Radiation Effects Analysis Tools

Review of Sira WP2

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Background

- Sira provided inputs to the WP1 study on ‘Space Radiation Effects for Future Technologies and Missions’
  - (WP1 report available on-line at http://www.integral.soton.ac.uk/dera/reat_docs.html)
- WP2 was concerned with radiation effects tools for the key areas identified in WP1 :
  - currently available tools
  - needs for new tools
- WP2 review held August 2001
- Final draft report submitted in December 2001
- Two new analysis tools were recommended for further study and possible implementation:
  - Multi-Layered Shielding Simulation Software [MULASSIS]
  - Geant4 Microdosimetry Analysis Tool [GEMAT].

Overview

- Displacement damage
- SEU prediction
- Other single event and transient effects
- Effects in biological materials
- Effects in insulators
  - polymers
  - photonic devices
  - fibres
  - glasses
- Transient effects in linear electronics - *including PSPICE modelling*
- Transient effects in fibre-optic links and optocouplers
- Dose enhancement
- Microdose
- Effects in crystal detectors for space science

Displacement Damage

- **NIEL hypothesis:**

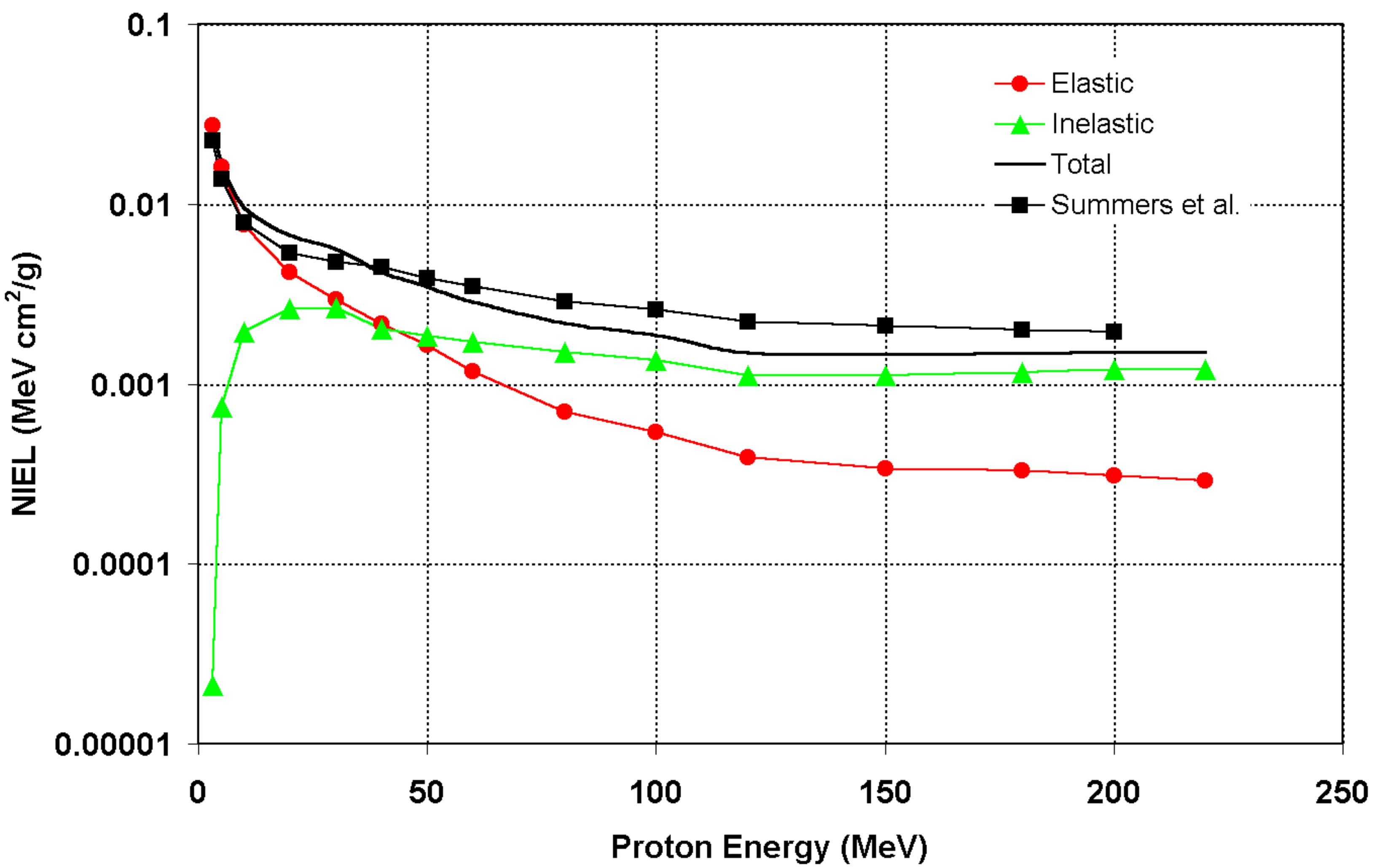
  device damage = $$K_{damage}\int_{E_2}^{E_1} NIEL(E)\frac{df}{dE}dE$$

- **The damage constant has to be determined experimentally**
  - **only one energy (and particle type) is needed *if* NIEL scaling is valid - *but may need to establish validity by testing at several energies (and particle types)***
  - **damage will often depend on *experimental conditions* (e.g. CTE in CCDs), also *annealing* can be important (e.g. in LEDs and laser diodes) and may have device to device variability**
- **Departures from scaling with theoretical NIEL:**
  - **oxygenated silicon (high energy physics)**
  - **solar cells**
  - **LEDs & laser diodes (now established theoretical NIEL is correct ?)**

Displacement Damage - conclusions

- **Displacement damage from secondary particles can be significant so a radiation transport tool is needed to calculate particle flux and deposition behind shielding materials [MULASSIS]**
- **For CCDs (for example) a tool to calculate NIEL deposition in microvolumes would be useful (e.g. to assess pixel-to-pixel non-uniformity) [GEMAT]**
- **Need to be aware of potential shortcomings of NIEL approach (dependencies on operating conditions, particle energy and annealing)**

Recent NIEL Calculations for protons on Si, Akkerman et al, Radiation Physics and Chemistry, 2001



SEU Prediction (1/2)

- **Usual methodology is to predict heavy ion and proton upsets separately.**
  - ***Heavy ion (direct ionization)*** **using cross section data and the dimensions of the sensitive volume (assuming a rectangular parallelepiped, RPP or IRPP methods)**
  - ***Proton (indirect ionization)*** **using Bendel/Petersen (or similar) semi-empirical model (based on nuclear reaction kinetics) and cross section data**
- **If only one set of data is available then methods such as the Petersen FOM can be used** ***(there a need for more accurate tools to derive one SEU rate from another)***
- **The SPENVIS tool (unlike CREME96 or SPACE RADIATION) does not at present allow input of experimental cross sections or Weibull fits (and so does not allow use of the integral RPP method) but this is planned for future upgrade**

SEU Prediction (2/2)

- MBU rate tends to increase as device geometry shrinks. A microdosimetry tool is needed to predict energy deposition in sensitive volumes from reaction recoils and products. This would also be useful for proton single event rate prediction. [GEMAT]
- There is a need to calculate thermal neutron fluxes in some cases [MULASSIS] (e.g. when have BPSG overlayers) - and to calculate the effect of the overlayers on secondary production and subsequent charge deposition [GEMAT]
- But will need to consider at some (later) stage how the radiation transport and deposition tools are incorporated into a rate prediction tool.

Other single event and transient effects

- **SEL and other single event effects can usually be predicted using the SEU methodology discussed above. There is a trend to use 200 MeV proton testing to simulate heavy ion latch-up - is more simulation (using geant4 ?) needed to validate this approach ?**
- **See later for SEE in linear circuits (and fibre links/optocouplers)**
- **In detector arrays the calculation of transient events is quite complicated (involves charge diffusion) but a first cut approach to calculate deposition by secondaries and reaction products in pixel microvolumes would probably be useful [GEMAT]**

Effects in biological materials (1/2)

- Most radiobiological data comes from high dose rate gamma irradiations. Use the formalism of ***equivalent dose*** $H_{T,R}$ (averaged over an organ)
  - $H_{T,R} = D\ W_R$ (dose x weighting factor)
  - weighting factor for particles > 1
  - average $H_{T,R}$ over all the organs to get ***effective dose, E***
- There is little data for low dose rate irradiations or for protons and high LET (HZE) cosmic rays - so weighting (quality) factors are not well characterized
- Also there are concerns for effects in DNA and the central nervous system where cell repair does not occur
  - can be susceptible to single particle effects (e.g DNA breaks)
- A formalism has been suggested involving risk cross cross sections (for each particle) but these are not yet known, so tend to fall back on the conventional quality factor formalism

Effects in biological materials (2/2)

- **Effects can be important for lightly shielded astronaut activity during solar particle events and (potentially) for long duration exposure to cosmic rays**
- **Prediction of particle fluences behind graded shielding is important (including ion and target fragmentation). No tools are presently available in Europe for prediction of secondaries. [MULASSIS]**

Effects in insulators (1/3)

- **Polymers**
  - **damage varies in a non-linear way with total ionizing dose, usually only important at very high dose**
  - **there seems to be evidence in some cases for particle-type dependence and temperature dependence. Data obtained in air is subject to oxidation and hence dose rate effects**
  - **a multilayer shielding tool may be useful for thin films [MULASSIS]**
- **Photonic devices (e.g. modulators and crystals)**
  - **emerging area**
  - **effects mostly at high total dose levels**
  - **special needs for tools not yet identified**

Effects in insulators (2/3)

- **Fibres**
  - **Complicated non-linear and annealing behaviour but effects not normally very serious for the short lengths used in space (but may be important for special fibres; e.g. polarization-maintaining and Erbium doped fibres)**
- **Glasses (based on notes from Dominic Doyle, ESTEC)**
  - **Dose Coefficients (DCs) are a valid approach within the total dose regime of < 1 Mrad and when the relaxation (annealing) effects are not significant (short irradiation times or at low temperatures). If relaxation is important the DC is still valid and is a useful part of the complete model which includes annealing.**
  - **It would appear that there is NOT an equivalence between DCs for different radiation types (e.g. gamma, electrons, protons), so important to apply the correct DC for each (or equivalence factor).**
  - **Need to consider Dose Depth Distribution**
  - **Database for DCs starting to be established**

Effects in insulators (3/3)

- Radiation induced refractive index changes in optical glasses are now well established, but the magnitudes of the changes remain at or below the nominal thresholds for the normal index tolerances in typical optical systems. Cerium doped glasses can be particularly susceptible.
- For an optical designer (who does not per se have an expert knowledge of radiation effects physics) the tools he requires to assess the radiation tolerance of his design are:
  - a database of dose coefficients and/or induced absorbtion spectra for all the commonly used and available optical glasses
  - an optical and optomechanical design of his system and a radiation sector analysis to give him the absorbed dose levels (dose depth distribution curves) and energy spectra at each component in the system
  - a computation tool to convolve the data from the database with his optical design and radiation environment analysis so as to produce a table of induced absorbtion and refractive index change for each component (and the total) system

Transient effects in linear electronics (1/3)

- Important for voltage comparators, regulators, operational amplifiers (as well as pulse width modulators and ADCs, DACs)
  - ions deposit charge near internal p-n junctions and transients produced at the device output
  - can be a problem if the transient is latched by following digital circuitry, ADCs are rather unique since mixed signal
- Can get a range of pulse widths and amplitudes (either polarity)
- Parts studied most are amplifiers and voltage comparators (LM124 and LM111)
- Even for studied parts, transients can depend on bias conditions and circuit values, and will be modified by follow-on circuitry
  - but difficult to model from scratch since full device details are not usually available
  - for given set of conditions can measure cross sections experimentally and predict transient rates in the usual way

Transient effects in linear electronics (2/3)

- Would be good to have a device level (equivalent circuit) SPICE model which could simulate the transients and could then be incorporated in a circuit level model
  - but can only apply pulses at the input (internal SPICE nodes are not representative)
  - hence cannot simulate hits on internal transistors - particularly a problem for some voltage comparators
- Used B2 PSICE A/D 2000 software for OP07, OP37, OP15, LM124, LM218 and CLC426 amplifiers and LM111 and LM218 comparators.
  - voltage controlled current pulse and switched capacitor inputs
  - both gave similar results - not surprising since circuit response is slower than the initial transient (~ 10 ns)
  - can generate output transients with required range of amplitudes for typical input charge pulses of 10-50 pC (but for comparators could only model 0V differential voltage condition).

Transient effects in linear electronics (3/3)

- Use of simple 'add-on' SPICE transient pulse generators can give representative transients at device outputs, particularly for operational amplifiers
- The SPICE method can be used as a precursor to device testing and to gauge the effect of external circuity (e.g. filter capacitors)
- It has to be emphasised however that simple SPICE modelling cannot fully simulate the complex interactions which occur in a real device and so can only be used as a rough guide.
- Another technique is simply to use a large amplitude voltage transient at the device output or a previously (experimentally) established worst case transient - only do detailed analysis if still a problem (see also Marec, RADECS2001)
- An alternative could be to irradiate a device ‘in situ’ in the circuit, e.g using a 200 MeV proton beam

Transient effects in fibre links and optocouplers

- **In both cases the transients tend to be caused by *<u>proton direct ionization</u>* within the (large area) photodetector**
- **For FOLs can use usual SEU formulism (Problem with CREME96 PUP)**
- **For optocouplers the above approach has also been recently discussed. Alternatively can measure angular dependence of cross section for a range of energies**

Dose enhancement

- Occurs particularly in electron and bremsstrahlung environments where high z layers are close to the SiO_2 layer of a device
- Departures from radiation equilibrium, backscatter of Compton electrons (generated by bremsstrahlung) or reflection of electron flux from high-Z layers
- Can get order of magnitude enhancements
- Can use CEPX/ONEBFP or ITS/EGS
- Could be use for MULASSIS

Microdose

- Oldham et al showed that a single heavy ion can deposit enough dose in the gate oxide above the small sensitive volume of a high density memory to cause a localized total dose failure (Single Hard Error, SHE or a 'stuck bit').
- In modern devices the error rate for stuck bits has remained low, probably because of architecture changes and the use of thin gate oxides.
- However, microdose effects still pose a potential threat, particularly for mass memories.
- Also, Pickel suggested that microdose effects may become important for high density CMOS readout circuits for infrared focal plane detector arrays.
- Could be a use for GEMAT

Crystal detectors for space science

- **Charge deposition spectra of ionizing radiation can be a major source of background**
  - **secondary radiation important (particularly for heavy spacecraft and detector systems) [MULASSIS]**
  - **limited by induced radioactivity [need optimised technique for producing spallation product and response function libraries]**