SEGR Study

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Effects of ion species, energy and oxide thickness

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OUTLINE

- Purpose of the study
- SEGR-tests on MOSFETs and MOS-capacitors
- Semi-empirical model for SEGR prediction
- SEGR in SiO_2–SiN sandwich
- What is the SEGR? – Aftermath of an ion strike
- Conclusions and future outlook

Purpose of the study

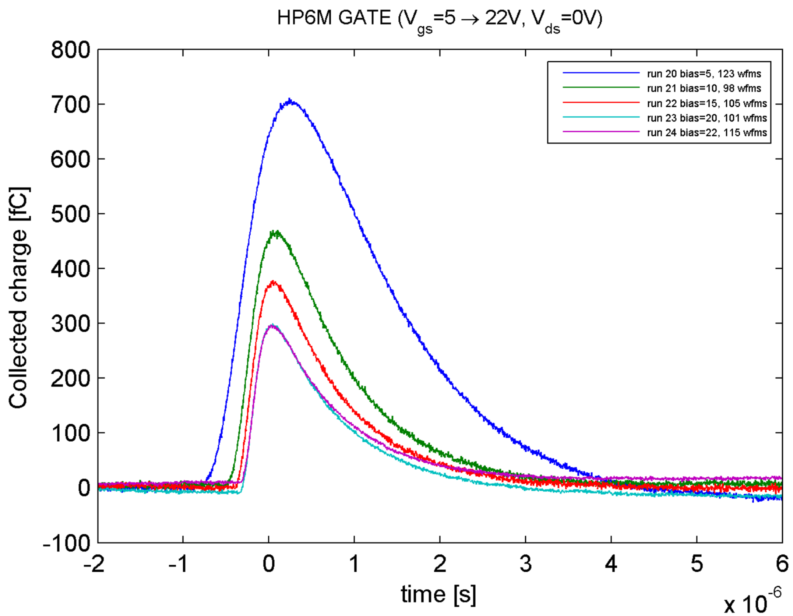
- Underlying physical processes in Single Event Gate Rupture (SEGR) are unknown
- *Oxide* breakdown dependence on
  - oxide thickness
  - penetrating ion (energy, LET, Z)

DEVICES UNDER TEST

- Manufactured by
  - STMicroelectronics, Catania, Italy
  - Sandia National Laboratories, NM, USA
- MOSFETs (power and regular) and MOS-capacitors with various SiO_2 thicknesses (20nm – 110nm)
- Also SiO_2 – SiN sandwich structures (various t_{ox}-t_{ni} combinations)

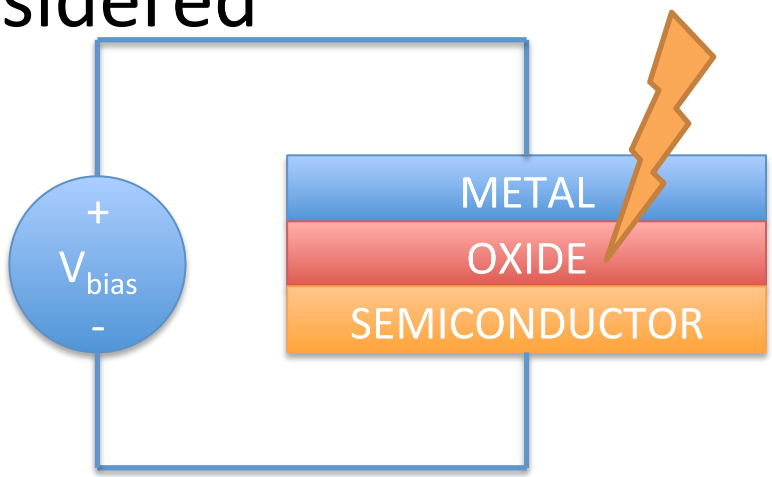
Charge collection measurements

- MOS-structure as a detector
- No clear signature prior to breakdown
- Gate current signal masked by the displacement current
- Metal-Insulator-Metal structures? In the future…

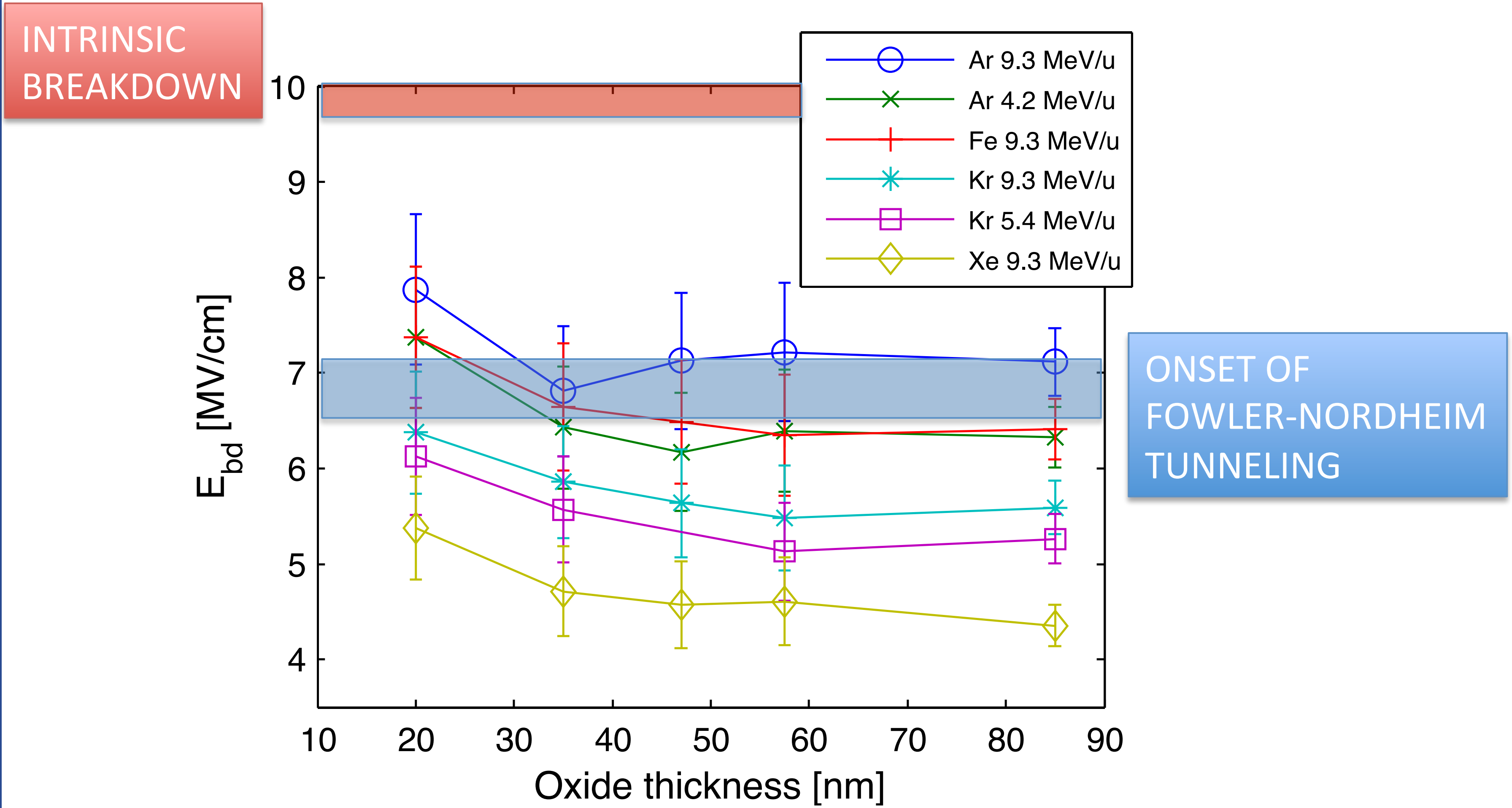


SEGR measurements

- Bias on the gate
- Drain and source grounded.
- Heavy ions from RADEF cocktail:
  - Xe, Kr, Fe, Ar
- Only the oxide was considered

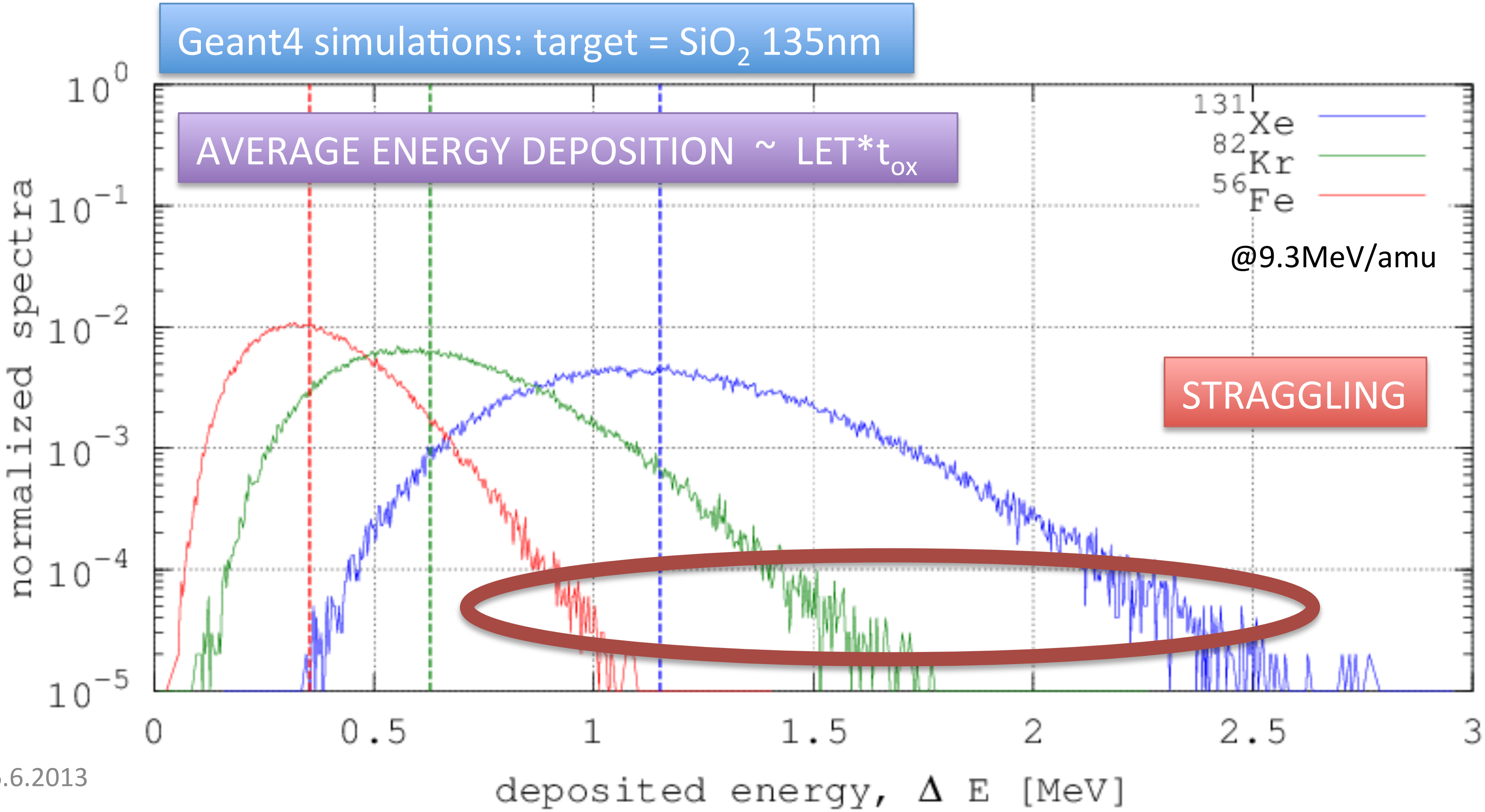


Breakdown field vs. t_{ox} vs. ion species



Heavy-ion energy deposition in small/thin targets

Stochastic process ≠ Average value



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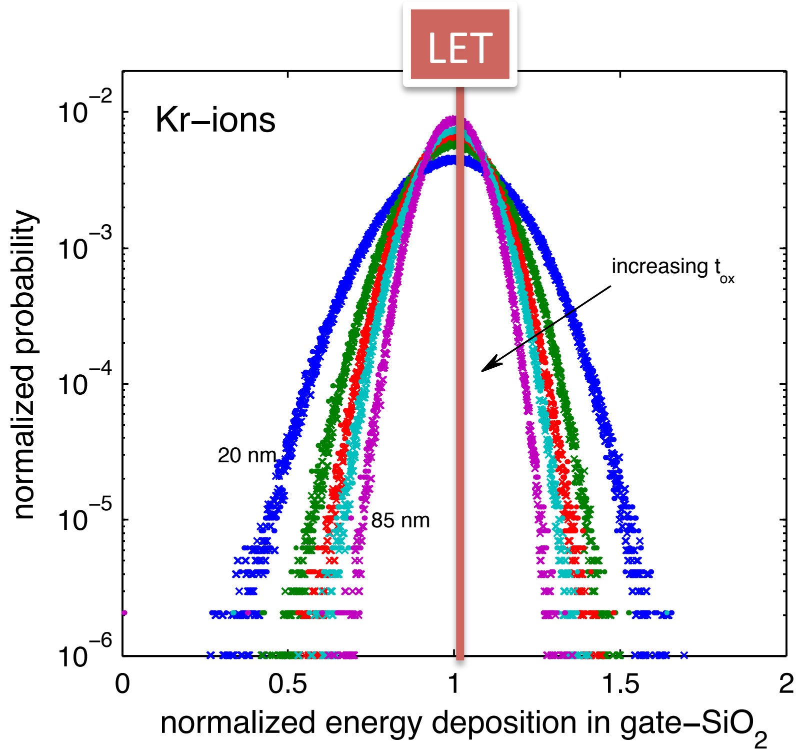
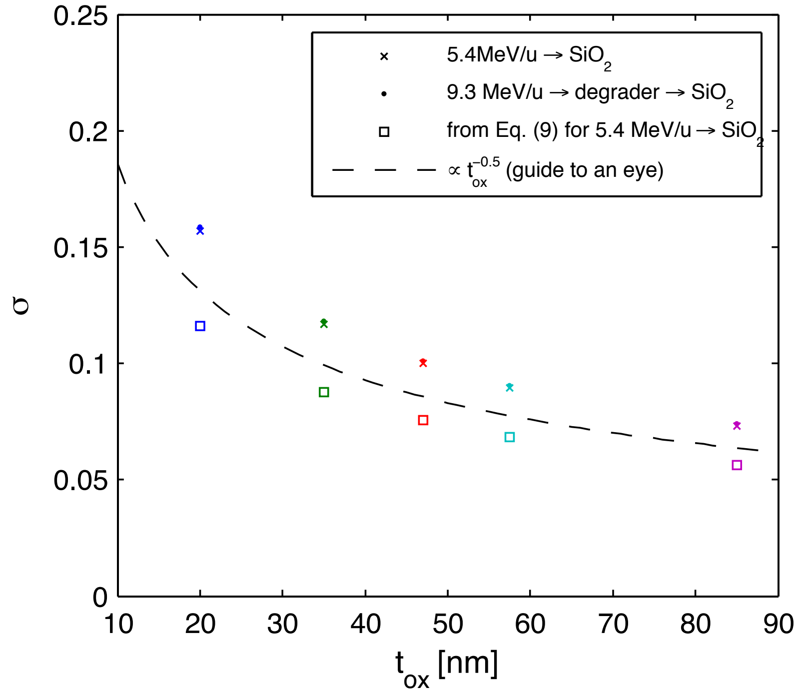
E_{dep} dependence on t_{ox}





G4-simulations

Theory:

$$\sigma = \frac{\Omega}{\langle \Delta E \rangle} = \frac{\Omega}{LET \cdot t_{ox}} \approx \frac{Z_1 \sqrt{A}}{LET \cdot \sqrt{t_{ox}}}, \qquad (9)$$

$$A = 4\pi(\alpha\hbar c)^2 N Z_2$$

NEW MODEL (2-parameters)

$$E_{bd}(\chi) = \frac{E_{int}}{1 + a \cdot (\chi)^{b}},$$

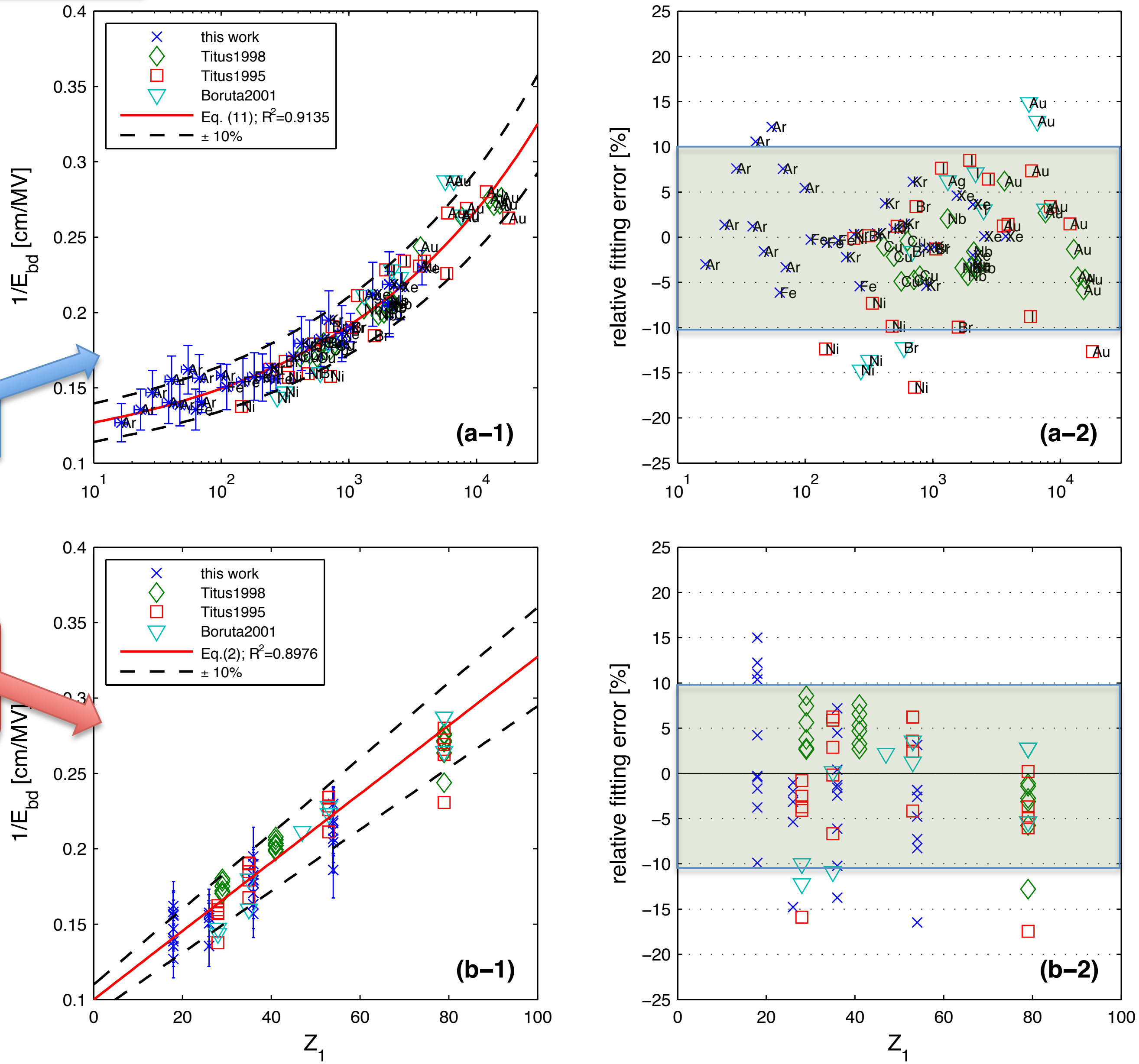
$$\chi = LET \cdot Z_1^2 \cdot t_{ox}.$$

$$a = 0.1465$$
$$b = 0.2649$$

BETTER CORRELATION

OLD MODEL (TITUS)

$$E_{bd}(Z_1) = \frac{E_{int}}{1 + \frac{Z_1}{44}}.$$



This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

Semi-Empirical Model for SEGR Prediction

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***Abstract*—The underlying physical mechanisms in single event gate rupture (SEGR) are not known precisely. SEGR is expected to occur when the energy deposition due to a heavy ion strike exceeds a certain threshold simultaneously with sufficient electric field across the gate dielectric. Typically the energy deposition is described by using the linear energy transfer (LET) of the given ion. Previously the LET has been demonstrated not to describe the SEGR sufficiently. The work presented here introduces a semi-empirical model for the SEGR prediction based on statistical variations in the energy deposition which are described theoretically.**

***Index Terms*—Modeling, MOS, SEGR, semi-empirical.**

I. Introduction

SINGLE event gate rupture (SEGR) is a destructive event occurring in the gate dielectrics, typically observed in metal–oxide–semiconductor (MOS) devices due to a heavy-ion impact. The SEGR can occur also in other device types. The fundamental physical mechanisms underlying the SEGR are not well known. Several authors (e.g., see [1]–[3], and references therein) have suggested that promptly (within picoseconds or even faster) after a heavy ion impact, a conductive path through a dielectric occurs. High enough potential difference across gate oxide coincidently with a highly localized energy deposition by an ion is assumed to cause a current spike, which in turn is considered to trigger the SEGR [1]. Contrary to the conclusions in [1], authors of [2] suggest that the ion-induced damage in dielectrics is not solely governed by the combination of the ion's LET and the electric field in the oxide. Also other the ion's energy (velocity). So far, the prediction formulae for SEGR are predominantly parametrized by using either the LET (see [4] and [5]), or the atomic number (Z_1) of the projectile (see [6] and [7]) as the determinant. The latter approach using Z_1 has been shown to give more accurate estimates than the one which uses the LET. The current work presents a model for SEGR prediction which can be shown to be even more accurate.

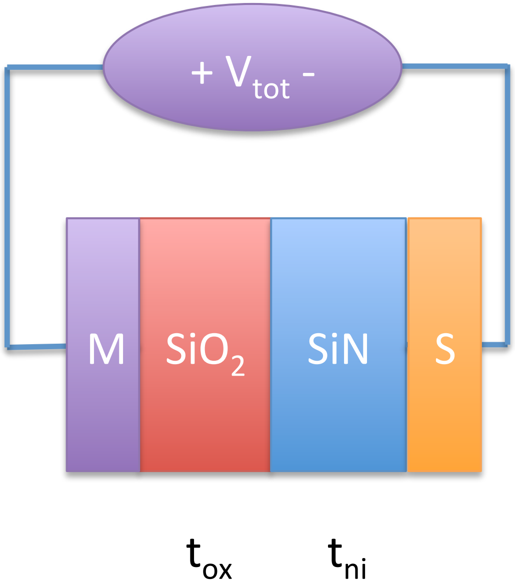
The energy loss, and thus the deposition also, of an ion traversing matter is a stochastic process. The LET value represents only the average ionizing energy deposition (or loss) of the ion per unit length. The statistical variations in the overall electronic energy loss within the target are described by the *energy loss straggling*. Detailed theoretical considerations about straggling are given. e.g., in [8], which is the main source of the theoretical derivations used in this work. The work presented here demonstrates that the electrical field at the onset of an oxide breakdown in case of SEGR, can be expressed as a function of the mean LET and the energy loss straggling. Moreover, the formulation has been simplified to include only the ion's mean LET, its atomic number and the oxide thickness of the studied devices. A semi-empirical formulations are presented.

The model presented here could give rise to a better understanding of physics behind the complex phenomenona of SEGR.

II. Experimental Setup

Experiments were carried out at RADEF Facility [9] in the University of Jyväskylä, Finland. The selected ions and beam energies are presented in Table I. All the ions are included in the

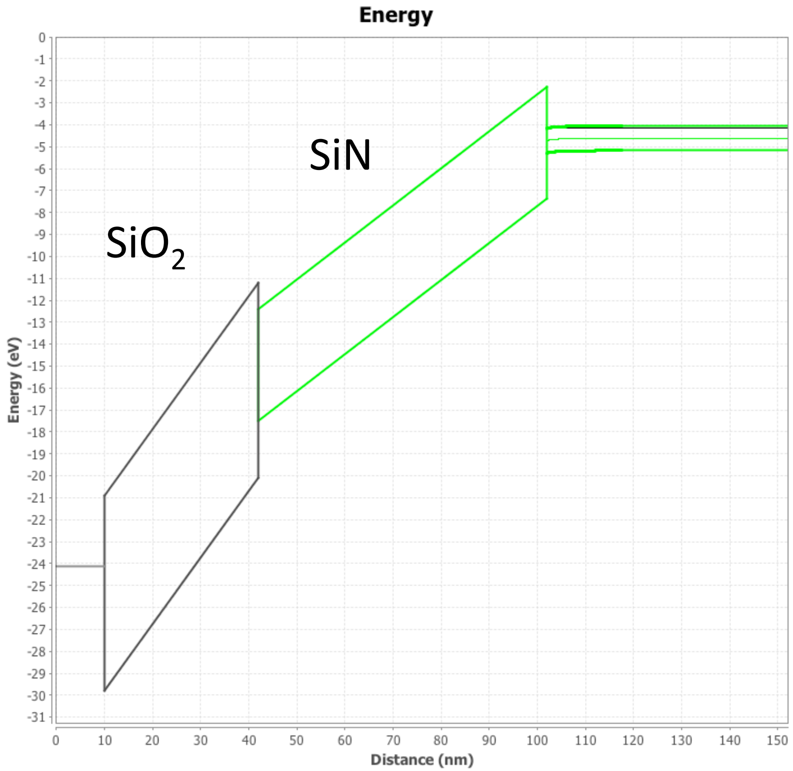
SiO2 – SiN sandwich structures



$$E_{ox} \approx \frac{V_{tot}}{t_{ox}\left(1+\frac{\epsilon_{ox}}{\epsilon_{ni}}\cdot\frac{t_{ni}}{t_{ox}}\right)}$$

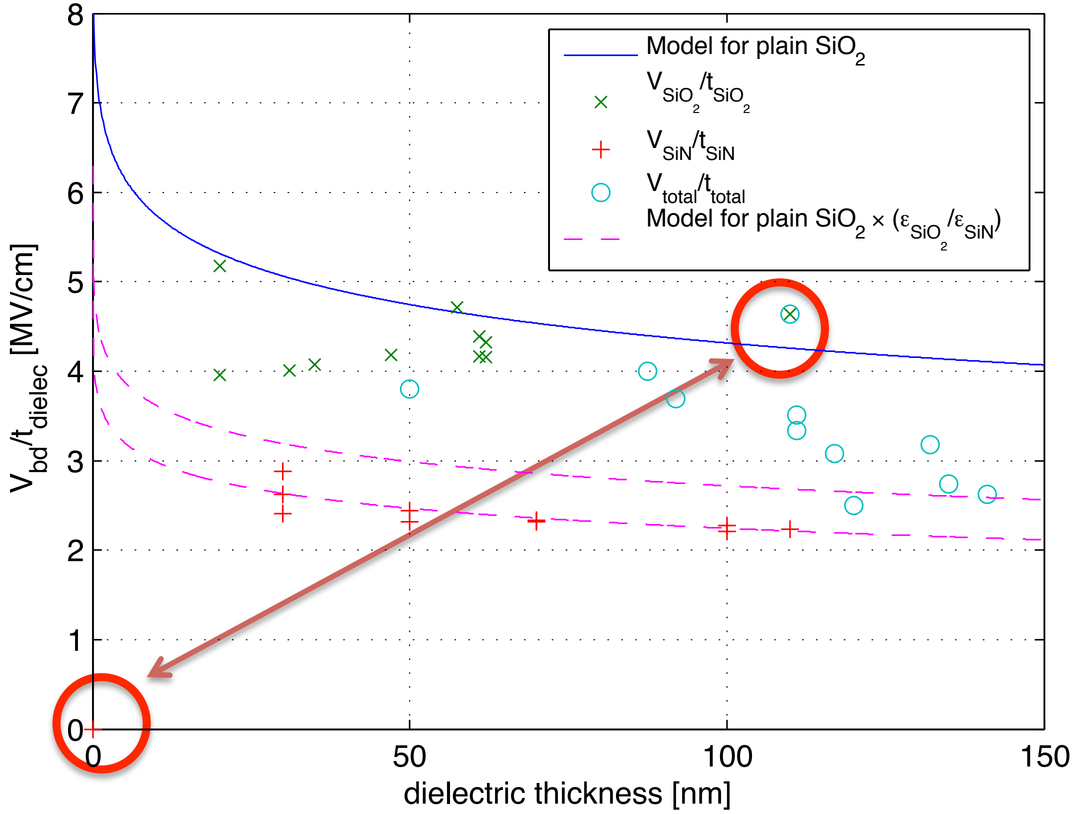
$$E_{ni} \approx \frac{V_{tot}}{t_{ni}\left(1+\frac{\epsilon_{ni}}{\epsilon_{ox}}\cdot\frac{t_{ox}}{t_{ni}}\right)}$$

$\epsilon_{ox} = 3.9$
$\epsilon_{ni} = 6.2 - 7.5$ (depending on the process)



Experiments vs. model

Xe-ion @ 1217MeV



Electrically:

$$\underbrace{100nm}_{SiN} \Leftrightarrow \underbrace{\frac{\epsilon_{SiO_2}}{\epsilon_{SiN}} \times 100nm \approx 52 - 63nm}_{SiO_2}$$

Model for sandwich structures

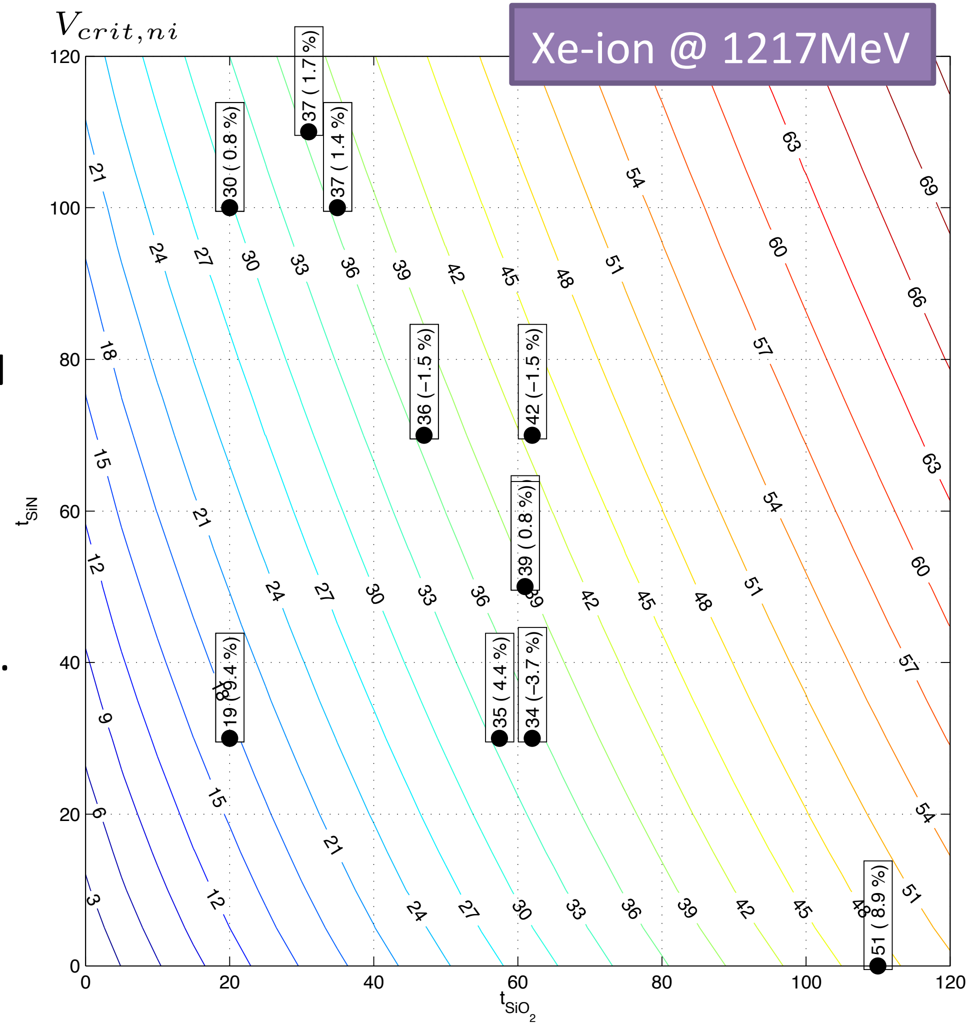
$$V_{tot,crit} = \underbrace{E_{bd}(\chi_{SiO_2}) \cdot t_{ox}}_{V_{crit,ox}} + \underbrace{(1 - \frac{\epsilon_{ox}}{\epsilon_{ni}}) \cdot E_{bd}(\chi_{SiN}) \cdot t_{ni}}_{V_{crit,ni}};$$

$$E_{bd}(\chi) = \frac{E_{int}}{1 + a \cdot (\chi)^b},$$

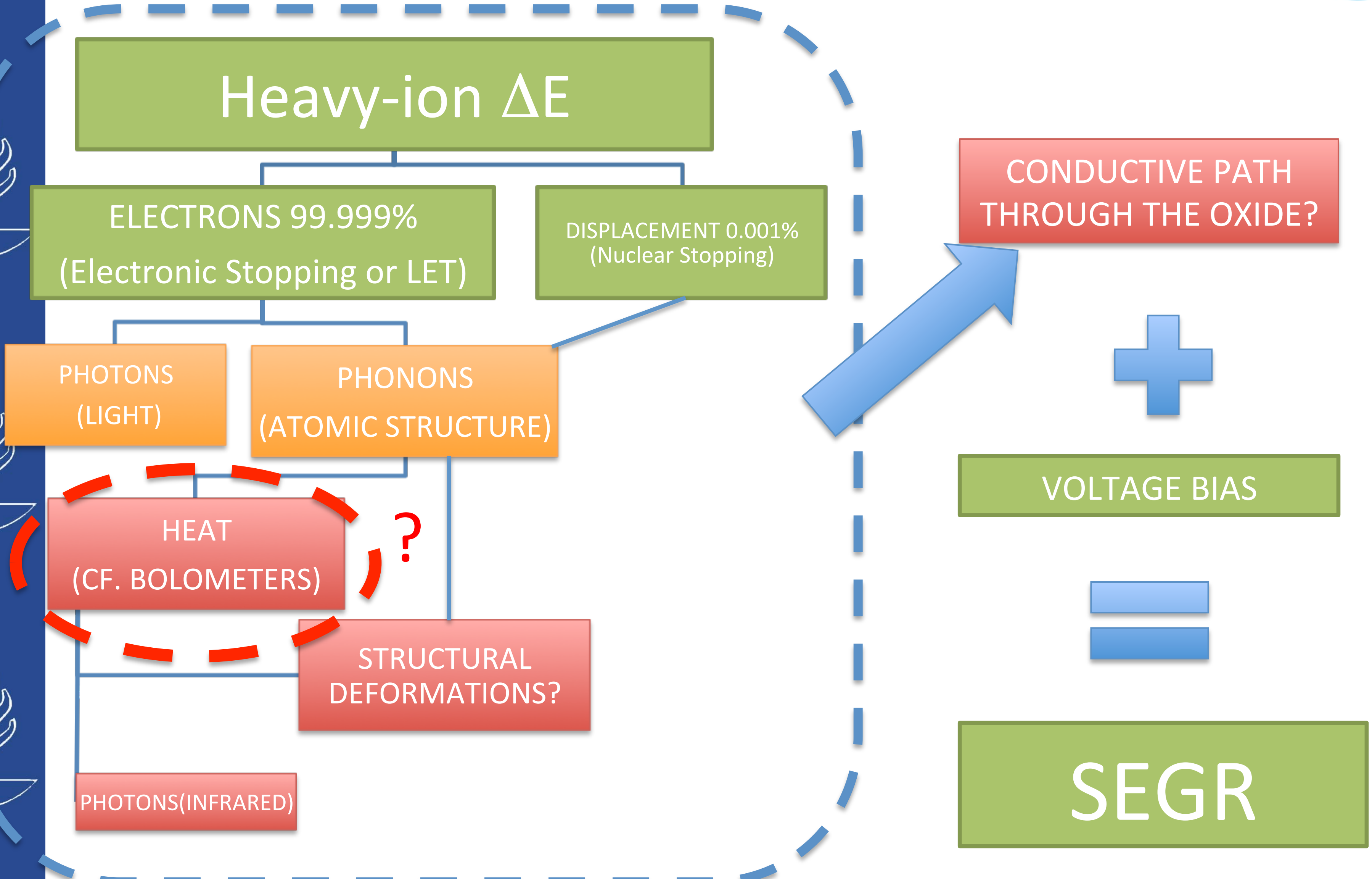
$$\chi = LET \cdot Z_1 \cdot t_{dielec}$$

- “Weighted” average of SiO_2 and SiN breakdown voltages normalized with permittivity
- Nitride more prone to breakdown (with Xe-ions)
- How about other ions? More tests…

Data to be published



Possible SEGR flowchart



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NIM B
Beam Interactions with Materials & Atoms

Track creation in SiO_2 and $BaFe_{12}O_{19}$ by swift heavy ions: a thermal spike description

M. Toulemonde [a,*], J.M. Costantini [b], Ch. Dufour [c], A. Meftah [d], E. Paumier [a,c], F. Studer [e]

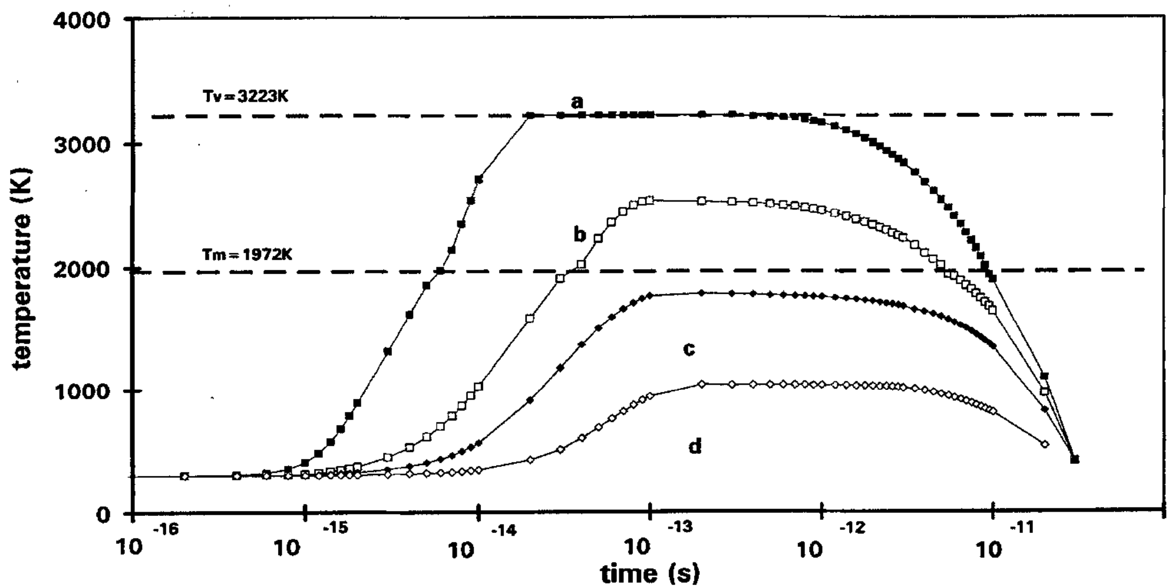

Fig. 1. For $\lambda = 4$ nm evolution of the lattice temperature versus time at a distance of 1 (a), 3 (b), 4.5 (c) and 8 (d) nm from the ion path in SiO_2. The krypton beam energy was 3.4 MeV/amu corresponding to a $S_e = 12$ keV/nm. The sample was at 300 K. T_m and T_v correspond to the melting and vaporization temperature respectively.

SIMULATION

Material	Melting point [K]	Boiling point [K]
SiO2	1972	3223
Si	1687	3538
Al	933	2792

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Molecular dynamics simulations of the structure of latent tracks in quartz and amorphous SiO_2

Olli H. Pakarinen [a,*], Flyura Djurabekova [a], Kai Nordlund [a], Patrick Kluth [b], Mark C. Ridgway [b]

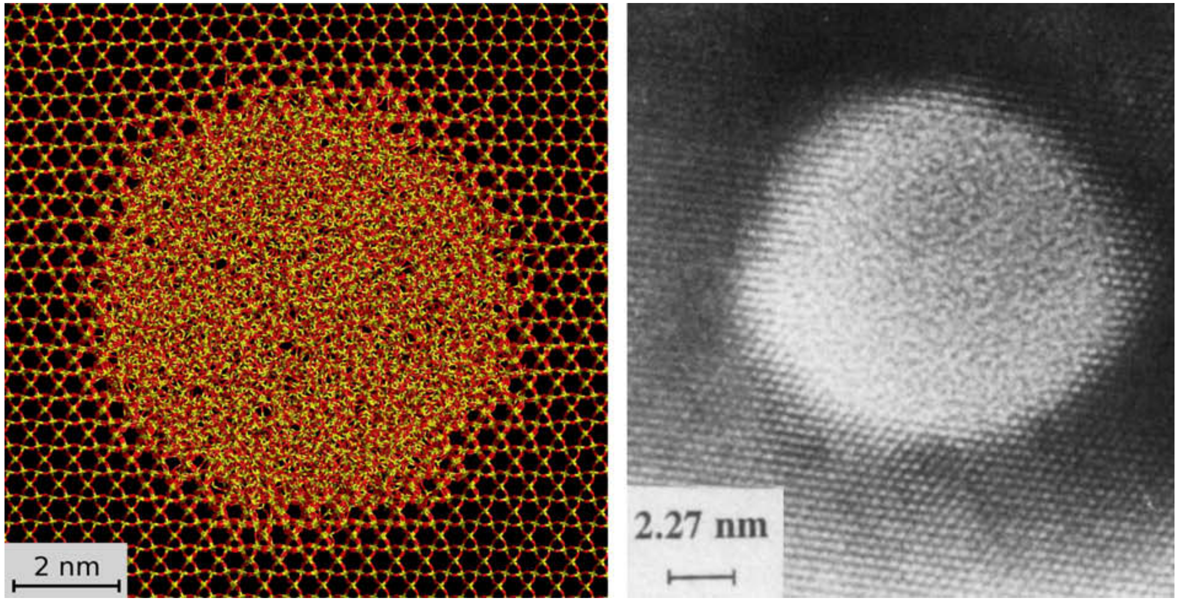

Fig. 1. (Left) Top view of a computational image of an ion track in crystalline quartz with 15.9 keV/nm energy loss. (Right) Experimental TEM image with 14 keV/nm energy loss [2].

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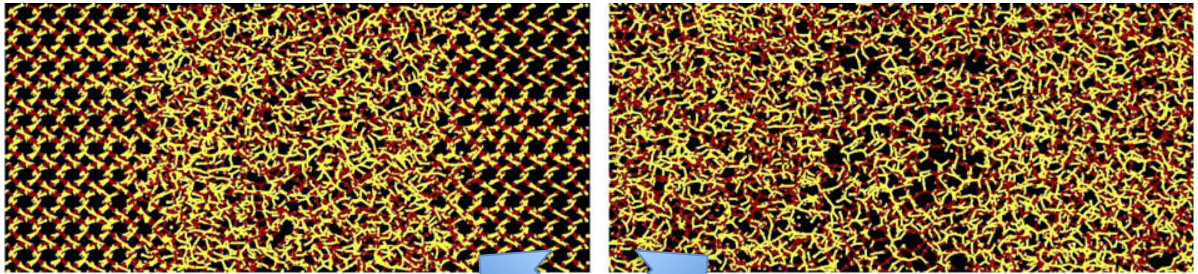

Fig. 2. Atomistic images of simulated ion tracks in crystalline quartz (left) wit[illegible] energy loss and in amorphous silica (right) with 10.8 keV/nm energy loss in side view. In quartz the heavy ion amorphises the track, whereas in amorphous silic[illegible]arest change is the strongly decreased density in the track core.

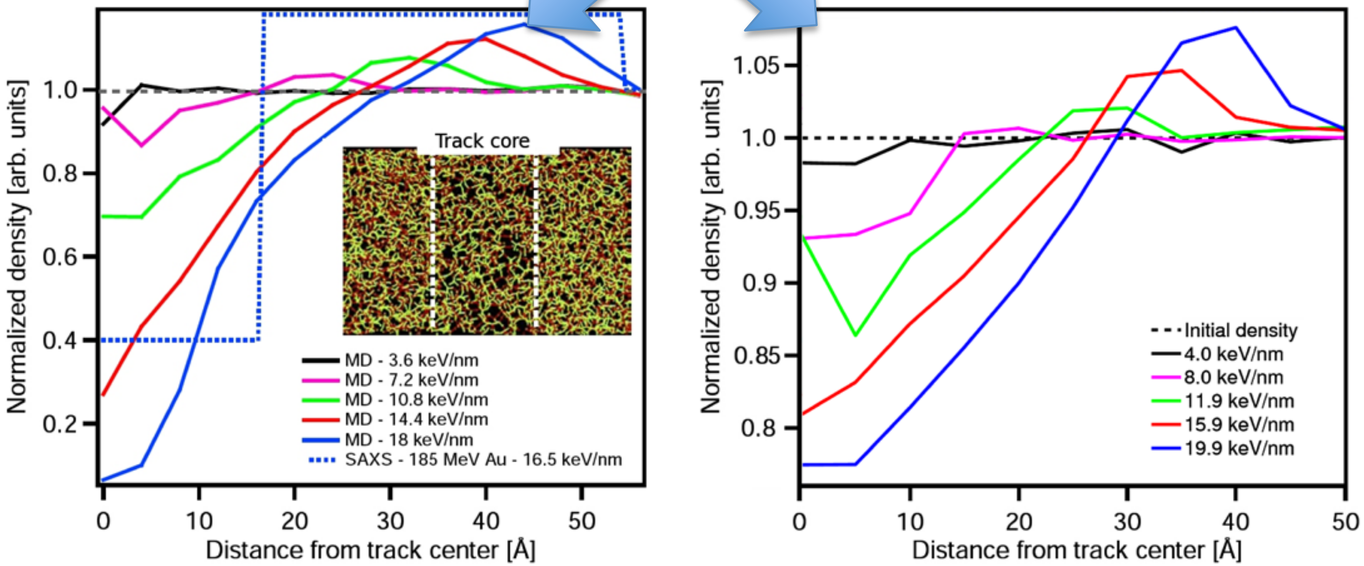

Fig. 3. Density as a function of distance from the track center in amorphous silica (left) and in crystalline quartz (right). The values at the very center of the track (distance = 0) are not statistically accurate due to the very low number of atoms in the center.

Conclusions

- New model for predicting SEGR critical gate voltage for SiO2-MOS was developed
  - Statistical variations in ΔE needs to be taken into account
  - oxide thickness also plays some role
- Model works also with Xenon ions for SiO2-SiN structures (other ions in the future)
  - SiN is more prone to SEGR at least in case of Xe-ions
- Where does the energy of the ion go in the end?
  - Thermal effects vs. electrical effects??
  - MD and G4 simulations and more measurements required

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- Heikki Kettunen, JYFL
- Mikko Rossi, JYFL
- Jukka Jaatinen, JYFL
- Alexandre Bosser, JYFL/Montpellier

Thank you for your attention

EXTRA SLIDE:
SEGR-statistics vs. G4-simulated ΔE