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Single event effects induced by heavy ions in SONOS charge trapping memory arrays

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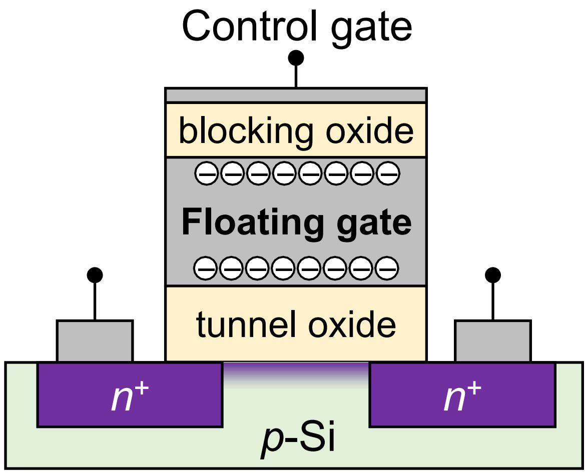
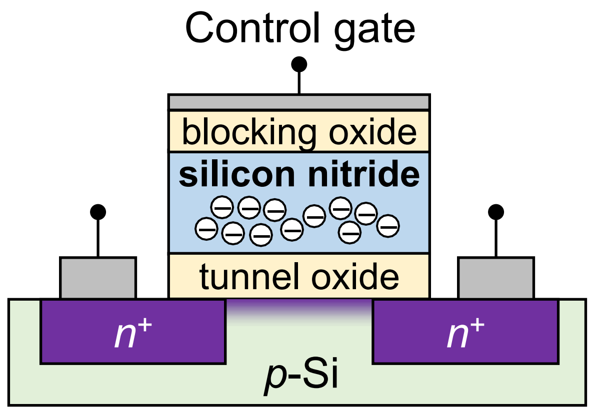
SONOS charge trap memory

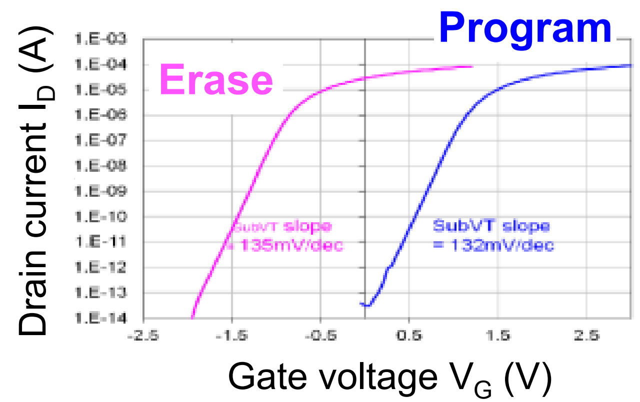
Floating-gate flash



SONOS flash

[Si-oxide-nitride-oxide-Si]





K. Ramkumar et al, *IMW* 2013

Stored charge is confined more strongly in a SONOS gate stack

- Improves retention
- Improves endurance & yield
- Enables thinner oxide
  - Lower programming voltage
  - Reduced cell cross-talk, more scalable
  - Simpler CMOS process integration
- Better radiation response?

infineon

SAMSUNG

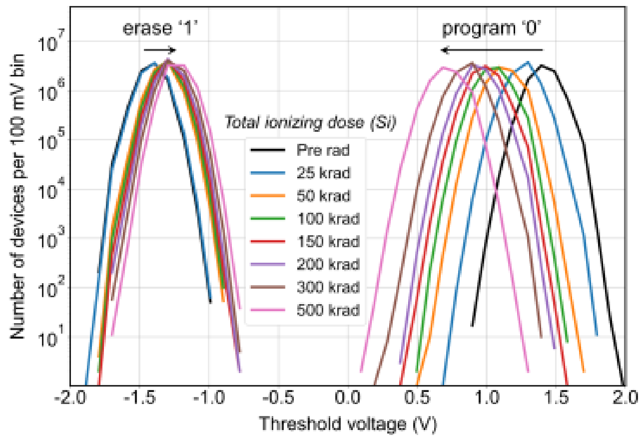
TOSHIBA + others

A quick survey of the radiation effects literature on flash memory

✓ = literature exists

	Floating-gate	SONOS
Total ionizing dose	✓	✓
Single event effects	✓	?

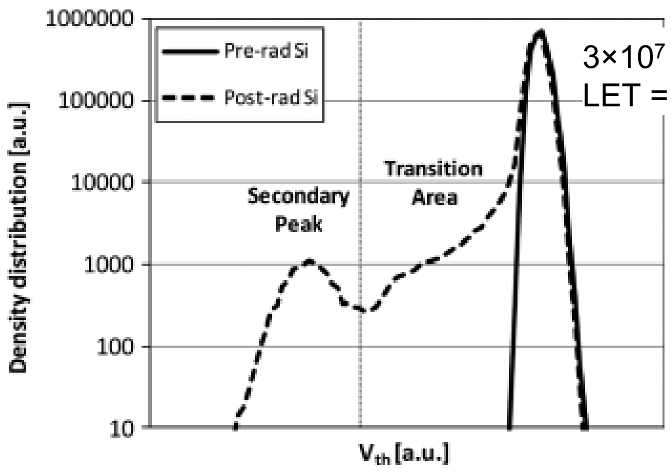
40nm Cypress (Infineon) SONOS



TID shifts the V_T distributions in both SONOS and floating gate

H. Puchner et al *TNS* 2014, T. Xiao et al *TNS* 2021

Numonyx (Micron) 65nm NOR floating-gate



3×10^7 Si ions / cm^2
LET = 9.8 MeV/cm^2 mg

Heavy ion irradiated floating-gate arrays show:

- A ***secondary V_T peak*** to the left of the main program peak
- An ***exponential tail*** of affected devices around each peak
- Little effect on the erase state

S. Gerardin et al *TNS* 2010, G. Cellere et al *TNS* 2006

Heavy ion irradiation experiments

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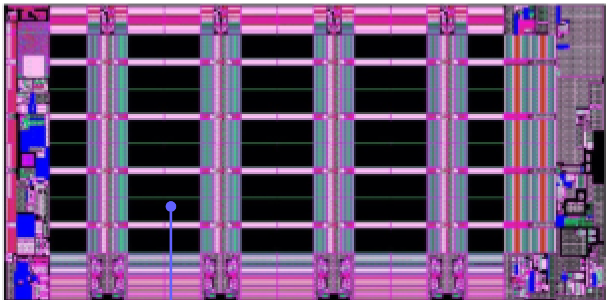
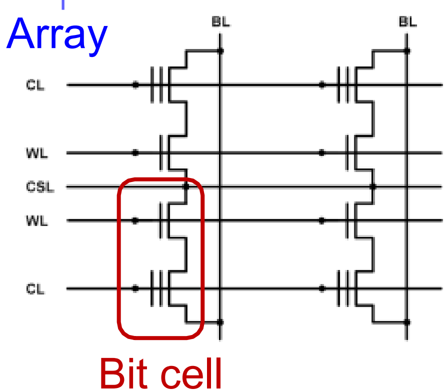
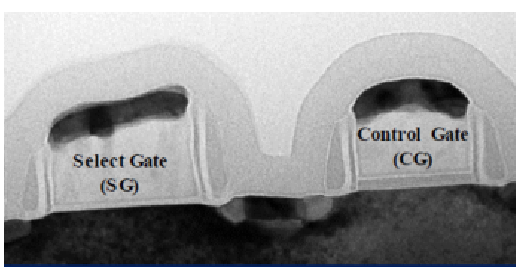
Infineon **40nm SONOS chip, 8 Mb**

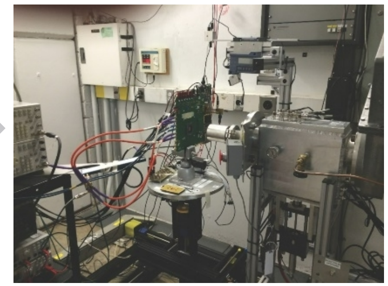






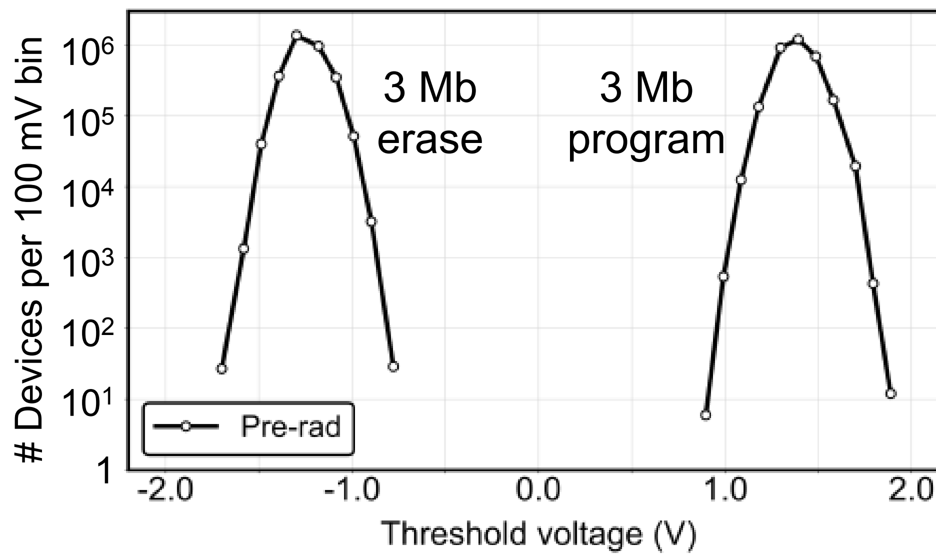
I. Kouznetsov et al, *IMW* 2018

Texas A&M University K500 Cyclotron



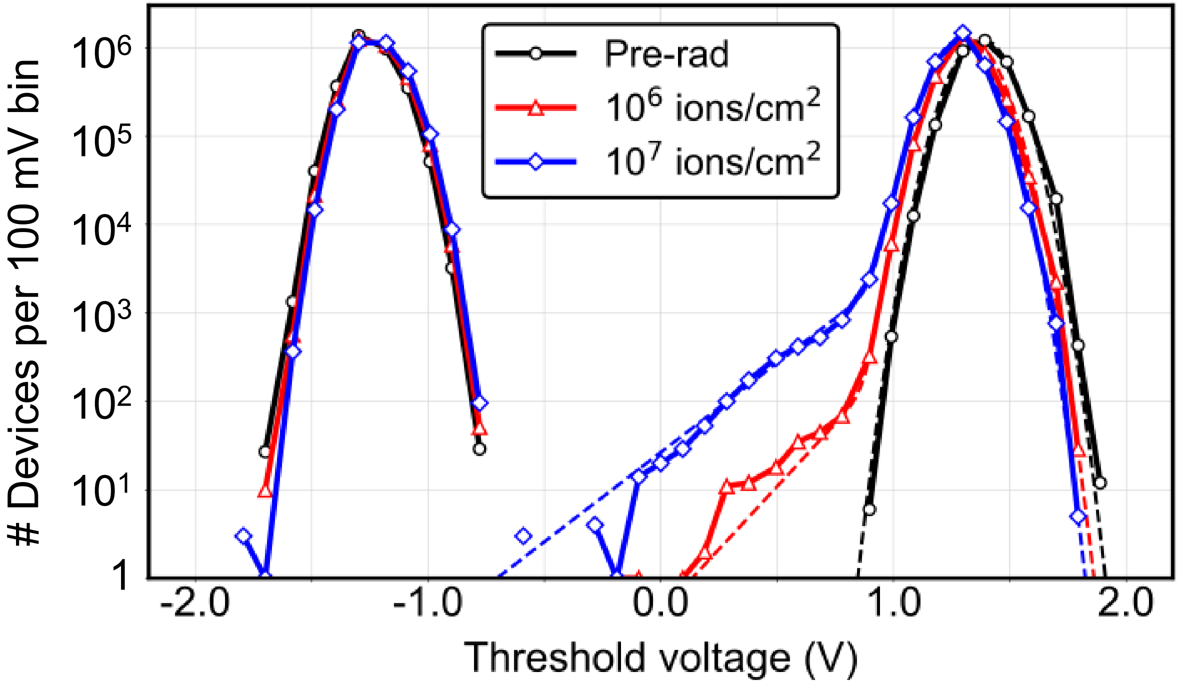
- Beams: 1259 MeV Kr, 599 MeV Ar
- Flux: 0.2-1.0 × 10^5 ions/cm^2/s
- Different tilt angles of beam relative to test chip to vary LET (10-51 MeV/cm^2mg)
- Cells left unbiased during irradiation, at 25°C unless noted

V_T distribution prior to irradiation **(6 Mb)**



Kr ion irradiation

LET = 51.1 MeV cm^2/mg in tunnel oxide



Analytical fit using normal distribution + one-sided exponential distribution

Fluence [ions/cm^2]	**# affected cells***
10^6	195
10^7 (exp 1)	1775
10^7 (exp 2)	2483

* Affected = V_T is more than 5σ below the mean *μ* of the normal distribution

- **No secondary V_T peak**
- Observed an exponential V_T tail of affected cells
  - The effect is linear with beam fluence
- No effect on the erase state (E-field ≈ 0)

Single event effects LET dependence

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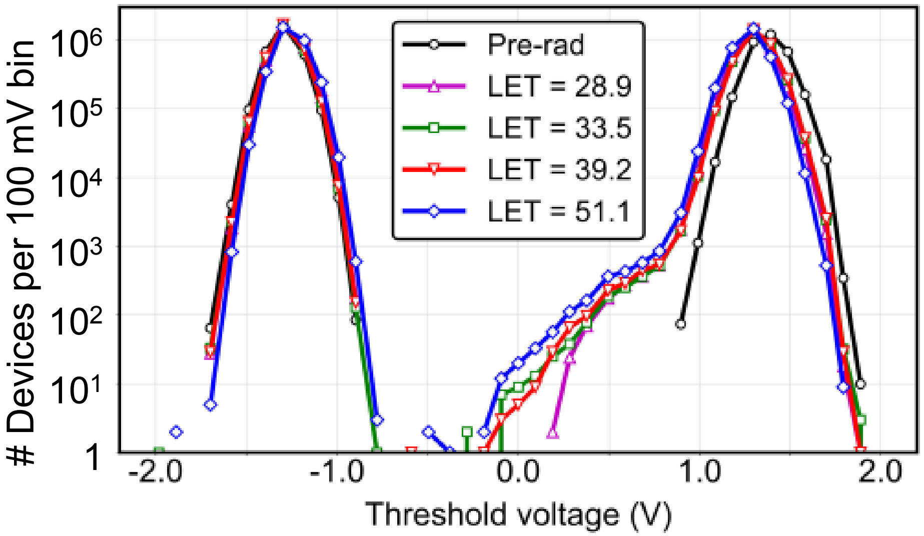
Test chip B (6 Mbit)

Kr ions at 0°, 30°, 42°, 55° incidence

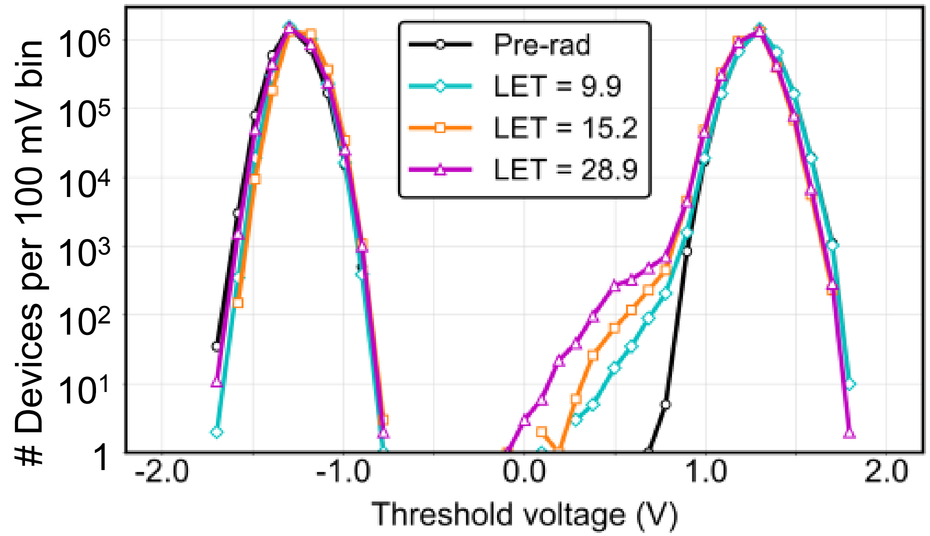
10^7 ions/cm^2



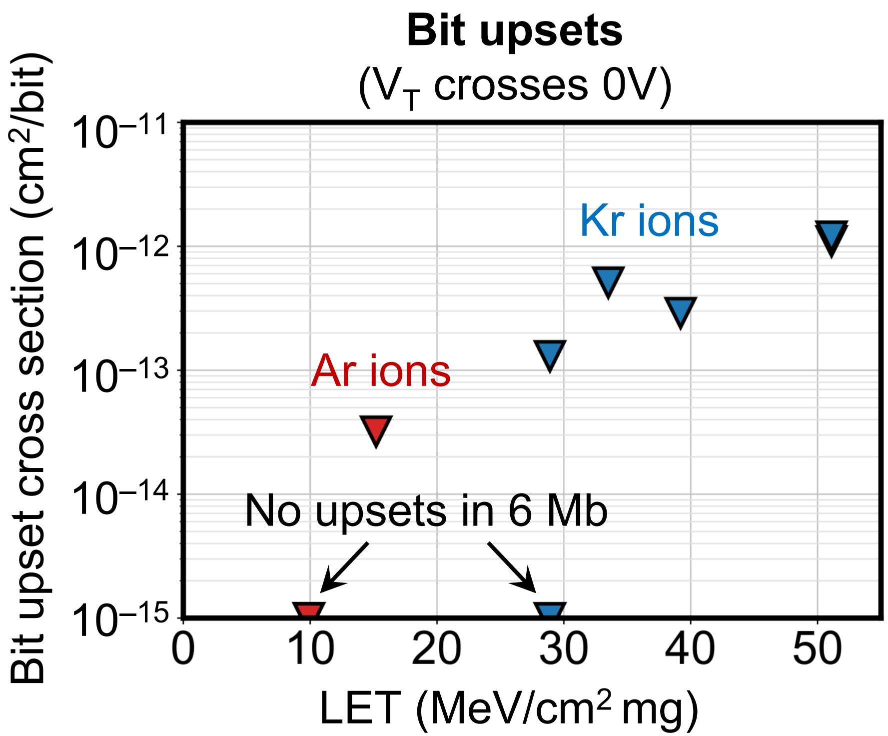
Test chip C (6 Mbit)

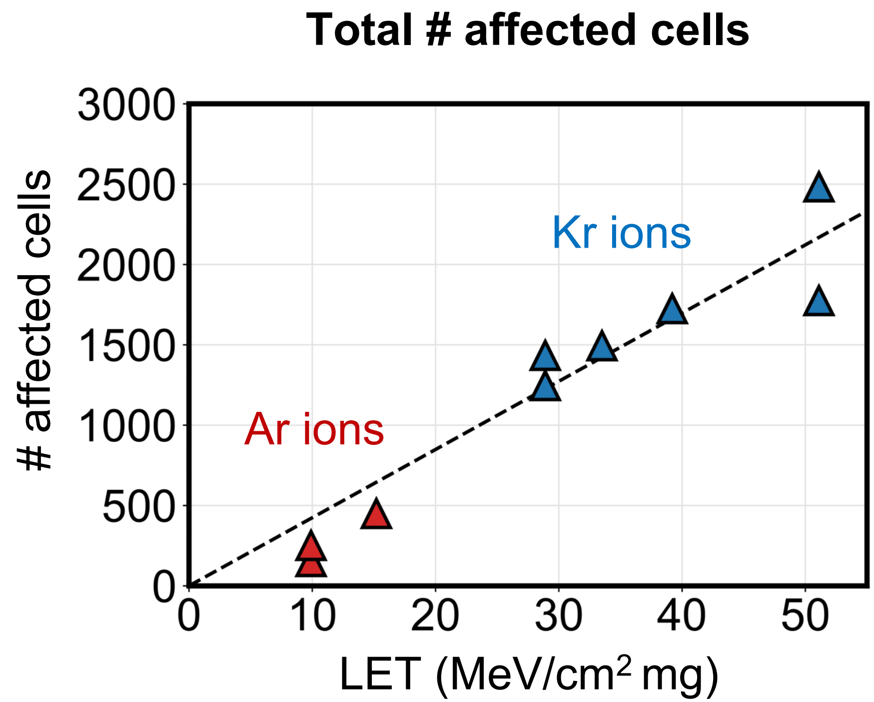
Kr ions at 0°, Ar ions at 30°, 55°

10^7 ions/cm^2



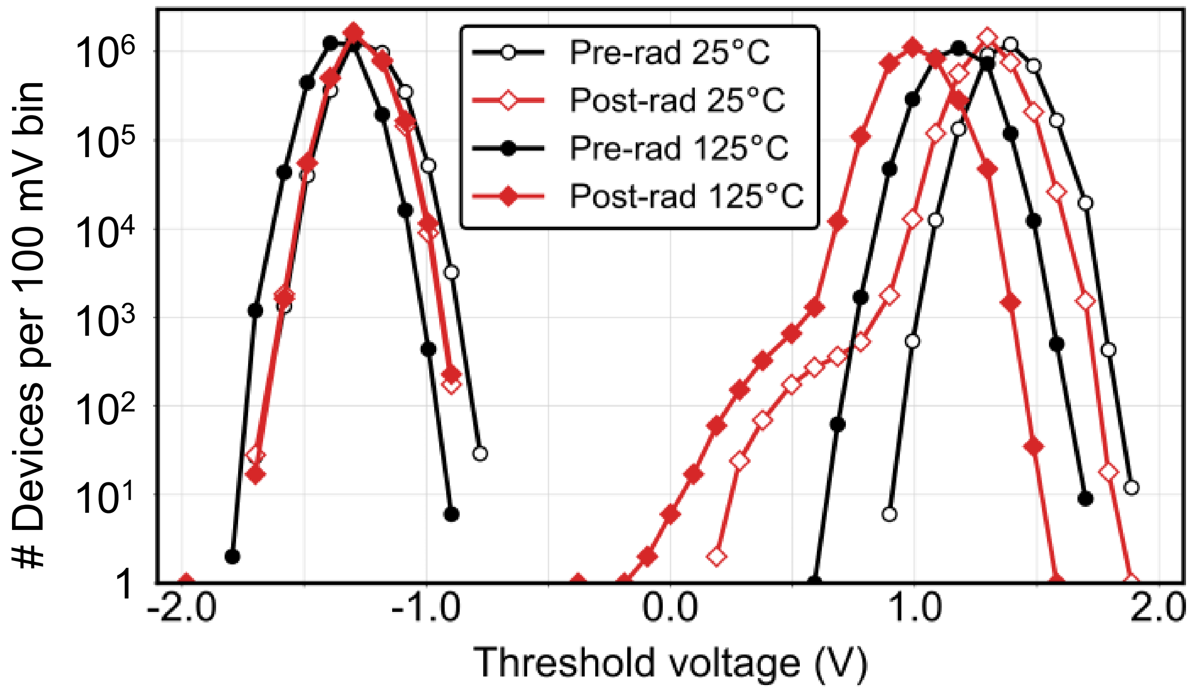
Single event effects LET dependence





- The number of cells in the tail is roughly linear with LET

Single event effects temperature dependence



- Lateral shift in both distributions likely due to temperature dependence of program circuitry
- Ion-induced V_T tail is narrower (lower average ΔV_T) at high temperature due to the lower program state electric field

The missing secondary peak (hypothesis)

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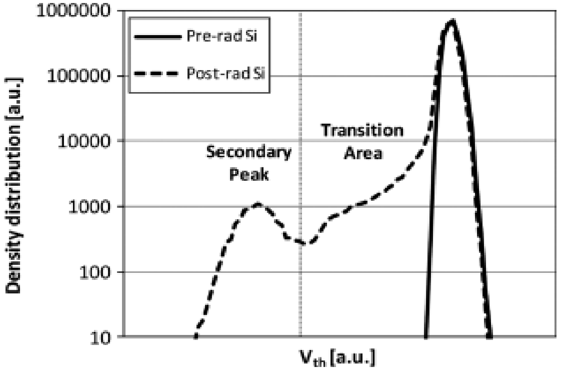
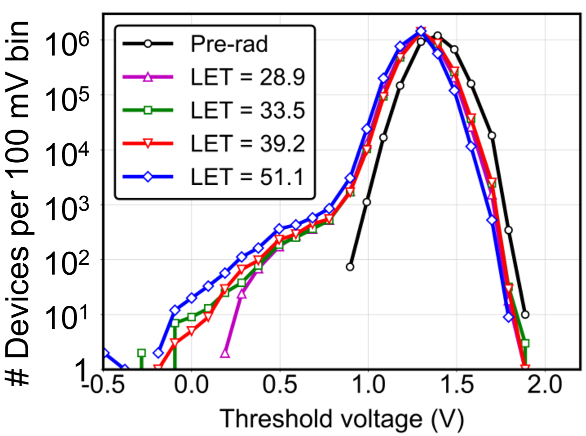
65nm floating gate



3×10^7 Si ions/cm^2, LET = 9.8 MeV/cm^2 mg
Gerardin et al, TNS 2010

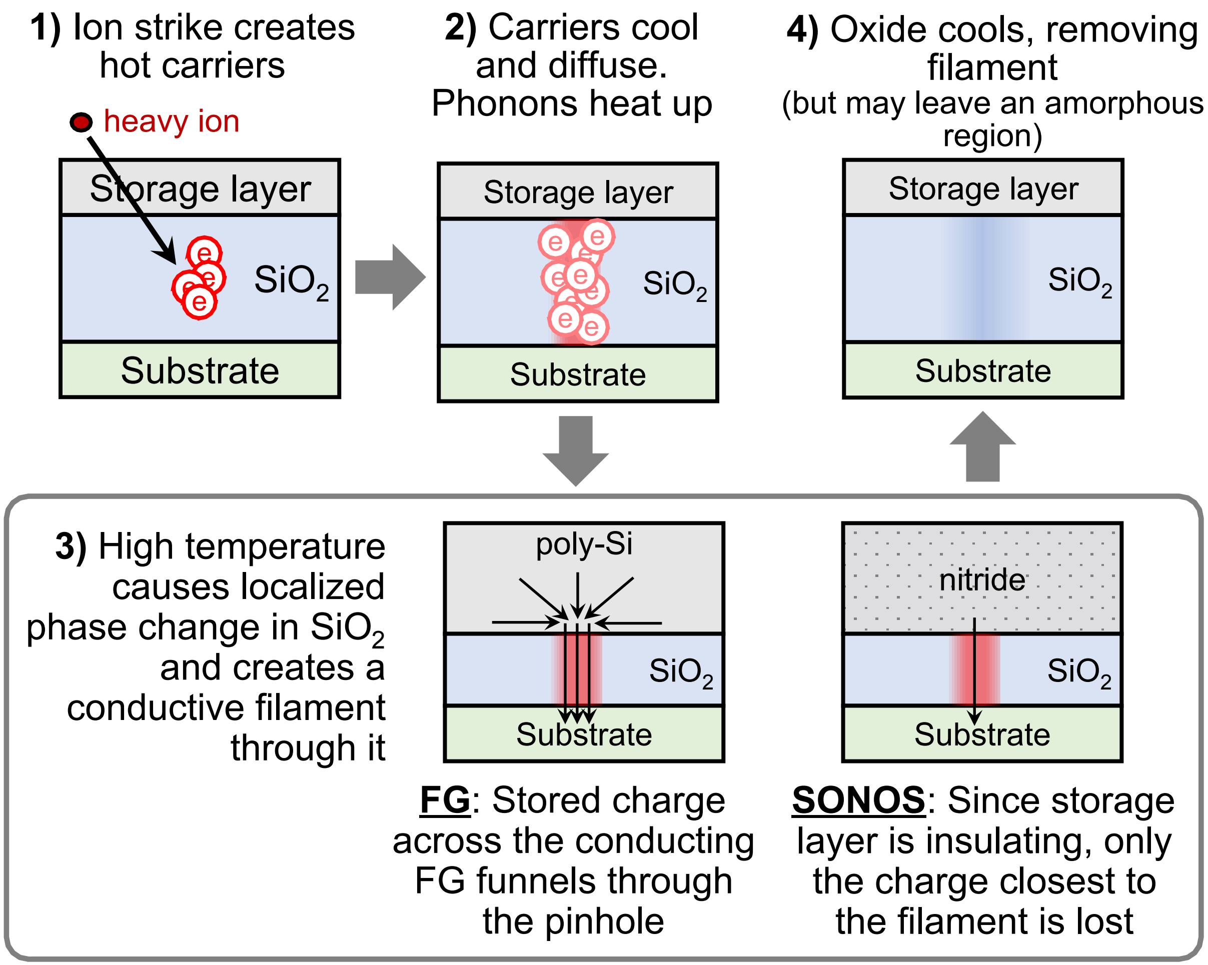
40nm SONOS



10^7 Kr ions / cm^2

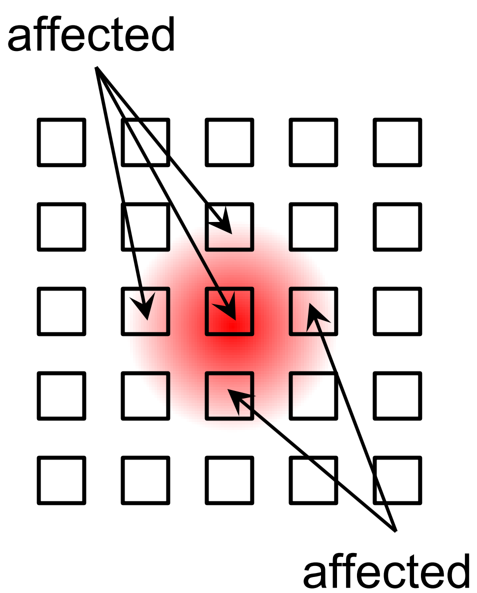
*Meftah et al, *Phys Rev B* 1994.
*Toulemonde et al, *Phys Rev B* 1992.
*Cellere et al, *TNS* 2006.

- In floating-gate, the secondary peak is believed to be caused by a direct ion hit to the gate stack. A prevailing theory for its origin is the *thermal spike model* [*]

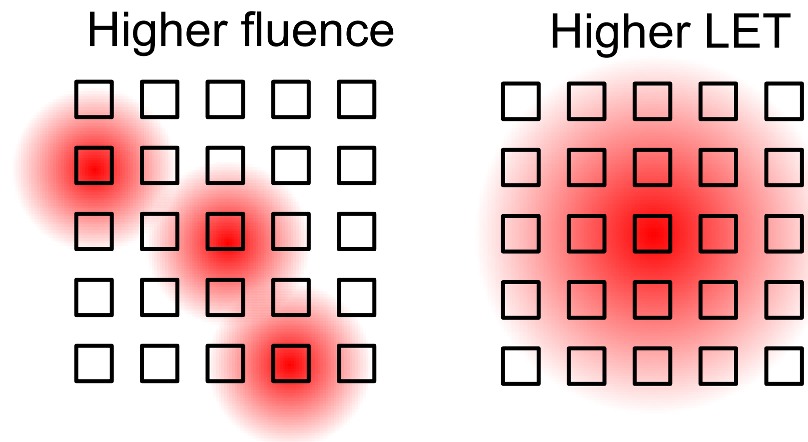


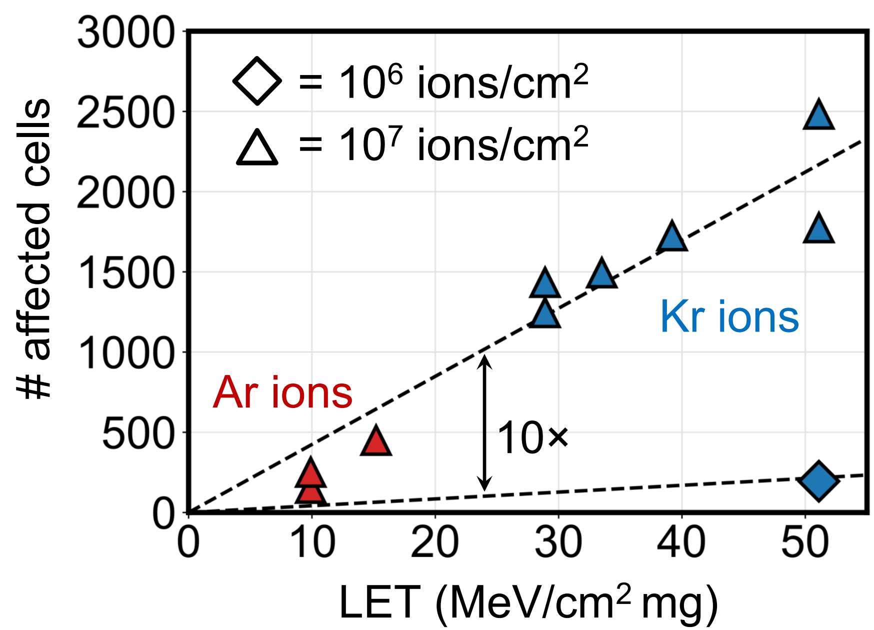
The exponential V_T tail (hypothesis)

Cells are affected by a nearby ion strike
Effect is similar to floating gate
(Gerardin TNS 2010, Cellere TNS 2006)



Energy of the ion strike diffuses laterally via carriers and phonons, and this energy promotes electrons out of traps





Conclusions

- We conducted the first study of heavy-ion-induced single event effects in SONOS flash memory
- No ion-induced secondary peak in the V_T distribution; SONOS cells that are directly struck by an ion are not strongly affected: **a significant distinction from floating-gate flash**
- An exponential tail in the distribution due to charge loss in cells in the vicinity of an ion strike; the further the cell from the strike, the smaller the V_T shift (similar to floating-gate)
- Future work
  - Stronger experimental validation of the thermal spike model for direct ion strikes
  - Better understanding of how energy propagates to distant SONOS cells to induce charge leakage

Thank you!