return on innovation

www.onera.fr
Comparison of numerical and experimental investigations on the ESD onset in the Inverted Potential Gradient situation in GEO

11th Spacecraft Charging Technology Conference, Albuquerque, NM, September 20-24, 2010

P. Sarrailh, J.-C. Matéo-Vélez, J.-F. Roussel, B. Dirassen (ONERA)
J. Forest, B. Thiébault (ARTENUM)
D. Rodgers, A. Hilgers (ESA)
Outline

• General overview on the ESD risk
• Experimental setup
• SPIS ESD tool
• Parametric study: comparison experimental/numerical results
General overview on the ESD risk
Spacecraft Charging at GEO in sunlight

- S/C structure at a negative potential several kV due to electron collection
- Photoemission on solar cell cover glass:
  - Dielectrics in sunlight more positive than S/C structure
  - Barrier of potential on the front side due to rear side negative potential
- This situation is the Inverted Potential Gradient (IPG)
IPG situation at the solar cell scale

- At the solar cell edge:
  - Gap surface covered with (photoconductive) kapton = S/C structure voltage
  - Solar cell voltage ~ S/C structure voltage (strings voltage ~100 V)
  - Cover Glass top surface is more positive than solar cell = differential voltage
- Triple point between conductor, dielectric and vacuum
- Uses of a simplified geometry (valid for interconnects) to compare experimental and numerical results
Microscopic structure and electron avalanche

Simulation at mesoscopic scale

Microscopic scale model

Fowler-Nordheim $e^-$

$\beta$ electric field amplification due to micron tip

Differential potential

Secondary emission by electron impact + recollection

Secondary emission $> 1$

Electron avalanche + Cathode spot creation

=> ESD

Fowler-Nordheim electron emission

Electric field on the tip
Tip geometry and field enhancement factor

- Field enhancement factor from 300 to 800
- Tip length: 1 μm
- Tip radius (from emitting area): 1 - 10 nm

Figure 5. Variation of field magnification factor with number of breakdowns for different sets of electrodes.

Figure 8. Variation of emitting area at breakdown with number of breakdowns for different sets of electrodes.

Figure 5 and figure 8 extracted from: *Effect of electrode surface finish on electrical breakdown in vacuum*, D W Williams and W T Williams, J. Phys. D: Appl. Phys. (5), 1972.
Experimental setup
Experimental Setup

- ONERA CEDRE vacuum chamber
  - Pressure: 3.10⁻⁶mbar
  - Barrier potential controlled by $V_{bias}$
  - Differential voltage by photoemission (as in flight)
Nominal case – Perpendicular TP with Aluminum and Teflon

- The triple point is irradiated by the UV source
- Only the chosen triple point line can generate ESDs thanks to a protecting mask

Dielectric FEP with aluminization on the rear side

Irradiated zone

40mm

Protecting mask

200 mm

UV Irradiation zone

sample
Nominal case – Perpendicular TP with Aluminum and Teflon

- The voltage on the FEP is close to 0V
- 8 ESDs have been obtained at different locations of the triple point edge
- The ESD threshold is about -800V

![Image showing ESD threshold and current graphs]
Results of the parametric study

- Nominal case
- Metal length 15mm
- CMX AR dielectric
- Change of incidence angle
- Gold
- Co planar (5nF)

Graph showing peak current (A) vs. differential voltage threshold (V):
- X-axis: Differential voltage threshold, V
- Y-axis: Peak current, A
- Legend for different cases:
  - Nominal case
  - Metal length 15mm
  - CMX AR dielectric
  - Change of incidence angle
  - Gold
  - Co planar (5nF)
SPIS ESD tool
The mock-up geometry and the boundary conditions

- Simulation conditions:
  - Teflon (127 μm) / aluminum (1.5 mm)
  - External box: 4 cm x 4 cm x 0.6 cm
  - TP zone: 1 μm
  - Tip length = 1 μm
  - Barrier potential from 500 V to 2000V
  - β from 800 to 300;

Barrier potential (Dirichlet condition)
Symmetry conditions
Dielectric (implicit solver)
Metal plane + triple point (Dirichlet; V = 0)
Refinement box
Triple point with field enhancement
11th Spacecraft Charging Technology Conference, Albuquerque, NM, September 20-24, 2010
**SPIS ESD tool**

- ESD prediction scenario, two imbricate loops:
  - Barrier potential prediction
  - Tip geometry evaluation: field enhancement factor $\beta$ loop (for a fixed tip length – 1$\mu$m standard)

- Tip model (*tipRecession* interactor):
  - Tip model based on a cylindrical geometry
  - Zero dimensional thermal model (*compared to Rossetti ....*)

**Diagram**

- Data from UI
- Init simulation
- Scenario
- Plasma integration
- SC/Plasma interactions
- Circuit solver
- Scenario end?
- Results to UI

**Flowchart**

- Potential sweep
- Tip and potential re-initialization
- Same potential
- Next tip (lower $\beta$)
- ESD?
- No
- Tip and potential re-initialization
- Yes
- Next time-step
- Same potential
- Next tip (lower $\beta$)
- ESD?
- No
- Tip and potential re-initialization
- Yes
- Potential sweep
Barrier potential and emitted currents

Barrier potential (V)

Current (A)

Time (s)
Electron emission: densities in volume

- F-N primary electrons:
  - directed toward the barrier potential
  - Max density can reach $10^{20}$ m$^{-3}$ (Space charge effect)
- Secondary electrons are present on the top side of the dielectric due to hoping
Parametric study: comparison of the numerical and experimental results
Reference case
Aluminum-Teflon 127 μm
3 mm Gap
Irradiated Gap
Parametric study – Sun incidence angle

Reference case
Aluminum-Teflon 127 μm
3 mm Gap

Irradiated Gap

Not Irradiated Gap
Aluminum-Teflon 127 μm
3 mm Gap

Peak current (A)

Differential voltage threshold (V)

Experimental results
Numerical results

400 V

350 V

40 mm

3 mm
Parametric study – Gap length

Reference case
Aluminum-Teflon 127 μm
3 mm Gap
Irradiated Gap

15mm Gap
Aluminum-Teflon 127 μm
Irradiated Gap

Experimental results
Numerical results

Differential voltage threshold (V)

Peak current (A)

900V

800V

40mm

3mm
Parametric study – Dielectric material

- Aluminum-CMX 100 µm
  - 3 mm Gap
  - Irradiated Gap

- Reference case
  - Aluminum-Teflon 127 µm
  - 3 mm Gap
  - Irradiated Gap

- CMX-AR $\sigma = 2.6 \times 10^{16} \, \Omega$
- CMX-AR $\sigma = 10^{16} \, \Omega$
- Teflon $\sigma = 10^{16} \, \Omega$

- Experimental results
- Numerical results

Graph showing the differential voltage threshold (V) versus peak current (A) for different materials and conditions.
Lessons to be taken from the experiments and numerical simulations

- The numerical results qualitatively agree with the experiments
  - It is definitely more difficult to trig ESDs in the following cases
    - Low photon incidence angle
    - Longer metallic plate
    - Co-planar geometry
    - More conductive dielectric

- Strong effect of
  - Surface resistivity of the front edge
  - Tip geometry (radius and shape)

- Need for complementary experimental data (surface resistivity measurement, surface distribution and type of microscopic structures)
Conclusion
Conclusion

- Large experimental parametric study

- SPIS ESD tool:
  - Complete ESD scenario:
    - 3D Electron avalanche
    - Thermal model of the tip
    - ESD threshold estimation
  - Simulation of the charging and electron avalanche well described
    - Automatically adapted time steps: from 1s to $10^{-12}$s
    - 3 length scales simulated

- Good qualitative agreement between experiments and numerical results

- Need of further experimental data to provide design engineers with quantitative/predictive ESD risk tool
Perspective

- Experimental investigation on surface resistivity to get more data
- Photo conductivity modeling improvement
- More complex geometry:
  - solar cell edge
  - here, it is close to the interconnects
- Effect of multiple tips (tip distribution on the surface)
- Emission from semi-conductors
- Model the plasma generation during the transition to arc
Questions ?