- 3 isolation techniques available to interrupt electron layer
- doping concentrations are critical
- isolation technique affects breakdown voltage and interstrip capacitance



Some data for p-spray

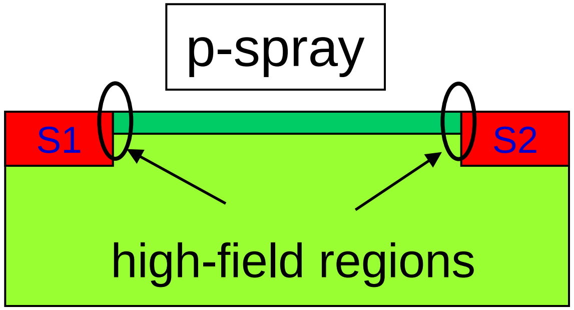
Irradiation at UCSC, ^{60}Co gamma source, 70krad steps



H. Sadrozinski et al., NIMA 579 (2007) 769

After irradiation:
- Breakdown voltage increases
- Interstrip capacitance decreases because oxide charge compensates p-spray

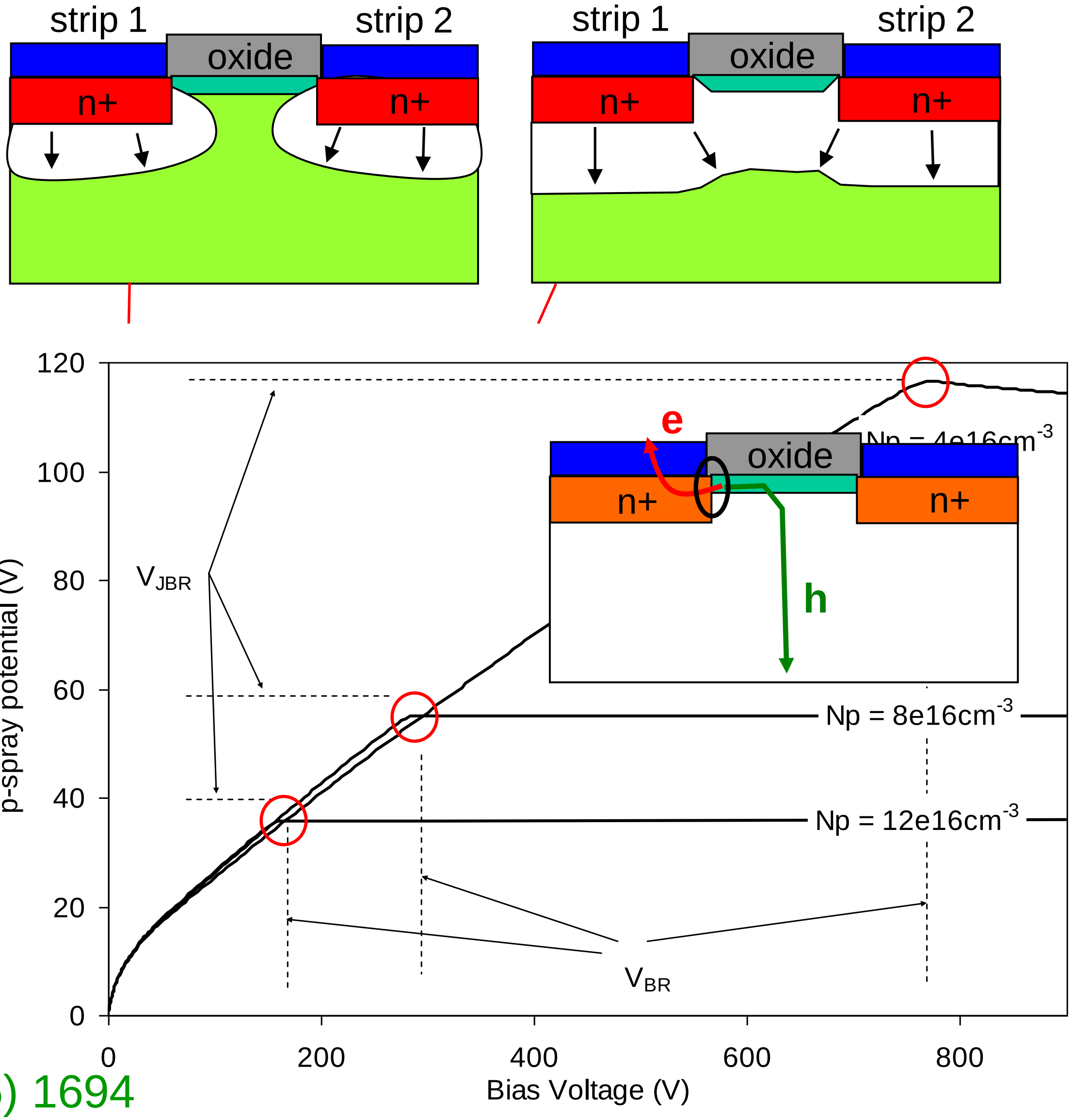
(annealing is detrimental in this case)



TCAD analysis: breakdown (1)

Three p-spray peak concentrations:

- N_{p1}=4e16cm^{-3}
- N_{p2}=8e16cm^{-3}
- N_{p3}=12e16cm^{-3}



V_{JBR} = potential difference between p-spray and strip which causes breakdown

V_{BR} = bias voltage for which we reach V_{JBR}

High Np => Low V_{JBR}
=> Low V_{BR}

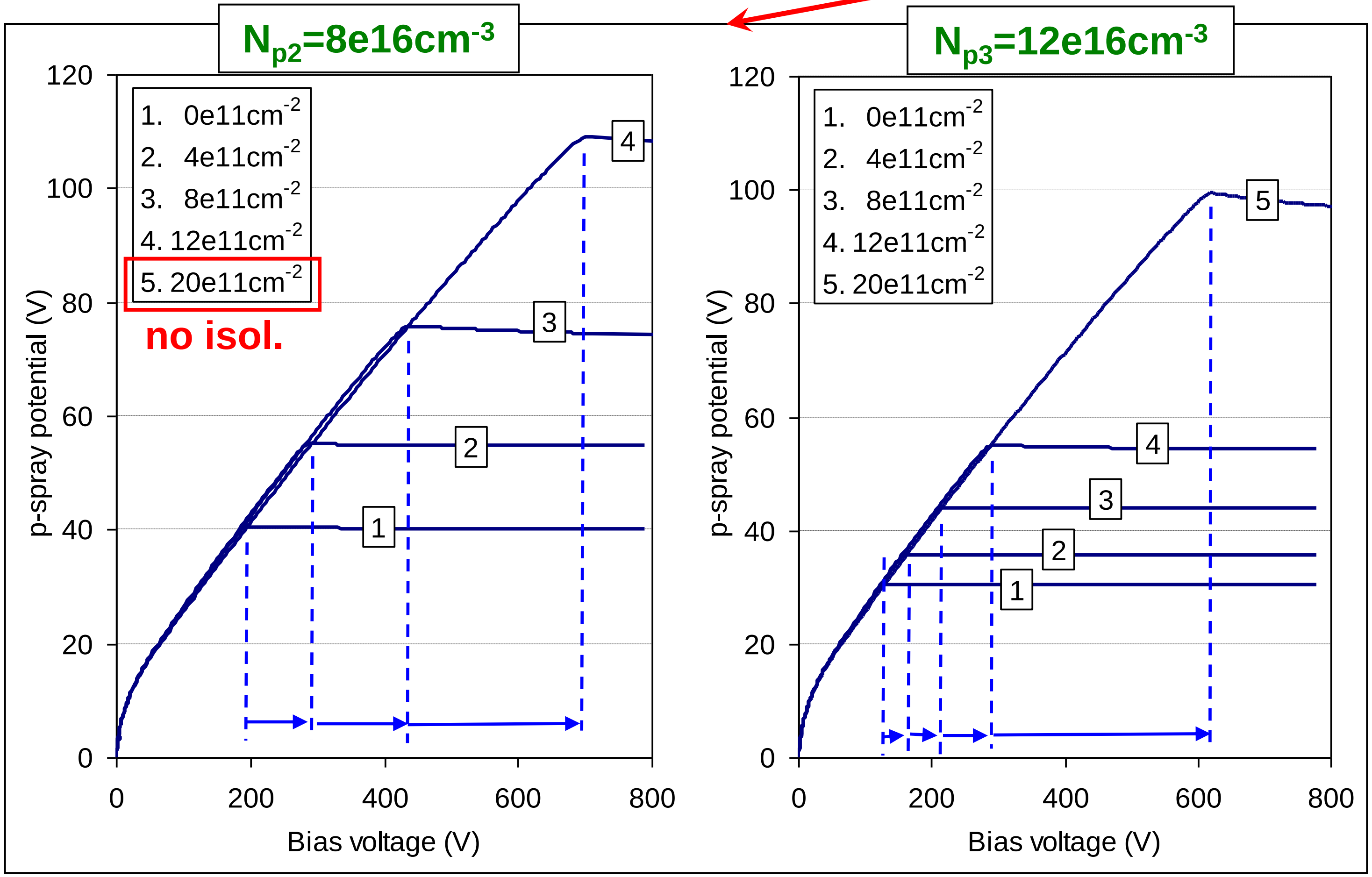
C. Piemonte, IEEE TNS 53(3) (2006) 1694

TCAD analysis: breakdown (2)

V_{BR} depends on:

1) $V_{p\text{-spray}}$ *vs* V_{BIAS} characteristic which depends on **w/p** and **N_a**

2) V_{JBR} level which depends on **N_P**, **Q_{OX}** **(and FP if present)**

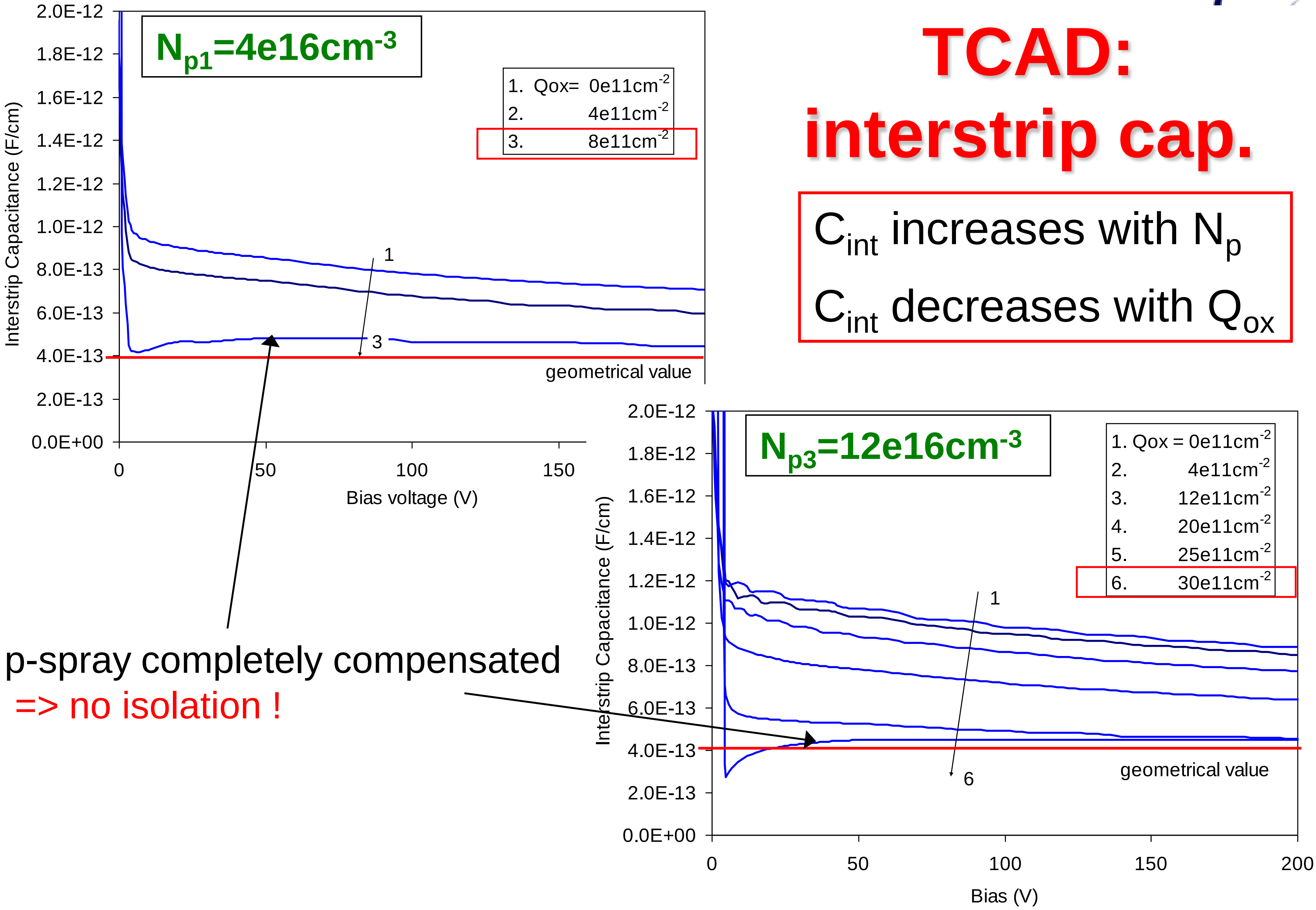


V_{BR} increases for increasing Q_{ox} because V_{JBR} level increases

TCAD: interstrip cap.

C_{int} increases with N_p

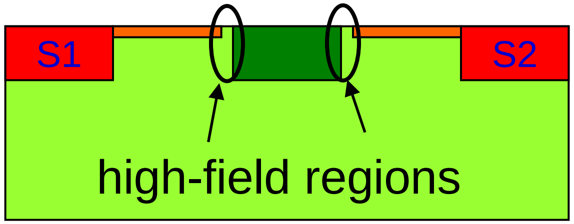
C_{int} decreases with Q_{ox}

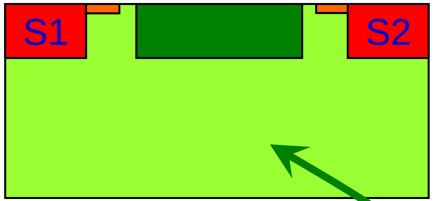


p-spray completely compensated

=> no isolation !

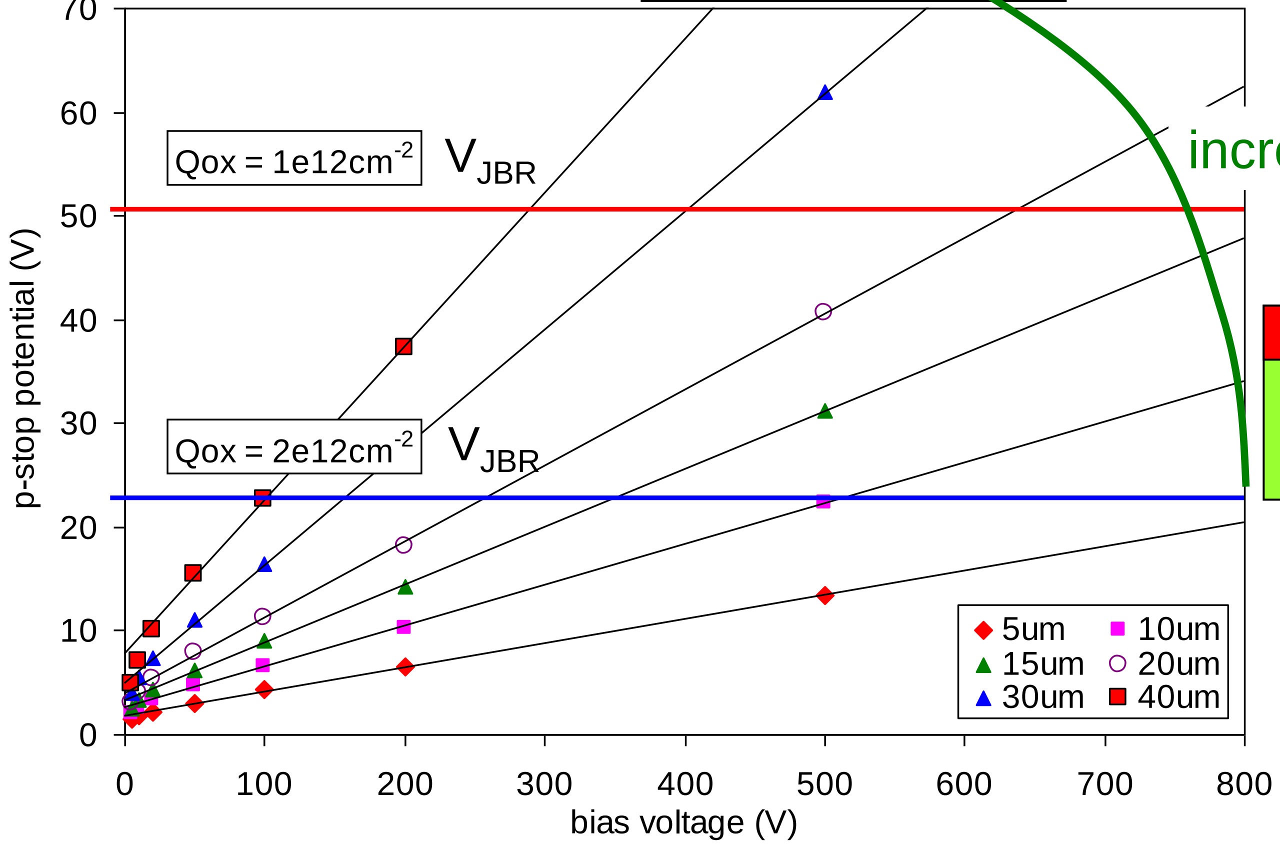
p-stop: breakdown



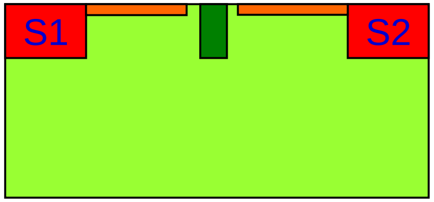


Similar approach to p-spray:

1. determine $V_{p\text{-}spray} = f(V_{BIAS})$
2. determine V_{JBR} level

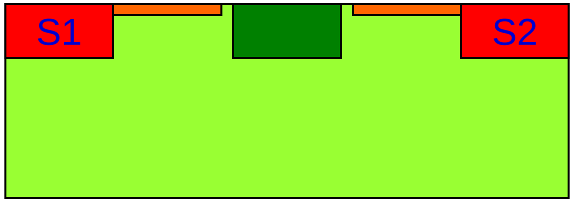


increasing p-stop width

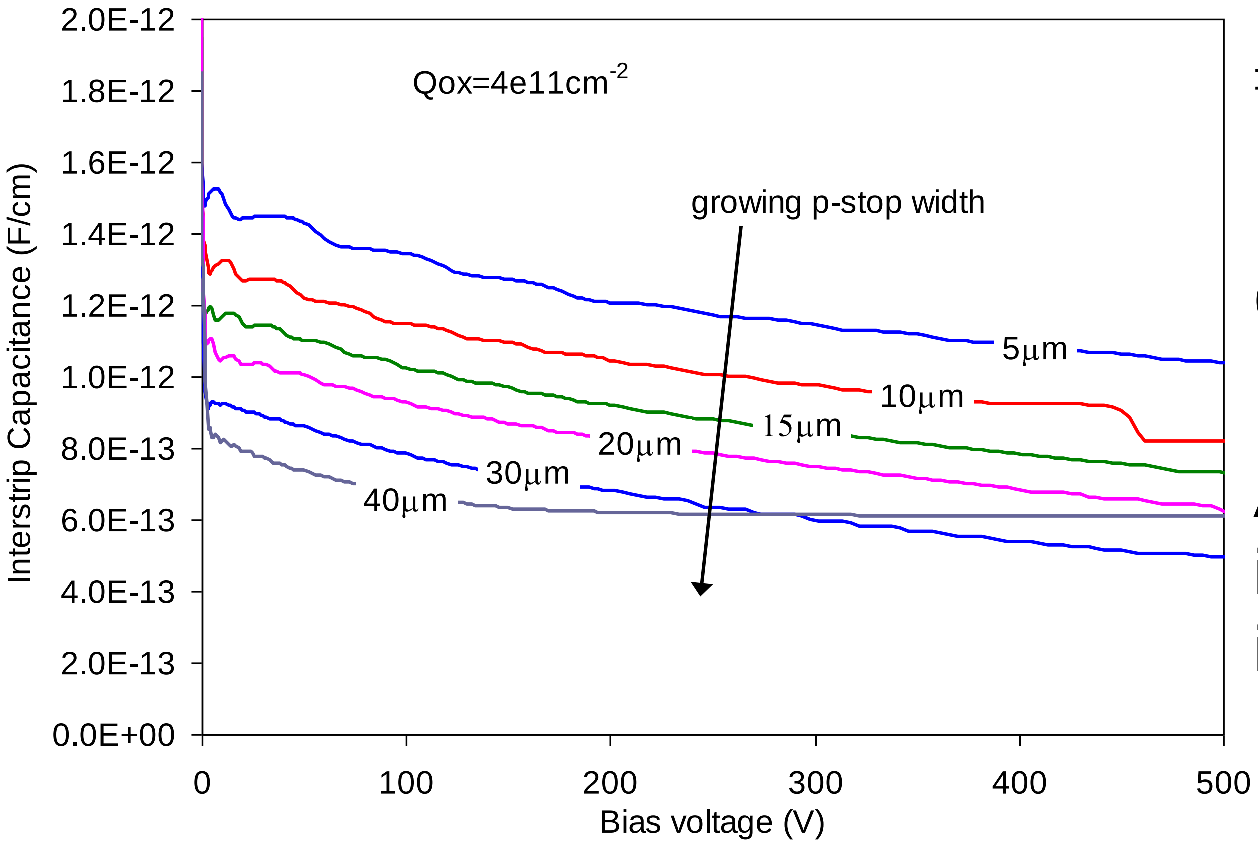


p-stop potential is higher for wide implants
⇒ better narrow p-stop from the breakdown viewpoint

p-stop: interstrip capacitance



electron inversion layer acts as an extension of the n$^+$ strip!



$\Rightarrow$ narrow p-stop implies higher capacitance

(opposite trend with respect to breakdown)

As Q_{ox} increases, interstrip capacitance increases

p-spray + p-stop: concept

p-spray: V_{BR} - low before irradiation
- improves for increasing Q_{OX}

C_{int} - improves with irradiation

improves with Q_{OX}

BUT

possible loss of isolation

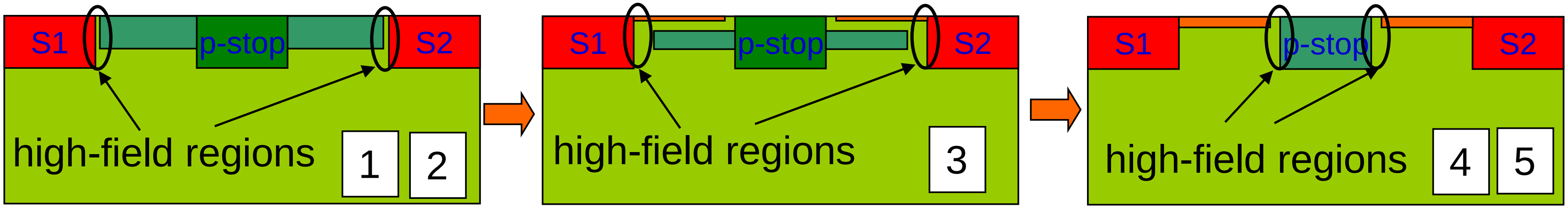
p-stop: V_{BR} - high before irradiation
- decreases for increasing Q_{OX}

C_{int} - deteriorates for inc. Q_{OX}

deteriorates with Q_{OX}

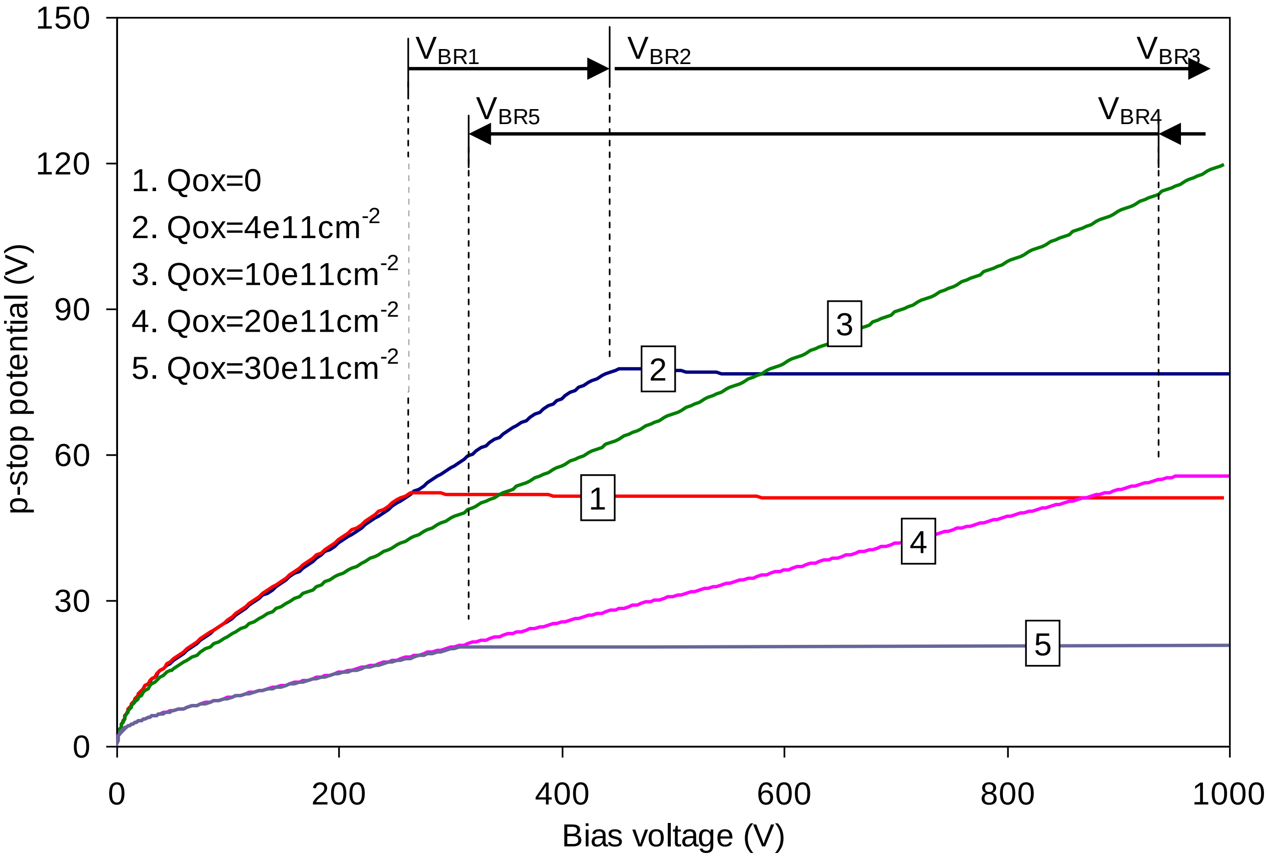
⇨ third solution is to combine the previous two using:
- medium dose p-spray (to have sufficiently high initial V_{BR})
- 20/30μm wide p-stop (to have low capacitance for high Q_{OX})

p-spray + p-stop: breakdown

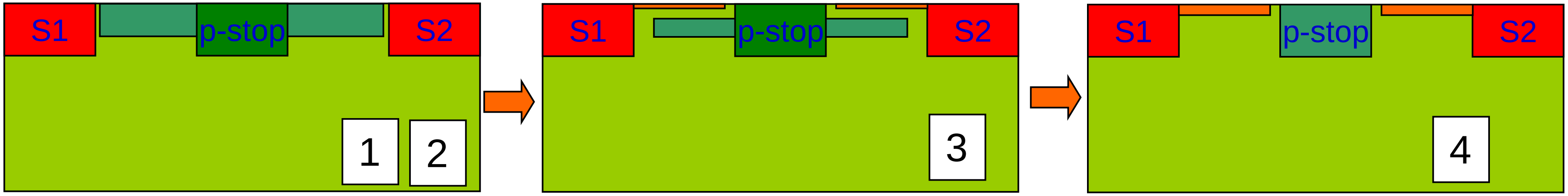


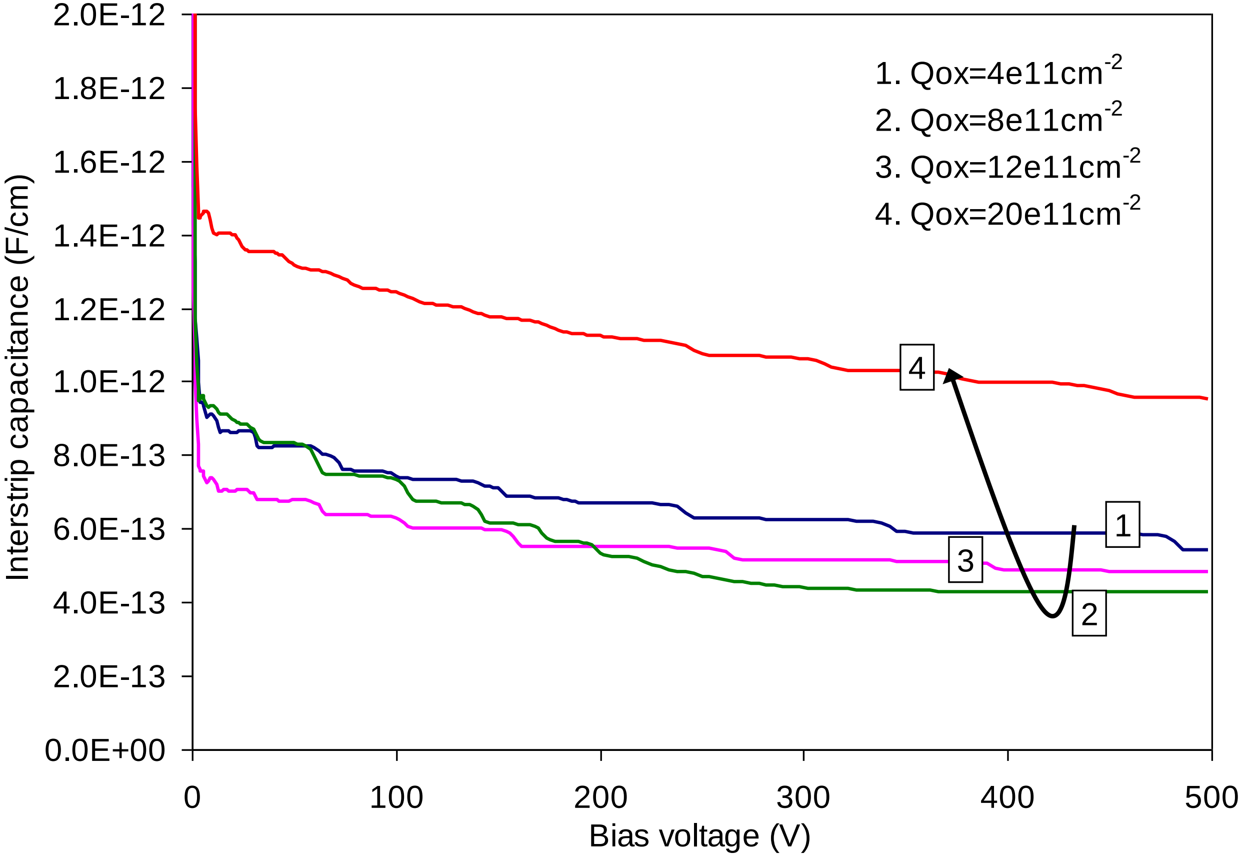
For increasing Q_{OX}:

V_{BR} first increases (typical of p-spray) than decreases (typical of p-stop) as Q_{OX} grows



p-spray + p-stop: interstrip cap.





C_{int} first decreases (typical of p-spray) than increases (typical of p-stop) as Q_{OX} grows

Conclusion

- Surface effects can strongly impact on detector performance and should be carefully considered
- Design/processing choices are normally the result of compromises between different parameters, among them breakdown voltage and parasitic capacitance play a major role
- Of course, optimal solutions vary with application and irradiation scenario
- TCAD tools allow for a quantitative analysis and prediction of detector performance

Acknowledgement

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- Dr. Nicola Zorzi (FBK, Trento)
- Dr. Marco Povoli (University of Trento)

Thank You