STUDY OF RADIATION EFFECTS IN CRYOGENIC ELECTRONICS AND ADVANCED SEMICONDUCTOR MATERIALS

ESTEC Contract 11938/96/NL/NB

IMEC, Leuven, Belgium

Project Structure

- **Project timing : May 97 - April 00**

- **2 Activities:**

  RADIATION EFFECTS IN CRYOGENIC ELECTRONICS

  - Presentation day ESA - 2000
  - ESA Deliverable - Literature Overview
  - "Low Temperature Electronics- Physics, Devices, Circuits and Applications", Academic Press, 2000

  RADIATION EFFECTS IN ADVANCED MATERIALS

  - ESA Deliverable - Literature Overview
  - Book in preparation - Springer Verlag 2001

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Final Presentation Day 2001

FOCUSSING ON THE MAIN EXPERIMENTAL WORK
PERFORMED DURING THE SECOND ACTIVITY

Radiation performance of Deep Submicron CMOS Technologies for Space Applications

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Outline

- **Introduction**
  - COTS approach
  - Trends in scaling: ITRS Roadmap
- **Impact Scaling on Radiation Hardness**
  - Different radiation mechanisms: NIEL & LET
  - Importance of ionization damage
  - Short channel effects Þ Gate length dependence?
- **Process Modules & Radiation Hardness**
  - Isolation schemes
  - Gate dielectrics
- **Conclusions**

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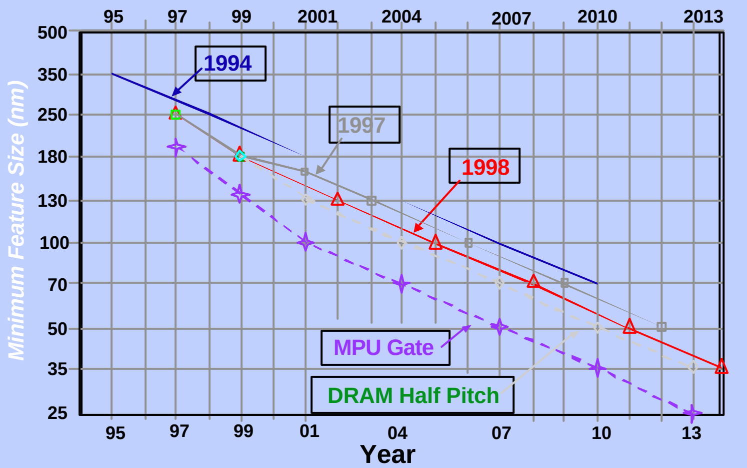
Introduction

- **COTS Approach**
  - Cost effectiveness
  - Use state-of-the-art components and circuits
  - Lifetime of a technology
  - Radiation hardness ?
- **Trend in downscaling**
  - Moore’s law
  - ITRS roadmap

Introduction

Acceleration SIA Roadmap



Impact Downscaling on Radiation Hardness

- **Physical Mechanisms of Radiation Response**
  - Ionization damage
    - electron-hole pairs in the oxide
    - Linear Energy Transfer (LET)
  - Displacement damage
    - radiation-induced lattice defects
    - Non-Ionizing Energy Loss (NIEL)
  - Single Event Upsets (SEU)
    - proton or heavy ions
    - scaling: natural alpha particles limit
    - 3D models needed
  - Single Event Latch-up (SEL)
    - reduces for thinner epilayer thickness
    - worse for scaled down technologies

Scaling: Ionization Damage

- **Dominant mechanism in CMOS devices**
- **Flatband voltage shift due to total dose**

Formula Johnston (IEEE Nucl Sci, 45, 1339, 1998)

$$\Delta V_{ot} = \Delta V_T = \frac{q}{\varepsilon_{ox}\varepsilon_0}[b(t_{ox} - 2h_1)]\frac{t_{ox}}{2}$$

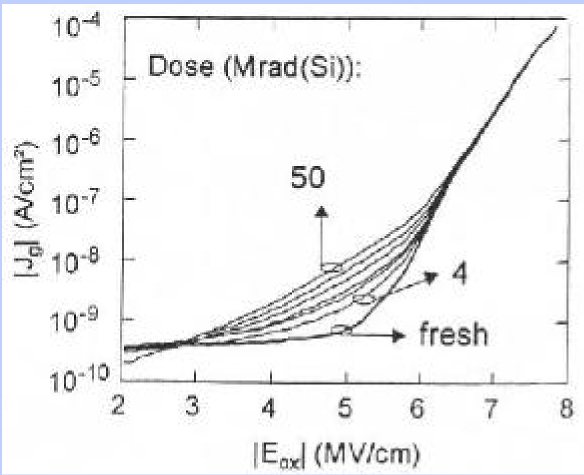
h_1: distance in oxide for the trapped holes ≈ 3nm
oxides < 6 nm: no net hole trapping

Scaling: Ionization Damage

- **Radiation-Induced Leakage Current (RILC)**
  Dose in the Mrad(Si) range
- **Charge Trapping in the Field Oxide !**
  Important in the bird's beak region
  function oxide profile
- **Interface Trap Generation**
  Remains important for scaled down technologies

Radiation-Induced Leakage Current (RILC)

M. Ceschia et al., IEEE Trans. NS, 45, 2375 (1998)



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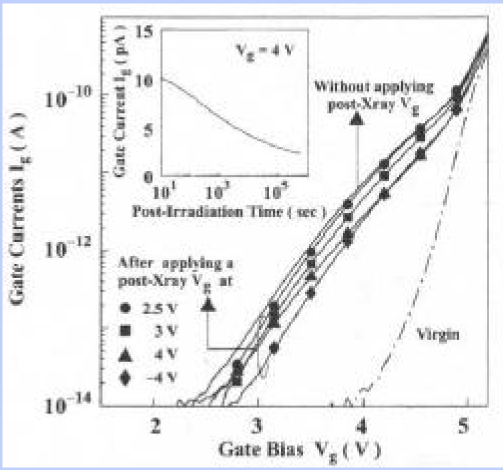
Radiation-Induced Leakage Current (RILC)

Chew-Hie Ang et al., Jpn. J. Appl. Phys., 39, L757, 2000



Radiation and Short-Channel Effects

- **Has Irradiation an impact on short-channel effect ?**
  - Conflicting data in literature
  - Experimental study:
    - 0.18 ■m CMOS technology:
      - 3.5 nm gate oxide
      - 3.5 nm NO gates
    - 60 MeV proton irradiation
      - $3x10^{10}$ & $1x10^{11}$ cm^{-2}
- **Different process modules (RTA, mechanical stress from silicidation, plasma processing, interconnect…) can influence the hardness**

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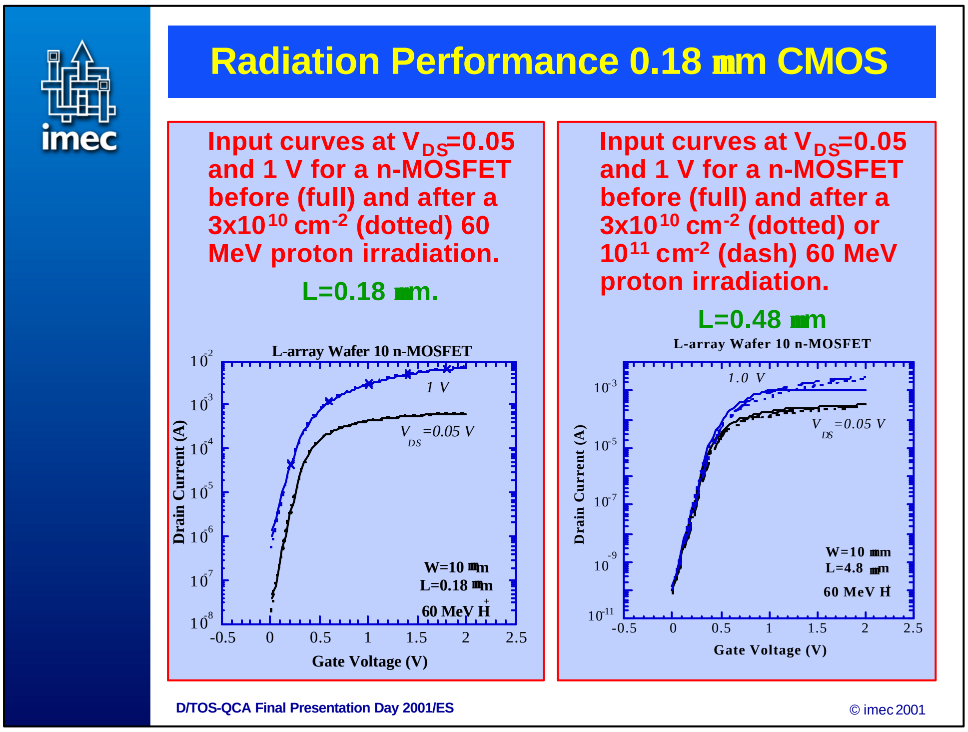

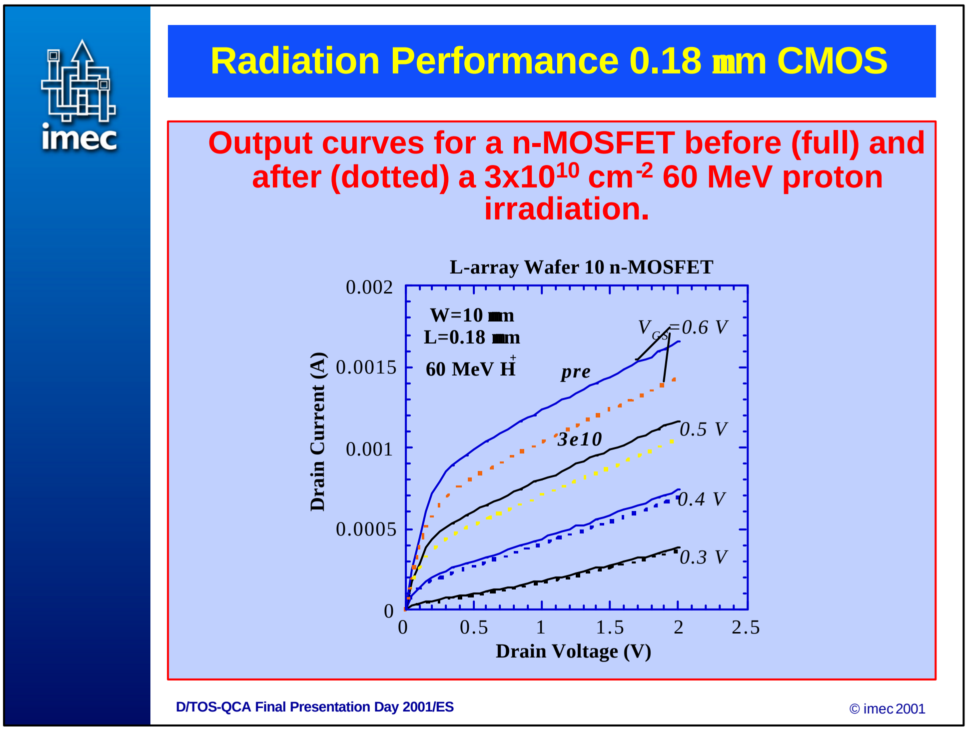

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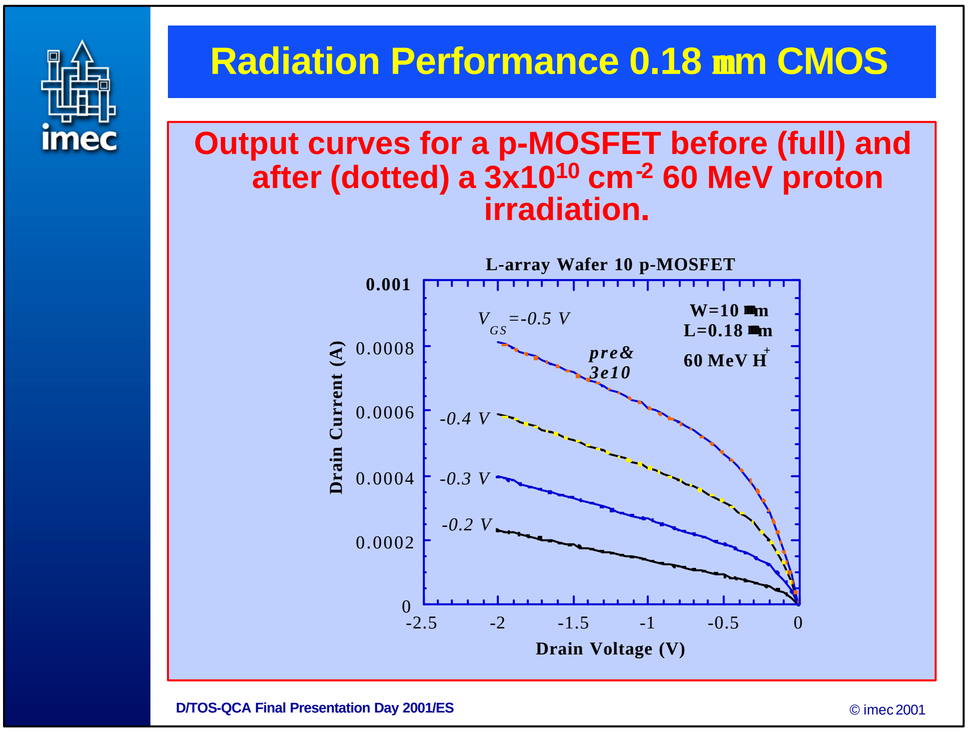

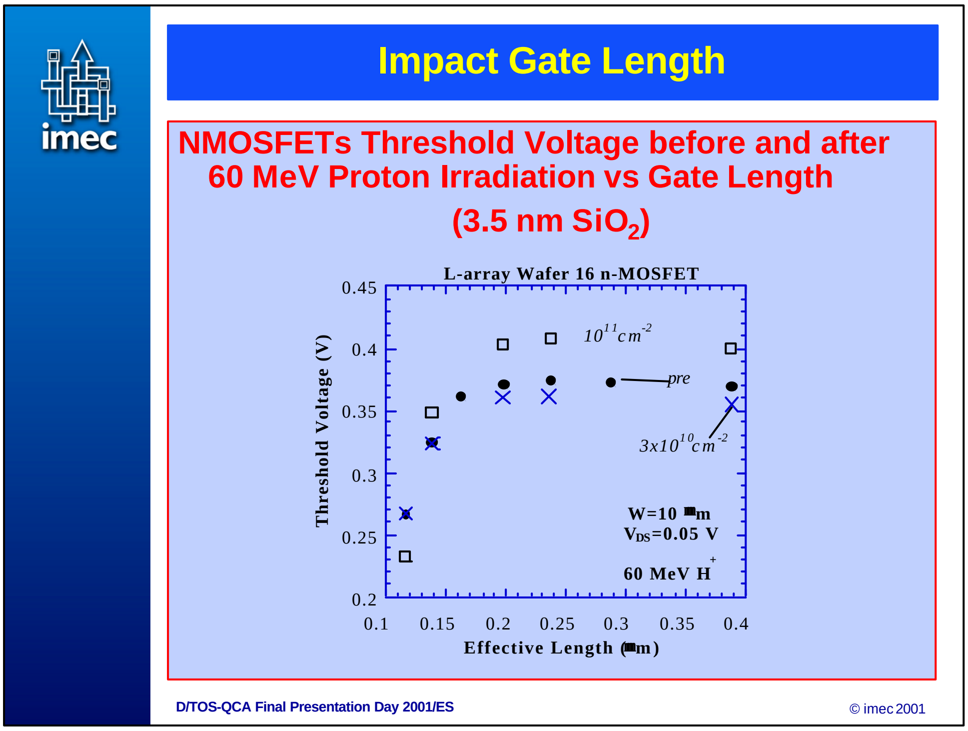

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Isolation Schemes

- **LOCal Oxidation of Silicon (LOCOS)**
  - **Most commonly used technique**
  - **Useful down to 0.5 µm**
- **Poly-Buffered and Poly Encapsulated LOCOS**
  - **Useful down to 0.25 µm**
- **Shallow Trench Isolation**
  - **Required for 0.18 µm and smaller**
  - **Stress generation near the corners**
  - **Corner radius, transition angle, degree overfilling**
    - **Shaneyfelt et al. (IEEE Trans. NS, 45, 2584, 1998)**
    - **Claeys et al. (Nasda Conference, Tsukuba 2000)**

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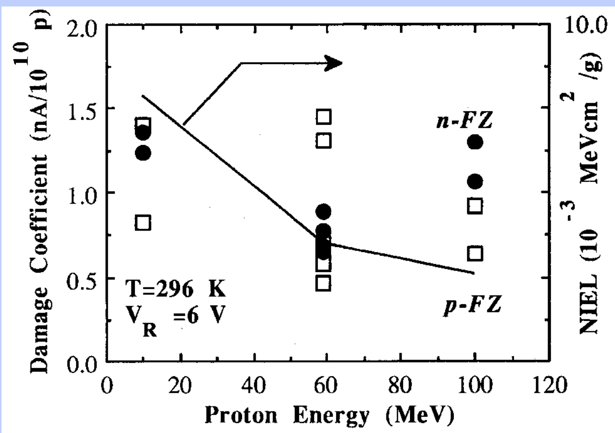
LOCOS-Diodes

Normalised reverse current damage coefficient and calculated NIEL versus proton irradiation energy (reverse bias 6 V)



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EXPERIMENTAL

- Standard IMEC 0.18 μm CMOS process
- STI Module
  - Dry etching trenches
  - Oxidation of the trench sidewalls
  - TEOX filling step
  - CMP planarization
- Deep (200 keV) + shallow (55 keV) B I/I
  - 850C, 10 min anneal
- Junction formation
  - As, 70 keV, 4×10^{15} cm^{-2} + 10 s 1100C ⇒ 0.1 μm
- Co/Ti silicide + TEOS IMD + Al-Si-Cu

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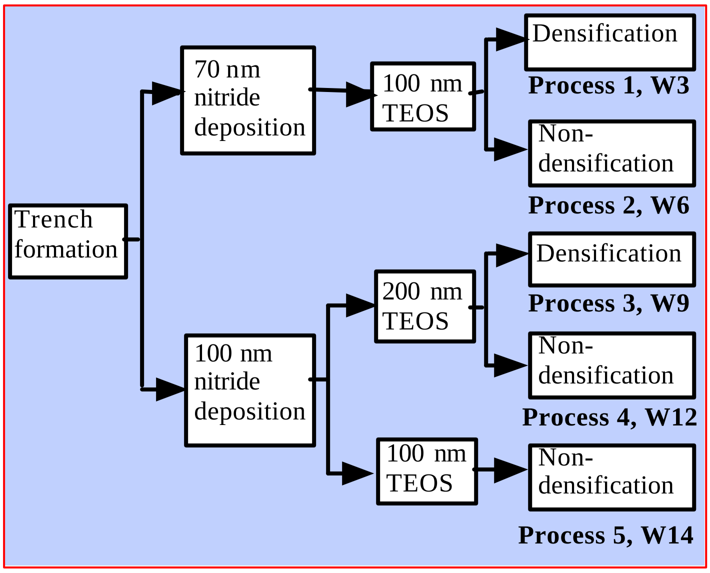
EXPERIMENTAL



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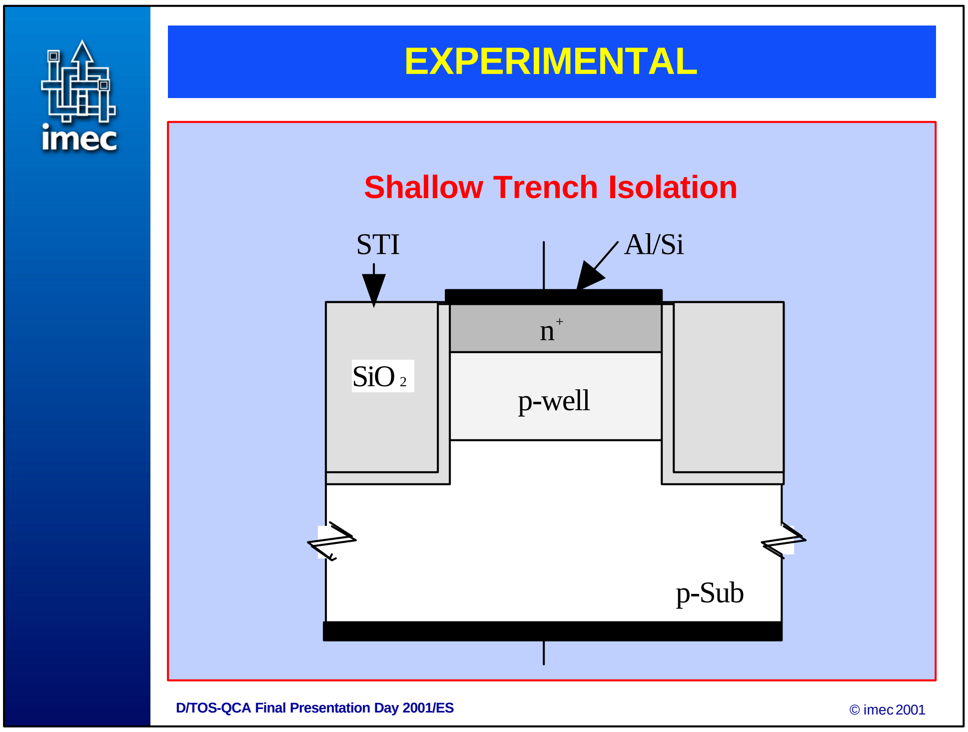

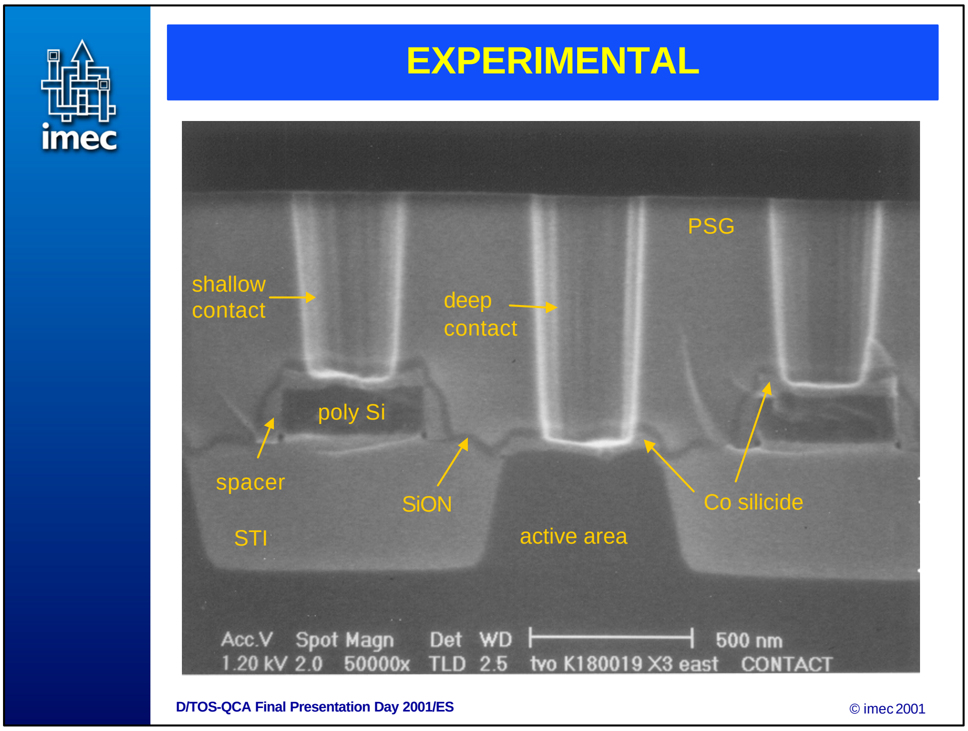

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EXPERIMENTAL

- **Proton irradiation**
  - 8 MeV: Demokritos/Greece
  - 60 MeV: Cyclone/Belgium
  - 20 MeV: Takasaki JAERI/Japan
- **Electron irradiation**
  - 2 MeV: Takasaki JAERI/Japan
- **Neutron irradiation**
  - 1 MeV: Rikkyo University/Japan
- **TO holders for electrons and neutron**
- **No bias during irradiation**
- **I-V and C-V measurements**
  - Leakage current component: geometrical/physical
- **DLTS & TEM**
- **Damage coefficients & NIEL**

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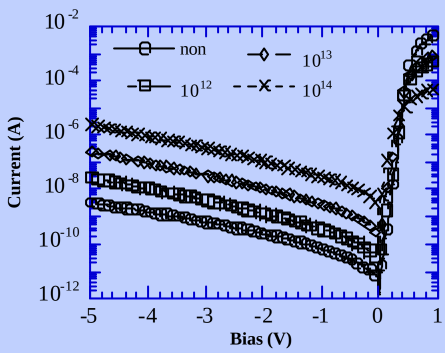
Radiation of STI Diodes

I-V characteristic of 20 MeV proton irradiated SQ1 STI diodes in function of the fluence F. Curve non corresponds to a non exposed sample.



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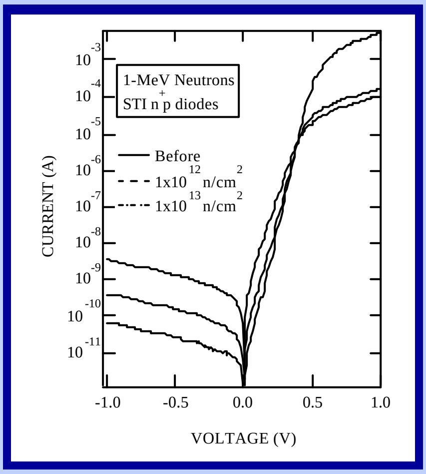
RESULTS AND DISCUSSION

I/V characteristics before and after 1 MeV neutrons



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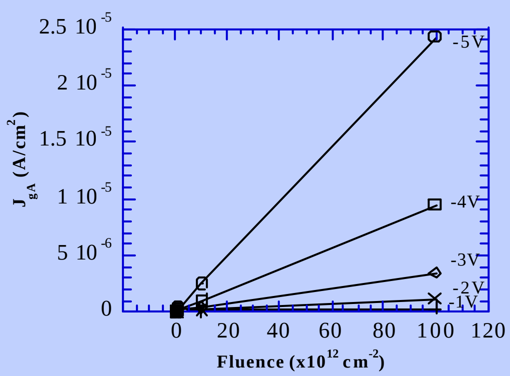
RESULTS & DISCUSSION

Generation current density vs 20 MeV proton fluence



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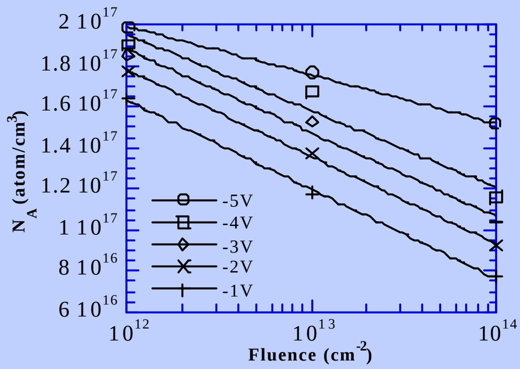
RESULTS & DISCUSSION

P-Well doping versus 20 MeV proton fluence



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RESULTS & DISCUSSION

The normalized J_{gA}/W_A damage coefficient (A/proton.cm) as function of the STI diode bias, calculated in different ways dependent on the selected proton fluence range

Bias (V)	10^{12}	10^{13}	Avg1	Avg2	Least square plot
-1V	8.75×10^{-17}	1.07×10^{-16}	9.86×10^{-17}	9.75×10^{-17}	1.08×10^{-16}
-2V	3.4×10^{-16}	3.97×10^{-16}	3.72×10^{-16}	3.68×10^{-16}	3.99×10^{-16}
-3V	1.06×10^{-15}	1.19×10^{-15}	1.13×10^{-15}	1.13×10^{-15}	1.20×10^{-15}
-4V	2.91×10^{-15}	3.19×10^{-15}	3.07×10^{-15}	3.05×10^{-15}	3.20×10^{-15}
-5V	7.4×10^{-15}	8.01×10^{-15}	7.74×10^{-15}	7.7×10^{-15}	8.03×10^{-15}

Damage coefficient of 10^{12} = slope a&b
Damage coefficient of 10^{13} = slope a&c
Damage coefficient of Avg1 = (½)(slope a&b + slope b&c)
Damage coefficient of Avg2 = (½)(slope a&b + slope a&c)
Damage coefficient of Least square plot = slope of fitting equation

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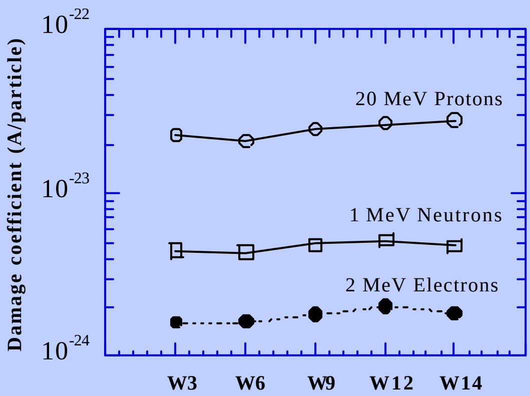
RESULTS & DISCUSSION

Leakage damage coefficient at -1 V for different particles



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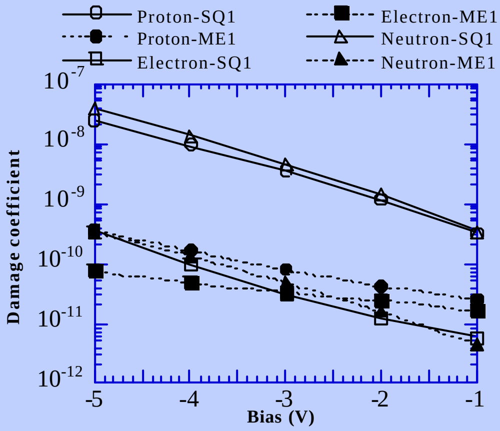
Radiation of STI Diodes

Damage coefficient at different reverse bias for the area (SQ1) and meander (ME1) diodes, for the different particle irradiations. T=25°C.



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CONCLUSIONS STI DIODES

- **Leakage current increases with fluence**
- **No direct correlation with NIEL**
  - **ionization effects important**
- **Boron de-activation important for high fluences**
- **Normalisation of the damage coefficient to depletion width is not sufficient**
  - electrical field effects

CONCLUSIONS STI DIODES

- **Highest damage coefficients are for protons, then neutrons and finally electrons**
- **The influence of the processing conditions are not very pronounced**
  - **further investigations needed**

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Gate Dielectrics

- **Thin SiO2 dielectrics have drawbacks**
  - Reproducibility and uniformity
  - Lower resistance to boron in-diffusion from the poly Si
  - Reliability limitations, especially at higher temperature
  - Reduced hot carrier immunity
  - Direct tunneling: exponential increase tunnel current
  - Quantum mechanical effects
- **High k-dielectrics are the solution**
  - Nitrided oxides (NO) or reoxidized nitrided oxides (RNO)
    - N in the oxide: barrier against B diffusion
      - mechanical stress
      - increase dielectric constant
  - More exotic materials are studied

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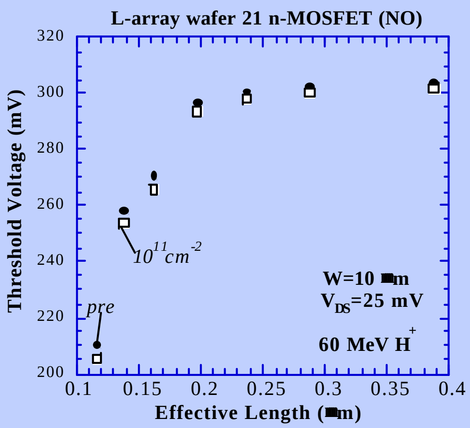
Gate Dielectrics

NMOSFETs Threshold Voltage before and after 60 MeV Proton Irradiation vs Gate Length (3.5 nm NO)



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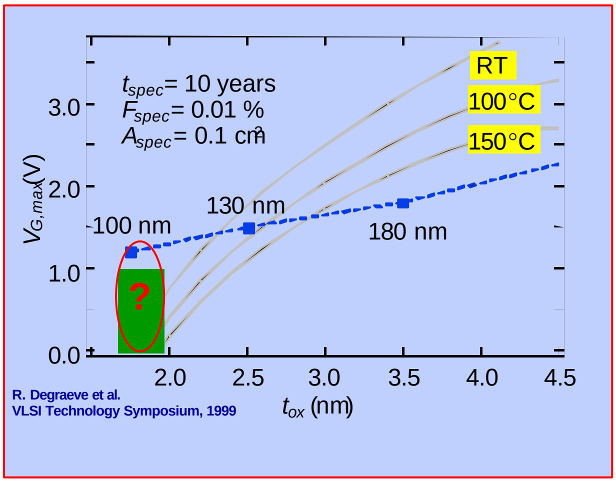
Oxide Reliability vs. ITRS roadmap



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Gate Dielectrics

- **Based on the statistics, field and temperature dependence of the oxide breakdown, oxide reliability may already be a potential problem at 100-130 nm.**
- **Therefore irradiation testing should also be done at higher temperatures.**

Shaneyfelt et al (IEEE Trans. NS, 45, 1372, 1998) - 4.5 nm

Higher T : increase interface & border traps

decrease net oxide-charge

Model based on hydrogen ion transport, trapping and release.

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Conclusions

- Deep submicron CMOS technologies for COTS components seems to be feasible
- Radiation testing of avanced process modules is a necessity
  - No good simulation models for these modules available
- Below 100 nm new or alternative radiation phenomena may be observed
- Technologies such as SiGe, BiCMOS and SOI are also gaining in importance.

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ACKNOWLEDGMENTS

The CMOS group at IMEC for supplying the 0.18 mm CMOS devices and stimulating discussions on process technology.

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