Statistical SEGR Radiation Test Method Study in Power MOSFETs

ESA contract n° 4000106795/12/NL/PA

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CNES/ESA Radiation Effects Final Presentation Days

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Outline

- Context / Motivation
- Summary of previous results
- Experimental Results
- Outcome

Context / Motivation

Context / Motivation

RHA involves:

- **Mission/system/subsystem requirements**
  - **Power, voltages, current, switching speed, size, quantity, etc.**

- **Radiation environment definition**
  - **Low Earth orbit (LEO)? Geosynchronous orbit (GEO)? ...**
  - **Heavy ion fluence, total ionizing and non-ionizing dose (TID / TNID) levels**

- **Part selection**
  - **Availability, cost, reliability, electrical performance**
  - **And for RHA, Single-event effect (SEE) & TID performance**

- **Part testing**
  - **Radiation source parameters, biasing conditions, test setup,**

- **Failure rate prediction:**
  - **method (?) and accuracy**

Context / Motivation

- **Follow-on to the ESA contract n°106795/12/NL/PA – WP2012**
- **Dealing with Statistical SEGR/SEB Radiation Test Method Study based on device simulation of the (SEB and) SEGR in Si Power MOSFETs**
- **In support of the European Radiation Hardness Assurance Standard and Irradiation Test Guidelines.**

Objective:

- **Recommendations on best trade-off on testing conditions and beam selection criteria based on statistical method**
- **Justification of the best statistical law, log-normal or Weibull, to fit SEGR and TDDB results**

Summary of previous results

Summary of previous results

3 different "non-US" Power NMOSFET types selected by ESA

- **HG0K 100V rated N-channel from STM**
- **2SK4219 100V rated N-channel from FUJI**
- **and BUY25CS12J 250V rated N-channel from INFINEON**

Low, medium and high energy beams used to cover a large energy spectrum and to be representative of the Heavy ion population in space

UCL (Université Catholique de Louvain-la-Neuve), Leuven – BELGIUM

RADEF (RADiation Effects Facility) Jyväskylä – FINLAND

GANIL (Grand Accélérateur National d'Ions Lourds), Caen – FRANCE

TAMU (Texas Agriculture and Mechanical University), Texas – USA

Summary of previous results

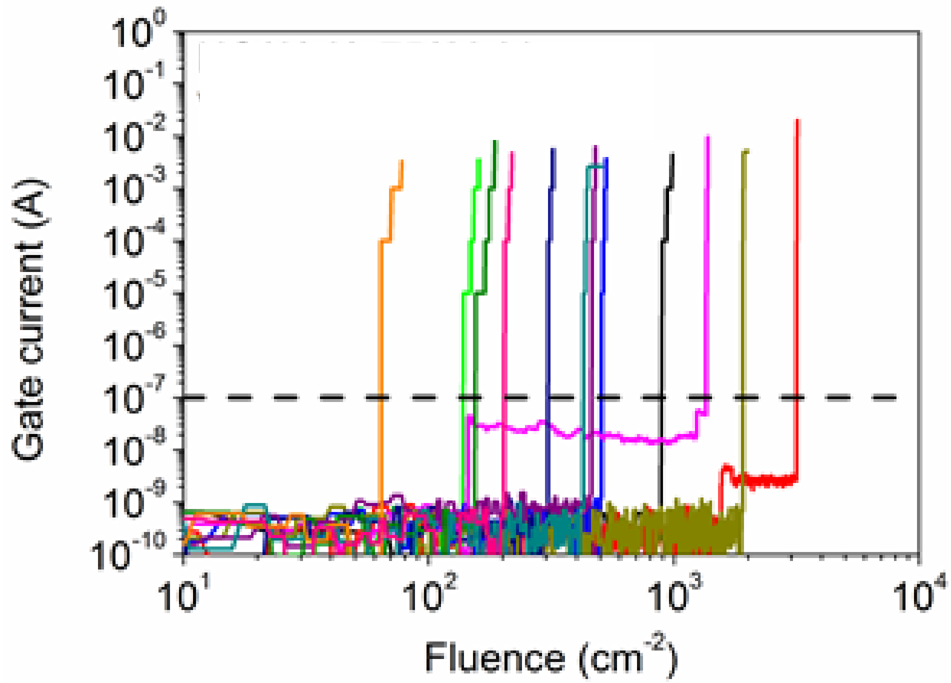
Statistical features of SEGR

The statistical SEGR responses were defined under worst-case applications conditions

Confirmation that SEGR is a real random mechanism induced by one heavy ion striking the device in the oxide with a worst-case deposited charge configuration.

✓ ***V_{GS} << 0V, V_{DS} max rating***
→ *SEGR detected during irradiation*

HG0K
V_{GS} = -10V,
V_{DS} = 100V



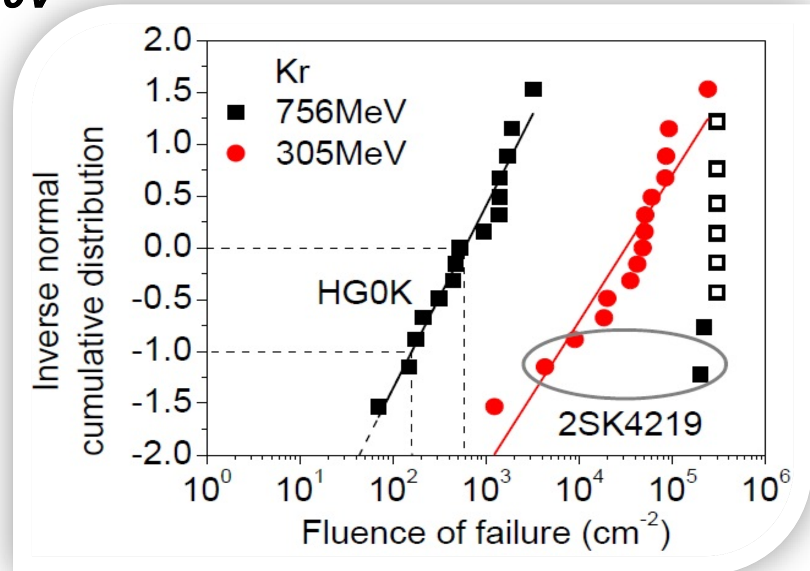
[RD1] Véronique Ferlet-Cavrois, Christian Binois, Aminata Carvalho, et al., NSREC2012 – IEEE TNS 59-6, pp. 2920-2929

Summary of previous results

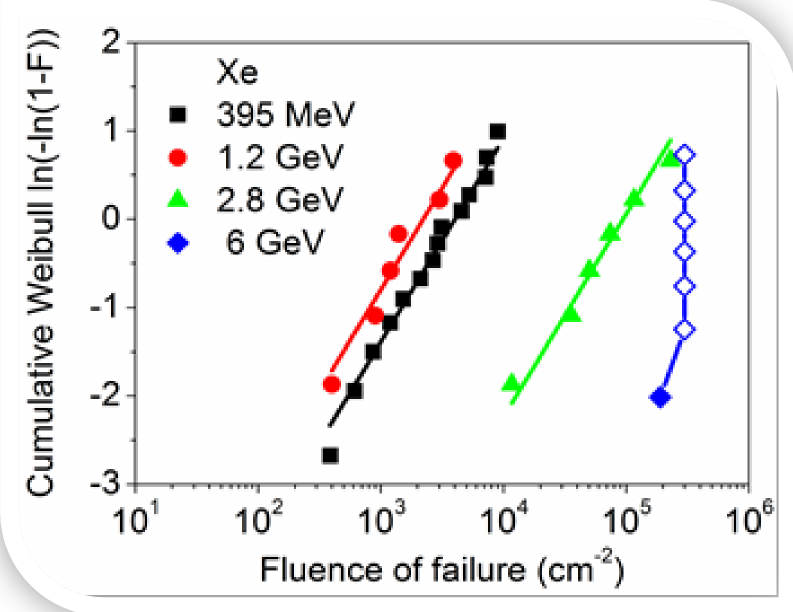
Statistical behavior of SEGR

- ✓ ***V_{GS} << 0V, V_{DS} max rating***
  - → *SEGR detected during irradiation*
  - → *8 to 16 samples irradiated in identical beam and bias conditions*
  - → *Weibull, shape factor of 1.*

HG0K and 2SK4219
V_{GS} = -10V,
V_{DS} = 100V



BUY25CS12J
V_{GS} = -25V,
V_{DS} = 250V

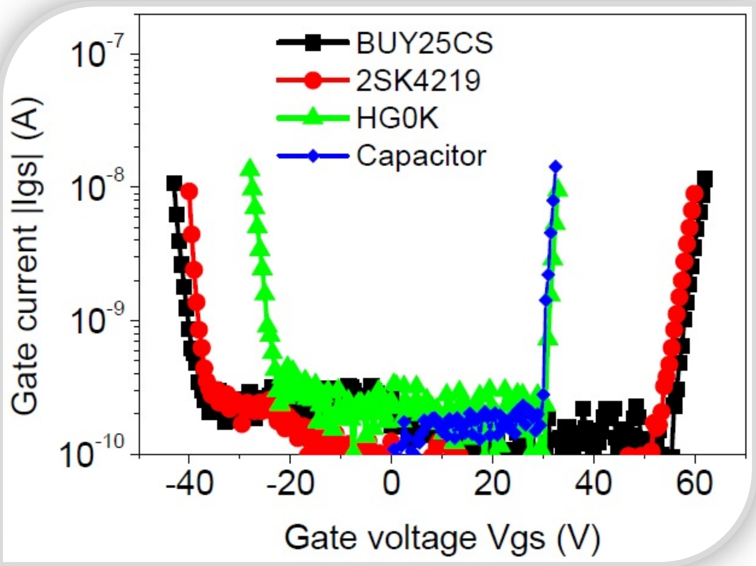


[RD1] Véronique Ferlet-Cavrois, Christian Binois, Aminata Carvalho, et al., IEEE TNS Dec, 2012

Summary of previous results

Extended PIGST method

	2SK4219 (FUJI)	HG0K (STM)	BUY25CS12J (INFINEON)
Standard specification	V_{GS} = +20V/-20V	V_{GS} = +20V/-20V	V_{GS} = +20V/-20V
Leakage onset (+100nA/-100nA)	V_{GS} = +60V/-45V	V_{GS} = +30V/-24V	V_{GS} = +60V/-45V
Chosen voltage limit leakage current	V_{GS} = +60V/-50V 200nA/-300nA	V_{GS} = +33V/-28V 200nA/-300nA	V_{GS} = +60V/-50V 200nA/-300nA



Absolute value of the gate current (in a logarithmic scale) versus gate voltage for the BUY25CS12J, 2SK4219 and HG0K power MOSFETs before irradiation. The other terminals (drain and source) are grounded.

Intrinsic breakdown voltage defined above the limit of V_{GS} =±20V

pre-selection method for devices that will be further SEGR-tested

Advantage of performing the extended PIGST before irradiation: possibility to prepare a higher homogeneous population by discarding outliers before irradiation.

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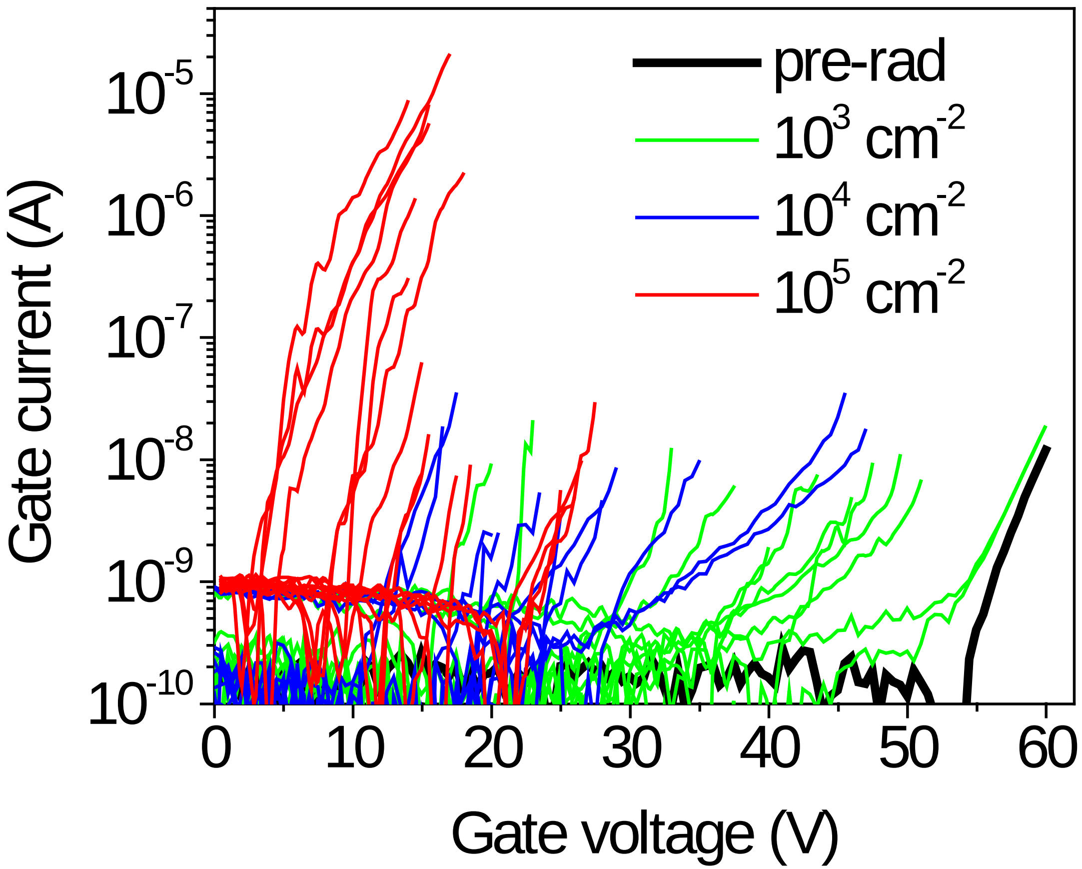
Summary of previous results

Post Irradiation Gate Stress Test (PIGST)

- ✓ ***V_{GS} = 0V, V_{DS} max rating during Irradiation***

  → *SEGR not observed during irradiation but revealed by a Post-Irradiation Gate stress Test (PIGST)*

2SK4219
V_{GS} = 0V,
V_{DS} = 100V



[RD1] Véronique Ferlet-Cavrois, Christian Binois, Aminata Carvalho, et al., NSREC2012 – IEEE TNS 59-6, pp. 2920-2929

Summary of previous results

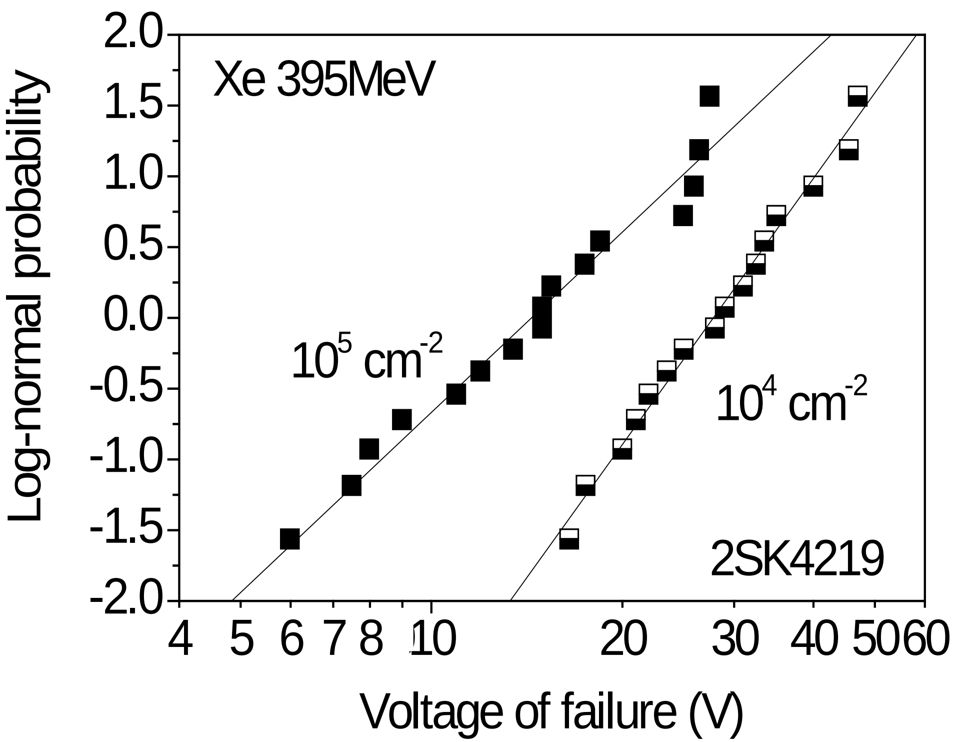
Post Irradiation Gate Stress Test (PIGST)

✓ ***V_{GS} < 0V, V_{DS} max rating***

→ *SEGR not observed during irradiation but revealed by a Post-Irradiation Gate stress Test (PIGST)*

→ *lognormal distribution.*

2SK4219
V_{GS} = 0V,
V_{DS} = 100V

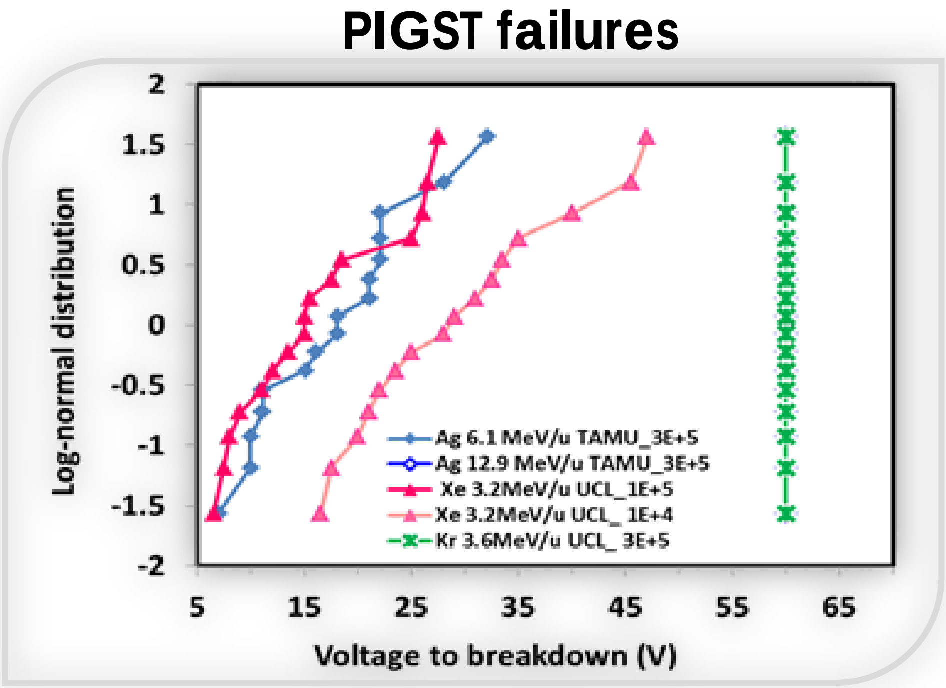


[RD1] Véronique Ferlet-Cavrois, Christian Binois, Aminata Carvalho, et al., NSREC2012 – IEEE TNS 59-6, pp. 2920-2929

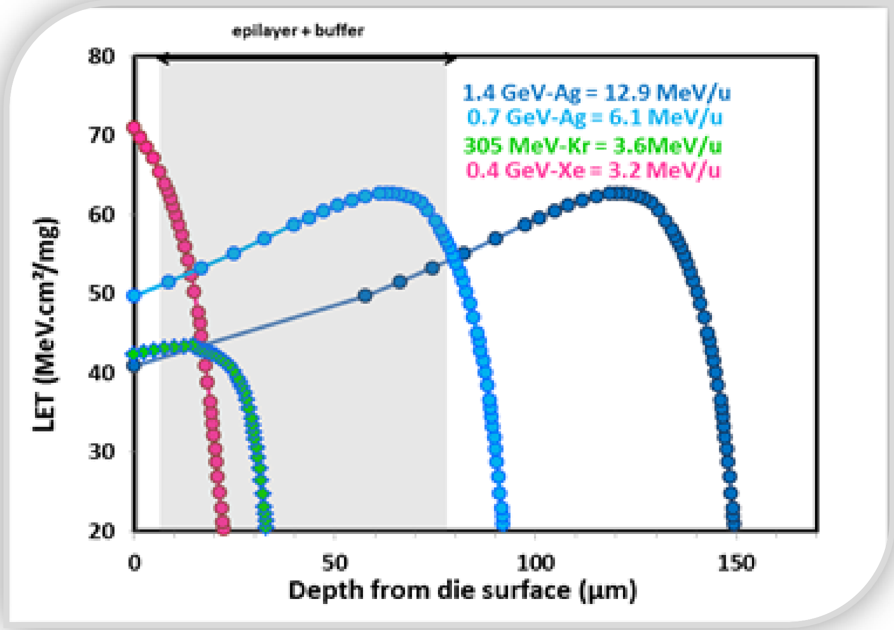
Summary of previous results

TAMU – UCL comparison, PIGST

Ion species and energy effect.



Cumulative log-normal distributions of the voltage to breakdown for the 2SK4219 irradiated at TAMU and UCL. The transistors were biased with t V_{GS} = 0 V and V_{DS} = 100 V during irradiation.



LET curves versus Range of medium to high energy beams used at TAMU and at UCL. Al degraders were used to vary the ion energy at the die surface. The approximate thickness of the low-doped region (epitaxial layer and buffer) of this device type is shown.

[RD1] Véronique Ferlet-Cavrois, Christian Binois, Aminata Carvalho, et al., NSREC2012 – IEEE TNS 59-6, pp. 2920-2929

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Summary of previous results

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- ✓ ***V_{GS} << 0V, V_{DS} max rating***
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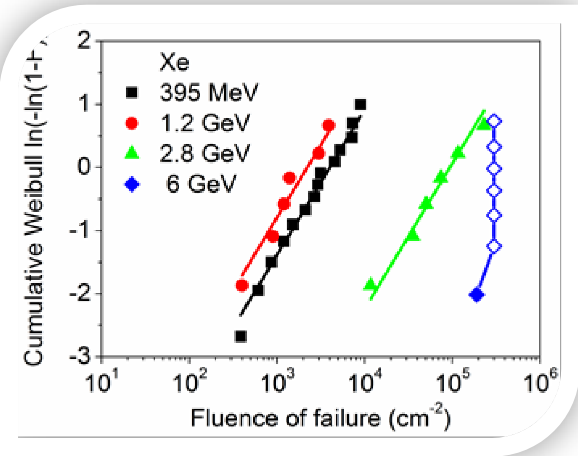
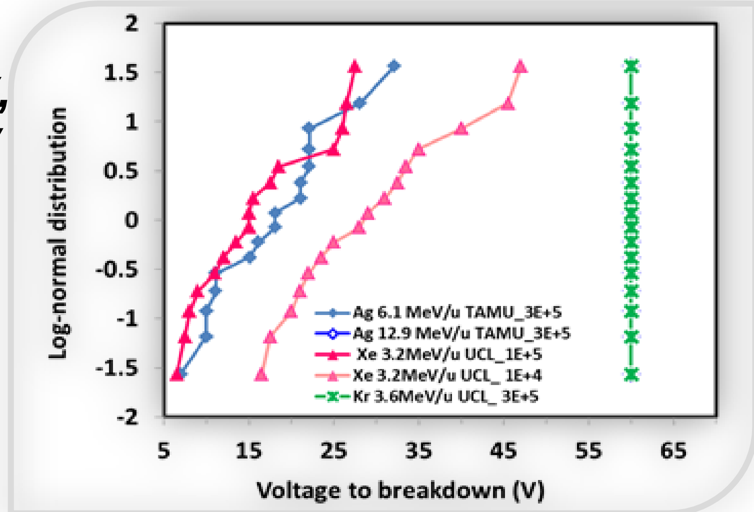
  → *Weibull, shape factor of 1.*

- ✓ ***V_{GS} = 0V, V_{DS} max rating***
  → *SEGR not observed during irradiation but revealed by PIGST*
  → *lognormal distribution.*

BUY25CS12J
V_{GS} = 0V, V_{DS} = 250V



2SK4219
V_{GS} = -10V, V_{DS} = 100V



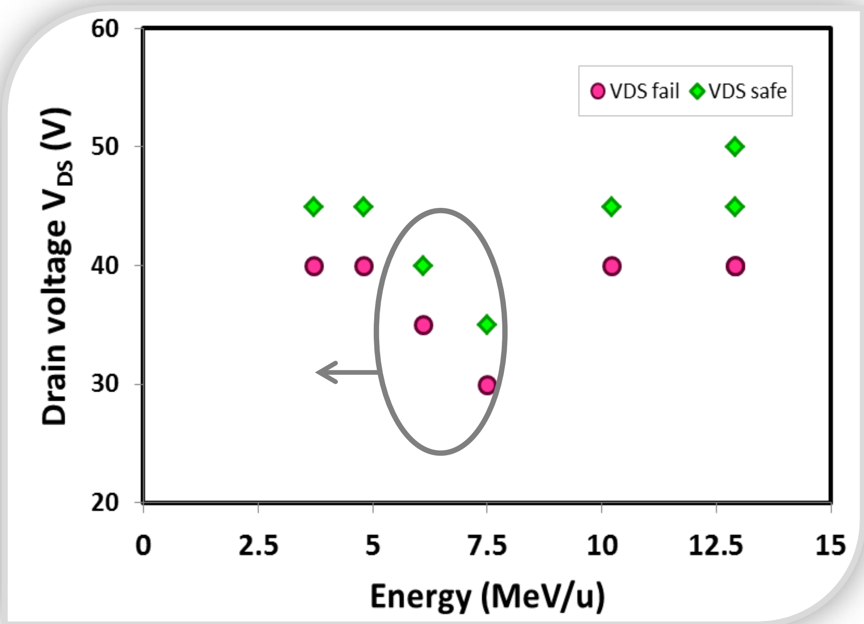
[RD1] Véronique Ferlet-Cavrois, Christian Binois, Aminata Carvalho, et al., NSREC2012 – IEEE TNS 59-6, pp. 2920-2929

Presentation of new results

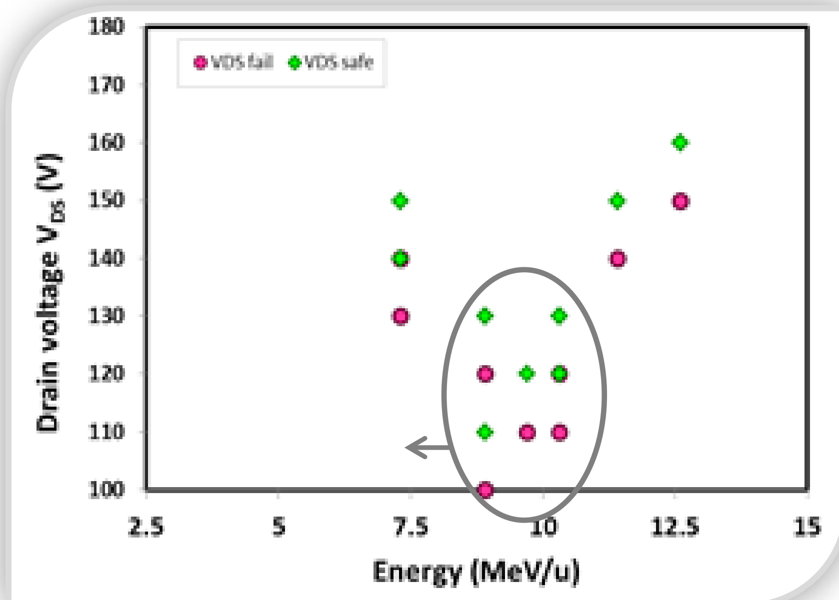
Presentation of new results – 1/10

Energy effect

Worst-case beam energy was shown not to correspond to the higher but to medium energy beams that place the Bragg peak close to the interface between the low-doped epitaxial layer and the highly-doped Si substrate.



2SK4219 – Drain voltage before and at SEGR as a function of the beam energy (3.7 MeV/u-Ag to 12.9 MeV/u-Ag beams used at TAMU). Al degraders were used to vary the ion energy at the die surface



BUY25CS54S – Drain voltage before and at SEGR as a function of the beam energy (7.3 MeV/u-Au to 12.6 MeV/u-Au beams used at TAMU). Al degraders were used to vary the ion energy at the die surface. The gate voltage V_{GS} was set to -15V during irradiations

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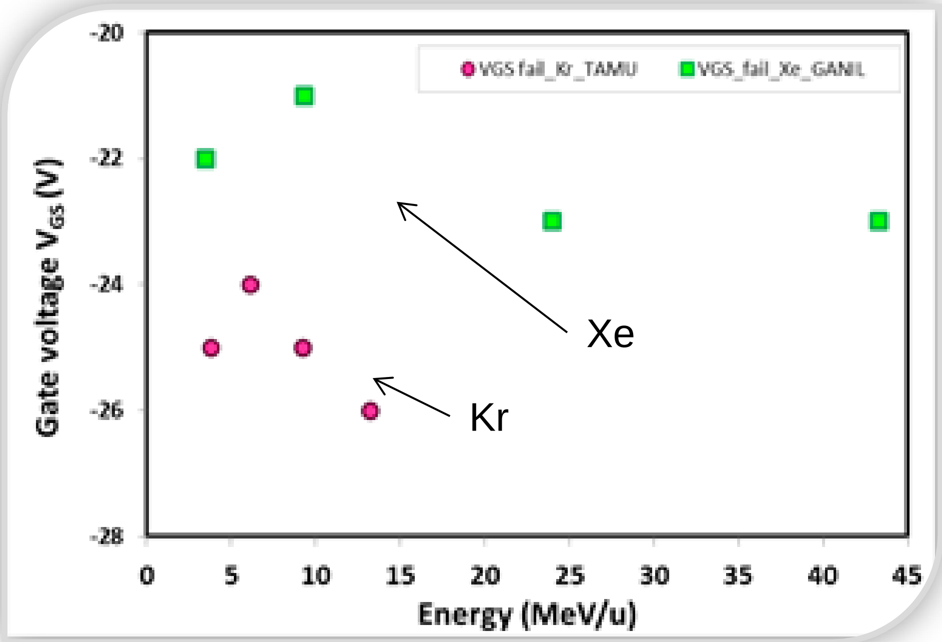
Presentation of new results – 2/10

Critical gate voltage for SEGR

- **The lower critical voltage for gate rupture corresponds to the heavier species.**
- **The minimum gate voltage required to provoke SEGR when no electrical field is applied to the drain (V_{DS} = 0V) is lower that the intrinsic onset breakdown voltage necessary to reach the Fowler-Nordheim regime.**



HG0K – Composite charts of critical gate voltage V_{GS} during SEGR versus Kr-beams energy at TAMU and Xe-beam energy at GANIL.

The drain was grounded during irradiations

	HG0K (STM)
Standard specification	V_{GS} = +20V/-20V
Leakage onset (+100nA/-100nA)	V_{GS} = +30V/-24V
Chosen voltage limit leakage current	V_{GS} = +33V/-28V 200nA/-300nA

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Presentation of new results – 3/10

Critical gate voltage for SEGR – Comparison with empirical models

- **Comparison with empirical formula**

  - **Titus's law**

$$V_{GS}crit_{ox}(V) = t_{ox}(nm) \times Ecrit_{ox}(V/nm)$$

$$V_{GS}crit_{ox}(V) = \frac{10^7}{1 + Z/44} \times t_{ox}(cm)$$

[RD2]

Where t_{ox} is the gate oxide thickness in *cm* and Z is the ion atomic number. This expression predicts that the heavier the ion the lower the onset of critical V_{GS} for SEGR

  - **Javanainen's law**

$$V_{GS}crit_{ox}(V) = t_{ox}(nm) \times \frac{Ecrit_{ox}(V/nm)}{1 + a \times (Z^2 \times t_{ox}(nm) \times LET(MeV.cm^2.mg^{-1}))^b}$$

$$V_{GS}crit_{ox}(V) = \frac{10^7}{1 + a \times (LET \times Z^2 \times t_{ox})^b}$$

[RD3]

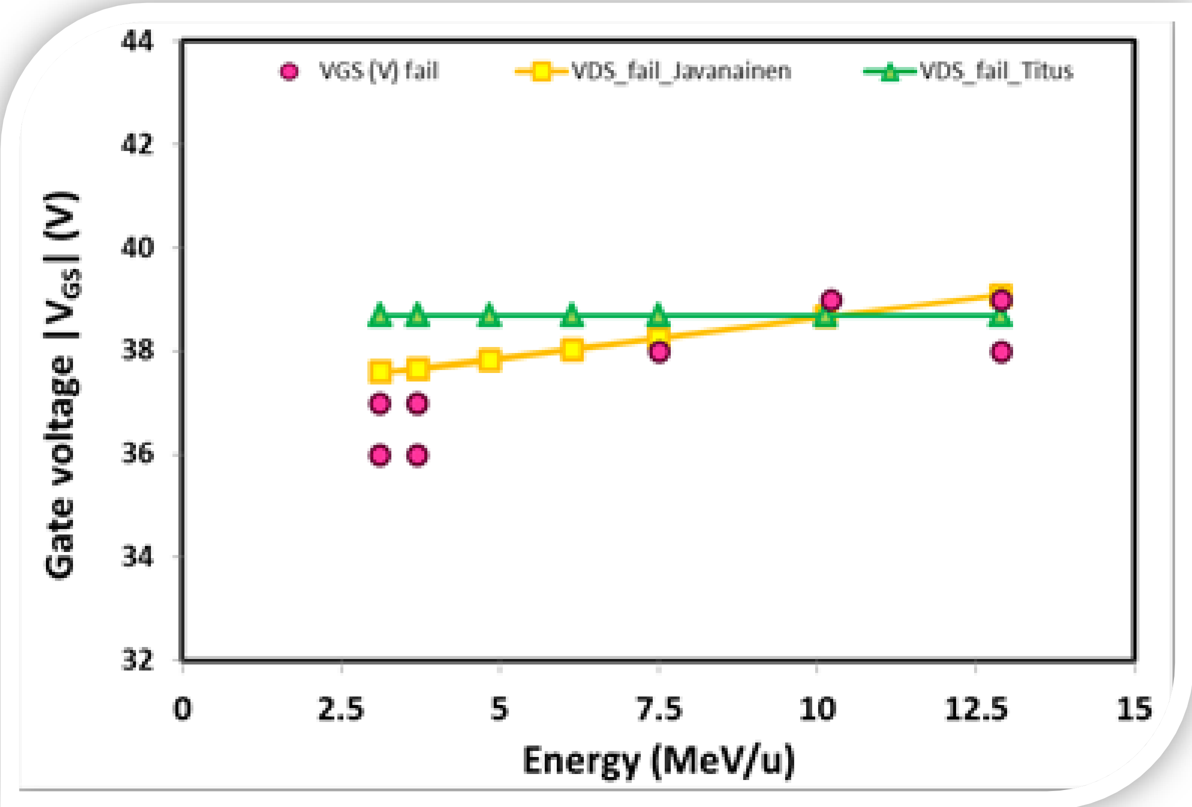
Where a = 0.1465 MeV^{-b} and b = 0.2649 are semi-empirical parameters.
The unit of (Z^2 x t_{ox}) is in *MeV*, t_{ox} is the gate oxide thickness in *cm* and Z is the ion atomic number

[RD2] J. L. Titus, C. F. Wheatley, et al., IEEE TNS 60-4, pp. 2492-2499 (1998)
[RD3]A. Javanainen, V. Ferlet-Cavrois, et al., TNS 60-4, pp. 2660-2665 (2013)

Presentation of new results – 4/10

Critical gate voltage for SEGR – Comparison with empirical models

- **Comparison with semi-empirical formula : Titus's law & Javanainen's law**



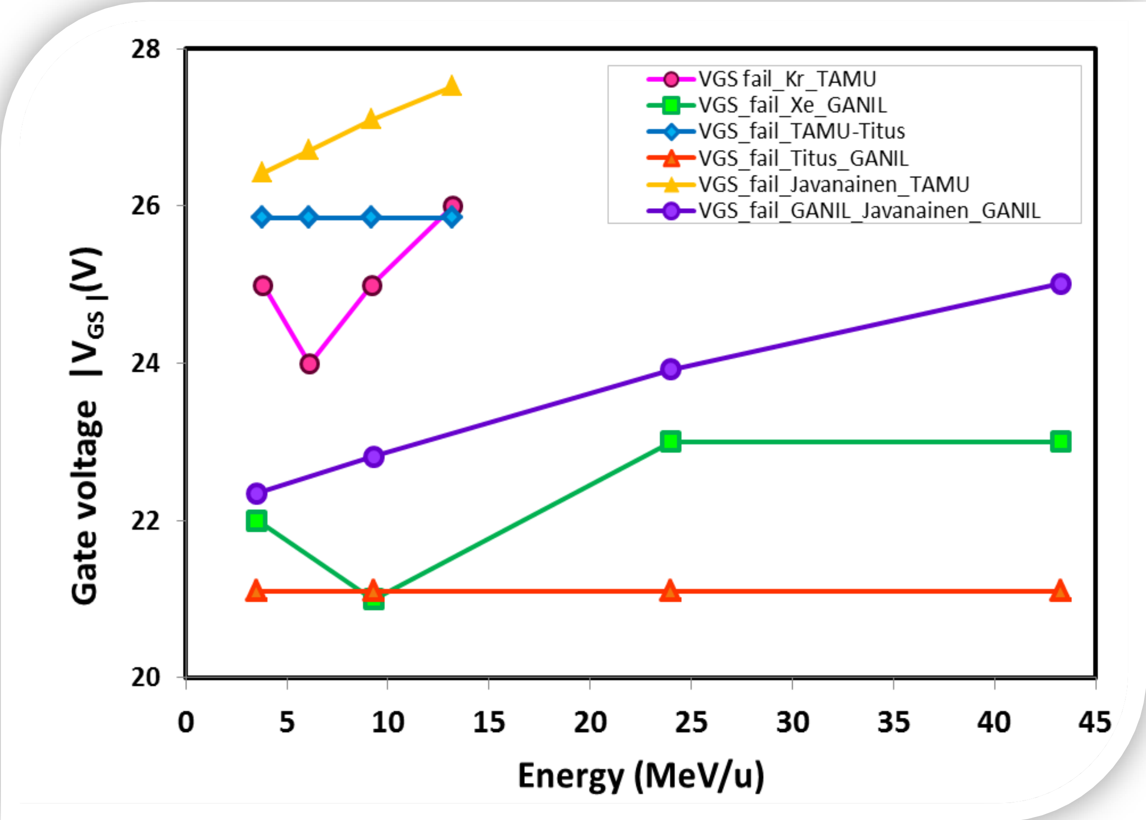
2SK4912 (FUJI): Good agreement with both models at medium energy

2SK4219 Composite charts – Comparison of minimum gate voltage V_{GS} during SEGR versus beam energy with semi-empirical models from Literature (Titus and Javanainen)

Presentation of new results – 5/10

Critical gate voltage for SEGR – Comparison with empirical models

- **Comparison with semi-empirical formula : Titus's law & Javanainen's law**



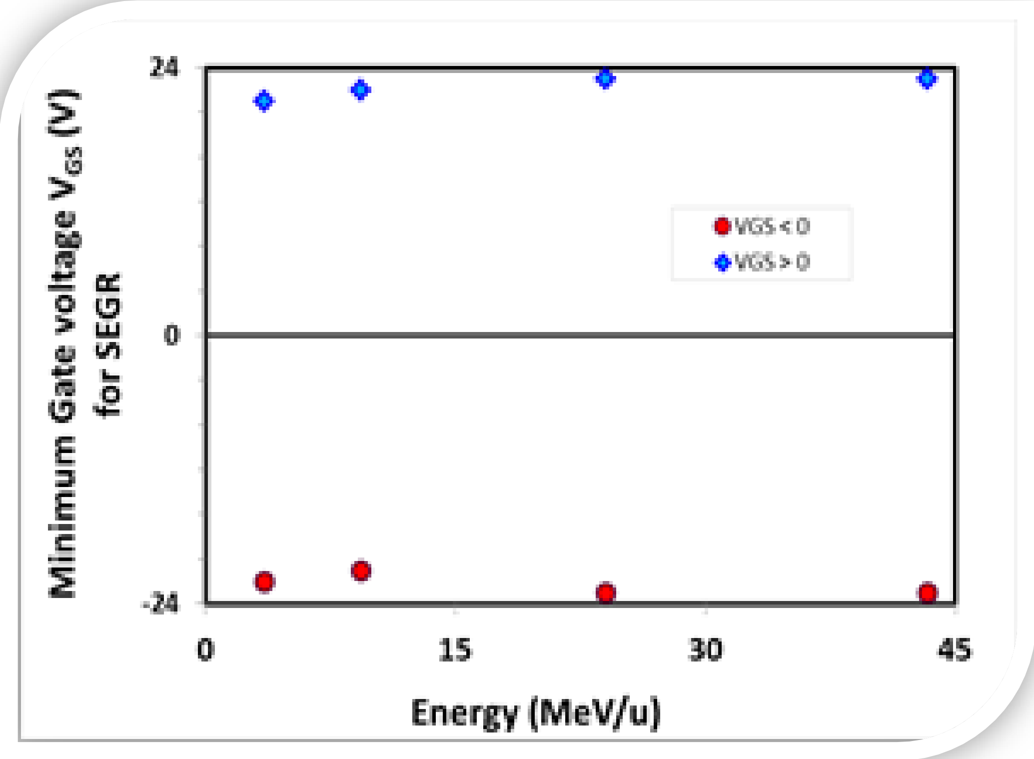
- **HG0K (STM): overestimation of critical V_{GS} with Javanainen model with both GANIL and TAMU beams**
- **Whereas underestimation with Titus's law of GANIL experiments and overestimation of TAMU experiments**

HG0K Composite charts – Comparison of minimum gate voltage V_{GS} during SEGR versus beam energy with semi-empirical models from Titus and Javanainen

Presentation of new results – 6/10

Symmetry of Critical gate voltage for SEGR

- **Regardless of the polarity, the minimum gate voltage for SEGR is "symmetric".**



HG0K – Minimum gate voltage V_{GS} during SEGR as a function of the beam energy (3.5 MeV/u-Xe to 44.5 MeV/u-Xe beams used at GANIL). Al degraders were used to vary the ion energy at the die surface. The drain was grounded during irradiations.

- **Experiment not performed with 2SK4912 (FUJI), however we assume that it exhibits the same behavior vs the critical gate voltage for SEGR since HG0K and 2SK4219 are both built with an HEXFET technology**

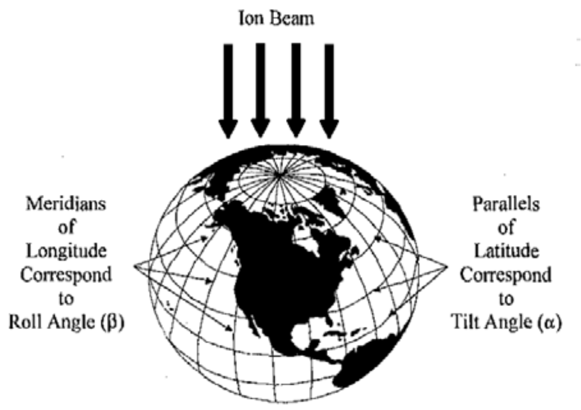
Presentation of new results – 7/10

Angular dependence of SEGR

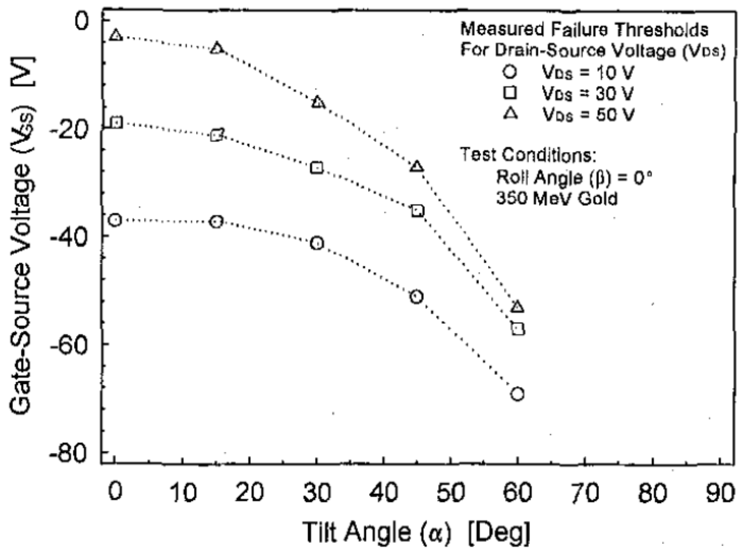
- SEGR susceptibility decreases when increasing the beam angle inclination from normal incidence

- Angular experiments important for cut-off angle determination for failure rates estimation purposes by limiting the solid angle of the ion flux to the cut-off angle instead of considering the omnidirectional feature of heavy ions fluxes in space

- Few results in Literature
- Both TILT and ROLL experiments performed.



Visualization of ion impact angles using Meridians of Longitude to represent roll angle and Parallels of Latitude to represent tilt angle.



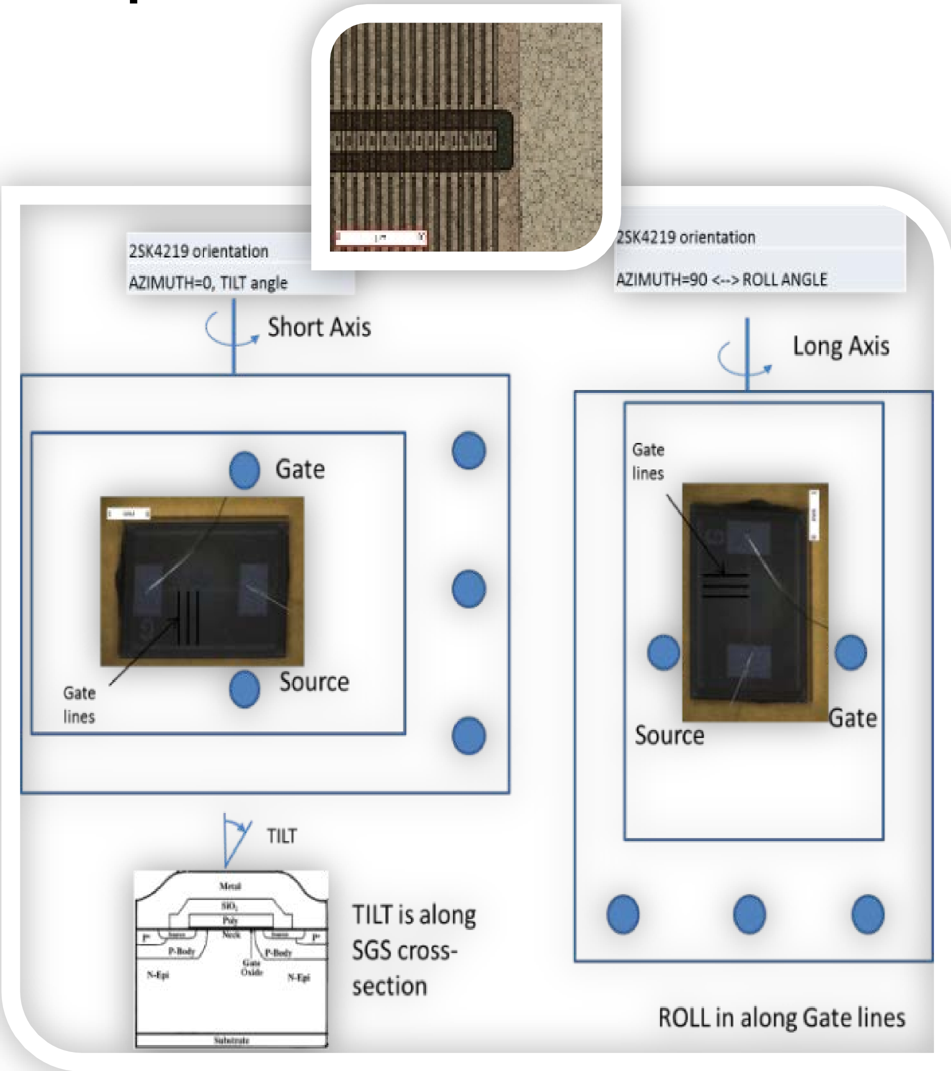
Angular response of FSL11A0 with roll angle, β, fixed at 0° and tilt angle, α, varied from 0 to 60°. Devices were irradiated with 350-MeV gold to a fluence of 1×10^5 ions•cm^{-2}.

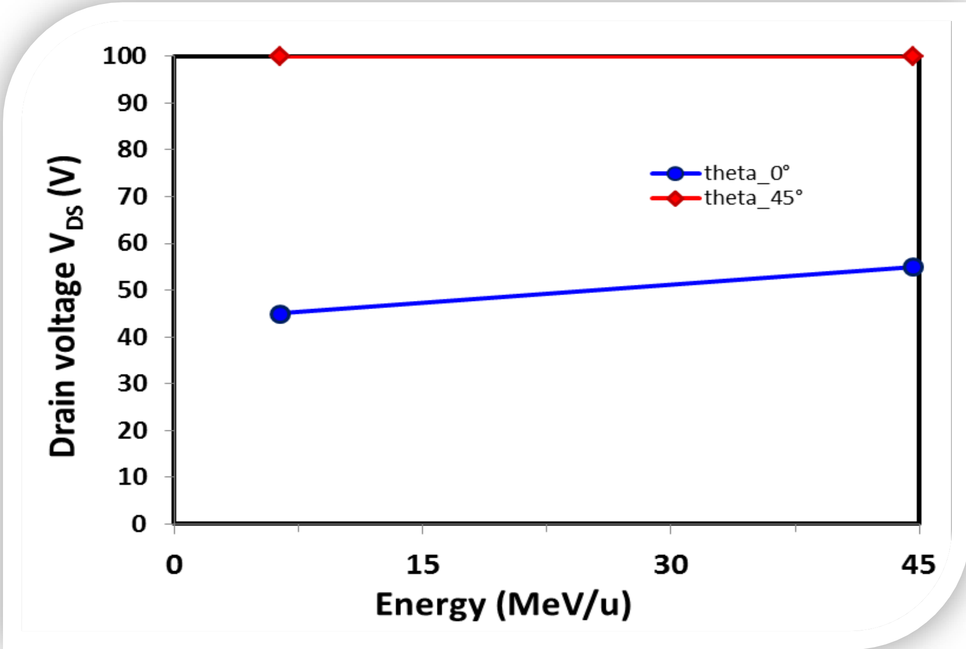
[RD4] J. L. Titus, C. F. Wheatley, et al., IEEE TNS 46-6, pp. 1640-1651 (1999)

Presentation of new results – 8/10

Angular dependence of SEGR

- **Tilting the beam parallel to the gate lines of the device is likely more favorable to provoke SEGR that when the beam axis is perpendicular to the gate lines.**





2SK4219 – Conventions for orientations during tilt and roll experiments with reference to the die surface and the direction of the gate lines plus Micrographs of the die showing its strip-cell features of the gate (left). Minimum drain voltage for SEGR as a function of the Xe-beam energy at different angles of inclination (tilt+roll) with high Xe-beam energy at V_{GS} = 0V. (Right)

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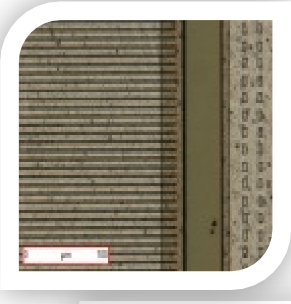
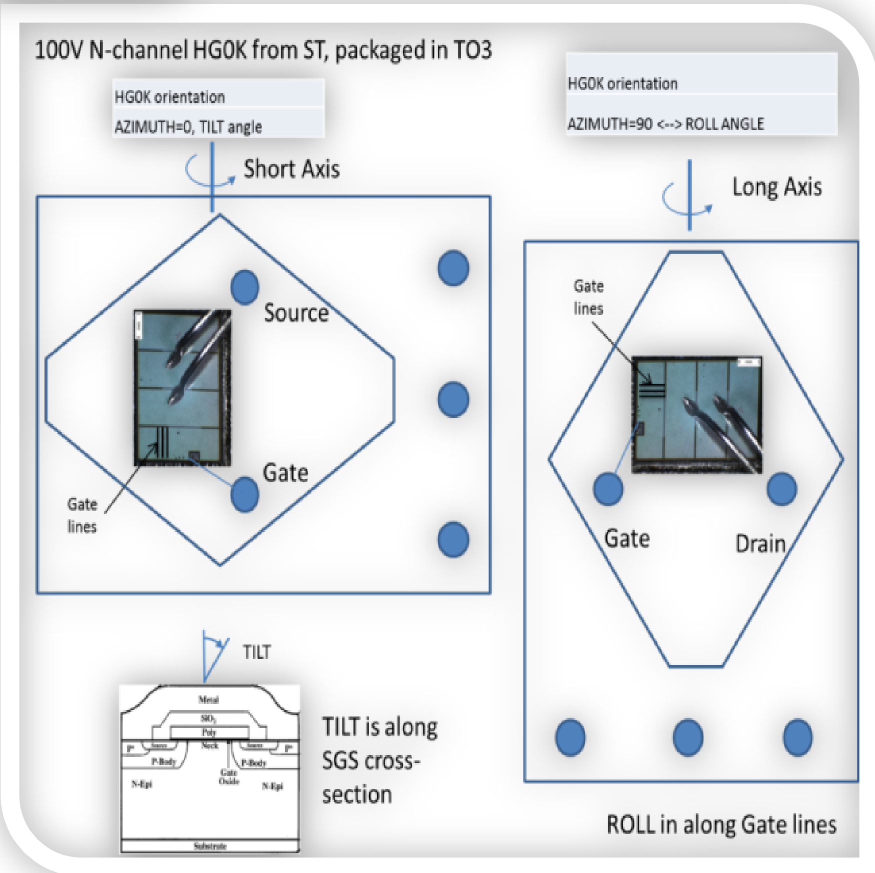
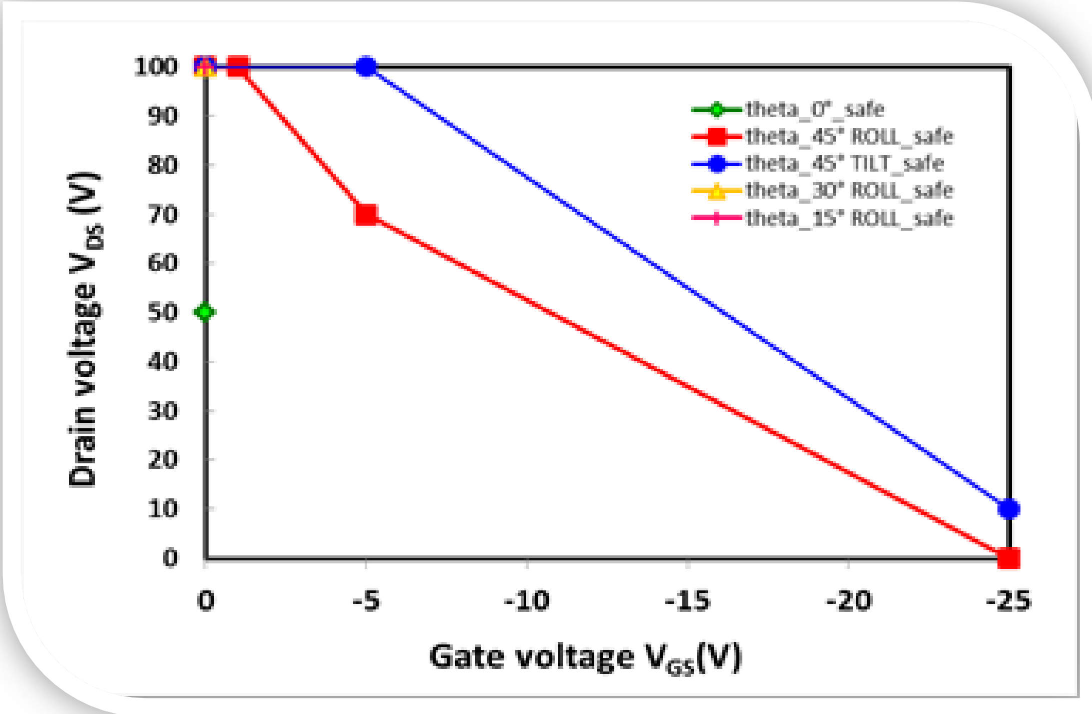
Presentation of new results – 9/10

Angular dependence of SEGR







HG0K – Conventions for orientations during tilt and roll experiments with reference to the die surface and the direction of the gate lines plus Micrographs of the die showing its strip-cell features of the gate (left). SOA for SEGR at different angles of inclination (tilt+roll) with high Xe-beam energy at V_{GS} = 0V. (right)

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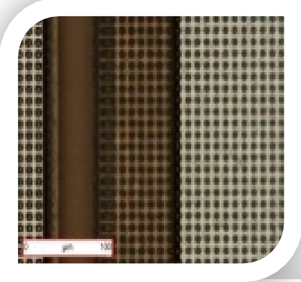
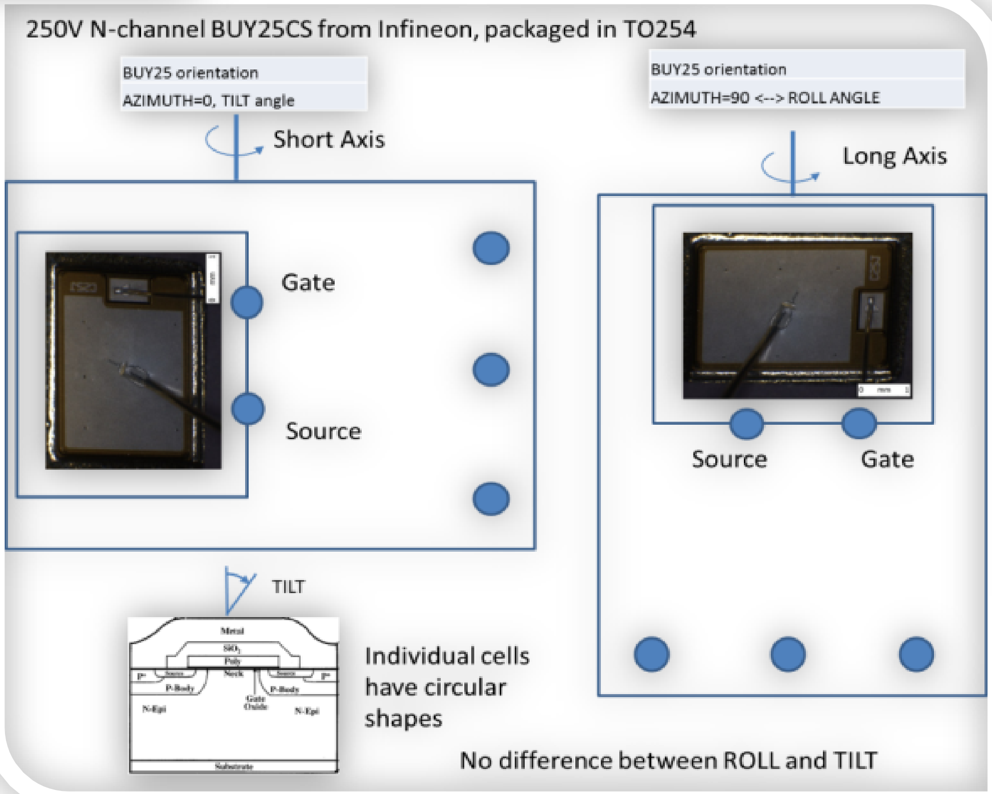
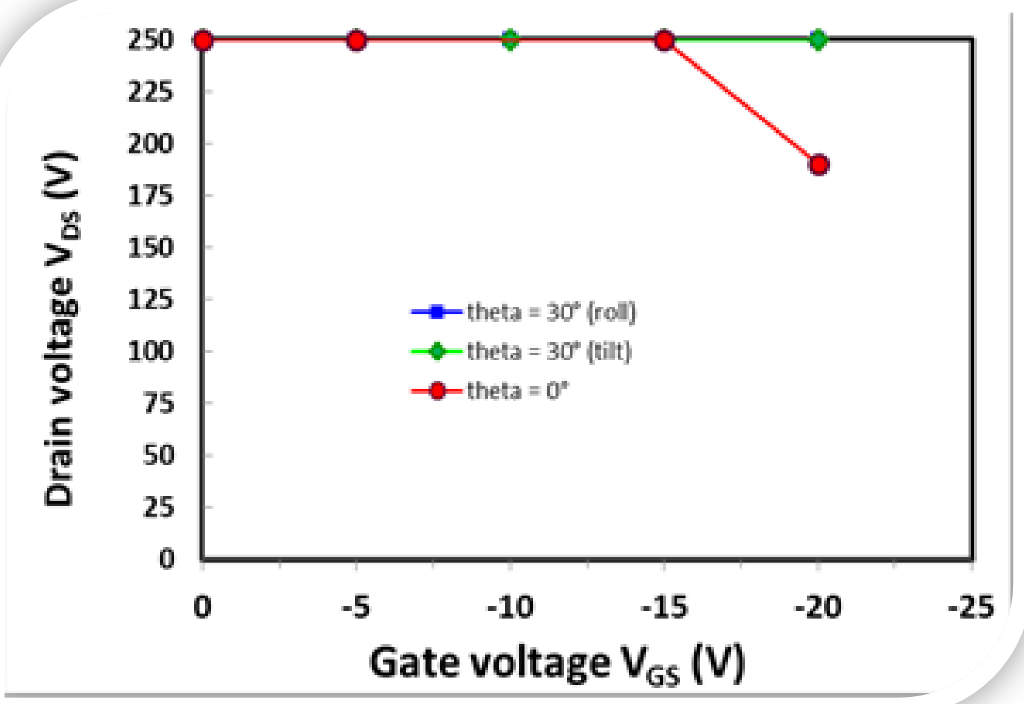
Presentation of new results – 10/10



Angular dependence of SEGR





BUY25CS12J – Conventions for orientations during tilt and roll experiments with reference to the die surface and the direction of the gate lines plus Micrographs of the die showing its strip-cell features of the gate (Left). SOA for SEGR at different angles of inclination (tilt+roll) with high Xe-beam energy at V_{GS} = 0V. (Right)

- **The sensitivity under ROLL orientation depends on the technology (strip-cell, hexFET, trench,…)**

Outcome

The results of the previous study confirmed the statistical nature of power MOSFET failure under heavy ion irradiation

- SEGR during irradiation (Vgs << 0V during irrad.) :
  - Weibull distribution with slope 1,
  - signature of a random phenomenon, SEGR induced by a single ion
- PIGST failure after irradiation (Vgs = 0V during irrad.)
  - log-normal distribution
  - Signature of a cumulated effect, several ions degrade the gate oxide

Outcome (con't)

The results of this study bring some insights into the characterization of Power MOSFETs

- Heavy ions species confirmed as a worst case wrt lighter species for SEGR
- Heavy ions of medium energy range confirmed as worst case
  - Bragg peak localized just beyond epi/substrate interface
- Comparison with semi-empirical models is consistent within 2V-3V with all MOSFETs technologies
- Angular dependence evidenced for various technologies;
  - Tilt and Roll results are different