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

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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 µm²) and Simple matrices (130X40 µm²). 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. Keihm talk at Pixel 2018

**Challenges:**
- Partially depleted substrate
- Technology and process dependent radiation hardness
- Highly Granular CMOS comes with additional Jlk, leakage
- Careful design and systematic study is required
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

- 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 (oxidation vacancies) during processing, a great source to leakage increase.
- Leakage current remains on the order of ~1uA/cm² 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.
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.

- Breakdown Voltage is beyond 50V
- Leaksage current is deviating the Arrhenius prediction.
- Leaksage current remains on the order of ~1uA/cm² or less at -10 °C.
- Several sample thinned down to ~100 um.

Non-Irradiated Trigger

E. Zaffaroni et. al. JINST (P10004)
Bern Proton Irradiated 5e14 n_{eq}/cm\(^2\)

- 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\times10^{-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 \( n_{eq}/cm^2 \)

- **Breakdown Voltage is beyond 80V (Simple and SimpleISO)**
- As expected, leakage current increases 50x more with higher fluence.
- **Damage constant rate is \( \sim 3 - 4 \times 10^{-17} \) (A/cm) before \( V_{bd} \) as expected.**
  - Dominated by bulk damage contribution
- **\( V_{bd} \) of Trigger matrix decreases to \( \sim 41 \) V**
  - Deep N-well is almost covering the pixel geometry \( \rightarrow \) more uniform electric field distribution
  - Triggers impact ionization at lower reverse bias
Bern Proton Irradiated 2e15 $n_{eq}/cm^2$

- 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, $\alpha^*$, $\sim 4 \times 10^{-17} (A/cm)$ before $V_{bd}$, as expected.
Breakdown voltage is beyond 70V (Simple and SimpleISO).

As expected, leakage current increases 40x more with higher fluence.

Damage constant rate is $\sim 10 \times 10^{-17} \text{ (A/cm)}$ before $V_{bd}$.

- Dominated by surface damage
- Dedicated edge-TCT investigations is required.

$V_{bd}$ of Trigger matrix increases to $\sim 68$V

- 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 $n_{eq}/cm^2$

- Breakdown Voltage is increased to 80V (*Simple and SimpleISO*).
- As expected, leakage current increases 100x more with higher fluence.
- Damage constant rate is $\sim 8 \times 10^{-17}$ (A/cm) before $V_{bd}$.
- $V_{bd}$ of Trigger matrix decreases to $\sim 64$V.
  - Uniform electric field distribution
  - Triggers impact ionization at lower reverse bias.
- A dedicated edge-TCT measurement is required.
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, $\alpha^*$, $\sim 6 \times 10^{-17} \text{ (A/cm)}$ before $V_{bd}$.
- Geometry dependent rate calculation.
- 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/cm²
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 background 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.
A small version of ATLASPix1 M2 Trigger matrix having pixel dimension 128X50 µm².

- 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 ATLASTpix2 (AMS)

- 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.
A similar AMS-ATLASPix2 have submitted TSI for reducing the fabrication lead time in very recent.

- It holds same trigger matrix flavour, pixel pitch 128X50 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!
- 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 $\sim$1uA/cm$^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 $\sim$5uA/cm$^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