GD2O3 Film Response to Neutron and Gamma Irradiation: Radiation Transport Simulations

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Simulations of the following film/substrate arrangements were conducted with GEANT4...

- Gd2O3 on Si (previously studied)
- Gd2O3 on GaN
- Gd2O3 on SiC
- Gd2O3 on Al2O3
- SiO2 on Si

Simulations estimate neutron and gamma interaction response, specifically energy deposition. Predicted current generated is calculated and ray tracing graphics produced.
GEANT4: GEometry ANd Tracking

Open source C++ code package maintained by CERN and used primarily in particle physics community
GEANT4: GEometry ANd Tracking

- Can model transport of various particle types including neutrons, electrons, light or heavy ions, photons, etc.

- Can implement physics processes such as neutron interactions, electromagnetic physics, radioactive decay, etc. through models and/or cross section data.

- Can simulate radiation sources of different energy profiles, shapes, directions, etc.

- Code design allow for flexible applications
Geometry

SUBSTRATE (Si, GaN, or Al2O3)

FILM (Gd2O3 or SiO2)

Dia = 1000 um

Thickness = 0.11 um

Thickness = ~0.993 um

Dia = ~281 um

Dia = 5.08 cm

Not to Scale
Theory – Estimation of Neutron Interactions

\[ 1 - \left( \frac{I}{I_0} \right) = e^{-\Sigma x} \quad \text{First Collision Interaction Probability} \]

\[ \Sigma = \sigma N \quad \text{is the macroscopic interaction probability} \]

\[ \sigma \quad \text{is the microscopic interaction probability} \]

\[ N = \frac{\rho N_a}{A} \quad \text{is the number density of atoms in the material} \]

\[ \rho \quad \text{is the material density} \]

\[ A \quad \text{is the atomic mass of the material} \]

\[ \left( \frac{I}{I_0} \right) \quad \text{is the probability of non-interaction} \]

\[ x \quad \text{is the thickness of material} \]

\[ 1 - \left( \frac{I}{I_0} \right) = e^{-\frac{\sigma \rho N_a x}{A}} \]
Theory – Estimation of Neutron Interactions

\[ 1 - \left( \frac{I}{I_0} \right) = e^{-\frac{\sigma \rho N_a x}{A}} \]

Probability of thermal neutron capture in 1 um thick Gd2O3 film...

\[ 1 - \left( \frac{I}{I_0} \right)_T = e^{-[\sigma_{T,Gd^{155}} N_{Gd}(0.146) + \sigma_{T,Gd^{157}} N_{Gd}(0.157)] x} = 0.12074 \]

Compared to ~0.088 in GEANT4 simulation

Mean free path of thermal neutron in Gd2O3 =

\[ \lambda_a = \frac{1}{\Sigma_a} = \frac{1}{\sigma_{T,Gd^{155}} N_{Gd}(0.146) + \sigma_{T,Gd^{157}} N_{Gd}(0.157)} = 7.77 \mu m \]
Theory – Estimation of Gamma Interactions

\[ 1 - \left( \frac{I}{I_0} \right) = e^{-\left( \frac{\mu}{\rho} \right) \rho x} \]

Gamma interaction probabilities are low and dominated by Compton scatter.

In a ~300 um thick silicon substrate, for example, the interaction probability is...

\[ \left( \frac{\mu}{\rho} \right)_{CS, Si} \approx 4 \times 10^{-2} \text{ cm}^2 / \text{g} \] Compton Scattering

\[ 1 - \left( \frac{I}{I_0} \right)_{CS, Si} = 2.79 \times 10^{-3} \]

With a mean free path of ~11 cm
Beam Port #4 Flux Profiles - Neutrons

No shielding of neutrons in beam port is assumed for neutron flux profiles.

Beam Port #4 Flux Profiles - Gammas

Measured

Simulated

Results

Energy Deposition and Current
Of all substrates, GaN shows the highest interaction rate with both gammas and neutrons and Si shows the least for both. If charge collection is over entire substrate then energy deposition by neutron/film interactions is overwhelmed by gamma response in substrate.
Current in most devices are dominated by gamma interactions. Current is dependent on various substrate properties and the relative magnitudes of gamma and neutron flux.
Charge Collection Region: Area Under Film

FILM (Gd2O3 or SiO2)

Dia = 1000 um

Thickness = ~0.993 um

Thickness = 0.11 um

Charge Collection Region Under Film Area

Dia = 5.08 cm

Thickness = ~281 um

Not to Scale
If charge collection is possible only in the volume under the film, the energy deposition by neutrons/film interactions can be competitive with that by gammas in the substrate. The higher energy deposition in GaN substrate is due to its higher relative density and interaction cross section (nearly an order of magnitude larger and includes an \((n,p)\) reaction; the proton will deposit most energy locally into substrate).
Looking closely at the mechanism of energy deposition, it is shown that a majority of energy deposited in the substrate is due to neutron interactions in the film. The reaction products (electrons) travel from the film to the substrate where they give up most of their kinetic energy. Gammas also deposit a relatively significant amount of energy in the substrate.
If current is collected only in the full thickness of the substrate under the film area, then neutron interactions dominate charge creation.
Current collected in the substrate then follows the mechanisms of energy deposition.
Charge Collection Area:

Charge Collection Region
Dia = 1200 um

Thickness = 0.11 um
 Thickness = ~0.993 um
 Thickness = ~281 um

FILM (Gd2O3 or SiO2)
Dia = 1000 um
Decreasing the depth of the charge collection region within the substrate causes a relatively large reduction in the gamma interaction rate, in turn leading to reduced energy deposition by gammas.
A closer look at energy deposition mechanisms reveals that decreasing the depth of the charge collection region within the substrate causes an increase in the importance of energy transfer from film to substrate, as compared to collecting charge under film over substrate thickness, or over entire substrate.
With a shallower charge collection region, current in dominated by neutron interactions.
Current closely follows energy deposition mechanisms as a majority of energy deposition is due to neutron interactions. Thus, current is essentially scaled linearly only with neutron flux.
Results

Electron Path Tracing
Gamma Source with Gd2O3 on Al2O3

Gd2O3 Film on Al2O3
Substrate as viewed from top.

Yellow dots = electron interaction in device
Red lines = electron escape from device

As with other substrates, gammas interact uniformly throughout substrate medium. Film is nearly “invisible” to photons (due to film’s relatively small thickness)

100,000 Gammas modeled
Neutron Source with Gd2O3 on Al2O3

Gd2O3 Film on Al2O3 Substrate as viewed from top.

Yellow dots = electron interaction in device
Red lines = electron escape from device

Neutrons tend to interact with film but also interact weakly in substrate.

100,000 neutrons sourced
Gamma Source with Gd2O3 on GaN

Gd2O3 Film on GaN Substrate as viewed from top.

Yellow dots = electron interaction in device
Red lines = electron escape from device

Gammas cause largest energy deposition in GaN substrate of the substrates studied, evidenced by the relatively longer paths of the electrons. This is due to the larger Z of Ga, which increases probability of higher energy transfer.

Gammas interact fairly uniformly throughout substrate. Film is nearly “invisible” to photons (due to film’s relatively small thickness).

100,000 Gammas modeled
Neutron Source with Gd2O3 on GaN

Gd2O3 Film on GaN Substrate as viewed from top.

Yellow dots = electron interaction in device
Red lines = electron escape from device

Neutrons tend to interact with film but also interact in substrate. Neutrons interact strongest and deposit most energy with GaN of the substrates studied. This is due to the relatively larger neutron interaction cross section with Ga and especially N through an (n,p) reaction.

100,000 neutrons sourced
Gamma Source with SiO2 on Si

SiO2 Film on Si Substrate as viewed from top.

Yellow dots = electron interaction in device
Red lines = electron escape from device

Gammas interact weakest with Si substrate of the substrates studied.

Gammas interact fairly uniformly throughout substrate. Film is nearly “invisible” to photons (due to film’s relatively small thickness)

100,000 Gammas modeled
Neutron Source with SiO2 on Si

SiO2 Film on Si Substrate as viewed from top.

Yellow dots = electron interaction in device
Red lines = electron escape from device

Neutrons interact weakest in Si substrate and SiO2 film, as expected.

100,000 neutrons sourced
Previous Work With Gd2O3 on Si – Gamma Interactions

Electron tracks (red) indicate fairly uniform gamma interaction within substrate with no preference of interaction with film or gold contacts.
Previous Work With Gd2O3 on Si – Gamma Interactions

Uniformity of electron tracks (red) through film edge further verifies unimportance of film or gold on gamma interactions.
Previous Work With Gd2O3 on Si – Neutron Interactions

Electron tracks (red) indicate preference of neutron interaction with film. Tracks also show the number of electrons escaping from front of device.
Previous Work With Gd2O3 on Si – Neutron Interactions

Pattern of electron tracks (red) through film edge shows importance of film on neutron interactions (left). The average depth of electron penetration into the substrate is about 30 um (right).