ECE695: Reliability Physics of Nano-Transistors
Lecture 38: Charge Generation by Particles

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Outline

1. Background information

2. Electromagnetic interaction and charge generation
   a) Proton, neutron, and alpha particles

3. Electron-hole pair generation

4. Permanent damage

5. Conclusions
On photons and particles

Light

Particles

Light and Particles
How do particles create charge

- Comic Ray
- Solar Wind
- Packaging
- Neutron
- Proton
- α-particle
- Nuclear reaction
Getting Rid of the Energy: Photoelectric Effect and lattice Vibration

Fermi-Pasta-Ulam problem .... Difficulty in reaching equipartition

Initial mode \((k, \text{red})\) and two neighboring modes \((k+1, \text{blue})\) and \((k-1, \text{green})\).

2.1 Protons interact with **bound electrons** by electromagnetic interaction

- **Proton** interacts with both nucleus and the electron cloud; the **nucleus-proton** interaction is elastic that randomizes proton momentum, while electron-proton interaction inelastic results in electron-hole pair generation.

- **Proton** sees charge distribution only at a single atom level, everything else further out is charge neutral (**nucleus-electron cloud**).

- To calculate energy loss, we take one interaction at a time (as it was there on its own) and then sum up over the volume.
2.1 proton, pion, muon: relative LET

\[-\frac{dE}{dx} = \frac{q^4}{8\pi\varepsilon_0} \left( \frac{\rho N_{AV}}{B} \right) Z_{\text{inc}}^2 M_{\text{inc}} \ln \left( \frac{4E_{\text{inc}}}{E_{\text{eh}}} \right) \]

\[-\frac{dE}{dx} \bigg|_A - \frac{dE}{dx} \bigg|_B = \frac{Z_{\text{inc},A}^2 M_{\text{inc},A}}{Z_{\text{inc},B}^2 M_{\text{inc},B}}\]

\[-\frac{dE}{dx} \bigg|_{\text{pion}} - \frac{dE}{dx} \bigg|_{\text{proton}} = \frac{Z_{\text{inc},\text{pion}}^2 M_{\text{inc},\text{pion}}}{Z_{\text{inc},\text{proton}}^2 M_{\text{inc},\text{proton}}} = \frac{1}{1} \times \frac{139}{938} = \frac{1}{6.5} \]

\[-\frac{dE}{dx} \bigg|_{\text{proton}} \bigg|_{2H} - \frac{dE}{dx} \bigg|_{\text{proton}} \bigg|_{3He} = \frac{Z_{\text{inc},2H}^2 M_{\text{inc},2H}}{Z_{\text{inc},3He}^2 M_{\text{inc},3He}} = \frac{1}{2} \]

\[-\frac{dE}{dx} \bigg|_{\text{proton}} \bigg|_{3He} = \frac{Z_{\text{inc},3He}^2 M_{\text{inc},3He}}{Z_{\text{inc},3He}^2 M_{\text{inc},3He}} = \frac{1}{4} \times \frac{1}{3} = \frac{1}{12} \]

Muon mass: 105.658 369(9) MeV/c^2, charge=-1
Pion mass: 139.6 MeV/c^2, charge=1
Proton Mass: 938.272013(23) MeV/c^2, charge=1
How do particles create charge

- Comic Ray
- Solar Wind
- Packaging

- Neutron
- Proton
- α-particle

- Nuclear reaction
How often does the nuclear reaction occur

\[ \sigma = \pi R^2 = \pi \left( (28)^{1/3} r \right)^2 = 5 \times 10^{-25} \text{ cm}^2 \]

**Probability of guaranteed strike ….**

Black Wall = \(1/(\text{area/atom})=2 \times 10^{24} \text{ atom/cm}^2\)

Interaction depth = Black Wall / (atoms/cm\(^{-3}\))

\[ = 2 \times 10^{24} / 5 \times 10^{22} = 40\text{ cm} \]

Probability of Hit: \(10 \mu m / 40\text{ cm} \sim 1 / 40,000\).

1 in 40,000 neutrons will cause nuclear reaction
Frequency of Nuclear reaction

Integrated neutron in 10 yrs
\[ = 0.5 - 1.5 \times 10^5 \times 10 = 10^6 \]

Number of hits \( \sim \)
\[ 10^6 / 40,000 = 25 \text{ hits/cm}^2 \]

Typical Active Area = 0.04 cm\(^2\)

Nos. of hits/IC = 25 \times 0.04 \text{ cm}^{-2} = 1

Almost every chip will have one radiation-induced error
2.2 Neutron-nucleus interaction: Size of an Atomic Nucleus

A nucleons
N neutrons, Z protons

\[ r = 1.25 \times 10^{-13} B^{1/3} \text{ cm} \]

\[ \sigma_{0,\text{Si}} = \pi r^2 = 45.34 \times 10^{-26} \]

\[ = 453.4 \times 10^{-27} \text{ cm}^2 \]

\[ \sim 500 \text{ mBarns} \]

1 barn = 10^{-24} \text{ cm}^2
Defined at Purdue during WWII
Size of a uranium atom is ‘as big as a barn’
2.2 Binding Energy of a Nucleus: droplet model

The binding energy of a nucleus can be calculated using the droplet model, which takes into account the contributions from the volume, surface, Coulomb, and n-p symmetry. The formula is:

\[ B.E = -15.75A + 17.8A^{2/3} + 0.71\frac{Z^2}{A^{1/3}} + 23.7\left(\frac{A - 2Z}{A}\right)^2 A + 34\frac{\lambda}{A^{3/4}} \]

- \(N\) = neutron
- \(Z\) = proton
- \(A = N + Z\)

The terms in the equation represent:
- Bulk energy
- Surface energy
- Coulomb energy
- n-p Symmetry energy
- Pairing energy, \(\lambda\)

The pairing energy is determined by the pairing constant \(\lambda\), which can be +1 for odd-odd, -1 for even-even, and 0 for odd-even.
2.2 Binding Energy of a Nucleus

\[ B.E. = -15.75A + 17.8A^{2/3} + 0.71\frac{Z^2}{A^{1/3}} + 23.7\left(\frac{A - 2Z}{A}\right)^2 A + 34\frac{\lambda}{A^{3/4}} \]

\[ \text{N}=\text{neutron} \]
\[ \text{Z}=\text{proton} \]
\[ \text{A}=\text{N}+\text{Z} \]

Remarkably good fit

Maximum at \( Z=20 \)

Eventually limited by \( Z^2 \) term.

Fission is exothermic

\[ \text{B.E.}/A \sim 8 \text{MeV} \]
2.2 Breaking a nucleus by a neutron

\[ a = R \times (1 + \varepsilon) \]
\[ b = R / \sqrt{1 + \varepsilon} \]
\[ V = \frac{4}{3} \pi ab^2 \]

\[ \Delta(E) = B.E.(\text{ellipsoid}) - B.E.(\text{sphere}) \]
\[ = \frac{1}{5} \varepsilon^2 A^{2/3} \left( 2a_2 - a_3 \frac{Z^2}{A} \right) > 0 \]
\[ Z^2 < 17.8 \times 2 / 0.71 = 50 \times A \]

A is the baryon number

Same for Boron in packaging materials, B10 (20%) in BPSG most dangerous

Ref. Asoke, p. 93
2.2 neutron interaction with SiO2

nucleon + target → x1+x2+...+residual

\[ r = 1.25 \times 10^{-13} \, B^{1/3} \, \text{cm} \]

\[ \sigma_{0,\text{Si}} = \pi r^2 = 45.34 \times 10^{-26} \, \text{cm}^2 \sim 500 \, \text{mBarns} \]

\[ n + ^{28}\text{Si} \rightarrow 2\,p + 3\,n + 3\,^4\text{He} + ^{12}\text{C} + \text{photons} \]

200 MeV →

\[ (2 \times 5) + (65.5+23+6.81) + (3 \times 10) + 4\text{MeV} \]

~ 4k of e-h pair/micron/per proton

~ 25k of e-h pair/micron/per alpha

Energy=8MeV/nucleon, cascade by 65,23 MeV possible ...
2.2 Reading the tables: example Problem

\[ n + ^{28}\text{Si} \rightarrow 2p + 2n + ^{25}\text{Mg}^*. \]

\[ ^{25}\text{Mg}^* \rightarrow n + ^3\text{He} + ^{12}\text{C}. \]

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**Table 2** Example of a high-energy reaction channel for 200-MeV n + ^{28}\text{Si}.

<table>
<thead>
<tr>
<th>Secondary particle</th>
<th>K. E. (MeV)</th>
<th>( dE/dx ) (keV/(\mu)m)</th>
<th>e-h pairs/(\mu)m</th>
<th>Range ((\mu)m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>5.224</td>
<td>13.51</td>
<td>(3.75 \times 10^3)</td>
<td>225</td>
</tr>
<tr>
<td>p</td>
<td>4.195</td>
<td>15.91</td>
<td>(4.43 \times 10^3)</td>
<td>155</td>
</tr>
<tr>
<td>n</td>
<td>65.478</td>
<td>0</td>
<td>0</td>
<td>(\infty)</td>
</tr>
<tr>
<td>n</td>
<td>22.958</td>
<td>0</td>
<td>0</td>
<td>(\infty)</td>
</tr>
<tr>
<td>n</td>
<td>6.815</td>
<td>0</td>
<td>0</td>
<td>(\infty)</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>12.218</td>
<td>79.91</td>
<td>(2.22 \times 10^4)</td>
<td>90.5</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>12.025</td>
<td>80.83</td>
<td>(2.25 \times 10^4)</td>
<td>88.1</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>7.381</td>
<td>108.84</td>
<td>(3.02 \times 10^4)</td>
<td>43.6</td>
</tr>
<tr>
<td>(^{12}\text{C})</td>
<td>4.138</td>
<td>1253.34</td>
<td>(3.48 \times 10^5)</td>
<td>3</td>
</tr>
</tbody>
</table>

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Final product ... Most occur at the tail end.
3.1 Critical charge and single event upset

Assume a transistor is doped to $10^{17}$ cm\(^{-3}\) and $V=1\times1\times10 \ \mu$m\(^3\) vol.)

Number of electrons in the device = $10^{17}\times1\times1\times10\times10^{-12} = 1 \text{ Million}$

Suppose we need 50% of this charge for an upset (simulation)
500,000 electrons = 80 fC

Yield per interaction with products of nuclear reaction…
  for alpha particles $(3 \times 25k \times 10 \text{ um}) = 750,000$
  for protons $(2 \times 4k \times 10 \text{ um}) = 400,000$

Minimum yield …. 1 Million

Every particle strike can cause an electrostatic upset!
Permanent damage: Perugia Model

<table>
<thead>
<tr>
<th>Type</th>
<th>Energy (eV)</th>
<th>$\sigma_e$ (cm$^2$)</th>
<th>$\sigma_h$ (cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>$E_C$-0.42</td>
<td>$2.0\times10^{-15}$</td>
<td>$2.0\times10^{-14}$</td>
</tr>
<tr>
<td>Acceptor</td>
<td>$E_C$-0.46</td>
<td>$5.0\times10^{-15}$</td>
<td>$5.0\times10^{-14}$</td>
</tr>
<tr>
<td>Donor</td>
<td>$E_v$+0.36</td>
<td>$2.5\times10^{-14}$</td>
<td>$2.5\times10^{-15}$</td>
</tr>
</tbody>
</table>

Leads to increased recombination and VT shift
Very important for low-noise detectors.
Conclusions

1. There are three types of particles of interest: alpha particles, high-energy neutrons, and low energy neutrons. Others do not make it to the surface in significant numbers.

2. Once the neutrons and alpha particles interact with nucleus, they may displace the atoms from their usual position, causing permanent damage in the process.

3. The protons released in the process interacts with the lattice by EM interaction and generate electron-hole pairs – which in turn leads to soft-errors and single event upsets.

4. It is relatively easy to calculate the net yield of charge per nuclear interaction in various materials by using semi-empirical approaches.
The Bethe-Bloch formula is derived in most textbooks on Nuclear Physics, see for example *Nuclear Physics in a Nutshell, by C. A. Bertulani, 2007* or, P. Sigmund, “Particle Radiation and Radition Effects. Sprigner Series in Solid Sate Sciences, 151, 2006.


The stopping distance formula is derived in “An approximate formula for electron energy vs. path lengths”, J. S. Greeneigh and T. Van Duzer, ITED, 1973.
Review Questions

1. What did Fermi-Pasta-Ulam do in 1950s that is relevant for the discussion today?

2. Do you expect the neutron to have longer mean free path than a proton? Why or why not?

3. What is a 'mass formula'? Why do we need a mass formula for?

4. What is Fermi? How is it related to Barns?

5. What is a blackwall? How does blackwall of Uranium compare to Si?

6. What is the definition of stopping distance? How do you calculate stopping distance?

7. Why is the emission from packaging so damaging to the ICs? Why doesn't Boron as a p-dopant cause the same problem?