Project Structure

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

- **2 Activities**:
  - **RADIATION EFFECTS IN CRYOGENIC ELECTRONICS**
    - Presentation day ESA - 2000
    - ESA Deliverable - Literature Overview
  - **RADIATION EFFECTS IN ADVANCED MATERIALS**
    - ESA Deliverable - Literature Overview
    - Book in preparation - Springer Verlag 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 ⇒ Gate length dependence?
• Process Modules & Radiation Hardness
  Isolation schemes
  Gate dielectrics
• Conclusions
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

Acceleration SIA Roadmap

<table>
<thead>
<tr>
<th>Year</th>
<th>Minimum Feature Size (nm)</th>
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<tbody>
<tr>
<td>95, 97, 99, 01, 04, 07, 10, 13</td>
<td></td>
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</tbody>
</table>

- MPU Gate
- DRAM Half Pitch

DTOS-QCA Final Presentation Day 2001/ES
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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)

\[
\Delta V_{ot} = \Delta V_T = \frac{q}{a_{ox}^2} \left[ b(t_{ox} - 2h_1) \right] \frac{t_{ox}}{2}
\]

- \( h_1 \): distance in oxide for the trapped holes \( \approx 3 \text{nm} \)
- oxides \( < 6 \text{ nm} \): 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)
Radiation and Short-Channel Effects

- Has Irradiation an impact on short-channel effect?
  
  Conflicting data in literature
  
  Experimental study:
  
  0.18 μm CMOS technology:
  
  3.5 nm gate oxide
  
  3.5 nm NO gates
  
  60 MeV proton irradiation
  
  $3 \times 10^{10}$ & $1 \times 10^{11}$ cm$^{-2}$

- Different process modules (RTA, mechanical stress from silicidation, plasma processing, interconnect...) can influence the hardness
Radiation Performance 0.18 μm CMOS

Input curves at $V_{DS}=0.05$ and 1 V for a n-MOSFET before (full) and after a $3 \times 10^{10} \text{ cm}^{-2}$ (dotted) 60 MeV proton irradiation. $L=0.18 \mu m$.

Output curves for a n-MOSFET before (full) and after (dotted) a $3 \times 10^{10} \text{ cm}^{-2}$ 60 MeV proton irradiation.
Output curves for a p-MOSFET before (full) and after (dotted) a $3 \times 10^{10}$ cm$^{-2}$ 60 MeV proton irradiation.

NMOSFETs Threshold Voltage before and after 60 MeV Proton Irradiation vs Gate Length (3.5 nm SiO$_2$)
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)

LOCOS-Diodes

- Normalised reverse current damage coefficient and calculated NIEL versus proton irradiation energy (reverse bias 6 V)
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
  - 850°C, 10 min anneal
- Junction formation
  - As, 70 keV, 4x10^{15} cm^{-2} + 10 s 1100°C \Rightarrow 0.1 \mu m
- Co/Ti silicide + TEOS IMD + Al-Si-Cu

EXPERIMENTAL

Trench formation

70 nm nitride deposition → 100 nm TEOS → Densification
Process 1, W3 → Non-densification
Process 2, W6

100 nm nitride deposition → 200 nm TEOS → Densification
Process 3, W9 → Non-densification
Process 4, W12

100 nm TEOS → Non-densification
Process 5, W14
EXPERIMENTAL

Shallow Trench Isolation

STI

Al/Si

SiO$_2$

n$^+$

p-well

p-Sub

STI active area

poly Si

Co silicide

shallow contact

depth contact

PSG

spacers

active area
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

Radiation of STI Diodes

I-V characteristic of 20 MeV proton irradiated SQ1 STI diodes in function of the fluence $\Phi$. Curve non corresponds to a non exposed sample.
RESULTS AND DISCUSSION

I/V characteristics before and after 1 MeV neutrons

RESULTS & DISCUSSION

Generation current density vs 20 MeV proton fluence
**RESULTS & DISCUSSION**

**P-Well doping versus 20 MeV proton fluence**

![Graph showing P-Well doping versus 20 MeV proton fluence]

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

<table>
<thead>
<tr>
<th>Bias (V)</th>
<th>( 10^{12} )</th>
<th>( 10^{13} )</th>
<th>Avg1</th>
<th>Avg2</th>
<th>Least square plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1V</td>
<td>8.75x10^{17}</td>
<td>1.07x10^{16}</td>
<td>9.86x10^{17}</td>
<td>9.75x10^{17}</td>
<td>1.08x10^{16}</td>
</tr>
<tr>
<td>-2V</td>
<td>3.4x10^{17}</td>
<td>1.19x10^{16}</td>
<td>3.72x10^{16}</td>
<td>3.68x10^{16}</td>
<td>3.99x10^{16}</td>
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<tr>
<td>-3V</td>
<td>1.06x10^{17}</td>
<td>1.31x10^{16}</td>
<td>1.13x10^{16}</td>
<td>1.13x10^{16}</td>
<td>1.20x10^{16}</td>
</tr>
<tr>
<td>-4V</td>
<td>2.91x10^{17}</td>
<td>3.19x10^{16}</td>
<td>3.07x10^{16}</td>
<td>3.05x10^{16}</td>
<td>3.20x10^{16}</td>
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<tr>
<td>-5V</td>
<td>7.4x10^{17}</td>
<td>7.74x10^{16}</td>
<td>7.74x10^{16}</td>
<td>7.7x10^{16}</td>
<td>8.03x10^{16}</td>
</tr>
</tbody>
</table>

- 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
RESULTS & DISCUSSION

Leakage damage coefficient at -1 V for different particles

Damage coefficient (A/particle)

-10^{-24}
-10^{-23}
-10^{-22}

W3 W6 W9 W12 W14

20 MeV Protons
1 MeV Neutrons
2 MeV Electrons

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

Damage coefficient

Bias (V)

Proton-SQ1
Proton-ME1
Electron-SQ1
Electron-ME1
Neutron-SQ1
Neutron-ME1
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
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

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

- L-array wafer 21 n-MOSFET (NO)
- \( W = 10 \mu m \)
- \( V_{DS} = 25 mV \)
- \( \mu = 12 \text{ cm}^2/Vs \)
- 60 MeV H

Threshold Voltage (mV)

Effective Length (\( \mu m \))

0.1 0.15 0.2 0.25 0.3 0.35 0.4

200 220 240 260 280 300 320
Oxide Reliability vs. ITRS roadmap

- $V_{G_{\max}}$ vs. $t_{ox}$
- $t_{spec} = 10$ years
- $F_{spec} = 0.01%$
- $A_{spec} = 0.1$ cm$^2$

R. Degraeve et al., VLSI Technology Symposium, 1999

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.
Conclusions

- Deep submicron CMOS technologies for COTS components seems to be feasible
- Radiation testing of advanced 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.

ACKNOWLEDGMENTS

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