PIXEL 2018 CONFERENCE

Electrical Characterization of AMS aH18 HV-CMOS after Neutron and Proton irradiation

D M S SULTAN
University of Geneva

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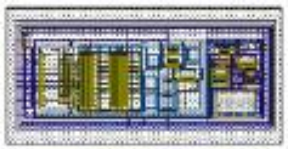
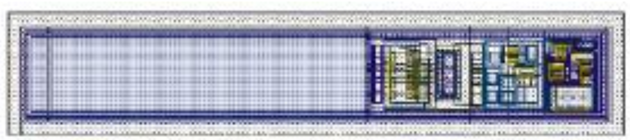
email: dms.sultan@unige.ch

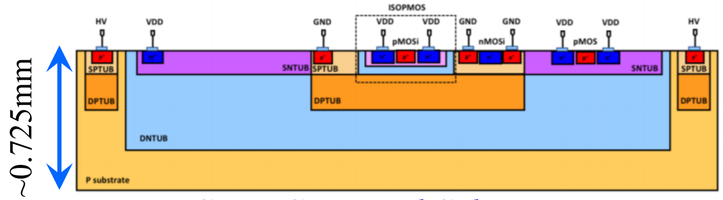
AMS ATLASPix1 180 nm Monolithic Chip



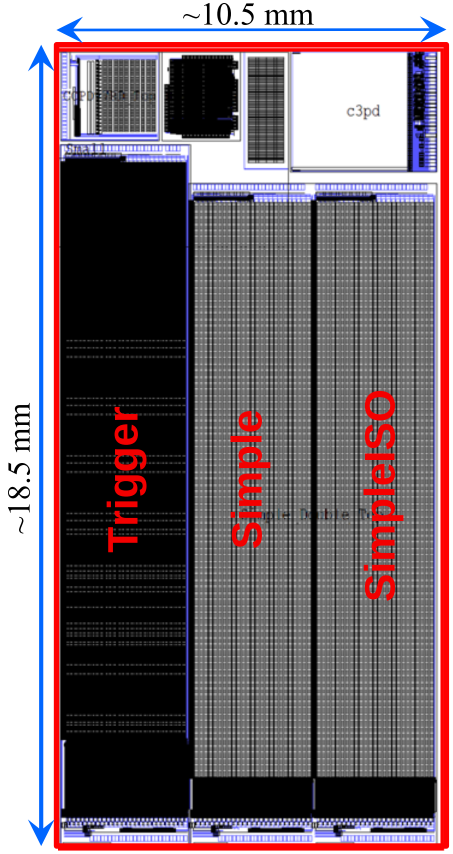
Top View Trigger Matrix



Top View Simple Matrices



Cross Sectional Schematics



- The prototype of 180 nm HV-CMOS Technology (large electrode design)
- Different flavors: Trigger (50X60 μm^2) and Simple matrices (130X40 μm^2). SimpleISO holds additional deep P-well.
- Several Substrate Resistivity: 20, 80, 200 Ω-cm.
- No active guard-ring is considered

Advantages:

- Commercially cost effective
- High yield and high efficiency
- Radiation Hard Capability

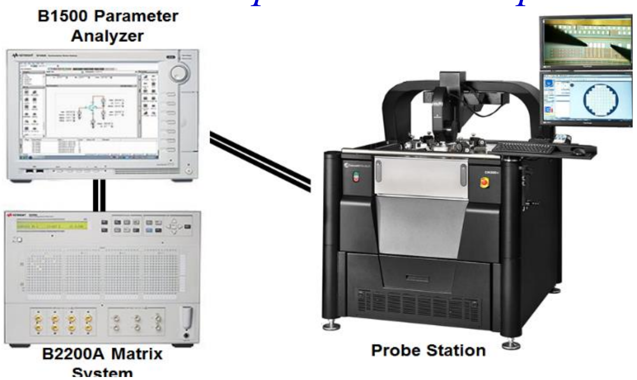
See More: *M. Keihn talk at Pixel 2018*

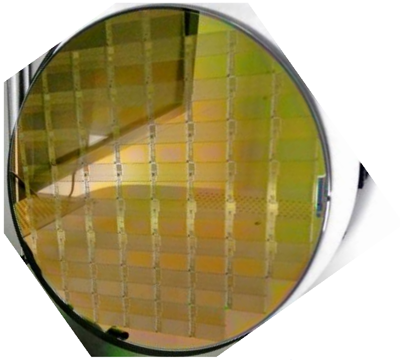
Challenges:

- Partially depleted substrate
- Technology and process dependent radiation hardness
- Highly Granular CMOS comes with additional J_{lk} , leakage
- Careful design and systematic study is required

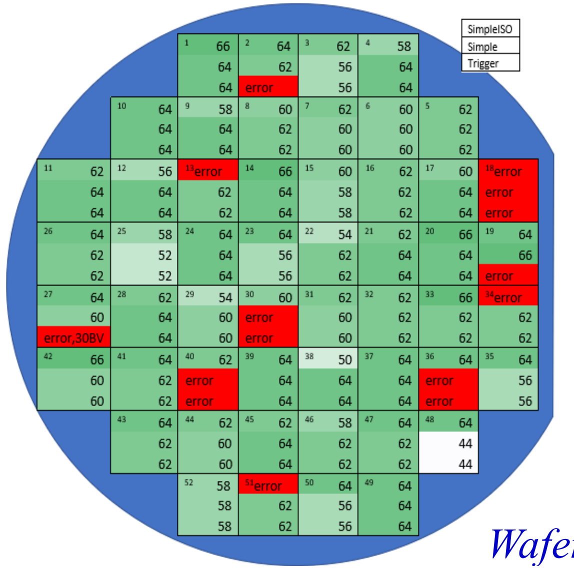
AMS ATLASPix1 180 nm Monolithic Chip

Experimental setup



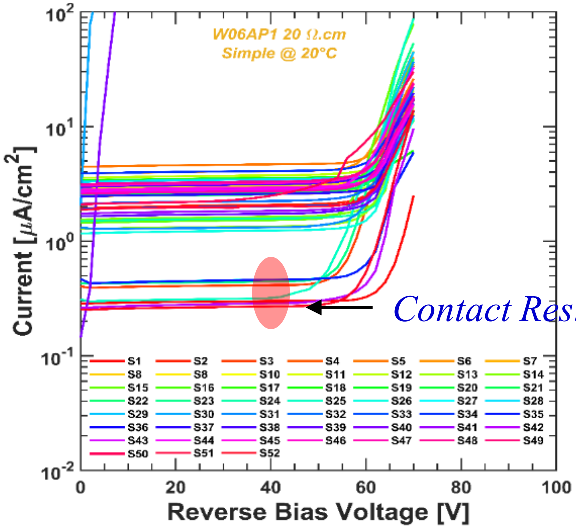


Wafer top View

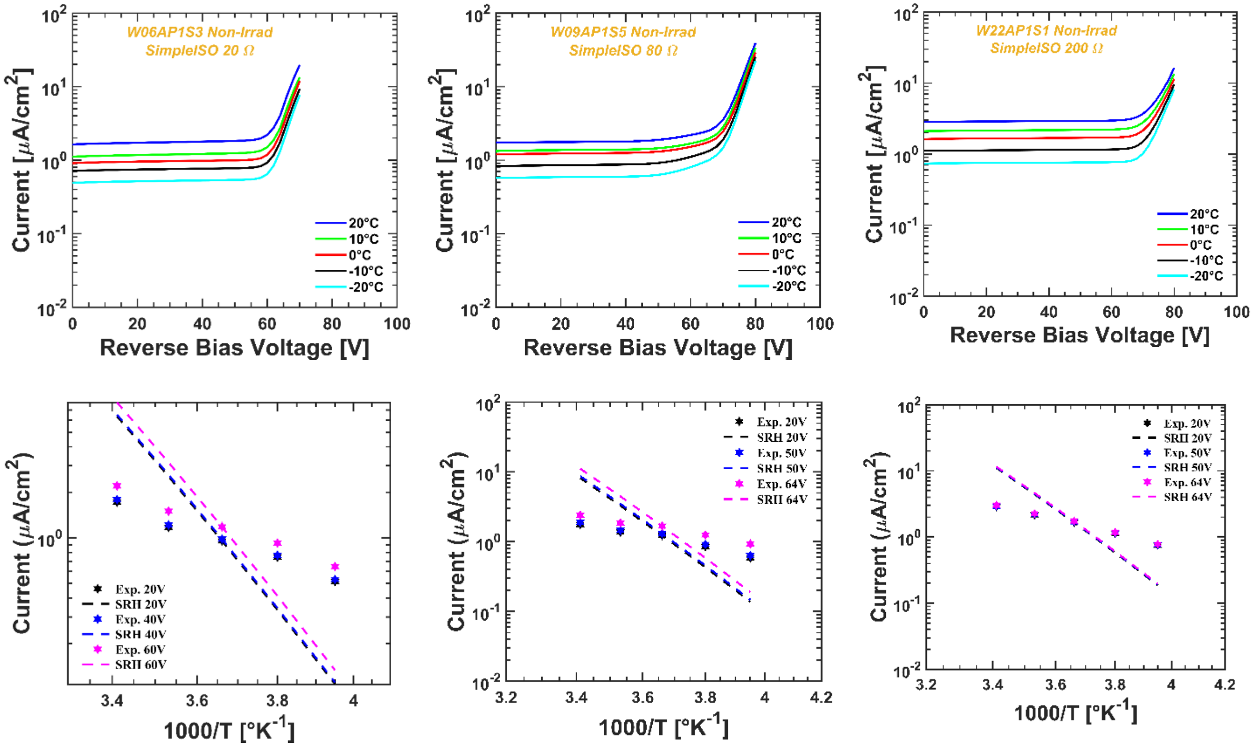


Wafer Map

- A systematic study made using Low leakage current complaint B2200A matrix and high precision ATT thermal conditioner used at dry-air condition.
- Electrical probing made with proper biasing to HV, VDDD (1.8V), VDDA (1.8V), and VSSA(1.0V) as per reference of ATLASPix1 design.
- At right. there is the wafer top view. Wafer map shows a systematic summary of ATLASPix pixel-matrices.
- Green marker has assigned to pixel matrix if the V_{bd} is greater than 30 V and leakage current is limited to 5μA/cm^2 before avalanche breakdown
- Around 80% dies seemed electrically qualified, means they have reasonable higher breakdown and power planes are isolated.
- Typical breakdown voltage ~50-60V. Adimensional function used for the breakdown evaluation for k(I,V)=4.



Non-Irradiated SimpleISO

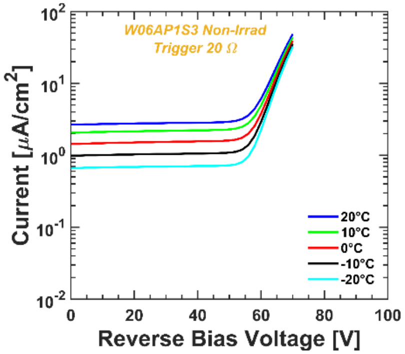


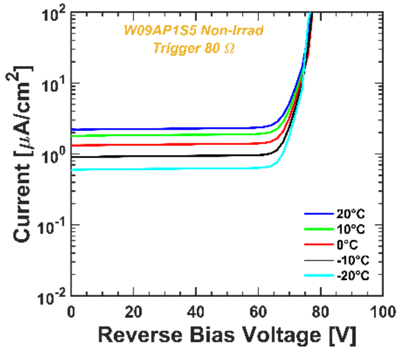
20 Ω-cm *80* Ω-cm *200* Ω-cm

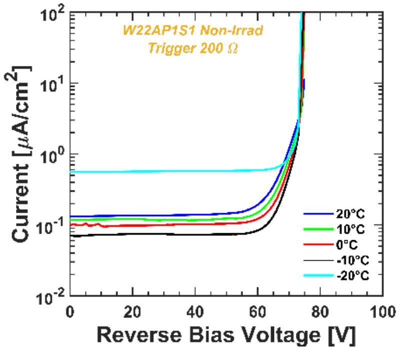
- Breakdown Voltage is beyond 50V
- Leakage current is deviating the Arrhenius prediction.
  - Leakage current is dominated by surface damage
  - AMS Design Kit-Generated HV Guard ring floating
  - MCz substrate wafer procures more thermal donor (oxigatnted vacancies) during processing, a great source to leakage increase.
- Leakage current remains on the order of ~1uA/cm^2 at -10 °C ambient condition.

- Layout improvement with additional or biased guard-ring should improve the situation.
- Additional long sintering step at the wafer level can improve the situation.

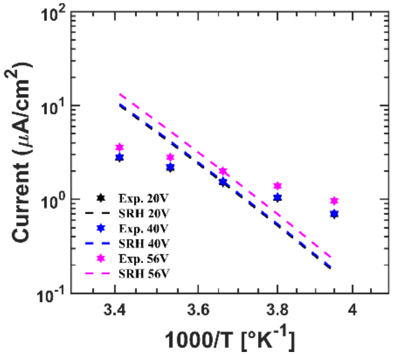
Non-Irradiated Trigger



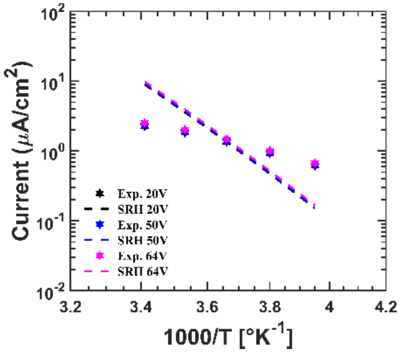




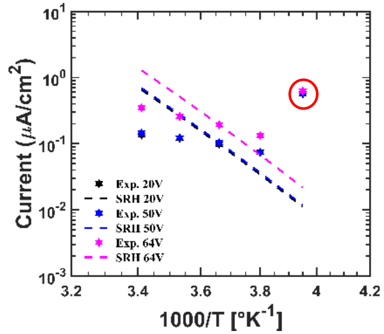
- Breakdown Voltage is beyond 50V
- Leakage current is deviating the Arrhenius prediction.
- Leakage current remains on the order of ~1uA/cm^2 or less at -10 °C.
- Several sample thinned down to ~100 um.



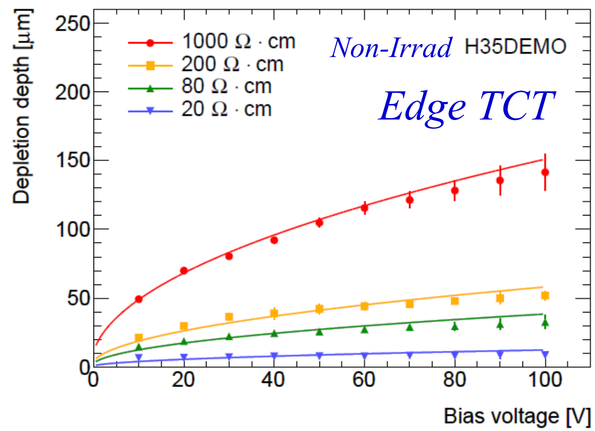
20 Ω-cm



80 Ω-cm



200 Ω-cm



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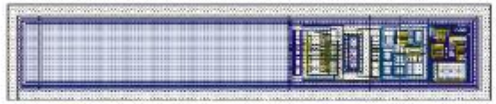
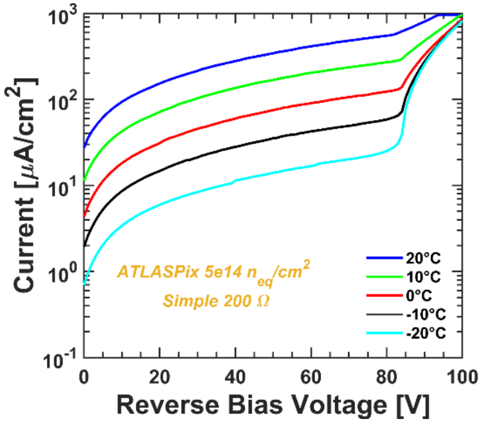
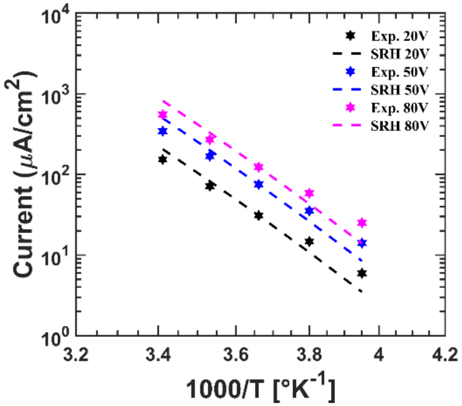
- At - 20 °C, some thin candidates show leakage abnormality than its higher ambient conditions.
  - Mean free path is enriched-› leakage current rise.
- Precise control in dicing thinning process could improve the situation

Bern Proton Irradiated 5e14 n_{eq}/cm^2

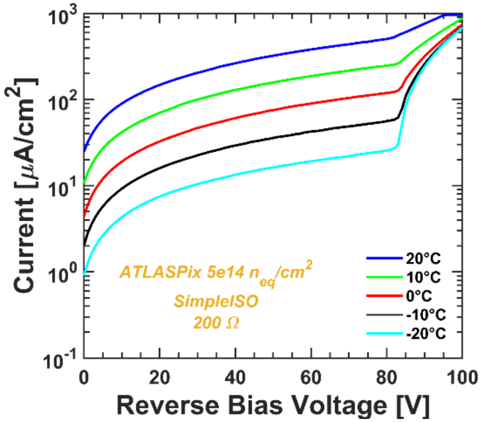


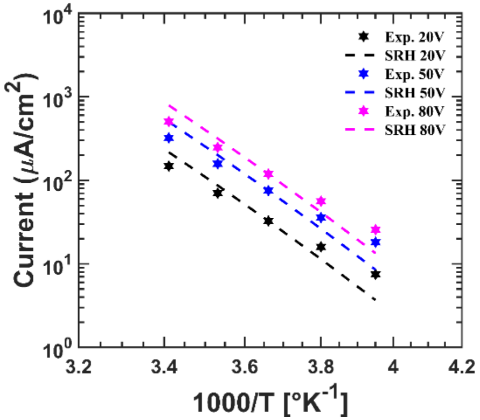
Layout Top View: Simple Matrices





ATLASPix1 Simple (200 Ω.cm)

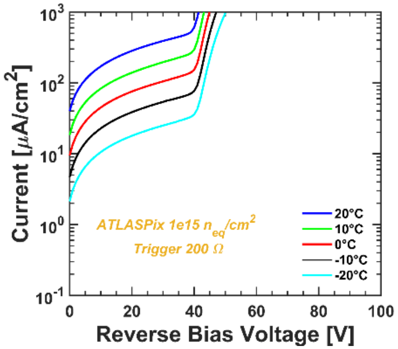


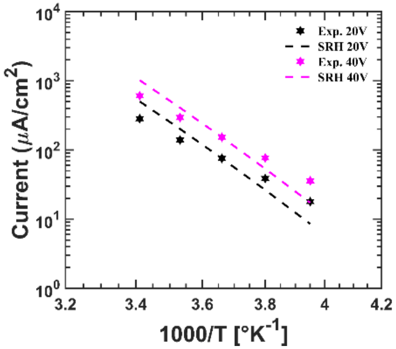


ATLASPix1 SimpleISO (200 Ω.cm)

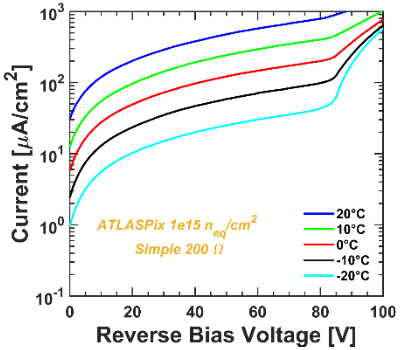
- Sample irradiated at BERN Cyclotron with 16.7 MeV Proton
- Breakdown Voltage improves beyond 80V simple matrices.
- Electrical distribution is not uniform.
  - A spatially dependent de-trapping require additional reverse potential
- Leakage current rises 20x magnitude higher.
  - Modification of effective doping concentration from both surface and bulk effect
- Damage constant rate is ~8×10^{-17} (A/cm) before Vbd , bit larger.
  - Less significant, requires dedicated depletion measurement
  - Peripheral current is still paying the role
- Arrhenius disagreement seen at non-irradiated candidate seems improving.
  - Intrinsic leakage is larger in scale

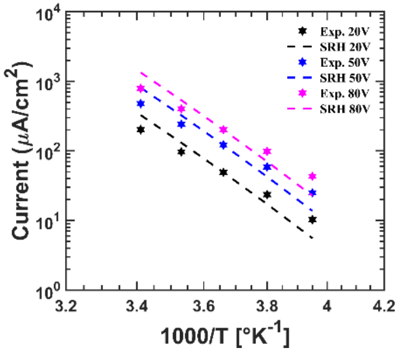
Bern Proton Irradiated 1e15 n_{eq}/cm^2



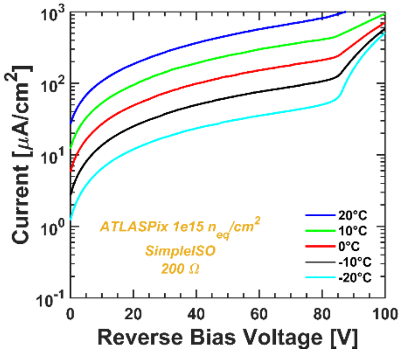


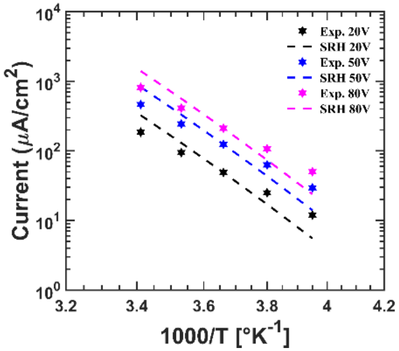
ATLASPix1 Trigger (200 Ω.cm)



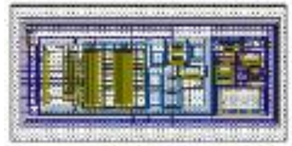


ATLASPix1 Simple (200 Ω.cm)





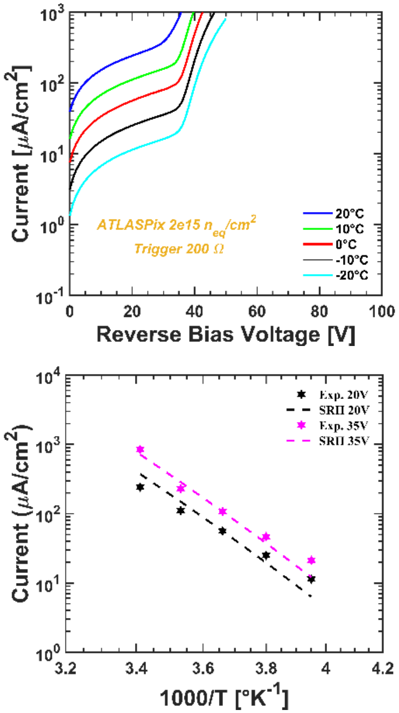
ATLASPix1 SimpleISO (200 Ω.cm)



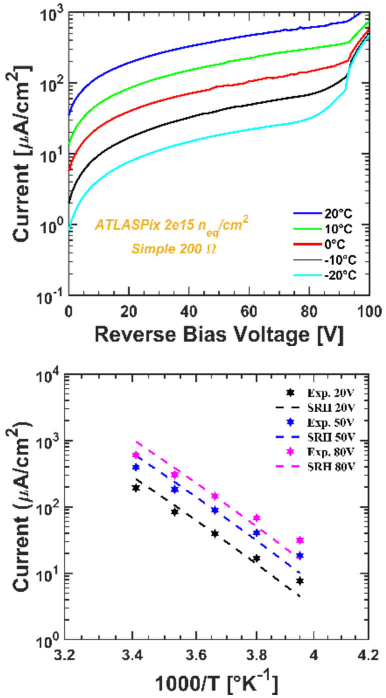
Layout Top View: Trigger

- Breakdown Voltage is beyond 80V (*Simple and SimpleISO*)
- As expected, leakage current increases 50x more with higher fluence.
- Damage constant rate is ~3-4×10^{-17} (A/cm) before V_{bd} as expected.
  - Dominated by bulk damage contribution
- V_{bd} of Trigger matrix decreases to ~41V
  - Deep N-well is almost covering the pixel geometry -› more uniform electric field distribution
  - Triggers impact ionization at lower reverse bias

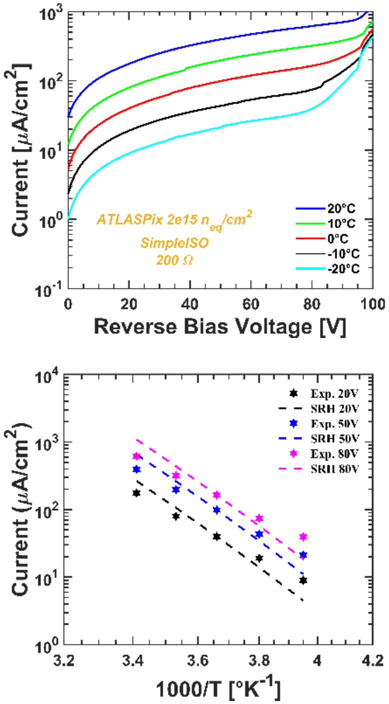
Bern Proton Irradiated 2e15 n_{eq}/cm^2



ATLASPix1 Trigger (200 Ω.cm)



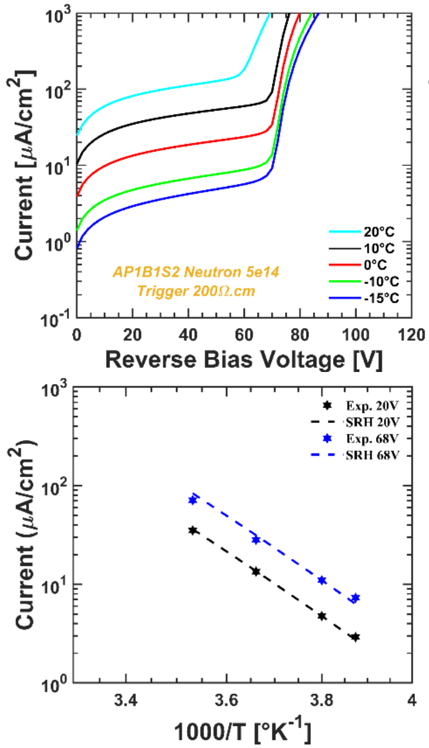
ATLASPix1 Simple (200 Ω.cm)



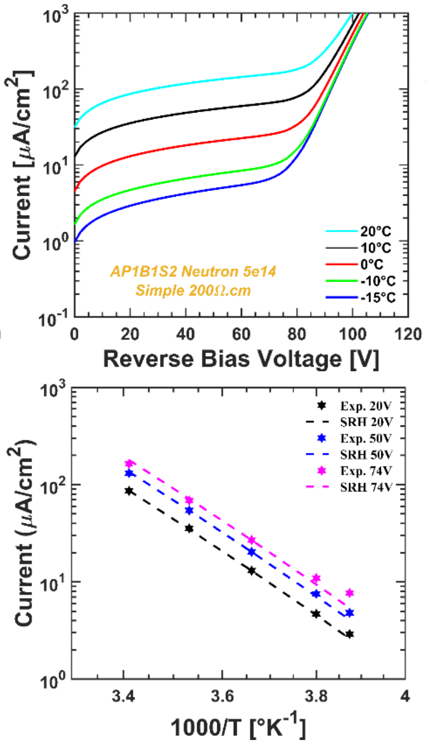
ATLASPix1 SimpleISO (200 Ω.cm)

- Breakdown Voltage of trigger matrix is ~36V
- As expected, leakage current increases 2 order magnitude higher fluence than non-irradiated case.
- V_{bd} at simple matrices increase beyond 90V.
  - Higher interface states and bulk traps -> larger reverse potential to de-trap the charges (spatially dependent)
- Still in better Arrhenius agreement with expectation
  - Peripheral leakage hinders underneath the larger intrinsic leakage scale.
- Damage constant rate, α^*, ~4×10^{-17} (A/cm) before V_{bd}, as expected.

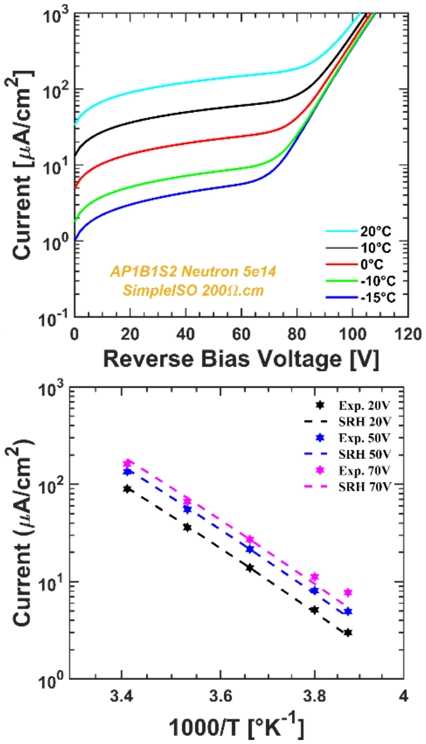
JSI Neutron Irradiated 5e14 n_{eq}/cm^2



ATLASPix1 Trigger (200 Ω.cm)



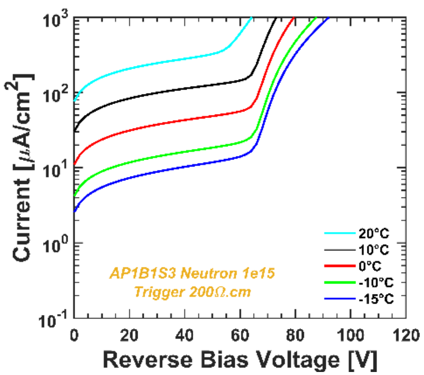
ATLASPix1 Simple (200 Ω.cm)

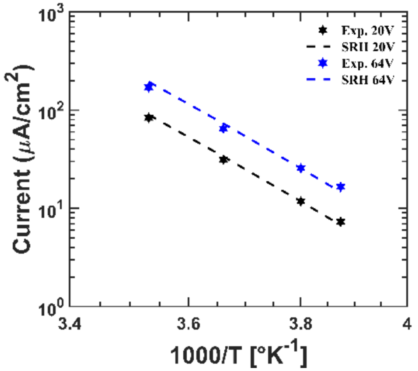


ATLASPix1 SimpleISO (200 Ω.cm)

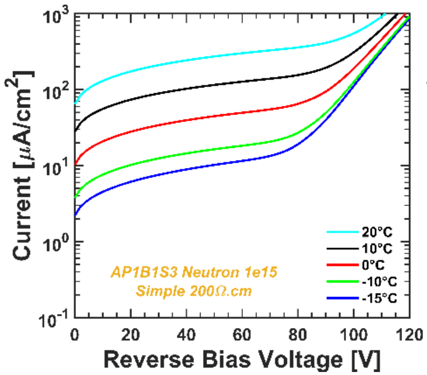
- Breakdown voltage is beyond 70V (*Simple and SimpleISO*)
- As expected, leakage current increases 40x more with higher fluence.
- Damage constant rate is ~10×10^{-17} (A/cm) before V_{bd}.
  - Dominated by surface damage
  - Dedicated edge-TCT investigations is required.
- V_{bd} of Trigger matrix increases to ~68V
  - Deep N-well is almost covering the pixel geometry -› more uniform electric field distribution
  - Triggers impact ionization at lower reverse bias

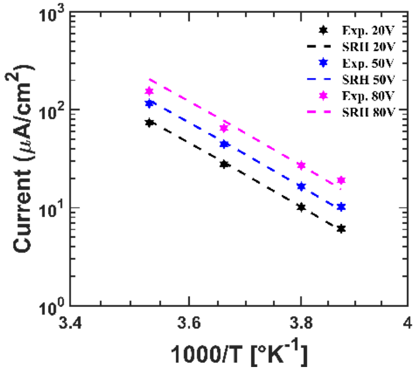
JSI Neutron Irradiated 1e15 n_{eq}/cm^2



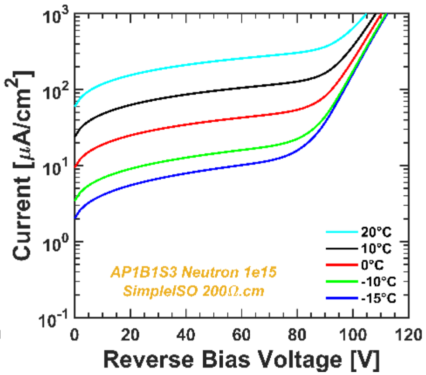


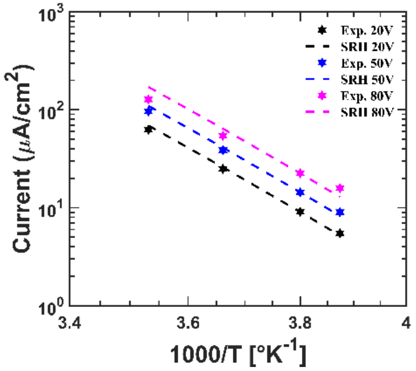
ATLASPix1 Trigger (200 Ω.cm)





ATLASPix1 Simple (200 Ω.cm)

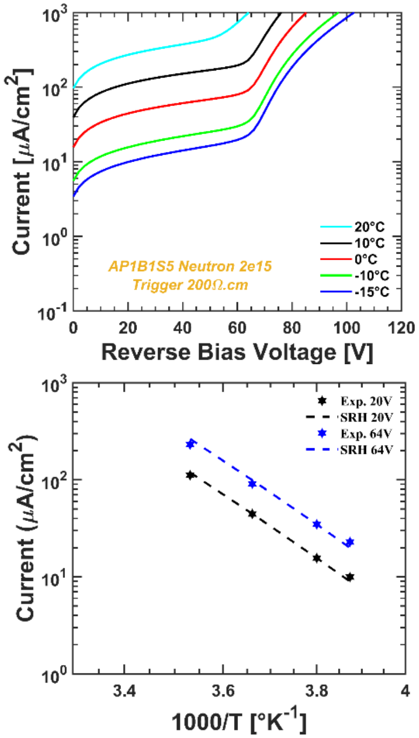




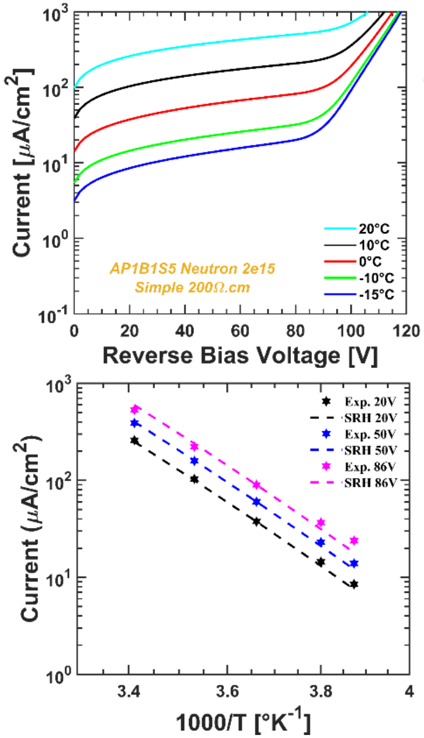
ATLASPix1 SimpleISO (200 Ω.cm)

- Breakdown Voltage is increased to 80V (*Simple and SimpleISO*)
- As expected, leakage current increases 100x more with higher fluence.
- Damage constant rate is ~8×10^{-17} (A/cm) before V_{bd}.
- V_{bd} of Trigger matrix decreases to ~64V
  - Uniform electric field distribution -› Triggers impact ionization at lower reverse bias
- A dedicated edge-TCT measurement is required.

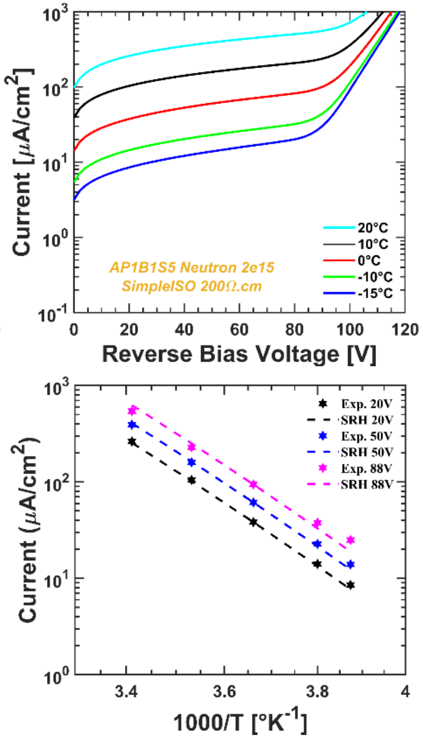
JSI Neutron Irradiated 2e15 n_{eq}/cm^2



ATLASPix1 Trigger (200 Ω.cm)



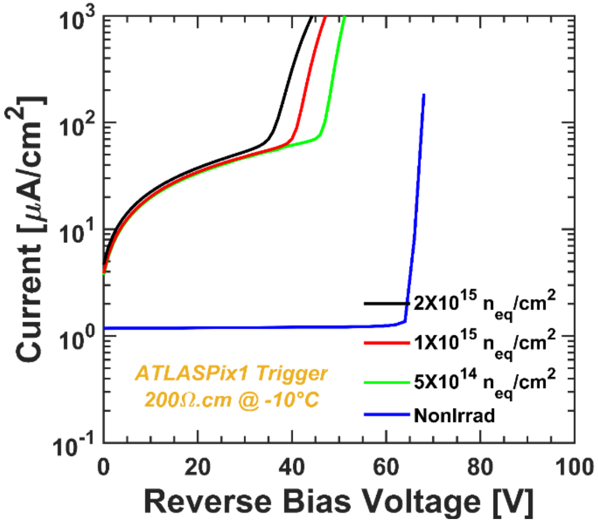
ATLASPix1 Simple (200 Ω.cm)

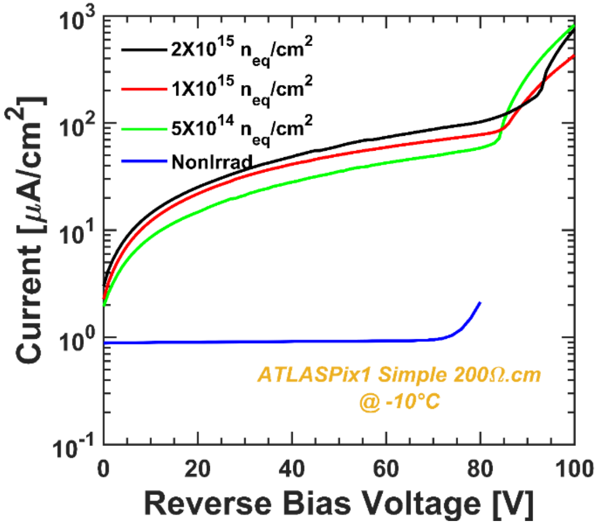


ATLASPix1 SimpleISO (200 Ω.cm)

- Breakdown Voltage of trigger matrix is ~62V
- As expected, leakage current increases 200x higher fluence than non-irradiated one.
- V_{bd} at simple matrices increase beyond 90V.
- Arrhenius prediction is well in agreement in all three flavors.
  - Peripheral leakage hinders underneath the larger intrinsic leakage generation.
- Damage constant rate, α^*, $\sim 6\times10^{-17}$ (A/cm) before V_{bd}.
  - Geometry dependent rate calculation.

Comparative Analysis ATLASPix1 Proton





- Trigger matrix goes to a decreasing breakdown with higher proton fluence
  - Peripheral current leads to occur impact ionization earlier
- Simple matrices goes to a increasing breakdown with higher proton fluence
  - Non-uniform electrical distribution beyond N-well, requires higher reverse potential to de-trapping the carrier
- Higher damage contribution with higher fluence leads leakage increase in all matrix flavors.
  - For the highest fluence, it remains ~ 100 uA/cm^2

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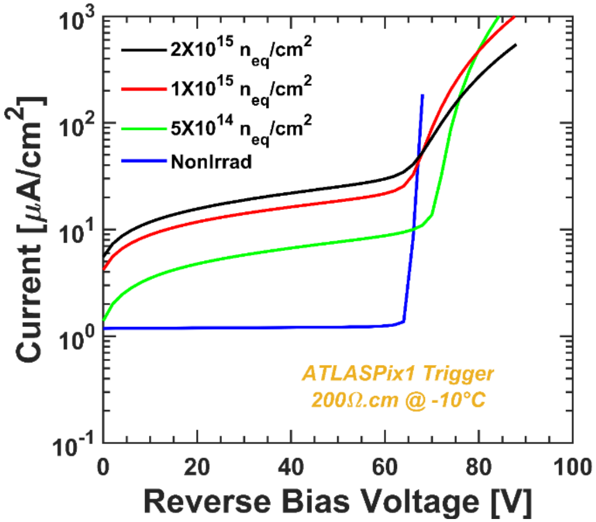
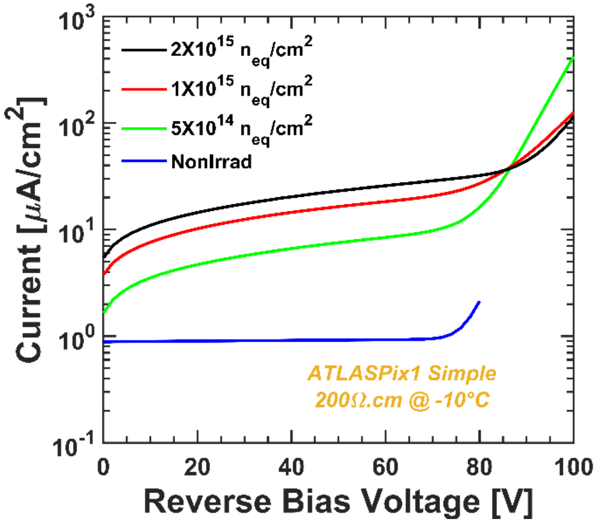
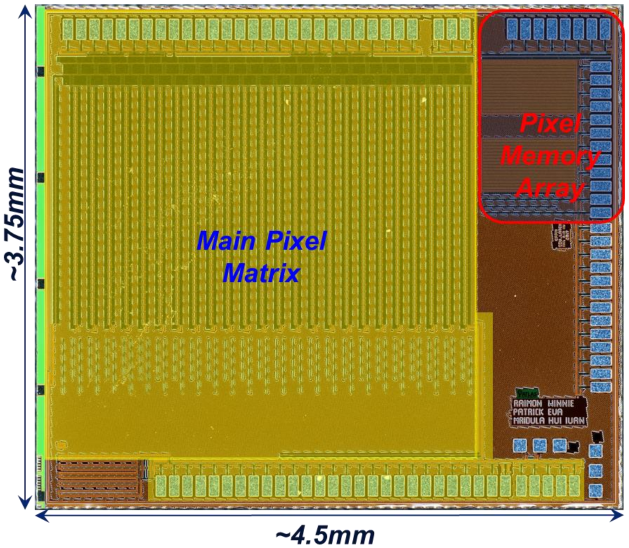
Comparative Analysis ATLASPix1 Neutron



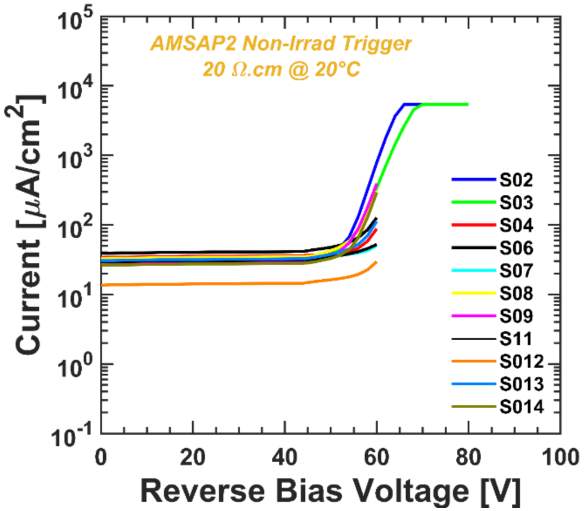


- With higher neutron fluence, breakdown voltage trigger matrix remains almost comparable to non-irradiated case.
  - Mass bulk damage, as expected
- A little decreasing trend of breakdown voltage at trigger matrix at higher fluence
  - Effect of back ground Gamma of reactor
- Breakdown voltage of simple matrices also goes to a increasing breakdown with higher neutron fluence
  - Geometrical difference of pixel pitch
- As expected, leakage current increases in with higher fluence irrespective to pixel flavors. flavors.

AMS ATLASPix2



AMS ATLASPix2

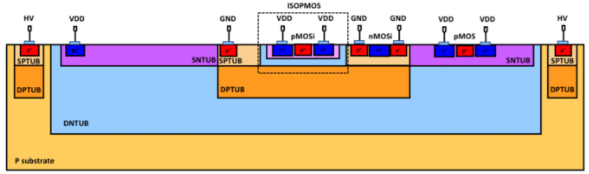


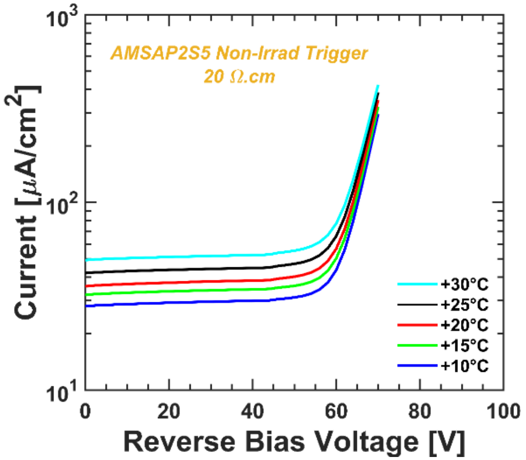
I-V Curves

- A small version of ATLASPix1 M2 Trigger matrix having pixel dimension 128X50 μm^2.
- Standard substrate resistivity (20 Ω.cm)
- Matrix size is of 24X36 pixels.
- Die Thickness ~220 µm.
- Die probing made with proper biasing to HV, VDDD (1.8V), VDDA (1.8V), and VSSA(1.0V).
- The left top-image is showing a die top view. It holds both small pixelated matrix and the Memory type test structures.
- Both Main Pixel Matrix and Pixel memory Array (PMA) share the same HV lines.
- PMA is intended to study SEU tolerant memory cells
- I-V reports the electrical behavior of several pixel matrices.

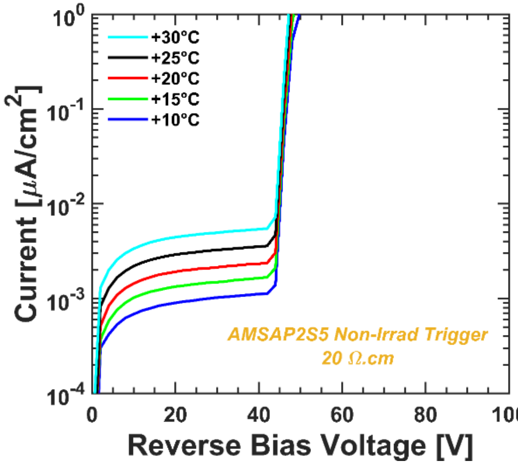
• Could be expected 1 order magnitude lower in scale @ -10 °C.
• Typical breakdown is beyond 50 V.

Non-Irradiated ATLASPix2 (AMS)

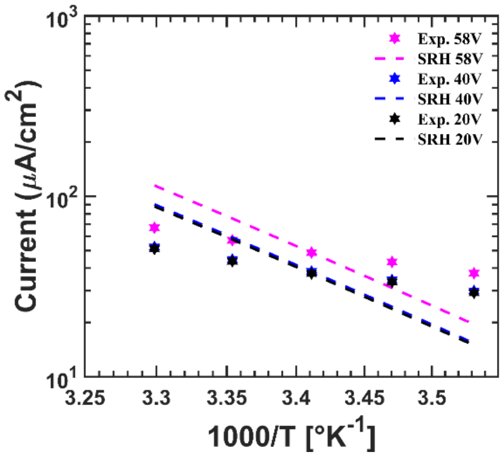


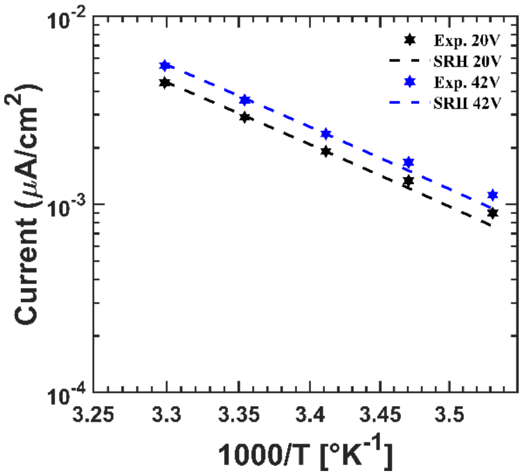


With Enabling CMOS



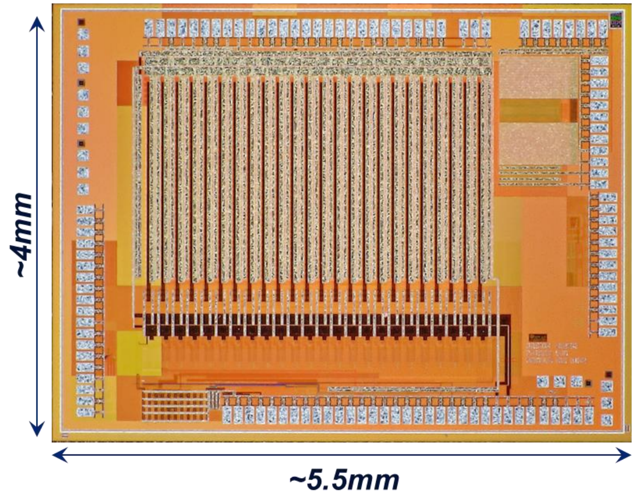
Biasing HV and N-well only



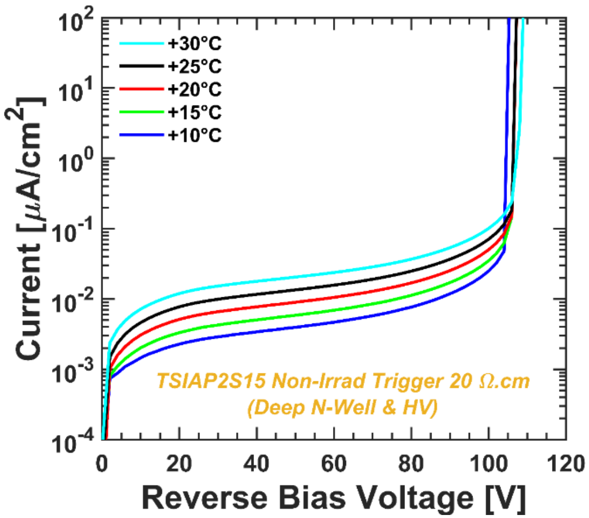


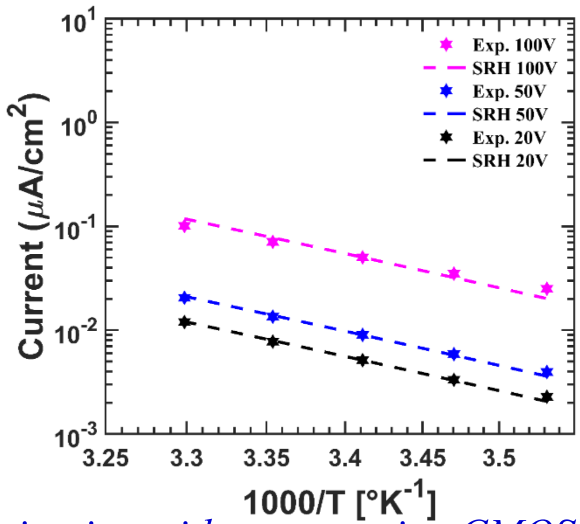
- Tested W/O powering CMOS
- Breakdown Voltage is around 50V
- Investigation was limited near room only.
  - Dry-air system is refurbishing currently
- With powering CMOS, both RO and diode leakage studied
  - Most share is from CMOS
- As expected, diode driven leakage is well agreement with Arrhenius Prediction
- Arrhenius disagreement seen at proper CMOS powering points surface damage at processing stage.
  - Foreseen layout design improvement in coming chip-submission should lead to a better condition.

TSISemi ATLASPix2



TSI ATLASPix2





Electrical and thermal investigation without powering CMOS

- A similar AMS-ATLASPix2 have submitted TSI for reducing the fabrication lead time in very recent.
- It holds same trigger matrix flavour, pixel pitch128X50 μm^2 and substrate resistivity (20 Ω.cm)
- Matrix size is still of 24X36 pixels and die thickness ~254 μm.
- Biasing HV and deep N-Well only, I-V reports similar leakage as seen in similar chip of AMS process at room temperature.
- Arrhenius prediction of thermal dependent carrier generation is well agreement with exp. data.
- Breakdown voltage reports beyond 100V!

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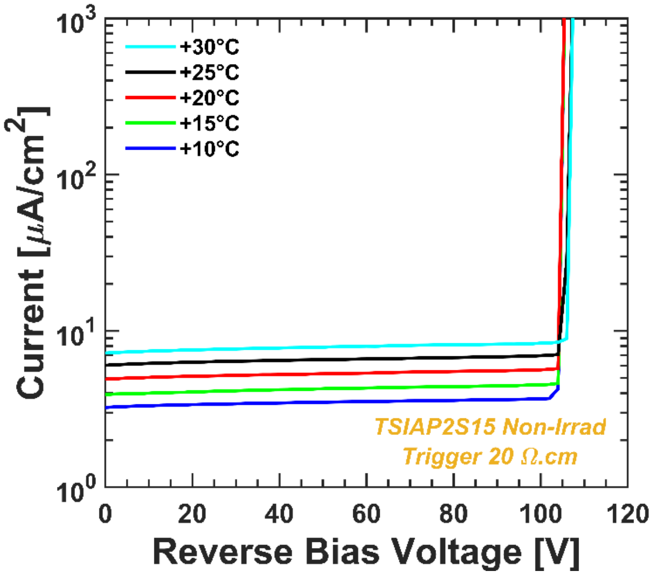
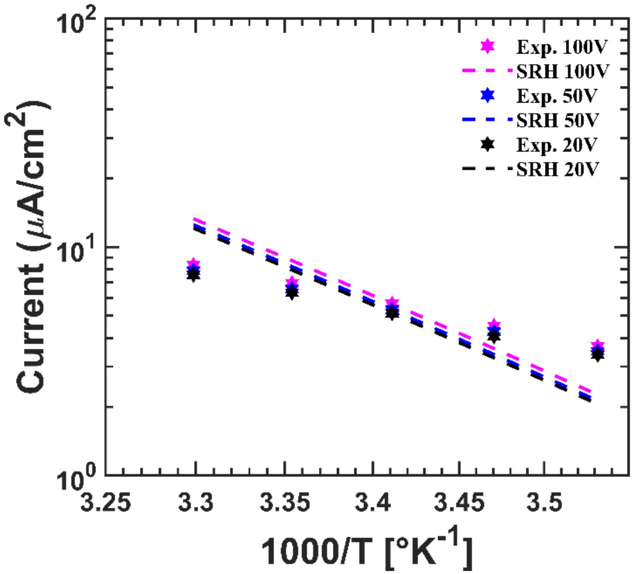


Enabling CMOS Power

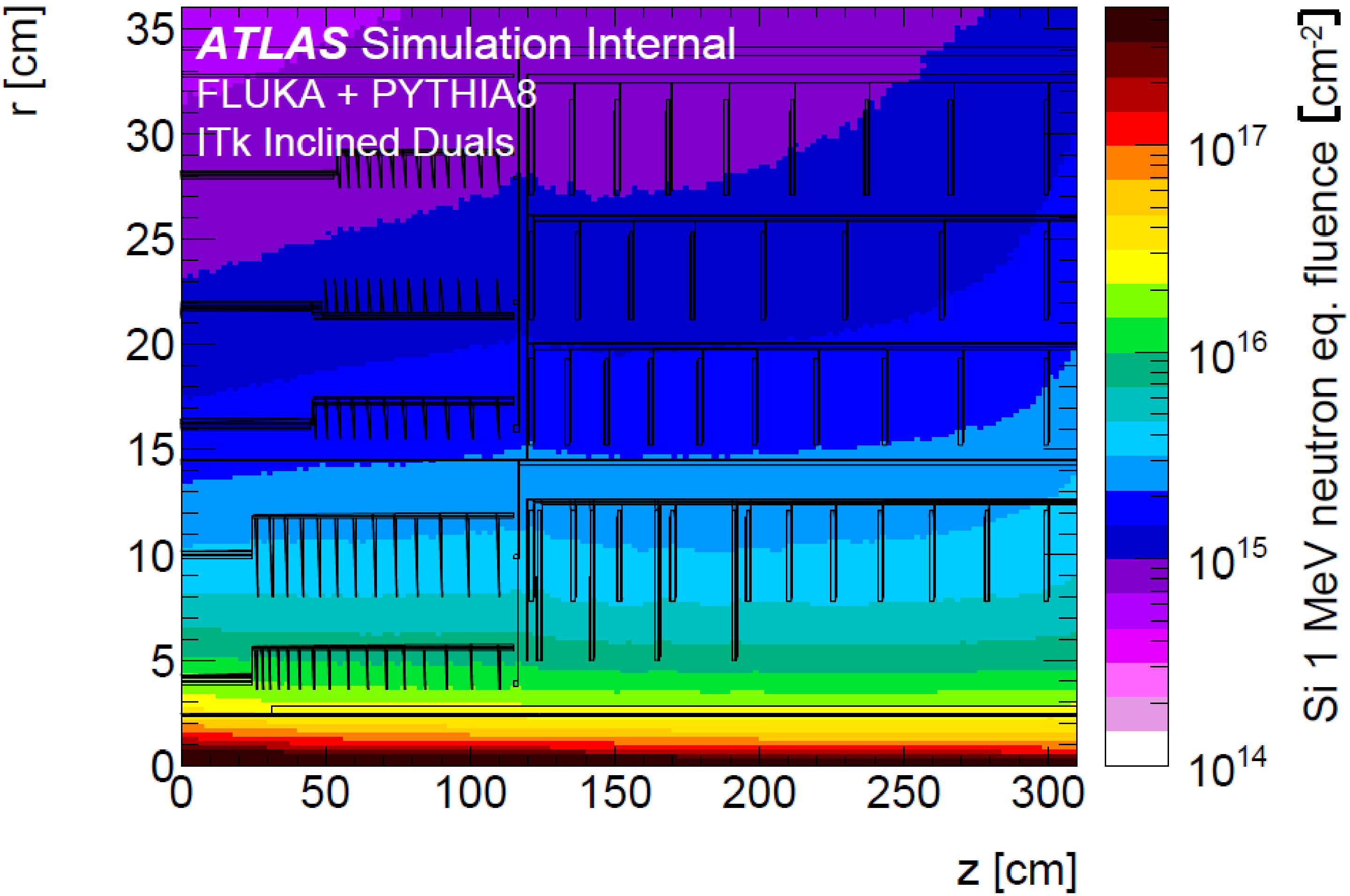


- Breakdown voltage TSI-Semiconductor chip report ~104-108V, as expected.
  - Almost double than AMS-candidates
- Disagreement with Arrhenius predictions still suggest the possible layout improvement (i.e. active guard-ring)
- Sharp breakdown and almost 1 order lower leakage scale than AMS-candidates, denote a greater TSI processing maturity.
  - Processing technology and instrumentation dependent

Summary

- Non irradiated ATASPix1 has ~1uA/cm^2 leakage at -10 °C, and breakdown voltage beyond 50 V.
- A post sintering step at wafer level (i.e. 420 °C at 60 mins) can be a great remedy to the oxygenated vacancy induced leakage.
- An active guard-ring structure has already accounted within foreseen chip submission to ensure the robust termination structures.
- Simple matrices of ATLASPix1 seem healing the surface peripheral leakage inflation with proton irradiation.
- Trigger matrix of ATLASPix1 also reports hindering the peripheral leakage with larger damage induces leakage. (an already good sign!)
- Neutron damage study proves that surface damage played vital role of earlier breakdown for trigger matrix as fluence increases.
- Non-irradiated AMS-ATLASPix2 chips have leakage ~5uA/cm^2 near room temperature, V_{bd} is similar to ATLASPix1.
- TSI Processed ATLASPix2 reports V_{bd} almost double of AMS production while leakage is 10x lower.
- More dedicated low temperature measurements, Edge-TCT and Irradiation study have targeted in near future investigations.

Thanking You


ATLAS Simulation Internal
FLUKA + PYTHIA8
ITk Inclined Duals
r [cm]
z [cm]
Si 1 MeV neutron eq. fluence [cm^-2]
0
5
10
15
20
25
30
35
0
50
100
150
200
250
300
10^14
10^15
10^16
10^17