Test Simulation of Neutron Damage to Electronic Components using Accelerator Facilities

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Motivation for the use of Accelerator Facilities

• Fast burst neutron facilities have been used to study the response of electronics to **displacement damage and ionization**

• The availability of fast burst neutron facilities is decreasing in the United States

• A new test methodology is being developed - high-fidelity computational models combined with testing of devices and circuits at alternative **accelerator** experimental facilities

• The computational models are initially validated at the fast neutron facilities and then applied to the test results at alternative facilities

• In the future, we will test and model at an alternate facility and then predict a neutron response
The Sandia Pulse Reactor SPR-III provided fast burst neutrons

Facility statistics – maximum pulse
- $4 \times 10^{14} \text{n/cm}^2$ 1 MeV Si equivalent
- 120 krad (Si)
- 100 $\mu$sec pulse @ FWHM
6.5 MV Tandem van de Graaff with a nuclear microprobe

- Ions: H to Au
- Si: 4.5, 10, 19, 28, 36 MeV
- Focused beam (mm – μm)
- Currents: nA (mm beam) – fA (subμ beam)
- Pulse length > 200 ns – seconds with a 90 ns rise & fall time

High energy ions are focused into a 1x1 mm^2 area to simulate neutron displacement damage conditions.
Little Mountain Test Facility (LMTF) is used to decouple displacement damage and photocurrent effects

- LINAC operated in electron beam mode
- Electron energy tuned from 5 to 30 MeV
- Pulse widths: 50 nsec to 50 μsec
- Beam currents: 0.1 to 2 Amps
- Dose rate: 5E6 to 4E13 rad(Si)/sec
  - achieved with a variety of diffusers, target positions, and pulse widths
- Beam diameters (with ~ 80% uniformity) range from 1 cm for high dose rates to 40 cm for low dose rates
- The facility can operate with a maximum repetition rate of 2 pulses per second
The transistor gain is a traditional metric

Maximum SPR pulse on a BJT 2N2222

Test circuit uses ASTM Standard F 980M-961 techniques

Gain = $\frac{IC}{IB}$  Inverse Gain = $\frac{IB}{IC}$
Si ions create a response in transistors similar to neutrons

**SPR fast neutron**
- $3 \times 10^{14}$ n/cm$^2$ 1 MeV Si Eqv
- $1 \times 10^9$ rad(Si)/sec
- 90 μsec pulse width FWHM

Displacement damage increases base current and decreases collector current

**IBL**
- 10 MeV Si
- $3 \times 10^{14}$ n/cm$^2$ 1 MeV Si Eqv
- 100 μsec pulse width FWHM
Deep Level Transient Spectroscopy (DLTS) relates ion to neutron damage at late times

- DLTS peak amplitude is proportional to number of traps.
- The type and number of defects are the same for a given 1 MeV Si eqv neutron fluence (matched late-time gain degradation).

The spectra of defects as measured by DLTS in the base of pnp transistors that are responsible for the gain degradation are the same after neutron (including SPR-III and ACRR) and ion irradiations.
The transient annealing factors between SPR neutron and ion beam irradiation are similar

SPR maximum pulse

\[ T3297 \ G_0 = 209, \ G_{\text{aut}} = 1.35 \]
\[ 13245 \ G_0 = 175, \ G_{\text{aut}} = 1.60 \]

\[ \text{le} = 0.22 \text{ mA, 2N2222} \]

**Annealing Factor**

\[ AF(t) = \frac{1}{G(t)} - \frac{1}{G_0} \]
\[ - \frac{1}{G_\infty} - \frac{1}{G_0} \]

AF uncertainty \(\leq 5\%\)

- Agreement between the annealing factors indicates that the annealing kinetics are similar for ion and neutron irradiations – critical for early-time predictive capabilities
- SPR-III gamma environment delays gain measurement compared to IBL

The SPR-III early-time **annealing factor** can be matched using ion irradiations (simulating a wide range of SPR-III fluence values).
Physics based modeling codes used in this study

- 1D
  - Numerically solves diffusion-drift equations similar to commercial device simulation codes
  - One dimensional
  - Single transistor
  - Includes defect production, migration & reactions, and charge change reactions by carrier capture & emission.
  - Includes photocurrent generation with synergistic displacement damage and annealing effects

- Xyce
  - a high performance Sandia developed SPICE compatible tool
  - “zero dimensional to half dimensional”
  - Single transistor to integrated circuits
  - Includes defect migration & reactions and charge change reactions by carrier capture & emission – defect production is an input
  - Includes photocurrent generation without synergistic displacement damage and annealing effects
Xyce and 1D are used to model transistor displacement damage at SPR and IBL.

Excellent agreement between the shape and the fluence dependence.
Xyce and 1D are used to model transistor photocurrent at SPR and IBL
LMTF is used to calibrate Xyce transistor photocurrent models

Photocurrent data (red) and simulation (blue) for ‘short’ pulses which are dominated by contributions from prompt photocurrent.

Photocurrent data (red) shown with simulated pulses where parameters are calibrated against all data simultaneously. These 5 μsec pulses have contributions from prompt and delayed photocurrents and are thus considered ‘long’ pulses.

Final calibration
For future tests, we must calibrate IBL photocurrent vs LMTF photocurrent.

- 1.27E-4 rad(Si)·cm²/ion
IBL photocurrent as a function of ion energy is being studied.

2n2222 cross section
Summary and Conclusions

- SNL will use accelerator facilities to simulate displacement damage and ionization effects observed in electronics at fast burst neutron facilities.
- We will use high fidelity computational models to confirm our ability to predict displacement damage and ionization effects at accelerator and neutron facilities.
- Ultimately, when fast burst neutron facilities are not available, tests at alternate facilities, combined with computational models, will be used to simulate fast burst neutrons.
- We have presented preliminary LMTF and IBL test and computational results.
- We observed excellent agreement between the experimental results and preliminary calculations at LMTF and IBL.