Radiation Hardness Studies

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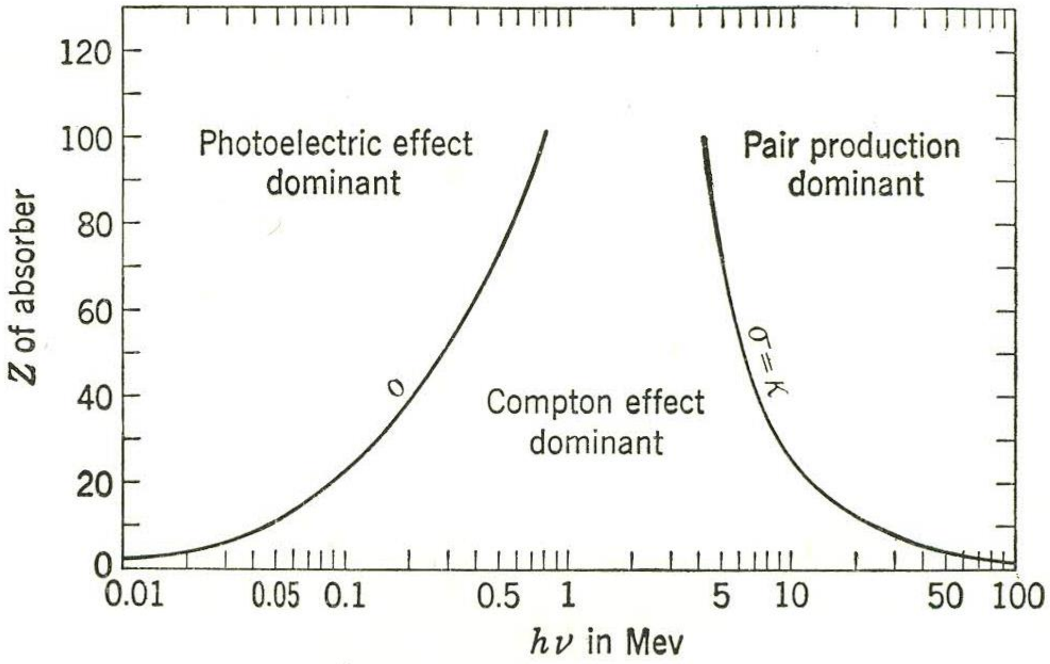
Similarities in Different Measurements

- There are 2 different ionizing radiation effects subjects addressed here.
- Optical materials
- Si- SiO_2 interface
- The two subjects seem disconnected but there are common factors in behavior.
- This is limited to ionizing radiation only (electron-hole pairs), meaning that there is no displacement damage from the radiation and no vacancies or interstitials created.
- Damage occurs primarily by the change of charge state on point defects (vacancies, interstitials, impurities), on surfaces or interfaces.
- First , consider sources of ionizing radiation what might be appropriate for radiation damage studies.

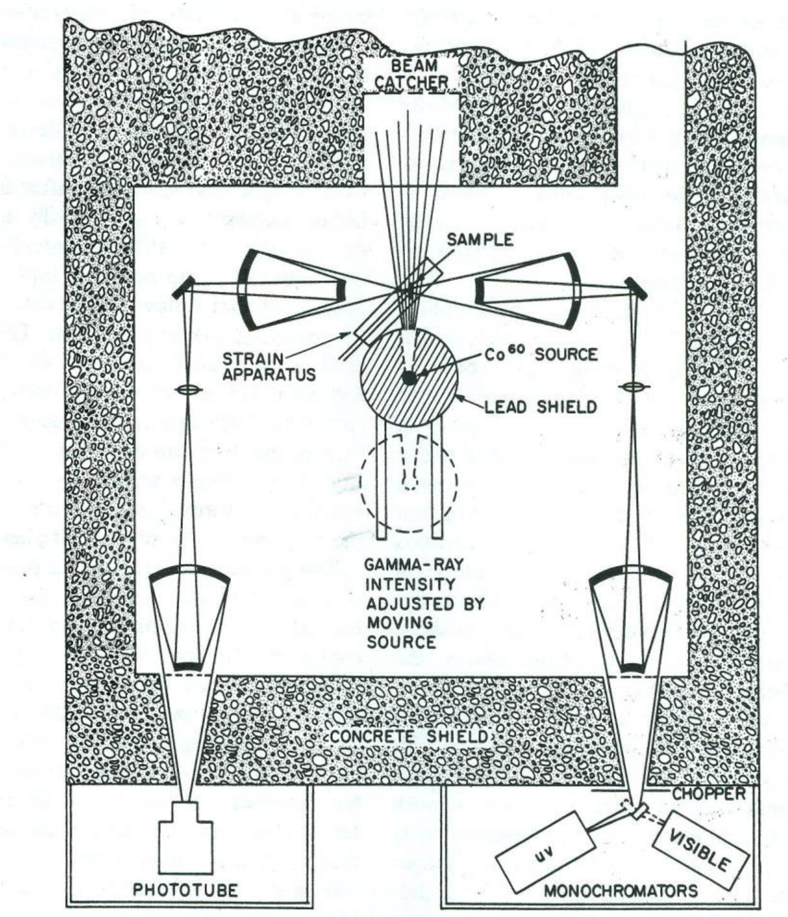
Effect of gamma or x-ray photon energy on testing

- Some care needs to be taken in selecting a radiation source for testing to avoid having the sample composition affect the deposited dose.
- Want the interaction to be Compton scattering, Why?
- ^{60}Co gammas average 1.25 MeV (1st order energy deposition is proportional to mass for all compositions)
- ^{137}Cs gamma is 667 keV (good for most materials)
- X-ray machines are useful in that high doses can be reached and the hazard goes away when they are de-energized. But they need to be considered carefully even for Z as low as silicon
- If available ^{60}Co is a very good general choice



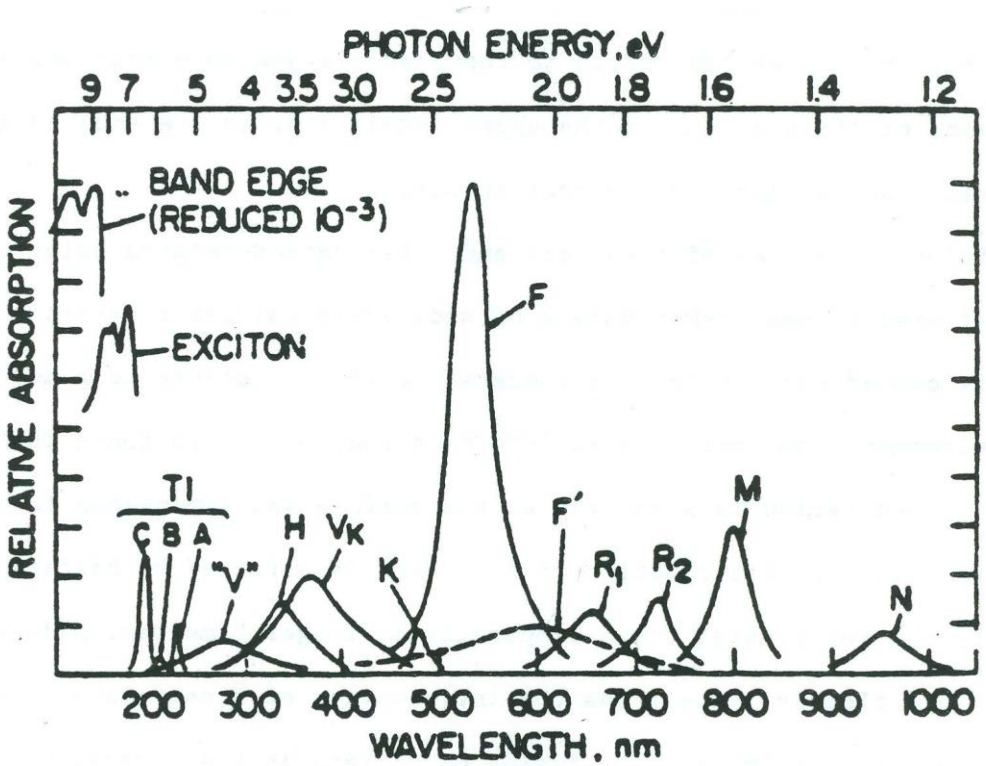
Solid State Gamma Irradiation Facility

- One facility that is available at Brookhaven is the Solid State Gamma Irradiation Facility which holds a 500 Ci ^{60}Co source.
- The facility is used for irradiation of materials and electronics but was originally used as a visible/UV spectrophotometer incorporating a radiation source. This was very useful for looking at optical materials during irradiation.
- Focal point of the optics in front of the source is fixed. The dose rate would be changed by moving the entire source shield.
- The optics beam is divided into sample and reference and also chopped.
- Luminescence in some samples interferes with the measurement and can be filtered through another monochromator (not shown).
- The spectrophotometer is not operational at this time.



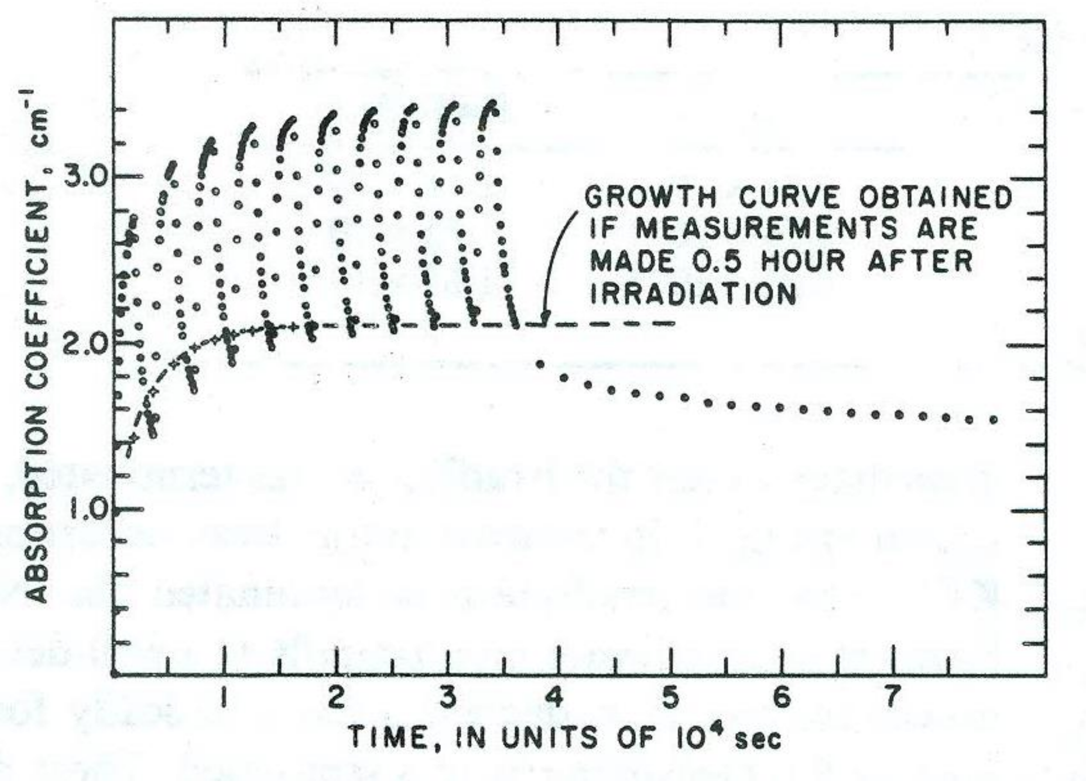
A typical example of point defect absorption bands in an Alkalai Halide

- Shown are some typical absorption in an alkalai halide crystal (NaCl, KCl, etc)
- An F-center is an electron trapped on a halogen vacancy site
- An M- center is made up of 2 adjacent F-Centers, R centers are 3 adjacent F-Centers
- Measuring at the peak of the absorption band during irradiation produces data proportional to the concentration of the center



Measurement showing growth and annealing of a color center

- Growth can be described by
- dn/dt = K(N-n), then n = N*(1 - exp(-Kt)) with no annealing
- n is concentration of color centers, N is number of precursor centers and K is proportionality constant incorporating dose rate, cross section for trapping, and so forth.
- Simultaneously there can be annealing described by
- -dn/dt=s*n*exp(-E/kT) = n * P
- s is attempt to escape frequency, E is trap depth, k is Boltzmann's constant
- Combining and solving gives n = N(K/(K+P)*(1 – exp(-(K+P)*t)) during irradiation
- The system is described by an exponential decay when the irradiation is interrupted
- Sample would trace out the lower curve if irradiated and measured after 30 minutes.
- There is some damage that does not anneal implying that the annealing is probably not from the F-center directly



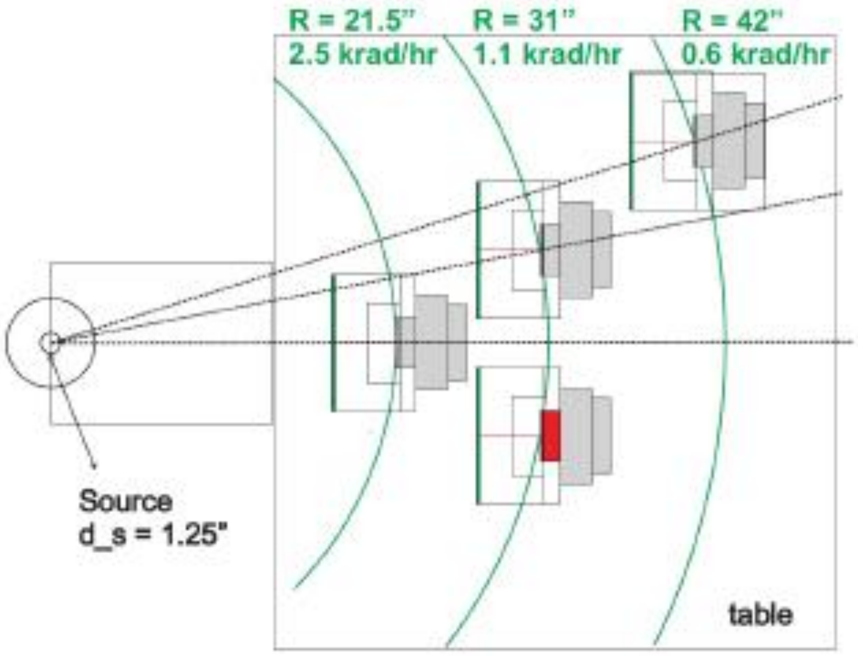
F-center absorption in KCl intermittently irradiated with ^{60}Co gamma radiation at 10 rad/hour. Irradiation is halted for 30 minutes and then resumed.

Observations from optical behavior

- Growth of an optical band might be described by a simple model for radiation induced coloring and thermal annealing
- If there are multiple overlapping bands this approach does not work
- If the measurement is made after irradiation there is a potential error based on the amount of annealing
- Preferable to measure during irradiation if possible
- This behavior (simultaneous growth and decay) describes other types of measurements during irradiation as will be shown in the example on CMOS

Radiation Test on 130 nm CMOS Technology Used in ABC Readout Chip

- The ABC (and ABC Star) readout chips are designed for use in the the Silicon Tracker in ATLAS
- There is expected to be high doses (Tens of Mrad over time) at dose rates of 5 Gray – 25 Gray/hour
- The chips are apparently immune from threshold voltage shift in gate oxides caused by trapped positive charge because the oxides are thin enough for tunneling electrons to recombine with the positive charge
- However, the field oxides are too thick for tunneling to work and so positive charge trapped along the interface with silicon causes current leakage
- The figure shows an experiment set up in the Gamma Irradiation Facility to test the leakage current generated by ionizing radiation at dose rates similar to the silicon tracker. Also at temperatures similar to the silicon tracker which are at -10 ^{o}C in this setup for 3 of the chips
- The leakage current is a function of Dose, Dose Rate, Temperature, and E- field.
- Leakage current measurements for any given ABC chip is at fixed temperature, fixed dose rate (irradiation is continuous) and fixed bias (e.g. fixed E-field) throughout the test

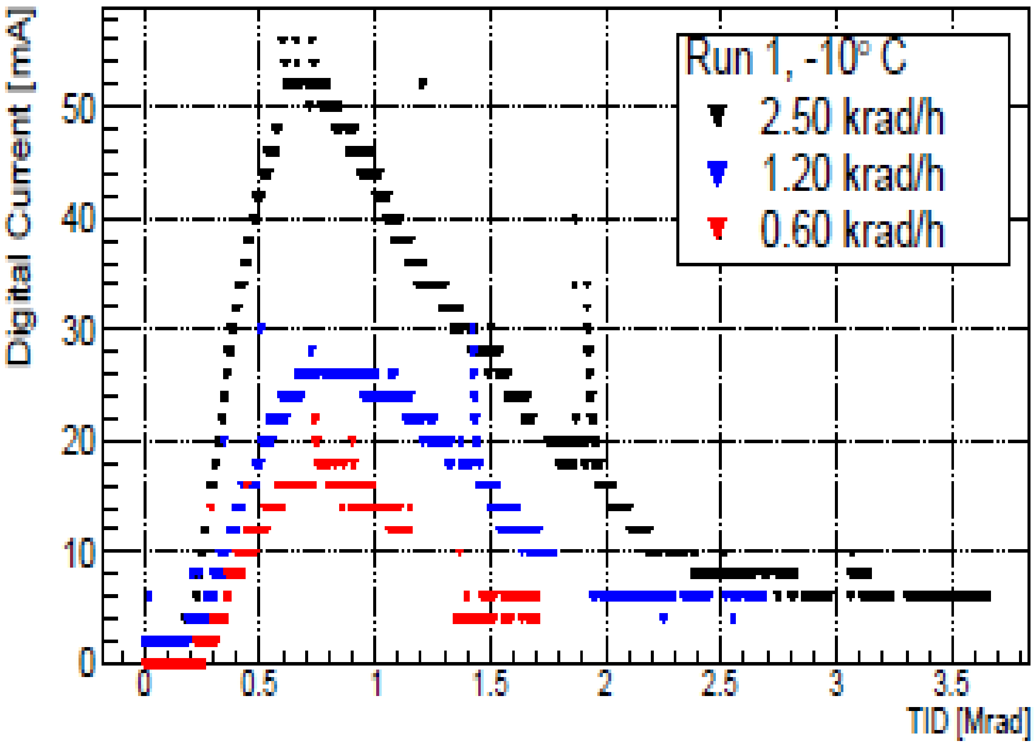


(a)

Stucci et al, TWEPP 2017

Leakage Current versus Dose for ABC chip

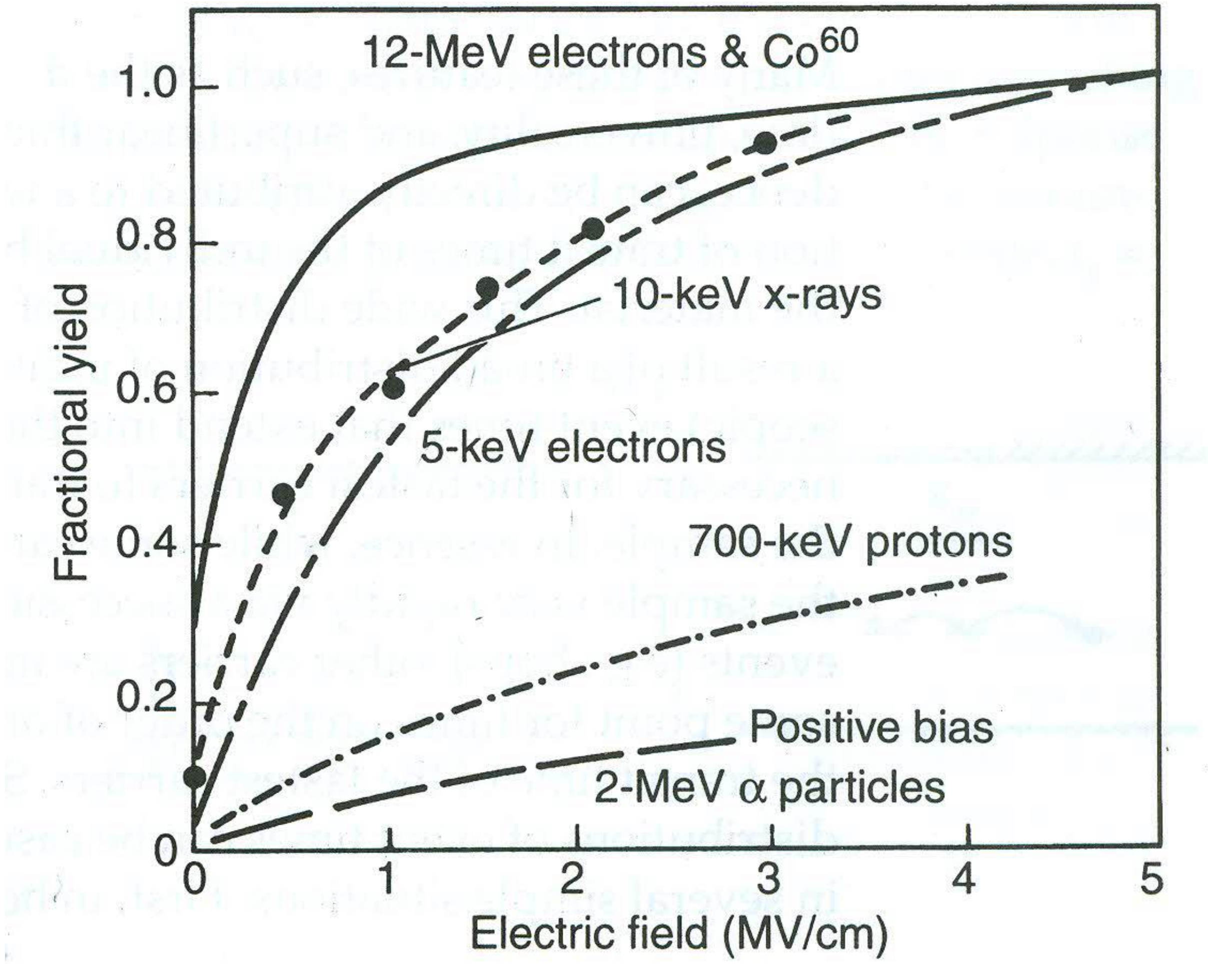
- Leakage current versus dose as produced by ionizing radiation is shown in the figure. The additional leakage current is a significant fraction of the normal operating current of the chip. Compensating for it requires a significant increase in the available power. This is inconvenient due to space requirements and the low operating temperature of the detector requiring an assessment of the cooling.
- Unfortunately, when the measurments were made the precision for the measurement of current was not as good as needed. This results in the step appearance of the curves.
- Qualitatively, the current increases to a maximum and then decreases to close to the starting value with sufficient dose. The maximum value increases with increasing dose rate.
- Following is some discussion on the physical basis for the leakage current.



Leakage Current induced by Ionizing Radiation in ABC read-out chip (Stucci et al, TWEPP 2017)

Fractional Electron/Hole Yield in SiO2 in E-field

- The E-field across the oxide affects the number of e-h pairs available for interaction with defects
- In the ABC read out chip the field is ~ E_{ox} = 1V/100nm = 100 kev/cm for the E-field across the field oxide
- The plot shows f_y (yield fraction) as a function of the oxide field for ^{60}Co, 12 MeV electrons and other ionzing radiations
- At 100 kev/cm, f_y is changing rapidly with electric field significantly changing the hole flux with field change. This is one possibility for how I_{leak} can change with E-field
- An E-field of 100 kev/cm on the unit cell level is ~ .005 eV/lattice constant so the field is ineffective in increasing diffusion or affecting tunneling.



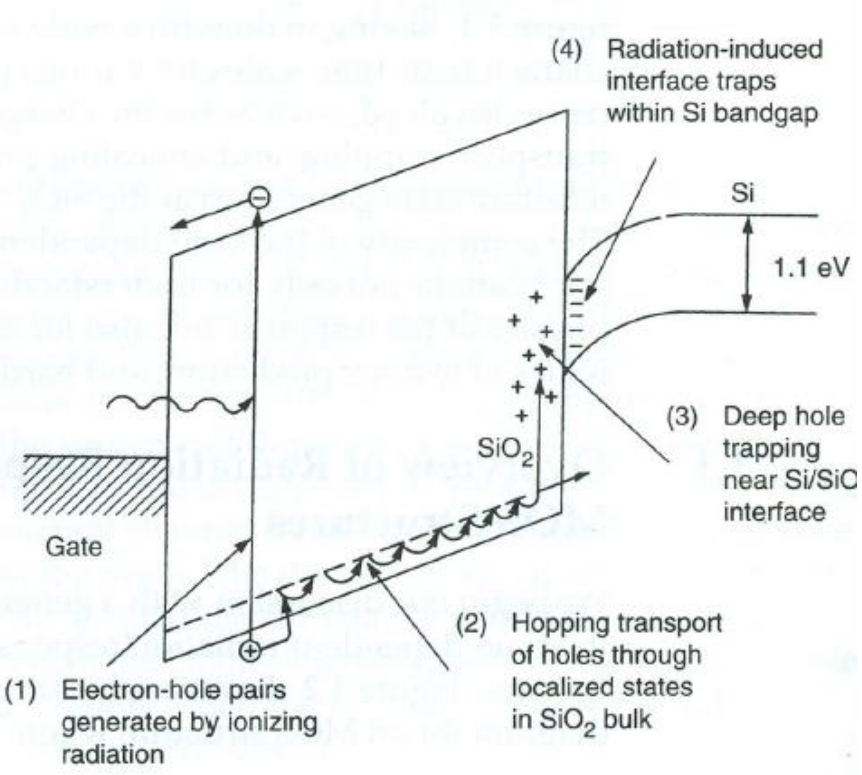
T. R. Oldham, *Ionizing Radiation Effects in MOS Oxides*. Singapore: World Scientific, 1999.

Defect Interactions

- Shown is a model of the field oxide with a biasing E-field during irradiation.
- The ionization electrons are swept out; the ionization holes “hop” to the interface and either recombine with electrons from the Si layer or get trapped in E’ traps (e.g. oxygen vacancies).
- A mobile radiation induced defect (e.g. neutral H, ionized H, hole) converts a Si bond into an electron trap. **Interface electron traps** are immediately filled with electrons when there is a positive bias across oxide.
- The hole traps (E’ traps) are concentrated along the interface between the oxide and the silicon because of the transition there from Si (no oxygen) to SiO^2
- The interface traps are too deep to thermally anneal at or below R.T. So are many of the hole traps (E’ traps).
- Holes that are in traps closer to the valence band may be thermally released (driven by trap depth and temperature).
- Holes that are close to the interface may be neutralized by electron tunneling (driven by distance from the interface, trap depth and E-field).
- The collective interaction of these processes make this difficult to accurately model.

This fraction depends greatly on the applied field

Figure 1.2. Schematic of radiation effects problem in MOS structures.



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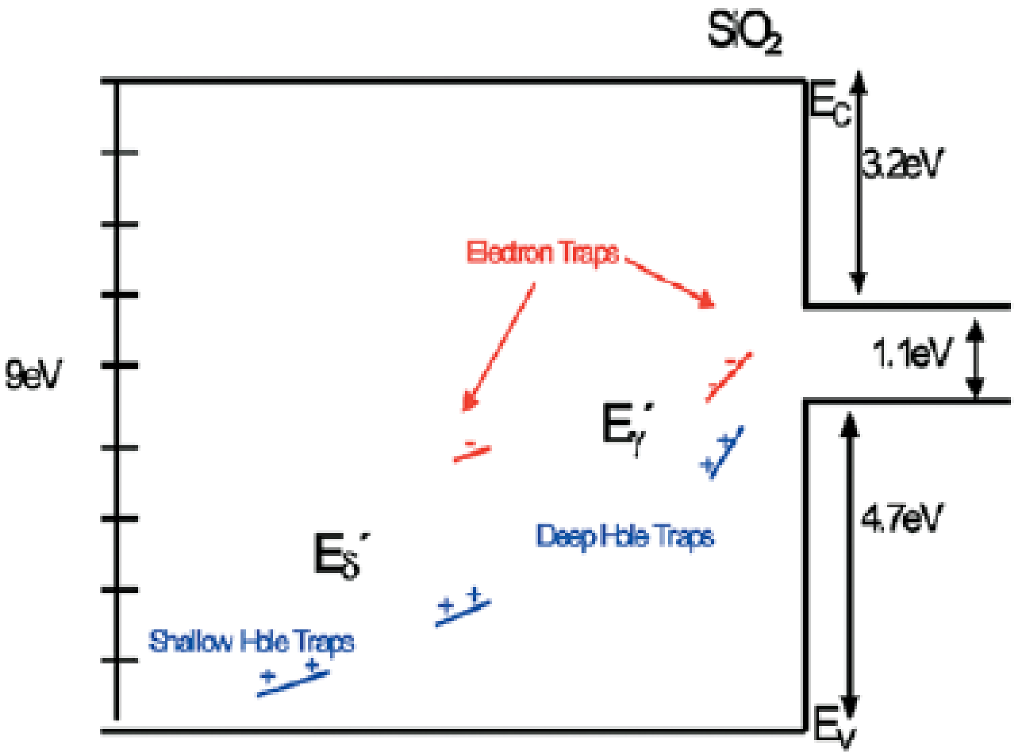
Oxygen Vacancy Trap Levels in Amorphous SiO_2

- The figure illustrates the energy levels of oxygen vacancies next to a silicon-silica interface.
- Oxygen vacancy traps in an amorphous SiO_2 structure are computed from 1st principles (Nicklaw et al, IEEE Trans Nuc Sci, Vol 49, p2667,2002).
- Blue represents hole traps, red electrons. The lines show the Energy depth range.
- The shallow hole traps are 0.5-1 eV in depth. It is likely that holes in these traps can be thermally untrapped at or below RT.
- The next group of traps according to the modeling is around 2 eV. These would be stable at RT.
- The trapped holes close to the interface can be neutralized by electron tunneling which represents another mechanism for recombination.



Leakage Current relations

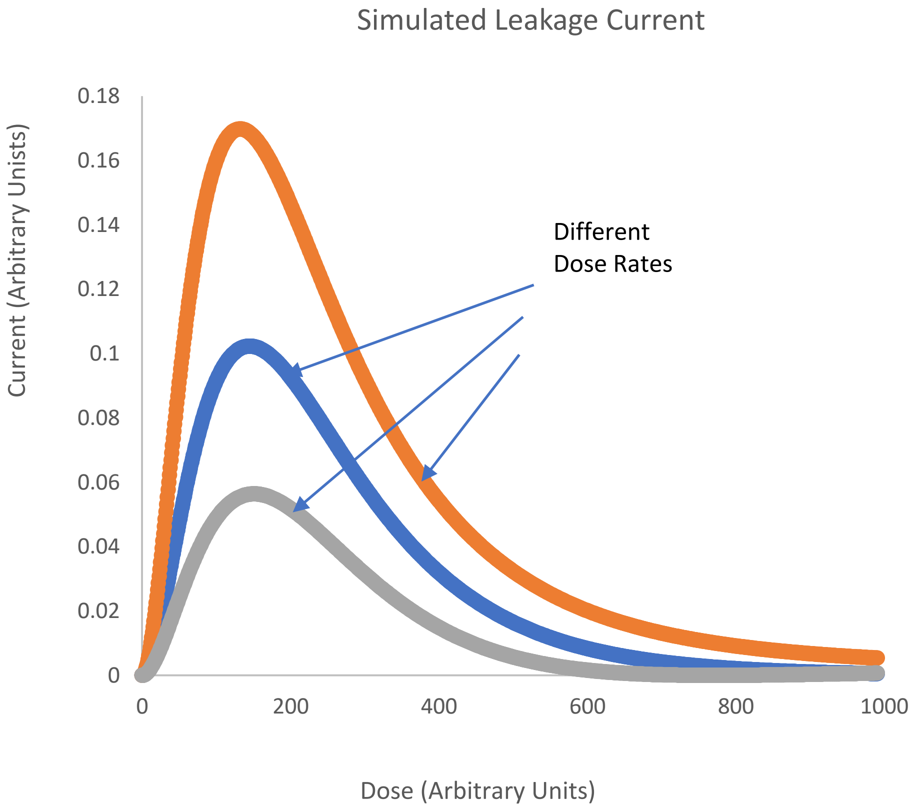
- The leakage current is caused by a net positive charge on the interface between the SiO_2 and the Si in some of the region of the field oxide
- $I_{leak} = K(n_E - n_i - N_{Thr})^2$, $I_{leak} = 0$ if $(n_E - n_i - N_{Thr}) < 0$
- K is a constant and N_{Thr} is threshold number of trapped holes needed to create any leakage current. Assume this is zero here. (e.g. $I_{leak} = K(n_E - n_i)^2$)
- n_E = number of trapped holes at time (or dose)
- n_i = number of activated interface states (trapped electrons) at time (or dose)
- It is assumed the number of precursors for n_E and n_i (oxygen vacancy hole trap, N_{Eh} and dangling Si bond, N_i) are fixed. It is also assumed that most of the oxygen vacancies are very close to the interface.
- n_E and n_i are in general functions of time, dose rate or dose, temperature and applied field (across the oxide). It is also assumed that the generation of n_E and n_i are totally independent.

Equations for Thermal Untrapping of Trapped Holes at a trap depth of E

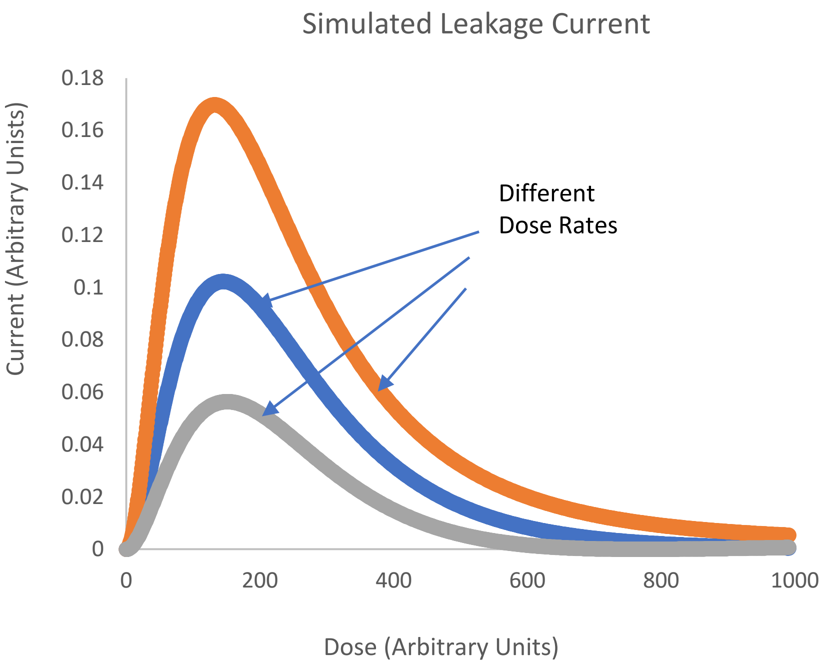
- The following assumes that untrapped holes migrate away from the hole trap leaving the original oxygen vacancy.
- N_{Eh} = hole trap concentration at a trap depth E(constant)
- n_E = concentration of trapped holes at trap depth E (variable)
- A = rate constant (scales with dose rate D_R), P_E = untrapping prob. at trap depth E (constant)
- $dn_E/dt = A(N_{Eh}-n_E) - P_E*n_E$ (1) then
- $n_E/N_{Eh} = ((A/(A+P_E))*(1-\exp(-t(A+P_E)))$
- $P_E=s_E*\exp(-E/kT)$, s_E is attempt to escape frequency, E is trap depth, and k is Boltzmann's constant
- Note at long times $n_E/N_{Eh} = A/(A+P_E)$
- This is an approximation since the traps are not all at the same trap depth. To cover all hole annealing the equation (1) above would have to be varied in E for the active traps near the valence band (< 1 eV depth at RT). This would still be a saturating exponential
- When the irradiation is stopped $n_E= n_{E0}* \exp(-tP_E)$ where n_{E0} is concentration at end of irradiation.
- This works for shallow traps at room temperature. Deeper traps have much longer time constants at RT
- Similar arguments apply to the hole traps neutralized by tunneling. This mechanism can also be represented by a saturating exponential,

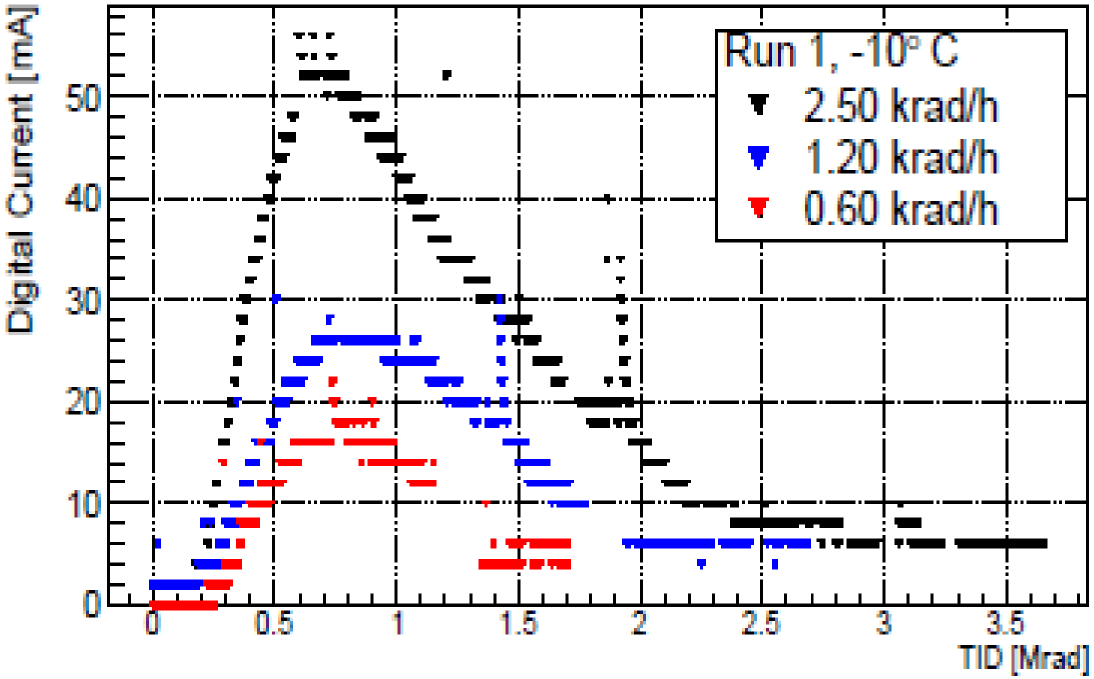
Dose Rate Effect on Leakage Current

- $I_{leak} = K(n_E - n_i)^2$ is leakage current relation, $n_E - n_i > 0$
- $n_E / N_{Eh} = (A/(A+P_E))*(1-\exp(-t(A+P_E)))$ is fraction of hole traps of depth E that are filled
- The fraction of interstitial electron traps filled is described in a similar fashion to the hole traps except that at room temperature the trapped electrons are do not thermally untrap.
- Then $n_i/N_i = (1-\exp(-A_i t))$, where n_i/N_i is fraction of interface traps filled and A_i is rate constant proportional to dose rate
- $I_{leak} = N_{Eh}((A/(A+P_E))*(1-\exp(-t(A+P_E))) - N_i(1-\exp(-A_i t)))^2$
- Varying dose rates gives the response in the figure.



Comparison of Simulation with Leakage Current Data from Readout Chips for Silcon Tracker, ATLAS





Stucci et al, TWEPP 2017

- In comparing the data against the simulation there is obviously similarity in behavior
- There is a new set of measurements that is ongoing which is very similar and curve fitting simulations are being done

Conclusions and Further Work

- This detail of study is warranted because the leakage current adds a significant increase to the power requirements of the detector.
- The readout chips are irradiated at different dose rates depending where they are located in the detector. Since the amount of leakage current is dose rate dependent this makes it difficult to predict the total leakage current from all the ABC chips
- The behavior of the leakage current is consistent with the model. However, remember that this only shows consistency and doesn’t prove the model is correct.
- Based on these types of measurements on the ABC chips serious consideration is being given to the idea of pre-dosing the chips on either the wafer or chip level. Since no bias would be applied this requires verifying that the leakage current behavior is similar under no-bias conditions

Thank You
For Your Attention!

Fractional Hole/Electron Yield

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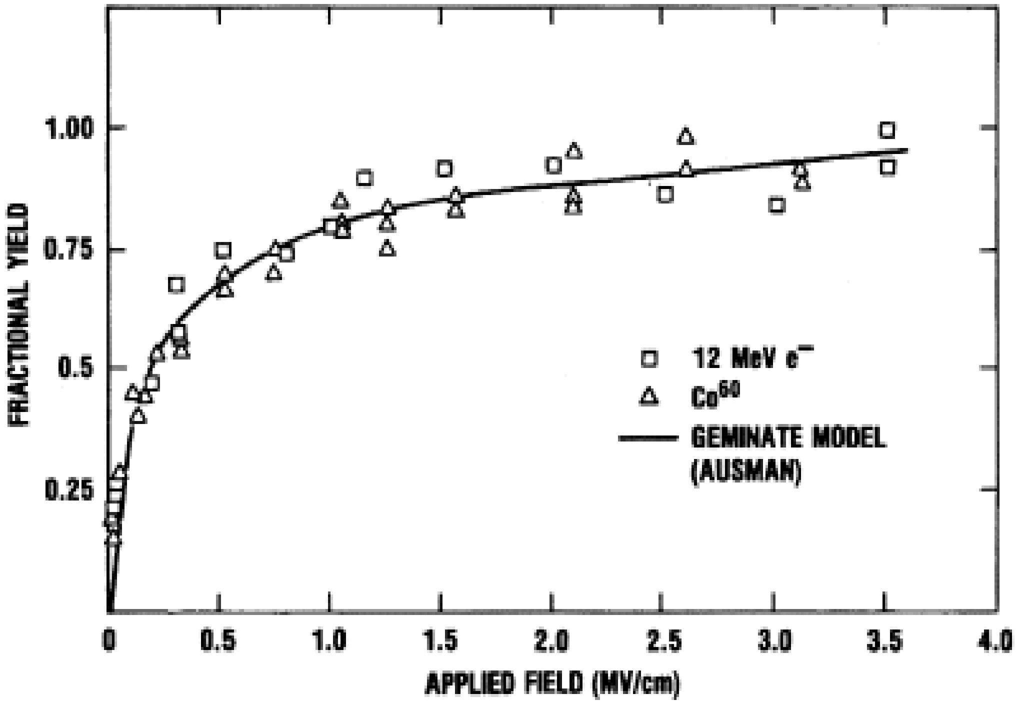

Fig. 5. Fractional yield as a function of applied field for Co60 gamma rays, 12-MeV electrons, and geminate model calculations [7], [11], [17].

Oldham and McLean IEEE Trans Nuc. Sci. vol 50, No.3 June 2003)