Radiation Hardness Assurance for Space Systems: Neutron Induced Damage on Microwave Devices and Solar Cells

ASI Workshop: A neutron irradiation facility for space applications

8 June 2015
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Selex ES
Outline

• Radiation Hardness Assurance (RHA) for Space Systems
• AESA Radar systems & T/R modules requirements
• GaN Technology for Space Application
• Selex ES Technology for Space Application
• Conclusions
Radiation Hardness Assurance (RHA) for Space Systems

- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment.
- Deals with environment definition, part selection, part testing, spacecraft layout, radiation tolerant design, and mission/system/subsystems requirements.

**Hardness Assurance Procedures**

- MIL-STD-750E - method 1080- Test methods for semiconductor devices - Single event burnout and single event gate rupture test
- MIL-STD-750E - method 1017- Neutron irradiation
Radiation Hardness Assurance (RHA) for Space Systems

Space Radiation and its Effects on EEE Components

Project Requirements Flow-Down

Level 1
- Level-1 Requirements Document

Level 2
- Project Plan
- Mission Requirements Document
- Mission Assurance Requirements

Level 3
- Subsystem Specifications
  - Therm Power RF GN&C Prop C&DH FSW Elec Sys Mech Gnd Sys

Level 4
- Var Emitter Coatings
  - Solar Array
  - Li-Ion Battery

- Magnetometer
  - Sun Sensor
  - Nutation Damp

- X-pander
  - Antenna

- uThruster

- Pressure Transducer
  - Thruster Cntl Elec.

- Power/FSW

- Autonomous Ground S/W

- Diag. S/W

- Propellant Tank

- Release Mech Actuators

EPFL Space Center 9th June 2009

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Radiation Hardness Assurance (RHA) for Space Systems

Radiation effects important to be considered for instrument and spacecraft design fall roughly into three categories, depending the degradation is due to:

- Total Ionizing Dose level (TID)
- Total Non-Ionizing Dose level (TNID) or Non-Ionizing Energy Loss (NIEL)
- Single Event Effect (SEE)

- Degradation from TID in electronics is a cumulative, long term degradation mechanism due to ionizing radiation—mainly primary protons and electrons and secondary particles arising from interactions between these primary particles and spacecraft materials
- Degradation form TNID or displacement damage is cumulative, long-term non-ionizing damage due to protons, electrons, and neutrons. These particles produce defects mainly in optoelectronics components such as APS, CCDs, and optocouplers. Displacement damage also affects the performance of linear bipolar devices but to a lesser extent
- SEEs result from ionization by a single particle as it passes through a sensitive junction of an electronic device. Environmental sources considered for single-event effects (SEE) include galactic cosmic rays, alpha particles, protons, and neutrons. The effects to be considered include single-event upset (SEU), single-event latchup (SEL), single-event burnout (SEB), single-event gate rupture (SEGR), and single-event transients (SET).

<table>
<thead>
<tr>
<th>Family</th>
<th>Sub-Family</th>
<th>TNIDL</th>
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<tbody>
<tr>
<td>CCD, CMOS APS,</td>
<td>all</td>
<td>all</td>
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<tr>
<td>opto discrete devices</td>
<td></td>
<td></td>
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<tr>
<td>Integrated circuits</td>
<td>Silicon monolithic bipolar or</td>
<td>&gt; 2x10¹¹ p/cm² 50 MeV equivalent proton fluence</td>
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<td></td>
<td>BiCMOS</td>
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<tr>
<td>Diodes</td>
<td>Zener</td>
<td>&gt; 2x10¹¹ p/cm² 50 MeV equivalent proton fluence</td>
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<td></td>
<td>Low leakage</td>
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<td></td>
<td>Voltage reference</td>
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<tr>
<td>Transistor</td>
<td>Low power NPN</td>
<td>&gt; 2x10¹¹ p/cm² 50 MeV equivalent proton fluence</td>
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<td></td>
<td>Low power PNP</td>
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<td>High power NPN</td>
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<td>High power PNP</td>
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</tbody>
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ECSS-Q-60-15C Space product assurance: RHA
Displacement damage

- Devices that depend on bulk physics for operational characteristics, such as solar cells, particle detectors, photonic/electro-optic components showing displacement damage sensitivity.
- Radiation particles such as neutrons, protons, and electrons scatter off lattice ions, locally deforming the material structure. The band-gap structure may change, affecting fundamental semiconductor properties.
- For example, the output power of a spacecraft solar array degrades during the mission life of a spacecraft because of displacement damage.
- Another example of displacement damage is an increase in recombination centers in a particle detector, ultimately leading to increased noise and consequent decreased energy resolution.
- Displacement damage also is important for photonic and electro-optic integrated circuits such as charge-coupled devices (CCDs) and opto-isolators.
- The amount of displacement damage is dependent on the incident particle type, incident particle energy, and target material. Displacement damage is similar to TID in that the effect is cumulative.
Data Search and Definition of Data Usability Flow

- Perform radiation test

  - Yes: Has process/foundry changed?
    - No: Test recommended but may be waived based on risk assumption
    - Yes: Same wafer lot?
      - No: Test method applicable?
        - No: Sufficient test data?
          - No: Data usable
          - Yes: Test method applicable?
            - Yes: Data usable
            - No: Sufficient test data?
              - Yes: Data usable
              - No: Sufficient test data?
AESA Radar systems requirements

Next generation systems for Terrestrial, Naval, Avionic and Space applications will be almost entirely AESA systems: For this reason Key AESA system technologies (i.e. T/R modules) are strategic and in full evolution.

- AESA T/R modules provides:
  - Input/Output signal duplexing (Ferrite circulator or SPDT switch)
  - High Power Transmitter (HPA)
  - Low Noise input signal Amplification (LNA) with high power signal robustness (limiter if needed)
  - Digital control of input/output amplitude and phase shifting signal modulation (Core Chip)

Next Generation AESA Modules Require Improvements in:

- **System Size, Weight and Power (SWaP)** – To guarantee more functionality and capability into new platforms
- **Higher Efficiency** – To improve Power Consumption, reducing Operating Cost
- **Reliability** – Long Mean Time To Failures (MTTF) Technology
- **Surface – Mount Technology (SMT)** – To utilize lower cost Commercial Manufacturing Processes
**T/R modules evolution**

- Power Amplifier, Robust LNA, low-loss – high power SPDT switches are the most critical device in Tx/Rx architectures

- High power density (>5W/mm)
- Noise performance comparable to GaAs
- High breakdown voltage (>100V)
- Better thermal properties ($R_{th} \approx 17$ C/W)

- T/R Modules include 40-80% of the cost of an AESA

- Control of “enabling technologies” is mandatory to overcome any restrictions on exports of critical components and therefore represents a strategic condition for the companies operating in military and aerospace market
The GaN-HEMT devices on SI –SiC substrates give performance advantages in terms of:

- Order of magnitude increase in power density compared to GaAs (10 W/mm)
- Increase in power amplifier circuit efficiency (circa 10%) resulting from more efficient power combining of high output impedance devices
- Improved low-noise figure of merit for robust gain amplifiers
- High reliability and/or high temperature operation
- High voltage operation (50 to 60 V versus 8 to 10 V for GaAs) resulting in increased system power efficiency
- Lower system cost resulting from simplified rf sub-system integration and thermal management issues
- Lower system weight
GaN Device

Ohmic contact
- Thickness of Ti/Pt/Ni/Au metal stack
- Rapid Thermal Annealing

Gate contact
- **Gate Foot:**
  - SiN plasma etch to reduce Current Collapse
- **Gate Field Plate (GFP):**
  - SiN thickness and GFP length
- **Source Field Plate (SFP):**
  - SiN thickness and SFP geometry for Gain enhancement

Device Thickness
70 ÷ 100 µm for microstrip structure
Electrical Degradation

HEMTs may degrade when submitted to reverse-bias stress

- Joh et al. suggested that there is a "critical (gate-drain) voltage" beyond which the device starts degrading, showing a permanent increase in gate leakage current.

- Degradation was ascribed to converse piezoelectric effect

  Joh et al., EDL 29, 287, 2008

- Recent reports indicated that reverse-bias degradation may occur even below the “critical voltage”

- **Degradation is a time-dependent process, possibly due to defect generation and percolation**

  See also:  
  D. Marcon et al., IEDM 2010  
  M. Meneghini et al., IEDM 2011
Hot Electron Degradation

- Hot-electron effects have been frequently quoted as a possible threat for the reliability of GaN HEMTs.
- Degradation is due to hot electron-induced trapping of negative charge in the access region.
- On-state degradation may occur at moderate VDS levels. Degradation consists in an increase in $R_{on}$, decrease in $I_D$.

Fujitsu hot-electron trapping scheme:
Gallium Nitride Radiation Hardness

• The AlGaN/GaN high electron mobility transistor (HEMT) is a prime candidate for high-power applications at microwave frequency. Compared with Si and GaAs-based devices, GaN-based devices are more radiation tolerant.

• Earlier studies have shown that GaN-based materials and devices are mainly influenced by the displacement damage.

• Neutron radiation effects in HEMTs have been reported by a few groups, but there is not a thorough understanding of the physical mechanism responsible for the degradation of electrical characteristics.

• Some experimental test reveal that in GaN/GaN HEMT, before and after neutron irradiation, the saturation currents ($I_{dsat}$) decrease after neutron irradiation.

• This may be caused by either a decrease in electron concentration in the channel or a decrease in saturation carrier velocity.

• It is observed also that neutron irradiation leads to the increase of the gate leakage current.

• Defects induced by irradiation in the band gap and near the metal/AlGaN interface may act as tunneling sites, leading to the increase of gate current tunneling probability and the decrease of the Schottky barrier height.


H 2009 Acta Phys. Sin. 58 511

Lu Ling, Zhang Jin-Cheng, Xue Jun-Shuai, Ma Xiao-Hua, Zhang Wei, Bi Zhi-We, Zhang Yue, and Hao Yue

Several passive elements such as a thin-film resistor, MIM capacitor, air-bridge and via-hole are required for MMICs completion:

- **Passive:**
  - NiCr thin film resistors;
  - MIM capacitors;
  - Inductors;

- **Electroplating:**
  - multi-finger pad connections by Air Bridge technique
  - thick line for Power handling increase.

Passive Device reliability is Mandatory
Neutron irradiation can create two kinds of defects, i.e. clusters and point defects.

It has been previously observed that the particle radiation primarily displaces gallium and nitrogen atoms from the crystal lattices and creates charged defect centers. Defect centers degrade the carrier mobility through Coulomb interactions and degrade the carrier concentration in the 2DEG through charge compensation and carrier removal.

Neutron irradiation introduces electron traps with the activation energy of 0.35 and 0.45 eV in the AlGaN barrier and hole traps with the activation energy of 0.26, 0.6, and 1 eV either in the GaN buffer or in the AlGaN barrier.

Ga vacancy ($V_{Ga}$) is an acceptor-like traps introduced which has relatively low formation energy in n-type GaN when Fermi level is close to the conduction band. Being an acceptor-like defect, $V_{Ga}$ acts as a compensation center. The Ga vacancies are mobile in a wide range of temperature. It is likely that they migrate and form complexes with more stable defects.

$V_{Ga}$-related defect introduced by neutron irradiation is probably the main reason for the degradation of the concentration of 2DEG in AlGaN/GaN HEMT devices.

Data about neutron irradiation tolerance on Selex ES GaN devices do not exist.

A neutron irradiation facility for space applications will be required in the next years.
Neutron Emission Test on Solar Cell
• Radiation effect on solar cell is simulated in the test using statistic function and considering the average quantity of atomic particles, which influence the devices.

• NIEL is calculated considering interaction cross sections and recoil kinematics for different kinds of incident particles.

• First approximation that was done is that only the not ionizing effects of the electron and proton are considered.
Advantages of the Neutron Radiation

Neutron Emission

Non Ionizing Effect: Displacement Damage

Bare Cell

- Neutrons are not charged particle and the evaluation of displacement damage caused by Neutrons are more “real” than the displacement damage deducted by protons interaction, which cannot be considered “not ionizing”

- Neutrons displacement damage in silicon is characterized by a cross section lower than protons. For this reason, the number of primary displaced silicon atoms will be relatively small

- Another difference involves the amount of energy transferred to the displaced silicon atom by the neutron. The effect brings to a displacement damage clustered near the site of the primary displacement
Neutron Single Event Effect

A single fast neutron that interacts with a nucleus may produce a variety of secondary particles – protons, neutrons, alpha particles and even heavy recoil nuclear fragments. Effect can be relevant in the linear and logic (OP, FPGA, etc) devices.

The neutron may interact with a silicon nucleus (see figure), but also with any other elements present in the device (packaging, metallizations, dopants, …)

Relevant effect doesn’t depend only by high speed neutron, but by Thermal Neutron that had important interaction with Boron-10, sometime present in the coverglass or when Boron concentration becomes extremely high (e.g. P-MOSFETs).

For the logic and memory family, the effect of neutron radiation can be relevant as for AIT activities as for launch phase.

BGR method can be applied to extend the results of neutron radiation to other environment.

Considering that part of equipment in use for space application is also used in Avionics is evident that effects of neutron radiation is unpredictable with other facilities.

Selex ES Experience:
Radiation Analysis for IXV program (Selex ES provided the PPDU unit) was requested to be done using neutron radiation environment.
Selex ES Technology for Space Application
QUAGAS: GaAs PHEMT 0.25 µm ESCC Space Evaluation

Partners:
- Selex ES; Università Roma Tor Vergata, Università di Padova, IMT

- Main objectives:
  - Promote the development of enabling technologies used in future space programs consistent with institutional ASI programs
  - Increase the competitiveness of the National and European industry
  - Obtain the EPPL from ESCC to increase the competitiveness of the National and European industry

- The project completion is scheduled to December 2015
Selex ES quarter-micron GaN technology reliability assessment

- Test campaign aimed at evaluating the reliability figures of Selex ES 0.25 µm GaN technology proposed to ESA in GSTP Framework with ASI endorsement.
- To perform a preliminary performance and reliability assessment of the Selex ES technology.
- To perform process optimisation and validation of a commercial European epi-supplier.
- Project start: Q3 2015
- Project duration: 28 months
The development plan is based on Selex ES internal funding and external ones.

Main External funding:
- Italian MoD
- ASI
Survival and successful operation of space systems in the space radiation environment cannot be ensured without careful consideration of the effects of radiation.

A key element of RHA is the selection of components having a sufficient tolerance to radiation effects for their application. However, RHA process is not confined to the part level. It has implications with system requirements and operations, system and subsystems circuit design, and spacecraft layout.

Only a limited number of devices with the required radiation hardness is currently available off-the-shelf, and mostly in export-controlled lists.

Reliability assessment of Selex ES 0.25 µm GaN Micro-Strip technology for Space application represents the beginning to promote a National GaN technology for the next European Space missions.
GRAZIE PER LA VOSTRA ATTENZIONE

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