Mechanisms and Temperature Dependence of Single Event Latchup Observed in a CMOS Readout Integrated Circuit from 16-300 K

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• Review of classical electrical and particle-induced LU in CMOS

• 1st observation of ‘anomalous’ electrical latchup (LU) from ~4 - 50 K by Deferm et al.

• Temperature dependent electrical LU results – 130 nm test structure

• Heavy ion SEL experiment on 0.5 µm ReadOut Integrated Circuit (ROIC)

• Discussion of particle-induced SEL mechanisms at 20 K
Cross coupled parasitic bipolar transistors inherent to CMOS Technology

- Current produced by ion strike can forward bias the base emitter junction and begin the SEL sequence
- Key device parameters for all temperatures:
  - Well & substrate resistivities
  - Well & substrate contact proximity
  - Minimum n+ - p+, or cathode-anode spacing

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After Johnston, TNS, 1996 & Bruguier and Palau, TNS, 1996
• Electrical and particle-induced LU susceptibilities decrease because:
  • Well & substrate resistances decrease due to increase in mobility and carrier freeze-out.
  • $V_{BE}$ required to support a given collect current increases.
  • Parasitic bipolar gain product is decreasing exponentially with temperature (and also via temperature dependence of the bandgap narrowing in the emitter).
    • Often has little quantitative effect on LU characteristics.
  • Below ~75-100 K, regenerative feedback is no longer possible, since $\beta_{nnp}\beta_{pnp} < 1$ for the two parasitic BJT common-emitter current gains.
Electrical LU is observed below ~ 50 K

- Deferm et al. suggest shallow-level impact ionization as the source of an exponential increase in free carriers once a threshold field is reached in the internal n- and p- regions of the parasitic pnpn structure, resulting in significant current flow.

- LU condition becomes:

\[ \beta_{n_{pn}}\beta_{p_{np}} > (M_nM_p)^{-1} \]

where \( M_n \) & \( M_p \) are the shallow level impact ionization coefficients (or rates) for electrons & holes

**Gain product \( \sim 1 \)**

*After Deferm et al., Cryogenics 30, 1990.*

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Temperature Dependence of Key LU Parameters

Electrical LU measurements via anode injection
130 nm IBM pn-pn test structure

- Note changes ~50 K where shallow level impact ionization becomes important.
- Triggering current and voltages required to initiate LU
  - Increase monotonically with decreasing temperature
- Vertical pnp gain much larger than for lateral npn

Gain product ~ 1

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Dominant Impurity Ionization Mechanisms vs Temperature

After Simoen et al., “Charge transport in a Si resistor at liquid –He temperatures,” JAP 68 (8), 1990.

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Dominant Impurity Ionization Mechanisms vs Temperature

- Shallow-level impact ionization (SLII) is field assisted ionization of frozen-out shallow dopants.
- SLII can lead to significant charge multiplication when modest electric field threshold is reached and excess carriers are present.

After Simoen et al., “Charge transport in a Si resistor at liquid –He temperatures,” JAP 68 (8), 1990.

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Heavy Ion SEL Test Description of 0.5 µm ROIC

- AMI C5 bulk process on lightly doped p-substrate
- ROIC fully functional during testing (4 channels at 500 kHz).
- Four key voltages & associated currents monitored every 25 µs
  - Real time visibility on all supplies
  - \( V_{pd} \) (logic portion of readout circuitry) was only supply to latch
- ROIC health monitored throughout the test.

He cryostat in front of TAMU beam line. Five ROICs tested.

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Temperature Dependence of Hard SEL Events

• Kr ions @ 60°:
  \[ \text{LET}_{\text{eff}} = 64 \text{ MeVcm}^2/\text{mg} \]
  and \( R_{\text{proj}} = 43 \mu\text{m} \)

• Cross sections comparable for 20 K & 300 K

• Very modest temperature dependence 200-300 K

• Holding voltages \( (V_H) \):
  - 4.1 – 5.6 V \( (T \leq 24 \text{ K}) \)
  - 1.9 – 2.8 V \( (T \geq 135 \text{ K}) \)

• Self quenching high current events observed in both transition regions

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Typical Hard SEL and Self-Quenching High Current Event Signatures

- Holding voltage = 2.8 V
- Note self quenching event had same current level as hard SEL event (~20 mA)

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ROIC Latchup Behavior at 20 K

- Diffusion from substrate is important
- No SEL observed for $\text{LET}_{\text{eff}} = 40$ & $R_p \sim 4-5 \, \mu m$
  - Ar-40 ion deposited 28 MeV
  - Only self-recovered high current events
- Ar-40 ion delivered 80 MeV within 10 µm
  - Penetrated the junction region
  - Both self-recovered and hard SEL events

$\text{LET}_{th} \sim 3.3$ at 20 K, but $15 < \text{LET}_{th} < 20$ at 300 K

‘Saturated’ cross section 2-3 X higher at 300 K
Shallow-Level Impact Ionization (SLII) Mechanism

- Free carriers produced by ion strike initiates exponential growth in free carriers in internal p- and n-region of parasitic pnpn structure that meet the modest electric field threshold for SLII (E_{th})

- The high $V_H$ we observed are expected for 1st order shallow level impact ionization LU model, and are comparable to those observed by Deferm et al.
  - $V_H = 2 V_{bi} + (E_{th}) / A-C$ spacing
  - $V_H \sim 4 - 5$ V for Deferm et al. at 4 - ~50 K

- Our data clearly indicate importance of lightly doped p-substrate
  - SEL cross section reduction striking for $R_p < 30$ µm at 20 K
  - Slight temperature dependence from 200-300 K
    - Changes in R & $V_{BE}$ with temperature decrease SEL probability
  - Charge collection efficiency may be greater at lower temperatures
    - Longer diffusion length and lower recombination efficiency

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Conclusions

• Cryogenic SEL is indeed possible and represents a new qualification concern.
  • Shallow-level impact ionization is a very plausible mechanism to provide a source of carriers below roughly 50 K.
  • NASA requires cryogenic operation for ROICs, ASICs and other CMOS devices for IR sensor applications as well as extreme environments.
• Very little data exists for ion-induced SEL below room temperature
  • We see a significantly lower SEL threshold at 20 K compared to room temperature.
    • ‘Saturated’ cross section is ~2 - 3 higher at 300 K.
  • Data in the ‘classical’ regime from 100 – 300 K show SEL behavior beginning at 135 K.
    • Very modest temperature dependence of the SEL cross section from ~200 – 300 K.
      • Similar results for 2nd ROIC on epi from different vendor.
      • ‘Test as you fly’

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