Updates on Punch-through Protection

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- Punch-through Protection against Large Voltages on Implants
- Testing of Field-breakdown with an IR Laser
- Comparison with DC measurements
- F. o. M. : Bulk Resistance / Saturation Resistance
- Extraction of PT parameters: DC 4-R Model
- Radiation and Temperature Effects
- P-Dose (spray and stop)
- Role of Implant Resistance: Mitigation ?
- (R-C Filter Circuit, looks ok, but work is not completed)

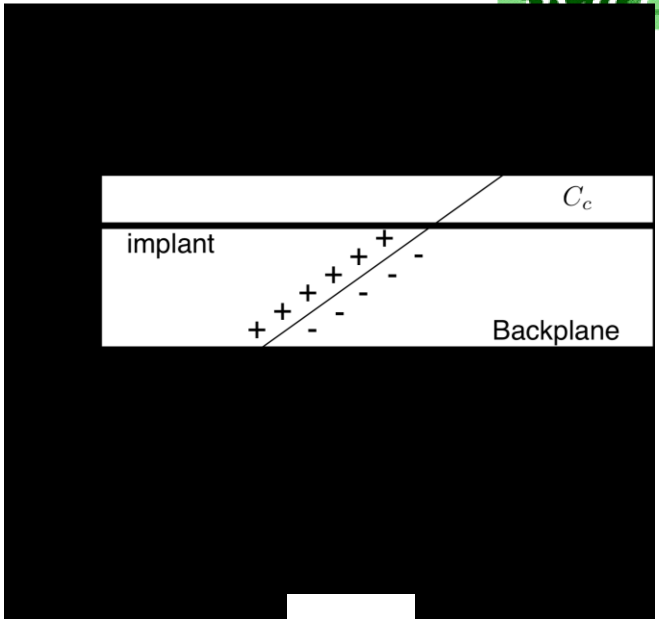
Damage from Beam Losses to AC-coupled SSD

- In beam accidents, the field inside the sensor breaks down when the deposited charge makes the sensor conductive. At that point, the bias voltage can reach into the sensor bulk and can impart large voltages to the implants, while the Al readout trace of AC coupled sensors are held at ground by the readout ASIC

- This can lead to the large voltages across the coupling capacitors and breaking.

- To check this, we used IR lasers to mimic the beam loss and we indeed observed large voltages on the implants

T. Dubbs et al., IEEE Trans. Nuclear Science 47, 2000:1902 – 1906.



- The reach-through (punch-through) effect was considered an elegant and effective way to limit the voltages on the implants. Special punch-through protection (PTP) structure can be designed where the geometrical layout determines the voltage limits on the implants.

J. Ellison et al., IEEE Trans. Nuclear Science, 36, 1989: 267 - 271.

- PTP structures were implemented in the p-on-n SCT sensors.

- But the PTP structure in SCT sensors were shown not to guarantee protection against large voltages across the coupling capacitors when IR laser pulses were used.

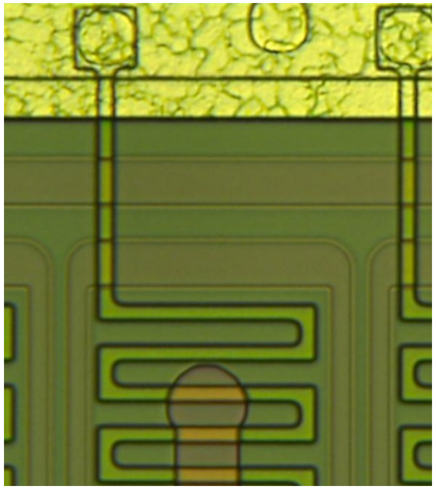
K. Hara, et al., Nucl. Instr. and Meth. A 541 (2005) p. 15-20.

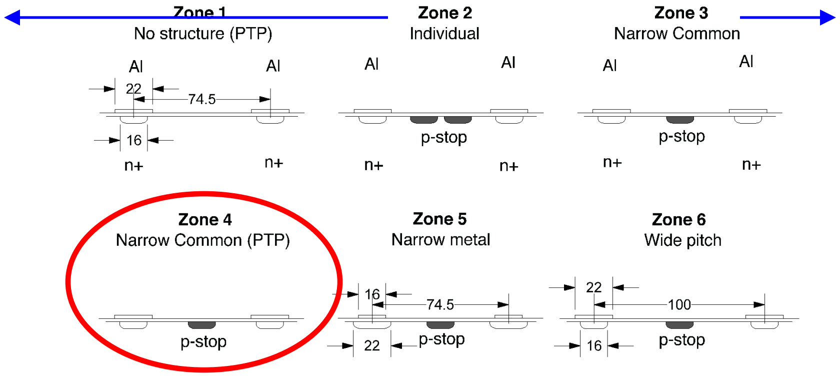
PTP in Upgrade Sensors ATLAS07

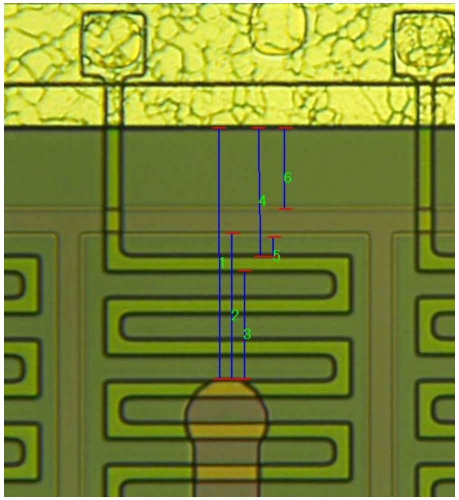
N-on-P full-size sensors and "mini's" to investigate PTP (in Zone 4A-4D)

Y. Nobu, et al., NIMA A (2010)doi:10.1016/j.nima.2010.04.080

No PTP structure

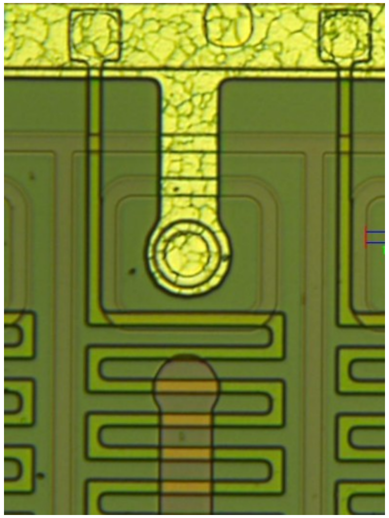




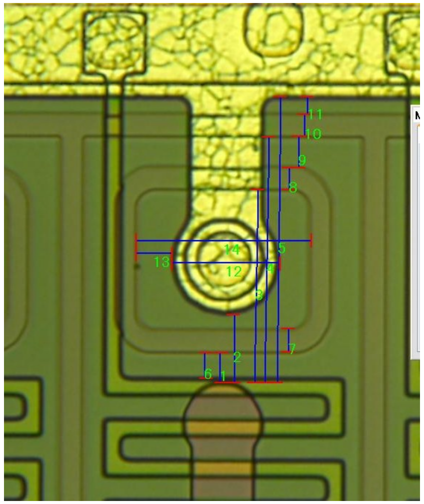


PTP structures

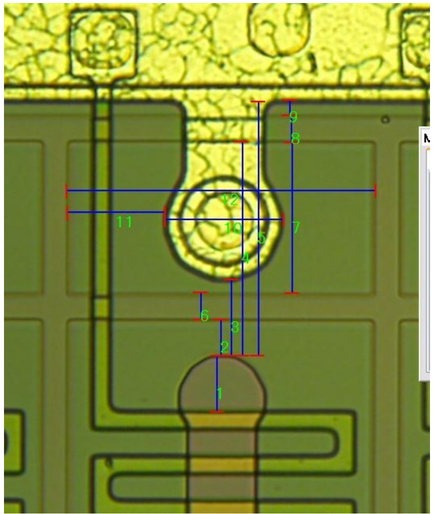
BZ4A



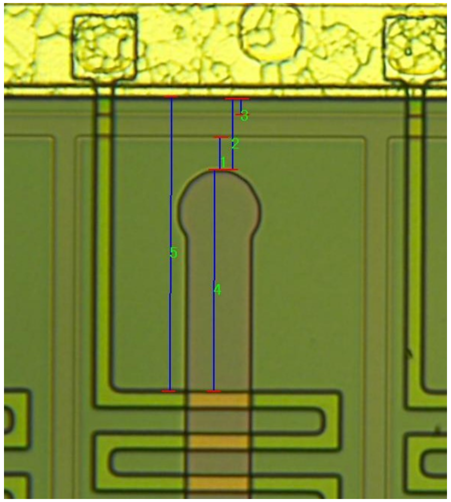
BZ4B



BZ4C



BZ4D

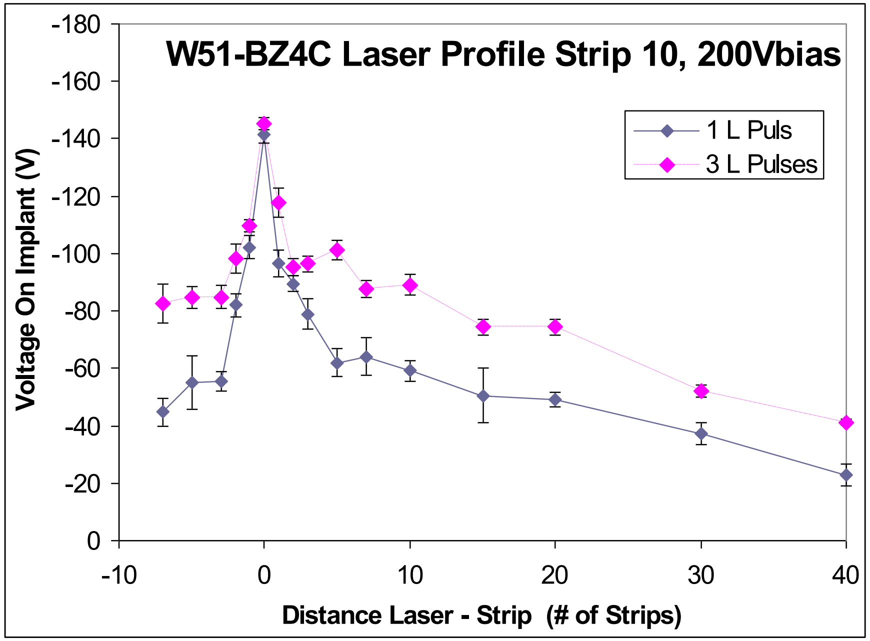


Testing Large Implant Voltages with Laser

T. Dubbs et al., IEEE Trans. Nuclear Science 47, 2000:1902 – 1906.

- Alessi IR cutting laser deposits large amounts of charge inside the detector which collapses the field(>10^{11} e/h pairs ~ 10^7 MIPs ~ 1 Rad / pulse).
- Intensity given by number of laser triggers ~ 4 μsec apart (we used up to 3).

- Bias ring is held to ground
- Voltage on a DC pad and/or AC pad are read via an high impedance voltage divider into pico-probe or digital scope.
- DC pad reflects biasing of strips,
- AC pad reflects instantaneous collected charge (~ depleted region)

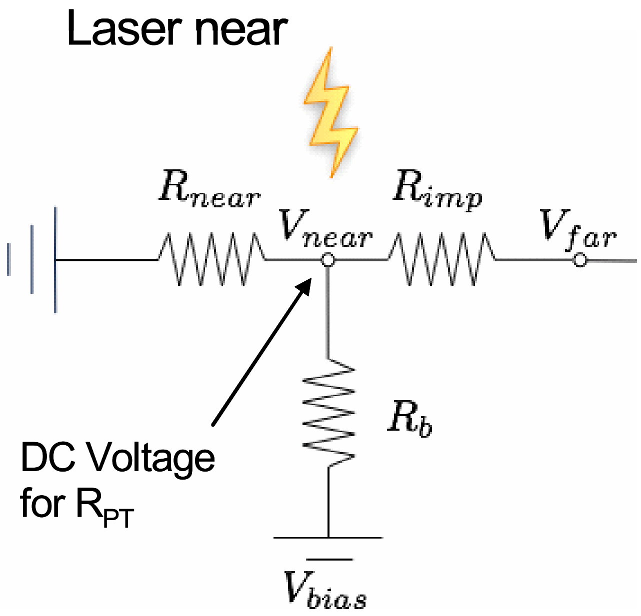


- Laser spot ~ 10 μm, but large DC voltages extend over few mm.

- Peak voltage independent of laser intensity, and AC grnd/floating

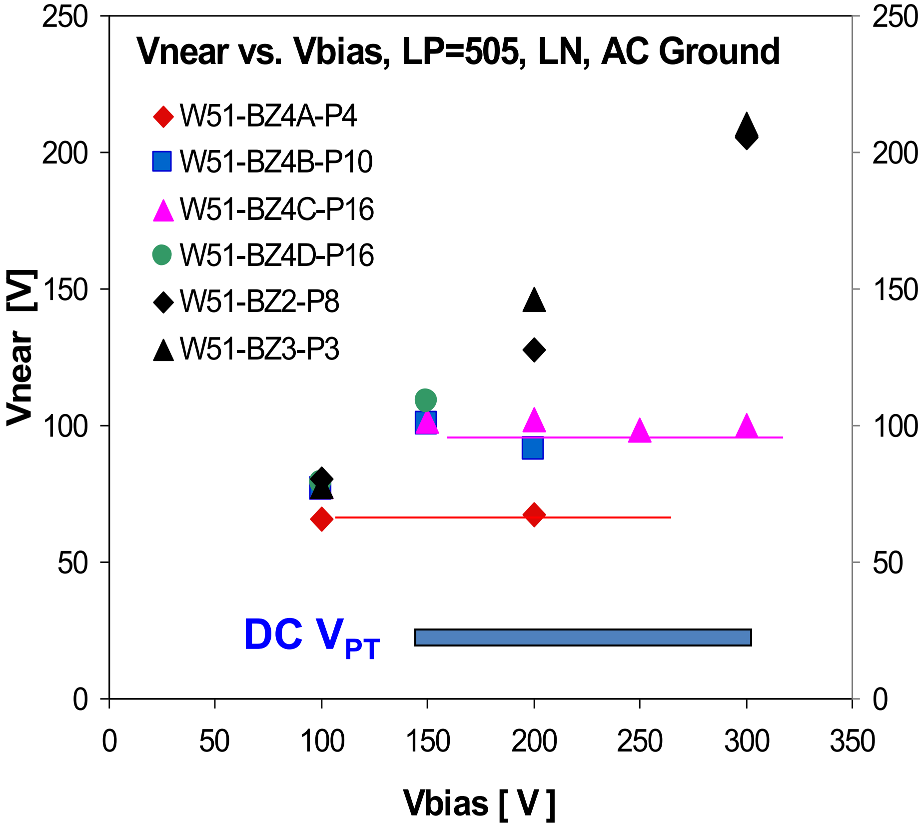
Voltages on strips are large, much larger than DC V_{PT} , comparable to bias voltage.

Laser implant voltages near R_{PT} vs. Bias



Laser near

DC Voltage for R_{PT}



$R_{near} = R_{PT}$ **in parallel to** R_{bias}

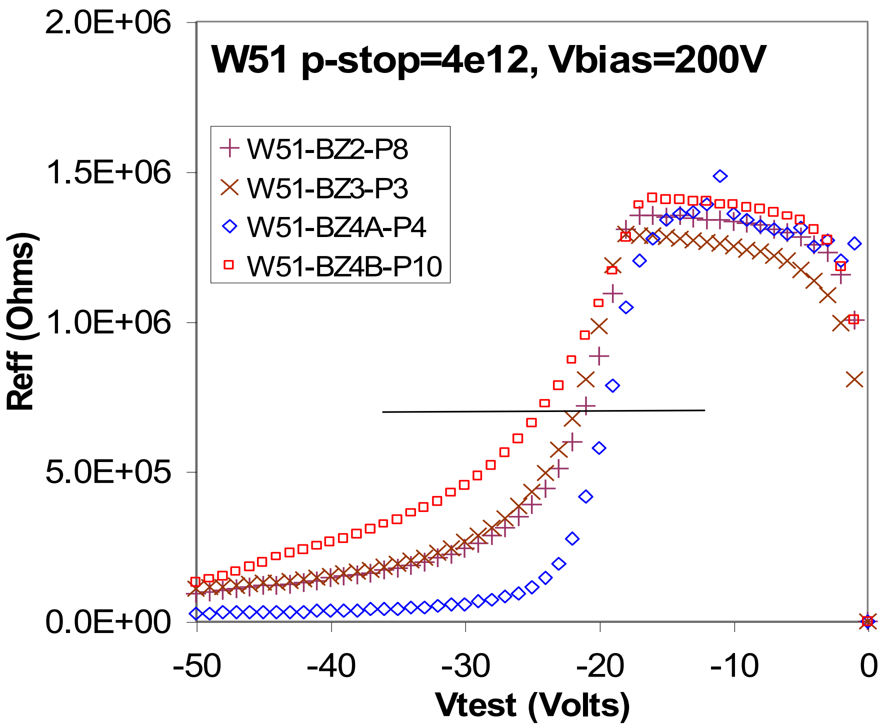
At high bias voltages, implant voltages for PTP structures saturate.
But the ones without PTP structures do not saturate
(even though DC VPT were very similar)

Can this be reconciled with the DC voltage dependence of R_{PT} ?

PTP Structure Effectiveness

- The effectiveness of PTP structures is determined in DC i-V measurements between the strip and the bias ring. One measures the “integral” effective resistance R_{eff}, (R_{near})which is the bias resistor R_{bias} in parallel to the PTP resistor R_{PTP}.
- The measure of the effectiveness of the PTP structure is the punch-through voltage V_{PT} , defined as the voltage at which

  $R_{PTP} = R_{bias}$, i.e. $R_{eff} = 0.5 * R_{bias}$.
- The PT voltage V_{PT} was measured to be a few 10’s of Volt.



S. Lindgren, et al., NIM A (2010) doi:10.1016/j.nima.2010.04.094

But:

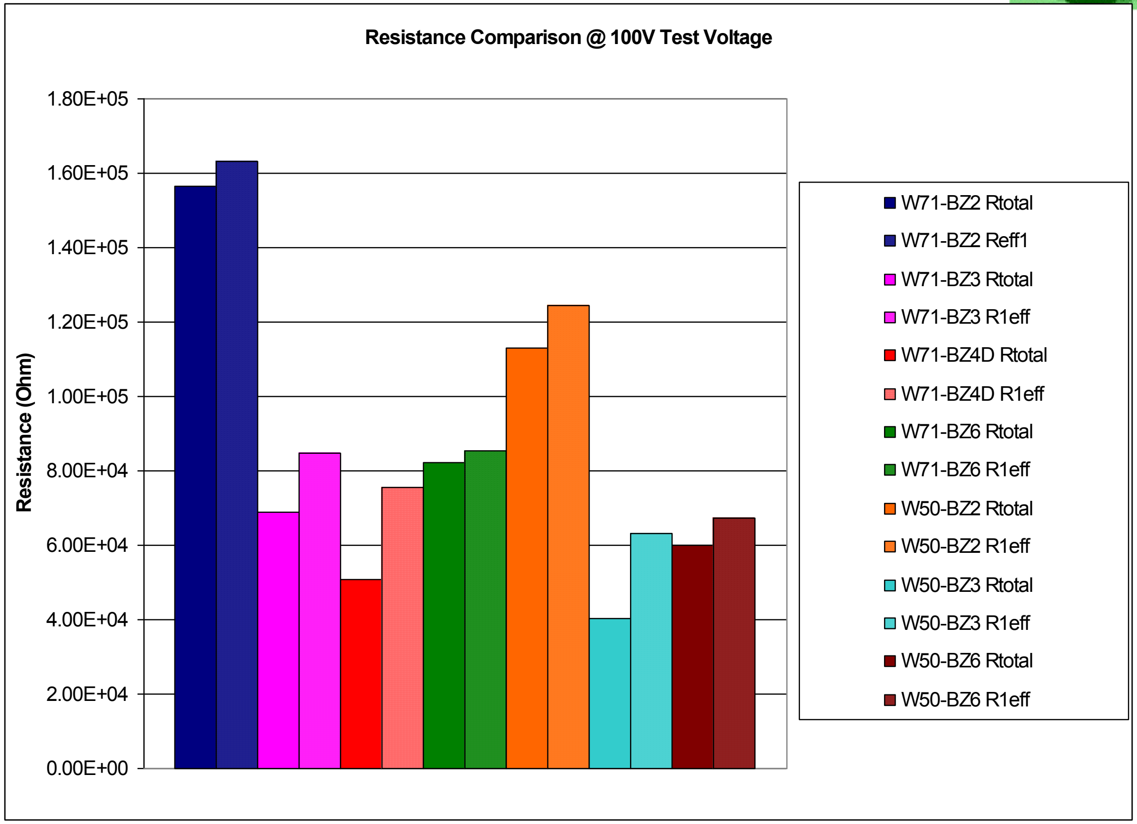
V_{PT} shows very little variation with the dimension of the PTP structure (channel length L):

	L [μm]	V_{PT}
BZ4A	21	20
BZ4B	21	24
BZ2 / BZ3	75 / 67	21

Issues with DC measurements

- In DC measurements interstrip punch-through can be significant:

  compare Rtotal (Vtest/Itest) and R_{near} @ 100V test voltage.
- In DC measurements, the neighbors are held to ground through the bias resistance, i.e. the test voltage is essentially applied between neighboring strips.
- In laser measurements much smaller voltage differences between neighbors are observed, since many strips are involved: no inter-strip PT!



Understanding PT Structures: I-V

- For V<Vpt the IV curve given by generation/recombination, surface leakage and bulk leakage
- For Vpt<V (punch-through regime), two models exist for IV curve
  1. IV governed by Thermionic Injection [J. Chu, G. Persky, S. Sze, J. Appl. Phys., Vol. 43, No. 8 (1972)]

     $$I(V) = I_o e^{q(V-V_{fb})^2/4kTV_{fb}}$$

  2. IV governed by Drift-Diffusion [J. Lohstroh et al., Solid State Elec. Vol 29 No. 9 (1981)]

     $$I(V) = I_{po} e^{q(V-V_{pt})/mkT}$$

     Drift-Diffusion

     where m is called the *non-ideality factor* and is a function of the voltage (current)
- For large current, IV becomes space-charge limited and is given by

  $$I(V) = \frac{2A\epsilon v_s}{L^2}(V - V_{fb})$$

  SCL,

  no dependence on V_{PT}
- No closed form solution for V(pt-mode)<V<V(SCL-mode)

PT Resistances and Voltages in SCL

$$R_{scl}(V) = \frac{R_{sat}}{1 - V_{fb}/V}$$

where

$$R_{sat}(I) = \frac{L^2}{2A\epsilon v_s}$$

$$R_{scl}(I) = R_{sat} + V_{fb}/I$$

$$V_n = V_{fb} + IR_{sat}$$

or in terms of Vbias

$$V_n = \frac{1}{1+\alpha}(V_{bias} + \alpha V_{fb})$$

$$\alpha = \frac{R_{bulk}(+R_{imp})}{R_{sat}}$$

Vn ~ Vbias when α is small, i.e. Rsat >> Rbulk: Not Good for PTP

Vn saturates to V_{fb} when α is large, i.e. Rsat << Rbulk : Good for PTP

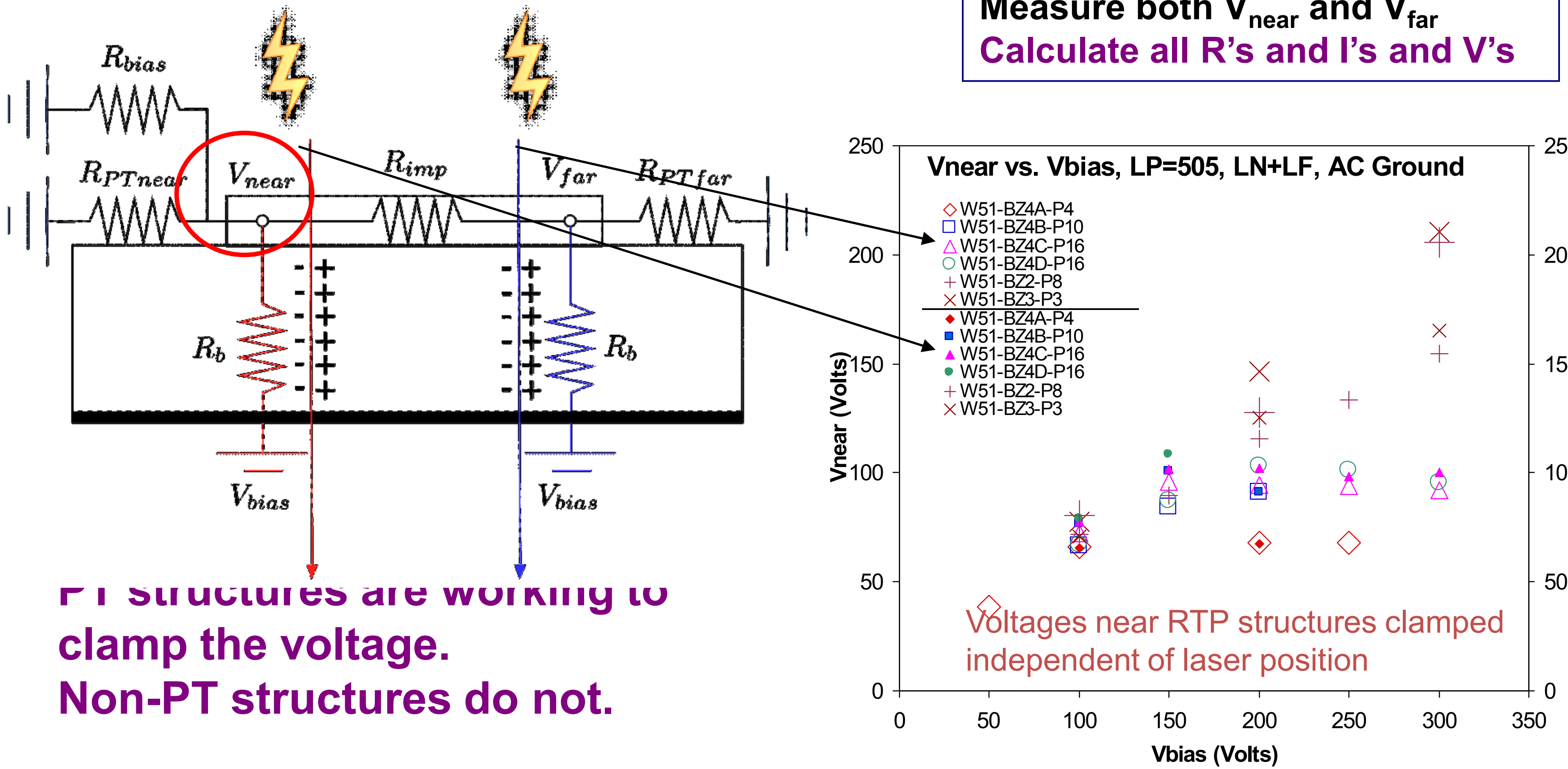
Investigate the dependence of PT parameters on geometry, doping levels, temperature, radiation

A DC “4R” Model works nicely

- After breakdown of field inside the sensor, deal with DC resistor chain only

R_{PTnear} = R_{eff} (R_{PTnear} ,R_{bias})
R_{PTfar} = R_{PT} on the far end of the strip, $R_{PTfar} > R_{PTnear}$
R_{imp} = Resistance of implant 15kΩ/cm
R_{bulk} = Bulk Resistance

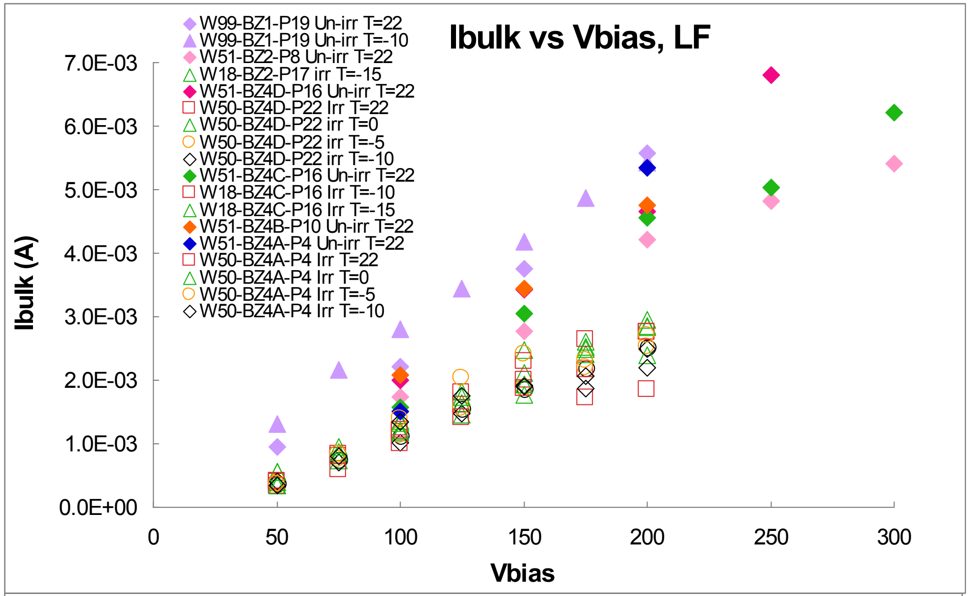
Important for 4R Model:
Fire laser both near and far.
Measure both V_{near} and V_{far}
Calculate all R’s and I’s and V’s

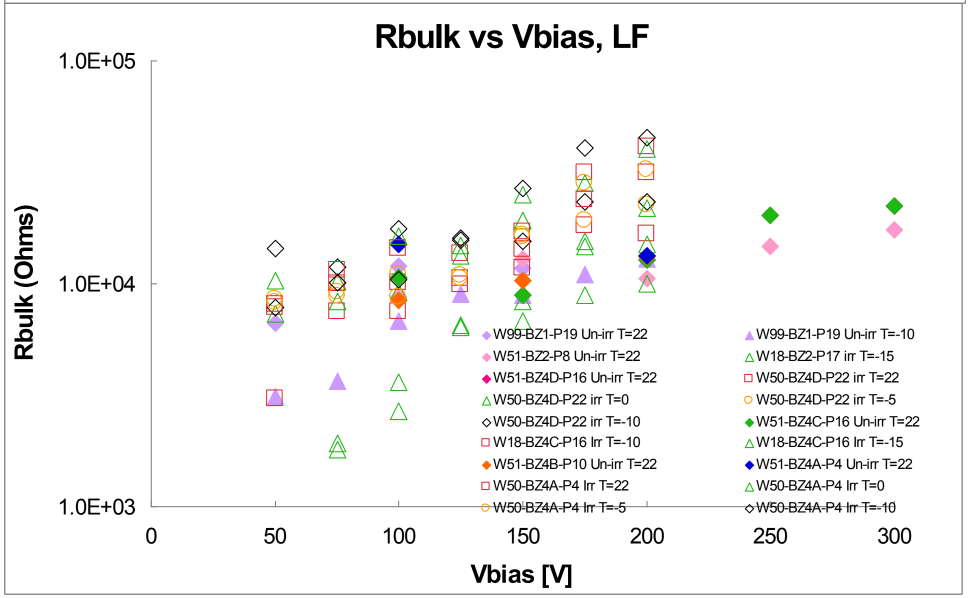


Voltages near RTP structures clamped independent of laser position

PT structures are working to clamp the voltage.
Non-PT structures do not.

Bulk has Resistance of 10’s kΩ





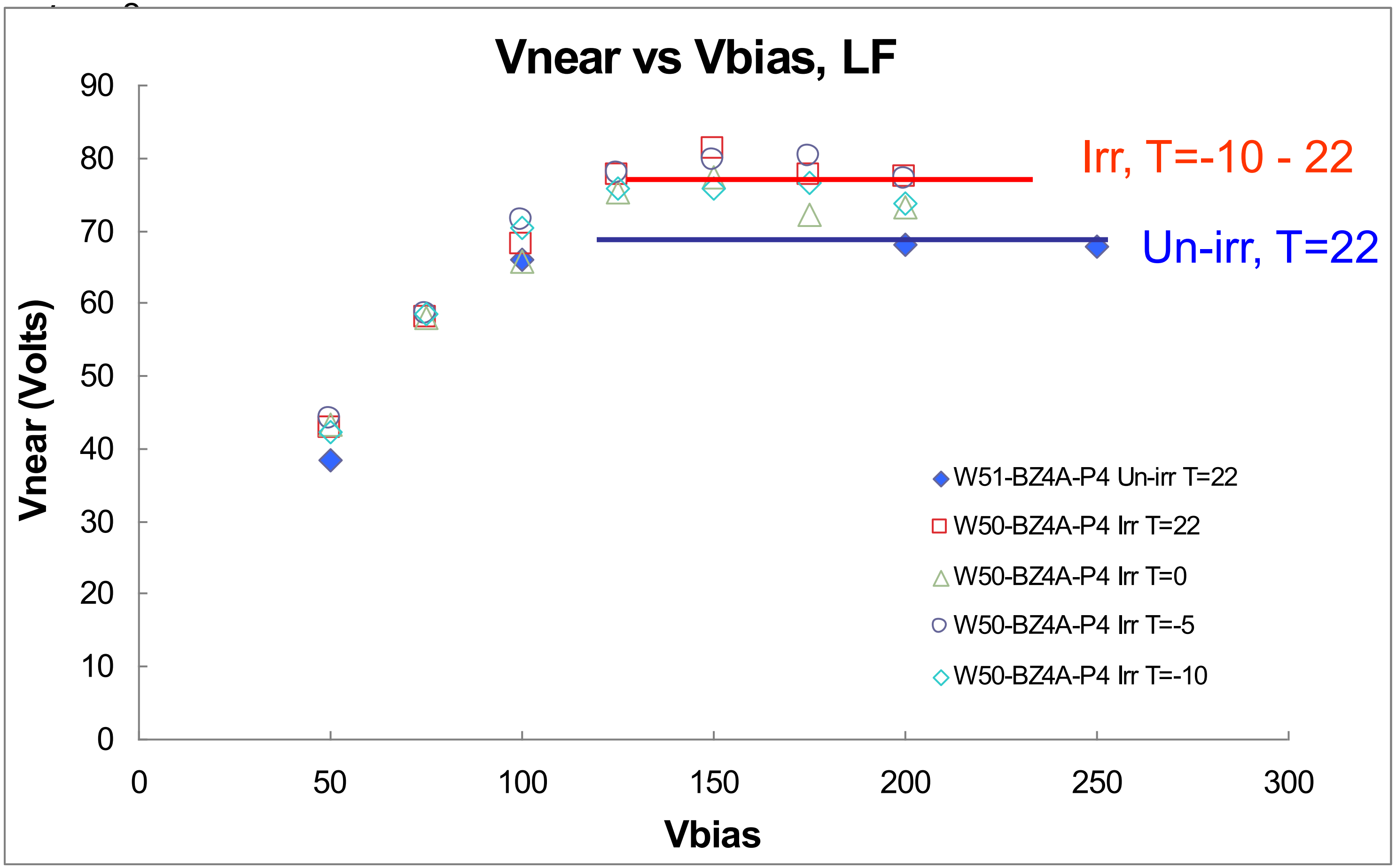
Filled symbols: un-irradiated, T=22
Open symbols: irradiated, T = -15 to +22
Depletion ~150 V

Independent of T
Dependent on Radiation (V_{fb}!)

R_{Bulk} ~> $10^4\Omega$
After depletion at 150V

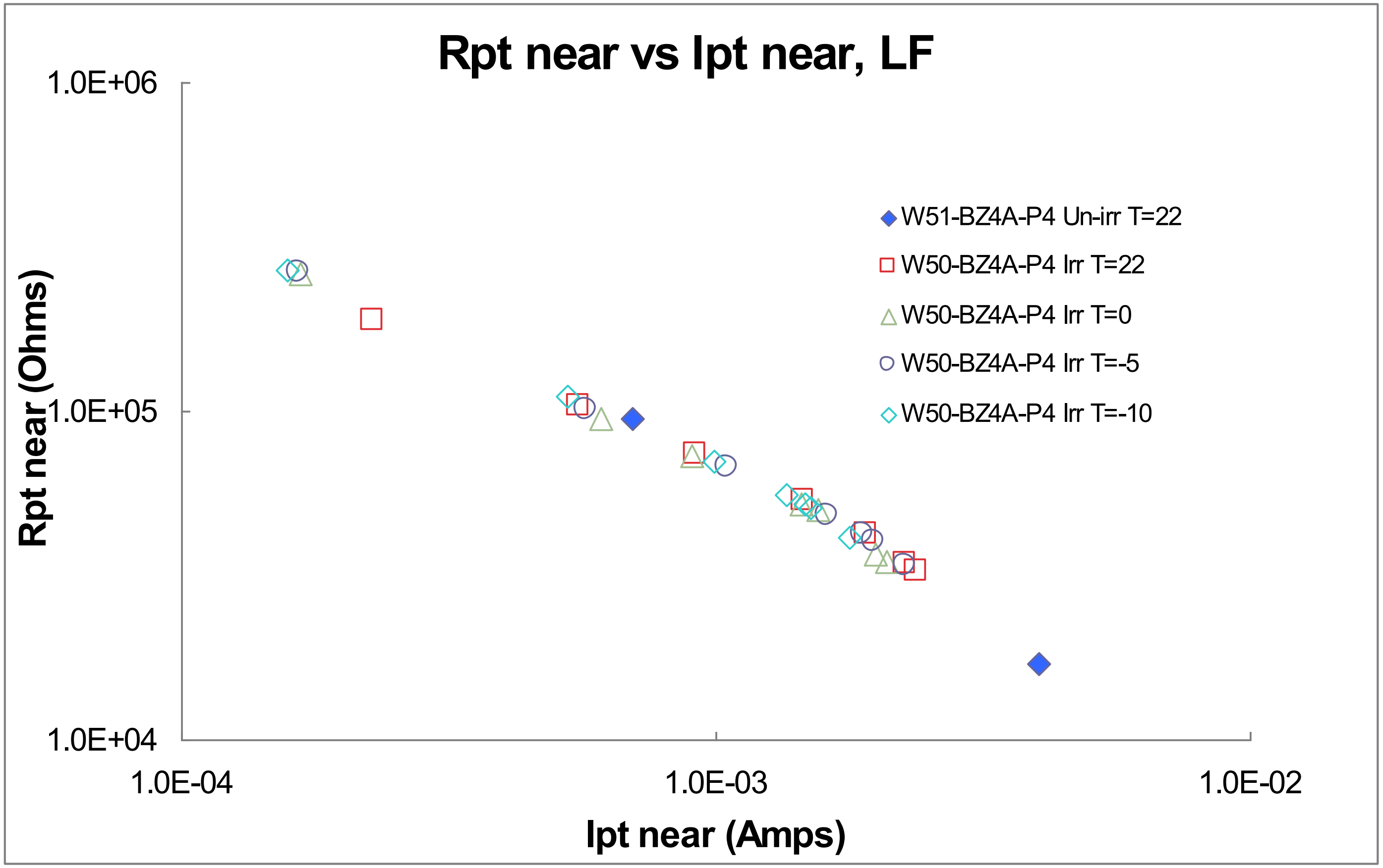
PT Structures have small R_{sat} (~100Ω)

Irradiation with 70 MeV protons to 10^{13}



Saturation of voltage persists post-rad, with small increase in Vnear (V_{fb} !)
No temperature dependence either pre- or post-rad. Need higher fluences!

PT Structures have small R_{sat} (~100Ω)

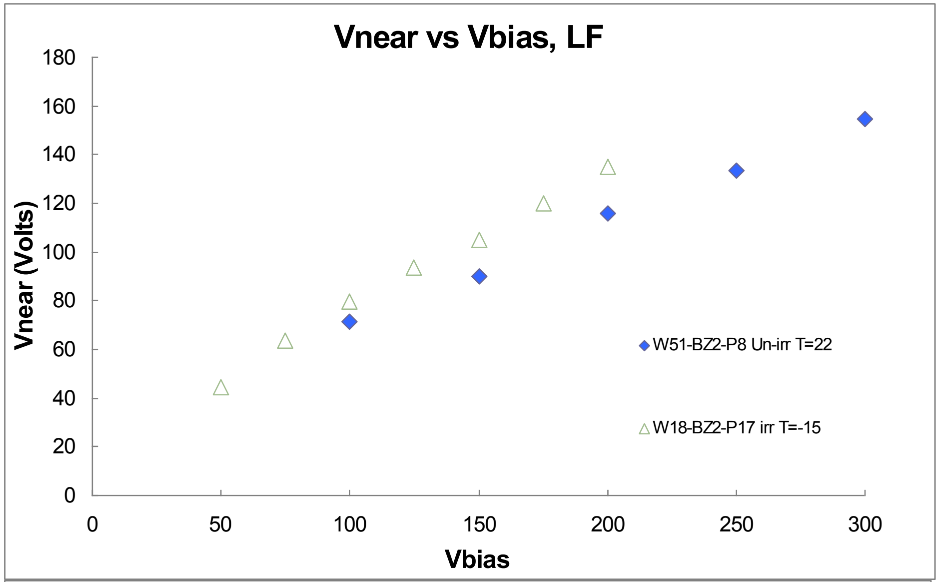


PT resistance $R_{PT} \sim 1 / I_{PT}$

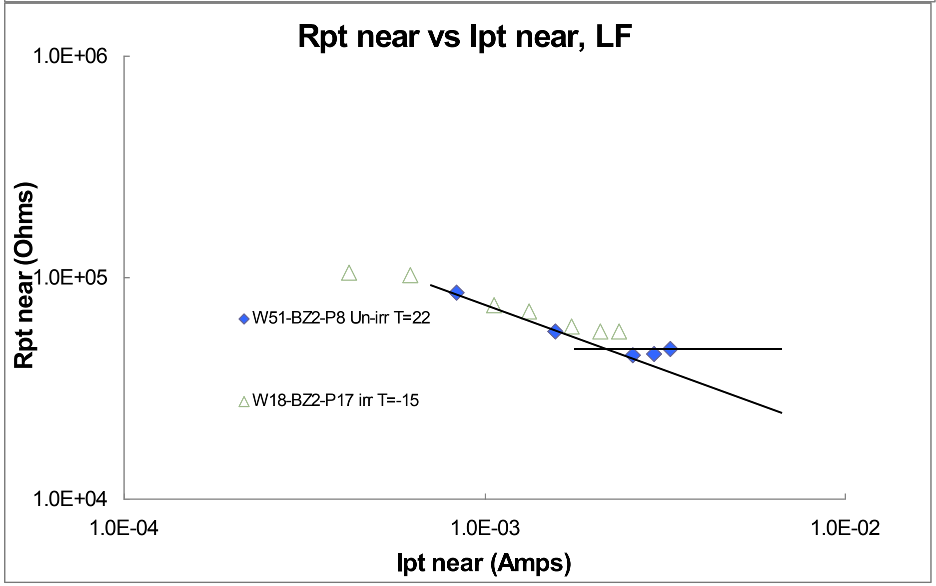
no T dependence

no radiation dependence (V_{fb})

Non-PT Structures have large R_{sat} (~30kΩ)

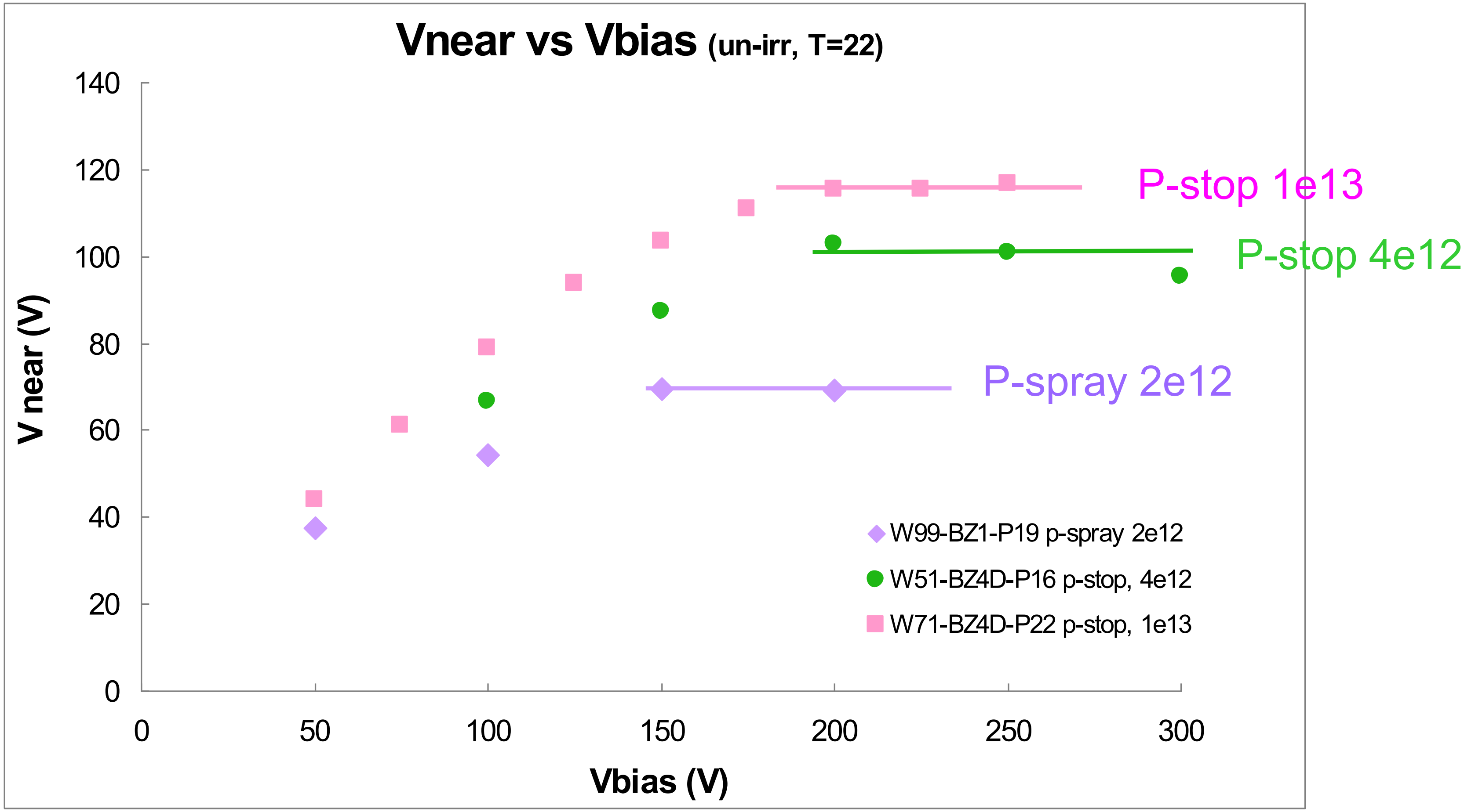


No Saturation of Voltage



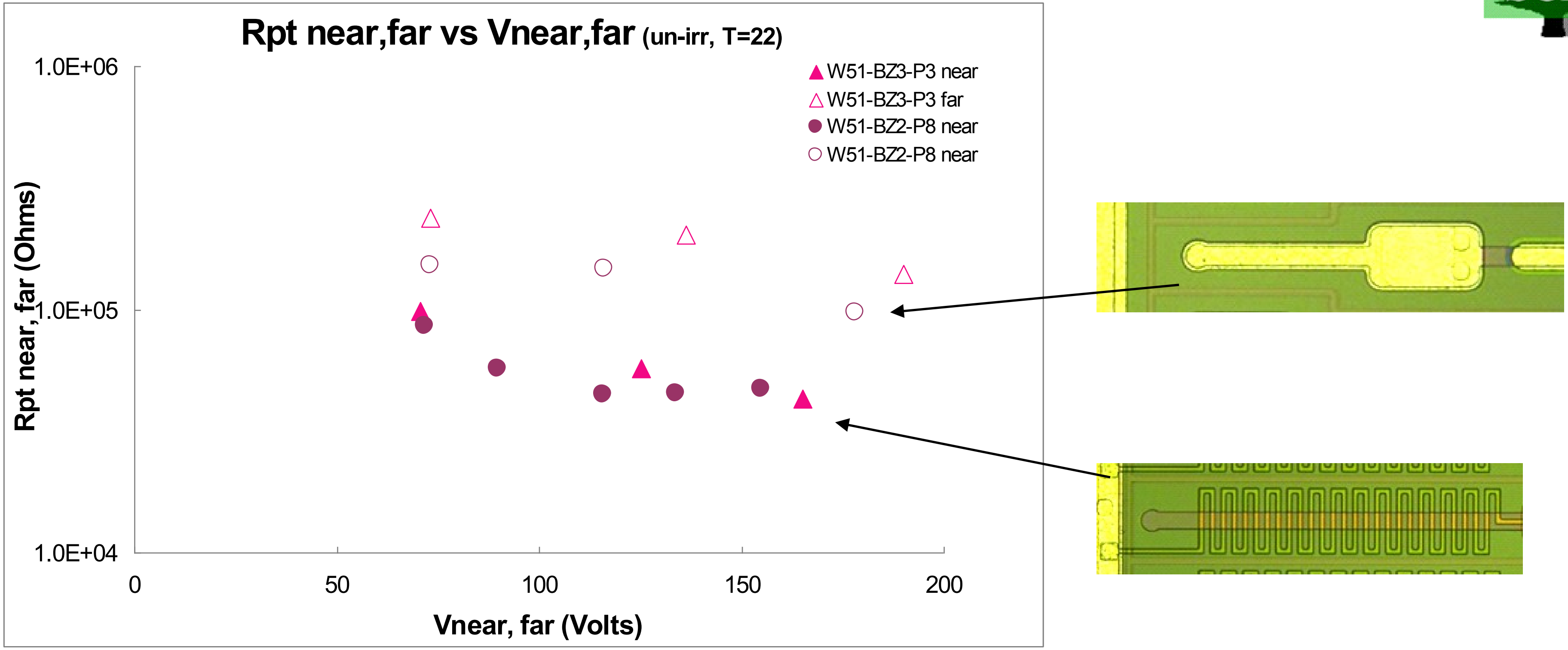
PT resistance starts to saturate

P-spray vs. P-stop (3 p-doses)

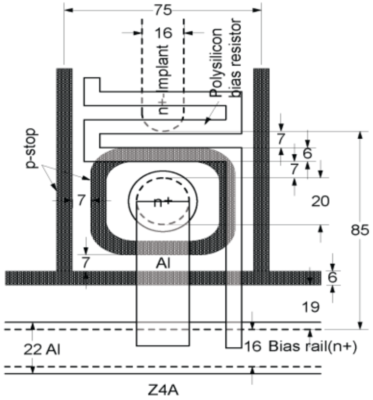


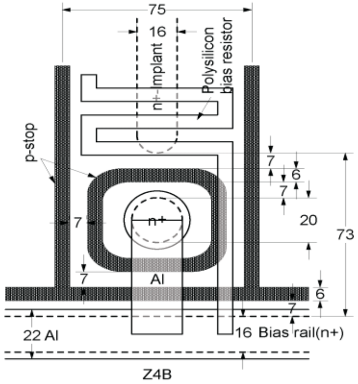
Increased p-dose increases Saturation Voltage – Flat Band Voltage V_{fb}

Gate Effect in R_{PT}(near)



Difference of "identical" near and far resistances in BZ2 and BZ3:
Strong gate effect of the Poly bias resistor (c.f. FOXFET)
Also: in BZ4A the Poly resistor has the best channel coverage

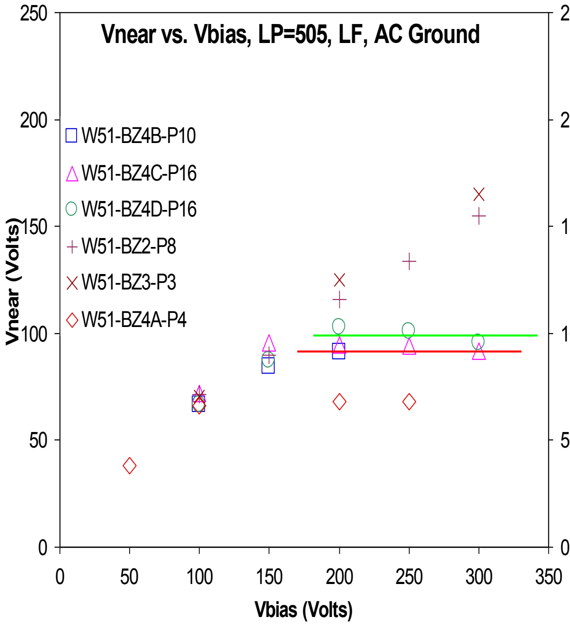


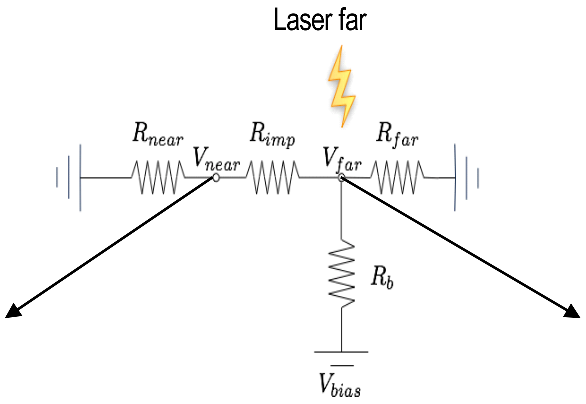


Effect of Finite Implant Resistance R_{imp}

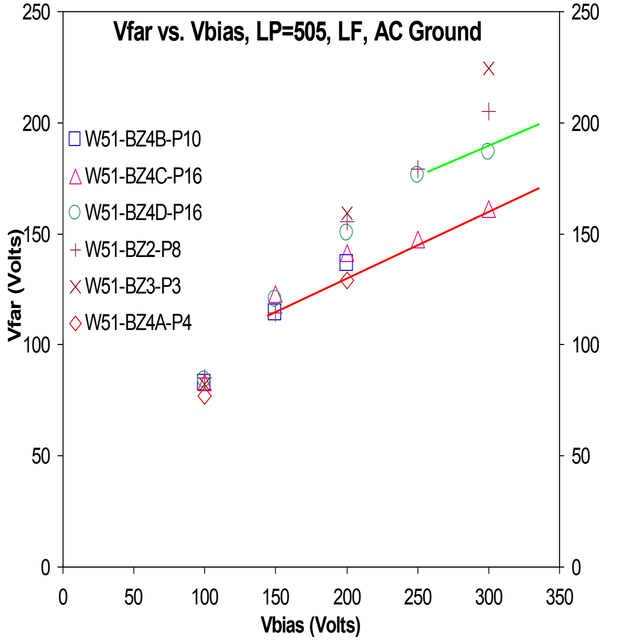
Fire laser at the far end of the 1 cm strip, measure both V_{near} and V_{far}

Near end, plateau
for some PT structures





Opposite end, no plateau.



$V_{far} > V_{near}$
Saturation in V_{near}
No saturation in V_{far}
RTP structure not effective for V_{far}

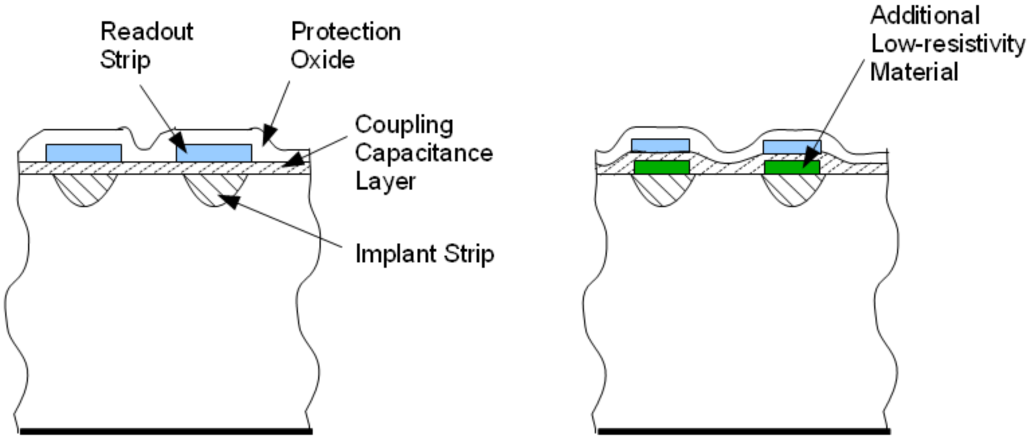
Limitation of application of PTP structures: finite R_{imp}

Implant Voltages do not saturate at high bias voltages, if finite implant resistance R_{imp} isolates PTP structure from breakdown region.

Proposal with CNM Barcelona to reduce strip resistance.

Reducing Implant Resistance (CNM – UCSC)

- Proposed solution:
  - A low effective resistance of the implant strips on a silicon sensor. A desired target value is 1.5 kOhm/cm
    - Not possible to increase implant doping to significantly lower the resistance
  - Instead deposition of Aluminum on top of the implant



  - A layer of high-quality oxide and nitride with metal strips on top to implement the AC-coupled sensor readout.

Conclusions

- An IR cutting laser mimics the beam accident conditions: large Q, collapsing E-field.
- Field breakdown size ~ 0.5 mm, with a much larger area with partial breakdown.

- The observed voltages and and voltages be explained by 4 resistor DC model :
  R_{PTP}(near), R_{PTP}(far), R_{bulk} , $R_{implant}$.
- Results are consistent with drift-diffusion in the SCL region
- Figure of Merit for punch-through voltage saturation : Rbulk / Rsat, if large then, PT.
- Saturation resistance ~ L^2, 100 Ω for PTP structures, 10 kΩ for non-PTP structures
- For PTP structures, the voltage near the laser V_{PTP}(laser, near) saturates.
  Then R_{PTP} ~20kΩ; I ~ 5 -10 mA.
- Saturation voltage determined by flat band voltage: Radiation sensitivity, no temperature dependence

- $R_{implant}$ is very important: the present value, ~15 kΩ/cm, can effectively isolate the collapsed field from the PTP structure, increasing voltages on the implants by 100's of volts => need low $R_{implant}$!
  Work with CNM Barcelona to reduce implant resistance.

- The effect of the R-C biasing network at the backplane is under study and no surprises seen, yet.