Electron and Proton Radiation Effects on Carrier Dynamics in MBE and MOCVD Grown Photovoltaic Test Structures

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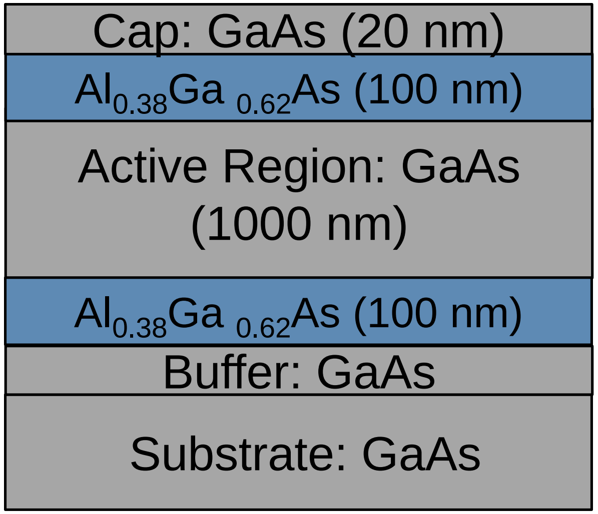
Project Overview

- Investigate effects of e^- and p^+ exposure on optoelectronic properties of AlGaAs/GaAs double heterostructure (DH) test articles using steady state and time resolved photoluminescence.

- Compare effects on MBE and MOCVD grown test articles.

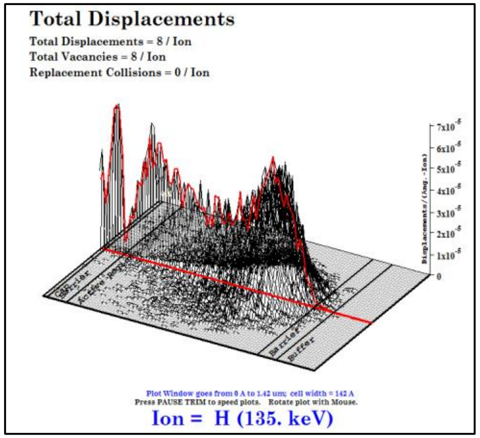
- Active regions doped unintentionally (UID), *p*-doped (Be or Zn) and *n*-doped (Si) to concentrations of approximately $1x10^{16}$, $5x10^{17}$ and $1x10^{19}$ cm^{-3}.



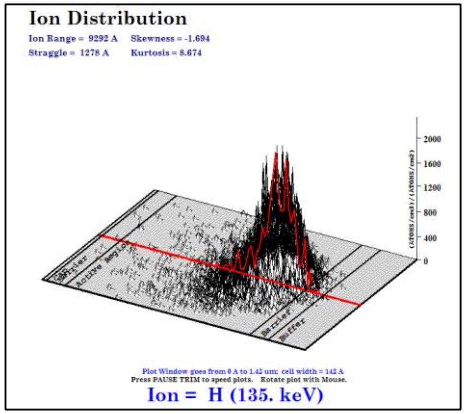
Particle Energies

- Electrons – 1 MeV. Capable of generating displacement damage and other non-ionizing effects.

- Protons – 135 keV. Ion implantation and radiation effects in DH's modeled using SRIM (Stopping Range of Ions in Matter) simulator.



Proton Generated Displacements



Proton Deposition

Defects form throughout the active region bulk. Protons implanted into active region.

Sample Exposure

- Protons - 135 keV. Doses: $1x10^{10}$, $5x10^{10}$ and $1x10^{11}$ p^+/cm^2. Sample irradiation at The Aerospace Corporation Low Energy Accelerator Facility (LEAF).

- Electrons – 1 MeV. Doses: $1x10^{12}$, $1x10^{13}$ and $1x10^{14}$ and $5x10^{14}$ e^-/cm^2. Sample irradiation at Boeing Radiation Effects Laboratory (BREL).

Steady-State Photo-Luminescence Characterization (SSPL)

- Steady-state (*i.e.,* time invariant) photo-luminescence at constant carrier density excited by controlled irradiance from continuous wave laser.

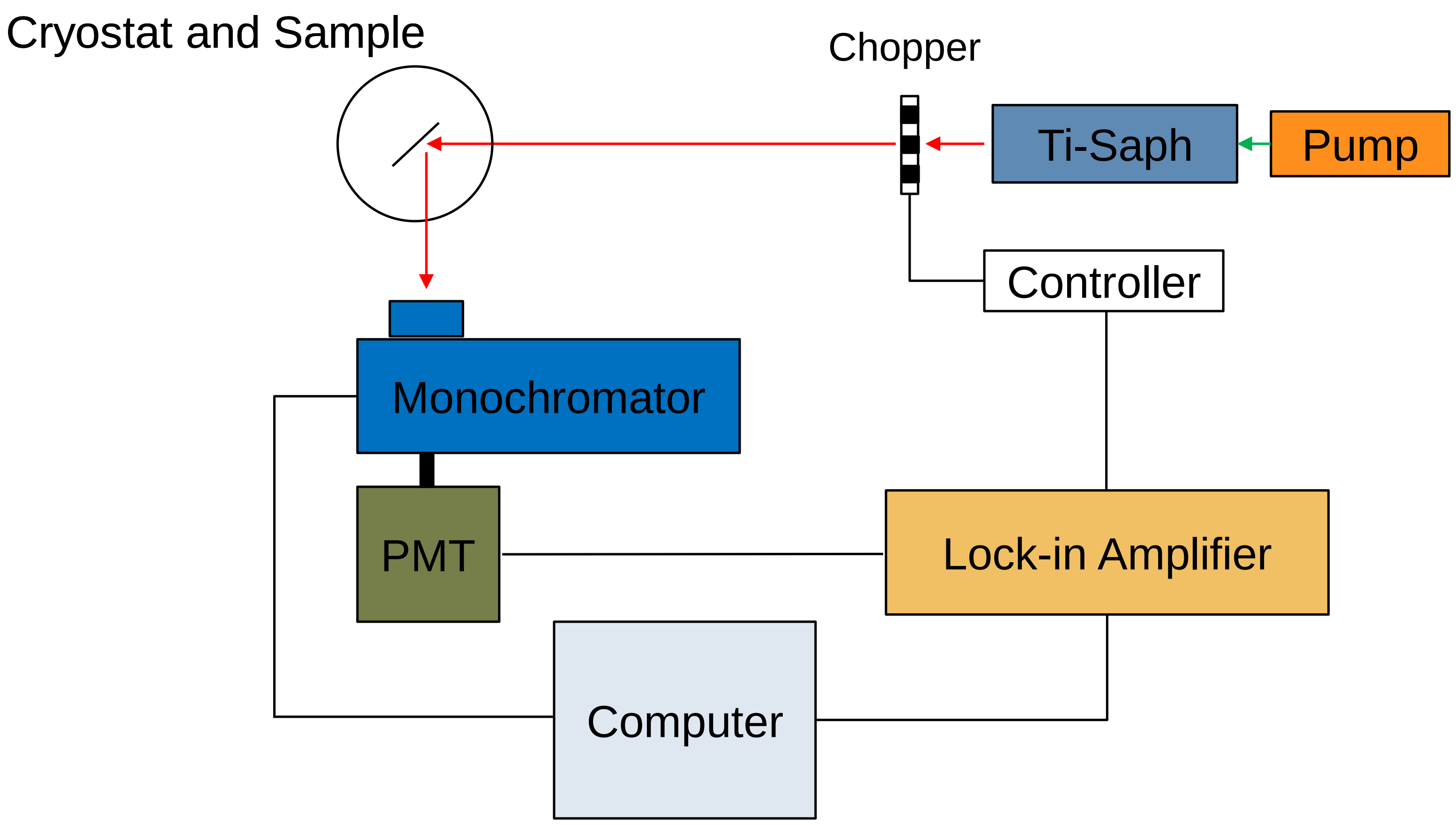
- Analysis of photo-luminescence spectra facilitates identification of radiation induced sub-bandgap energy states.

- Performed at ~ 5 K to resolve energy states via carrier recombination.

- Not as comprehensive as deep level transient spectroscopy for defect identification. However, SSPL can reveal the possible presence of specific trap states[1].

[1] Appl. Phys. Lett., 36(8), pp. 664-666 (1980).

SSPL Characterization System



Exciton Defect States

Defect mediated recombination at cryogenic temperatures

Free-To-Bound Transitions[2]

(eV +/- 0.3 meV)	Δ (1.519–FB)
C: 1.4935	25.5 meV
Si: 1.4850	34.0 meV
Ge: 1.4790	40.0 meV
Sn: 1.349	170.0 meV
Zn: 1.4888	30.2 meV
Cd: 1.4848	34.2 meV
Be: 1.4915	27.5 meV
Mg: 1.4911	27.9 meV

Exciton Bound to Neutral Acceptor Transitions[2]

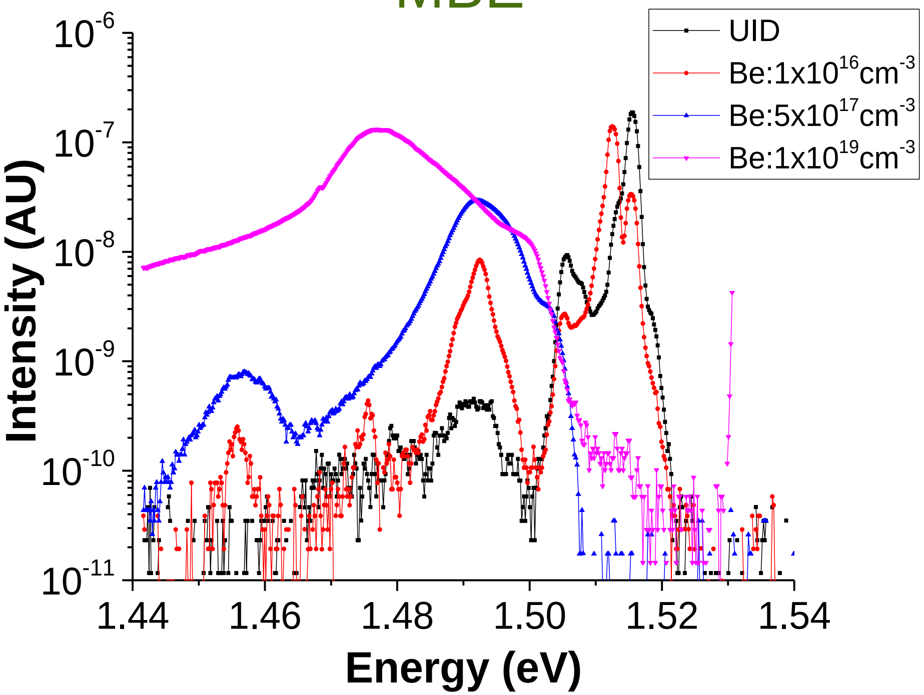
(eV +/- 0.05 meV)	Δ (1.519–BE)
C: 1.5124	6.6 meV
Si: 1.5123	6.7 meV
Ge: 1.5126	6.4 meV
Sn: 1.5067	12.3 meV
Zn: 1.5122	6.8 meV
Cd: 1.5123	6.7 meV
Be: 1.5124	6.6 meV
Mg: 1.5124	6.6 meV

Red: candidate assignments for measured spectra.

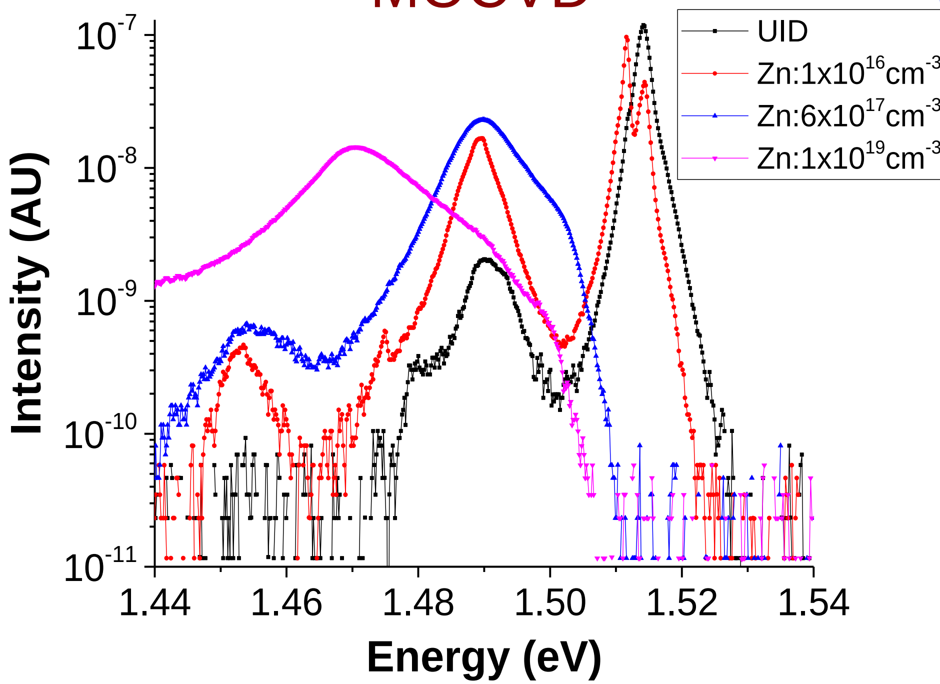
[2] ***J. of Phys. and Chem. of Sol., 36, pp. 1041-1053 (1975).***

DH Characterization Prior to Irradiation: MBE and MOCVD Grown UID and p-Doped (Be or Zn) – 5 K

MBE



MOCVD



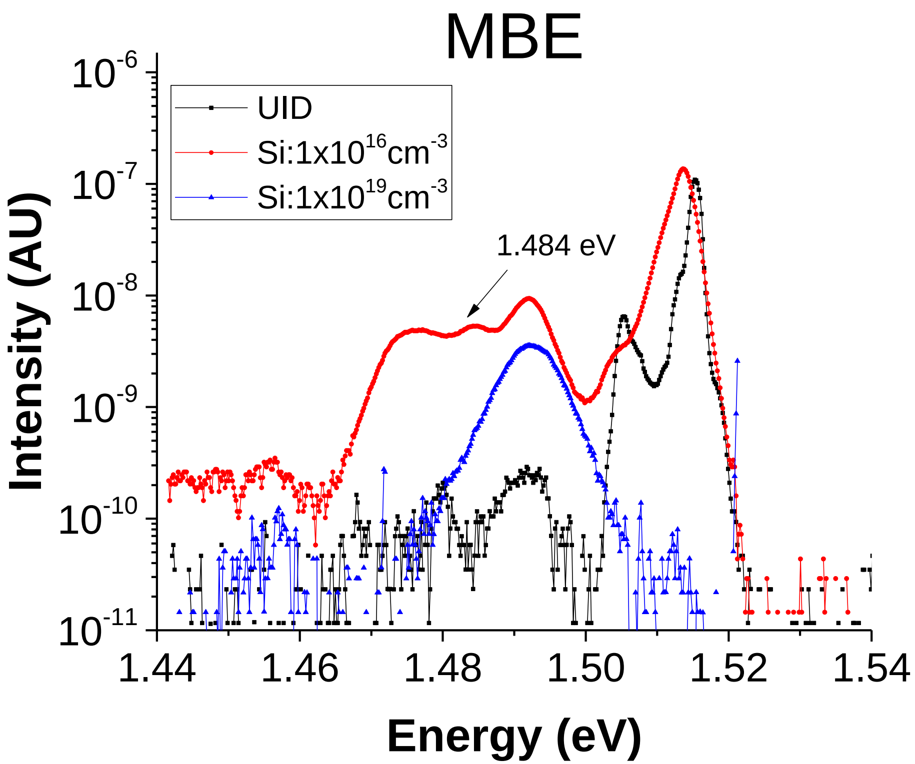
***MBE**: possible phonon mode at ~ 1.456 eV. Possible Be defect in UID and p-GaAs DH (Be $1x10^{16}$ cm^{-2}) at ~ 1.492 eV.*

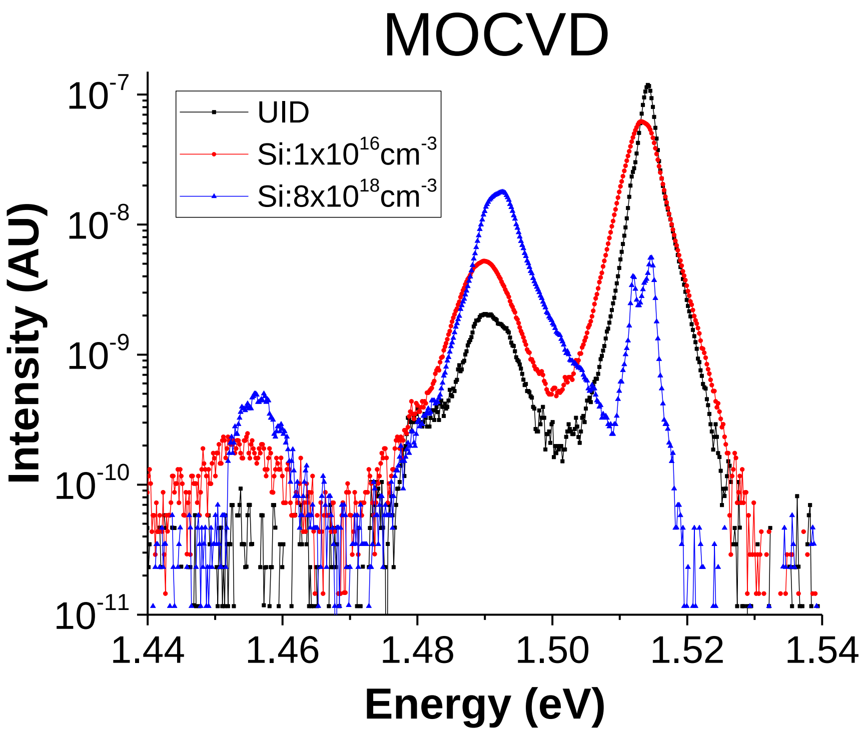
***MOCVD** Potental phonon mode and defect state energies similar to those for MBE samples. 1.505 eV feature specific to MBE growth.*

MBE and MOCVD - Bandstructure broadening for Be ($5x10^{17}$ cm^{-2}) at ~ 1.492 eV and Be ($1x10^{19}$ cm^{-2}) at 1.477 eV may indicate Mott transition and bandgap renormalization respectively[3].

[3] Fund. of Semicond., Phys. and Mat. Prop., pp. 342-355, 4^{th} Ed., Springer (2010).

DH Characterization Prior to Irradiation: MBE and MOCVD Grown UID and n-Doped (Si) – 5 K



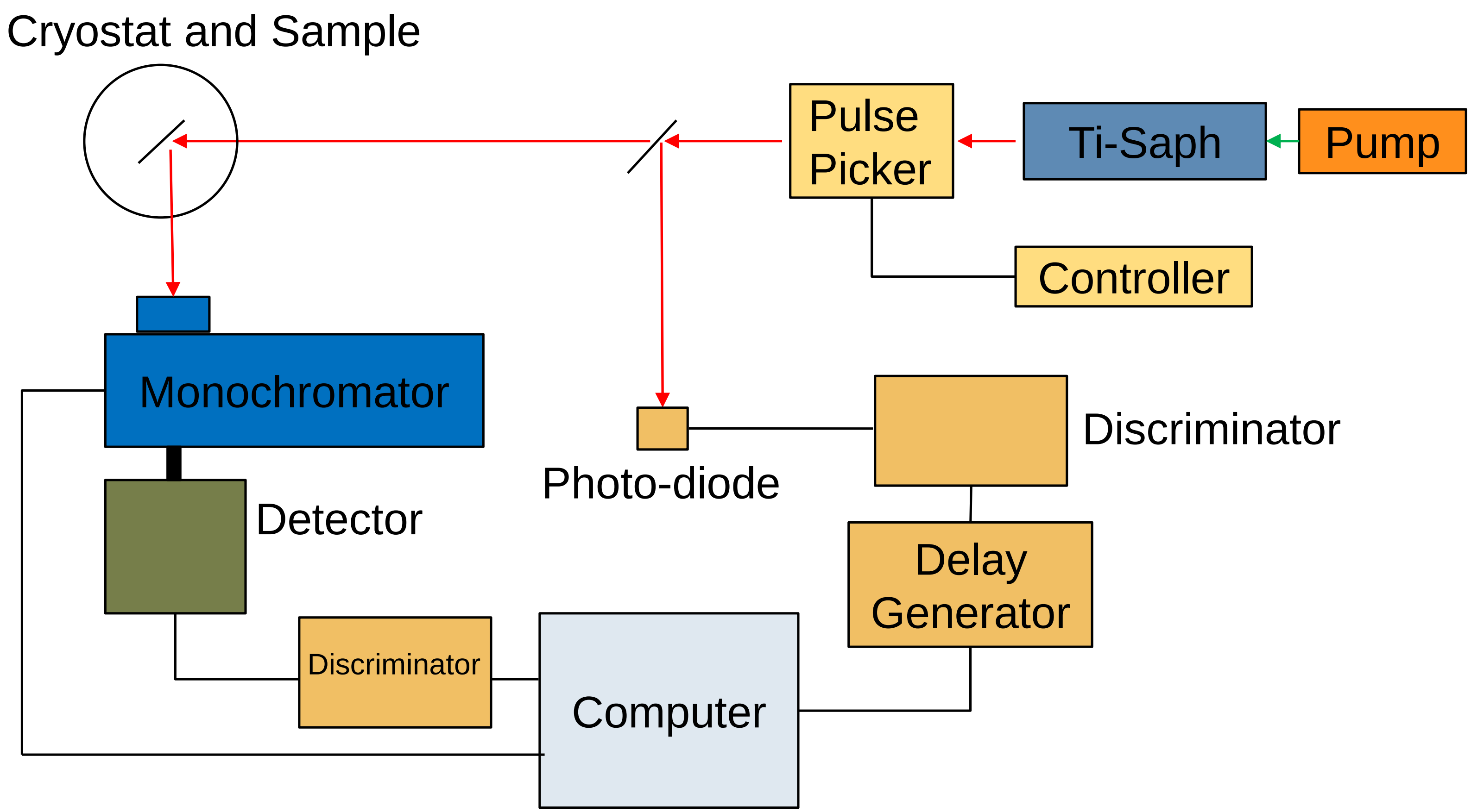


MBE - State at ~ 1.484 eV, left, could be bandedge phonon mode or a silicon defect state.

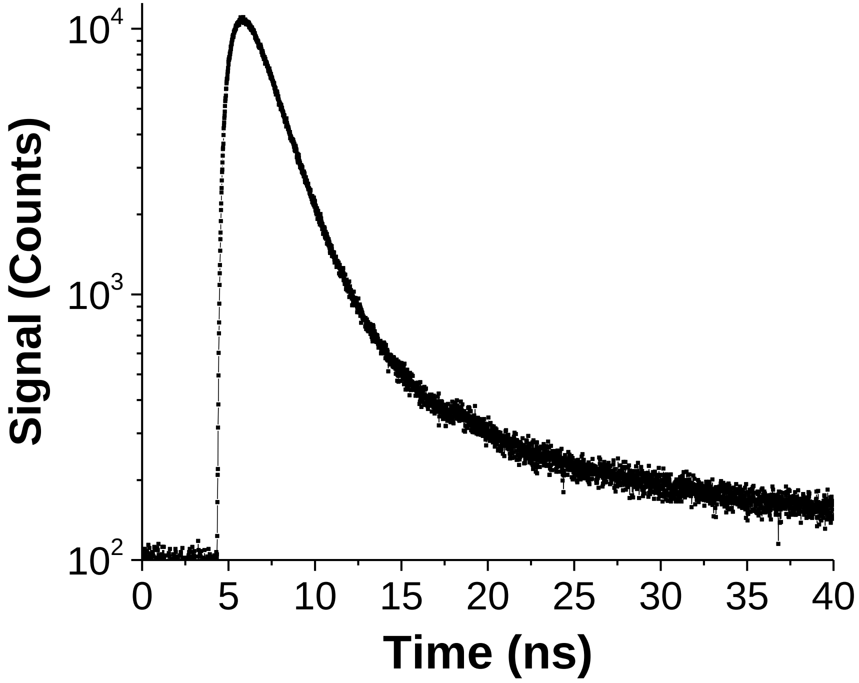
Time Resolved Photo-Luminescence Characterization of Materials (TRPL)

- Transient population of carriers excited by mode-locked Ti:Sapphire laser operating with ~ 200 femtosecond pulse duration.
- Pulse rate adjusted (via pulse picker) to ensure complete excess carrier relaxation prior to next excitation pulse.
- Time-correlated single photon counting (TCSPC) used to monitor radiative carrier relaxation.
- Performed at room temperature for examination of bandedge luminescence lifetimes exceeding detector impulse response function (IRF) limit.

TRPL Characterization System



TRPL Measurements of Carrier Recombination

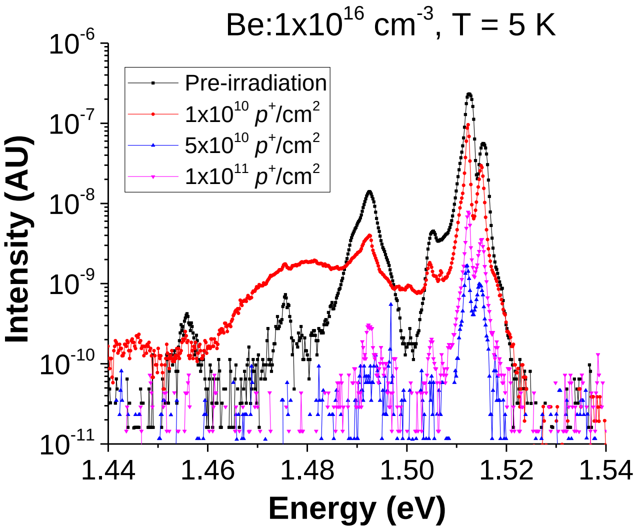


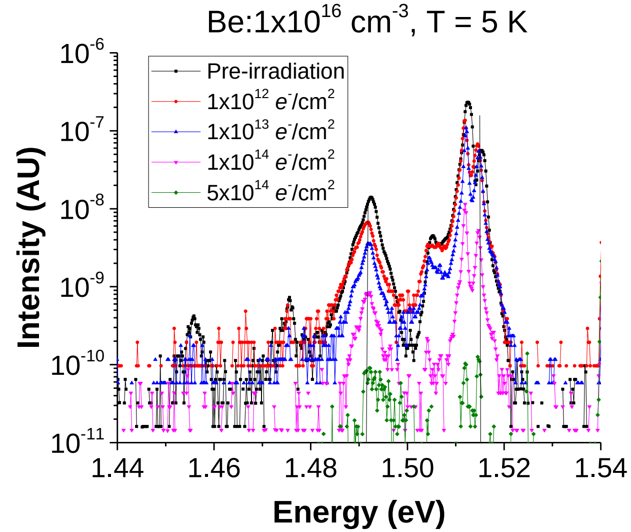
- Decay not first-order: multiple independent carrier recombination channels and/or carrier density dependent effects.
- Intensity weighted average lifetime characterizes overall carrier relaxation rate. The time constants from each multi-exponential term is weighted by its fractional contribution (f_i) to the decay profile: $\tau = \sum_i f_i \tau_i$, $f_i = A_i\tau_i/(\Sigma_i A_i\tau_i)$ where A_i, τ_i are the amplitude and e^{-1} time of i^{th} exponential.

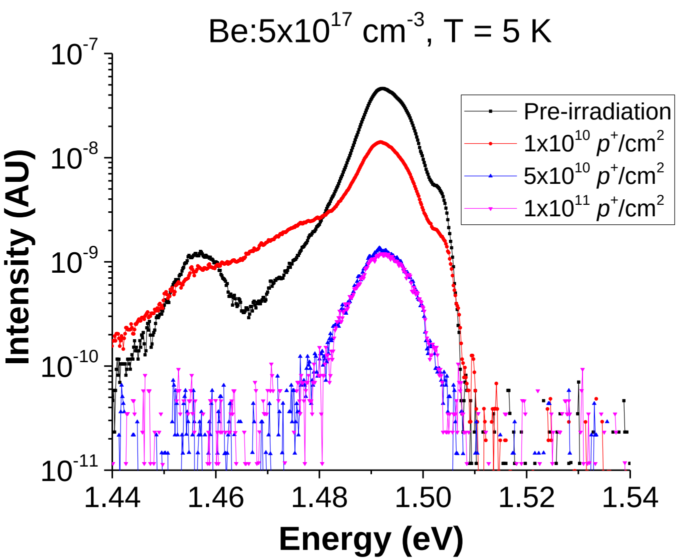
Radiation Effects on Low Temperature Bandedge/Defect State Emission

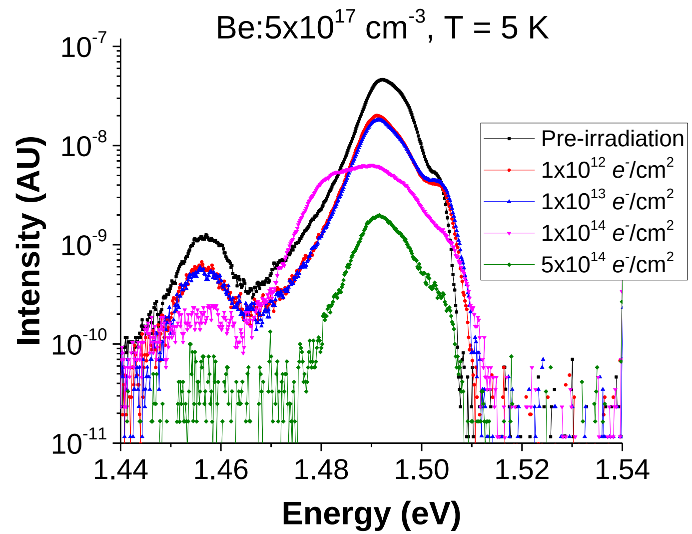
Proton and Electron Exposures: p-type

MBE







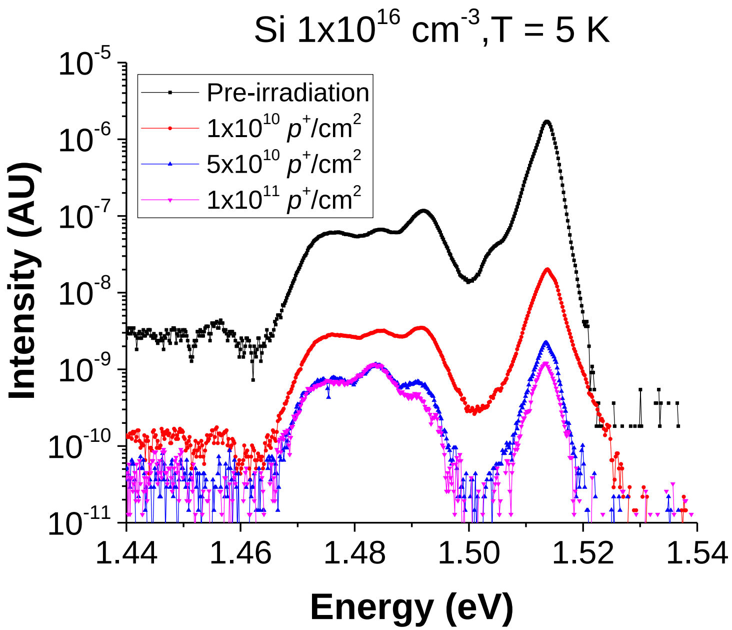


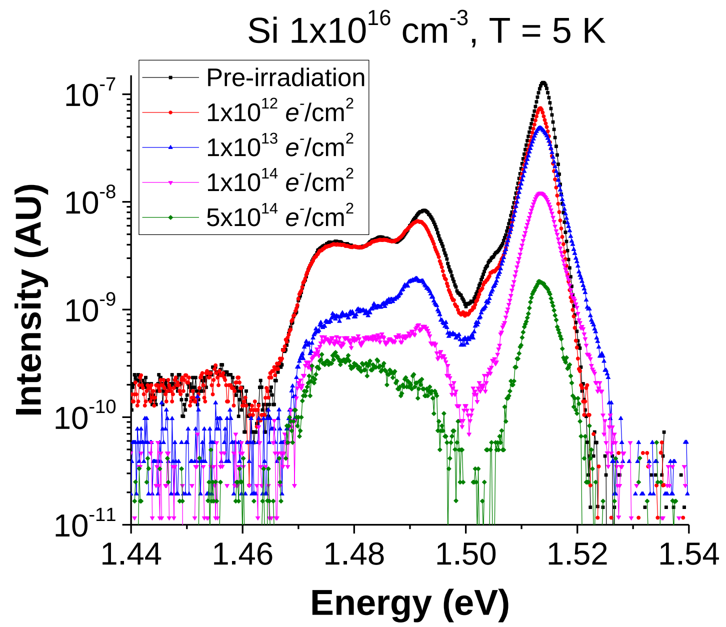
Implanted protons constitute trap centers in GaAs[4] (left, features induced at lowest dose in lowest p-doped samples).

[4] J. Appl. Phys., 100(034503), pp. 1-7 (2006).

Proton and Electron Exposure Comparison: n-type

MBE

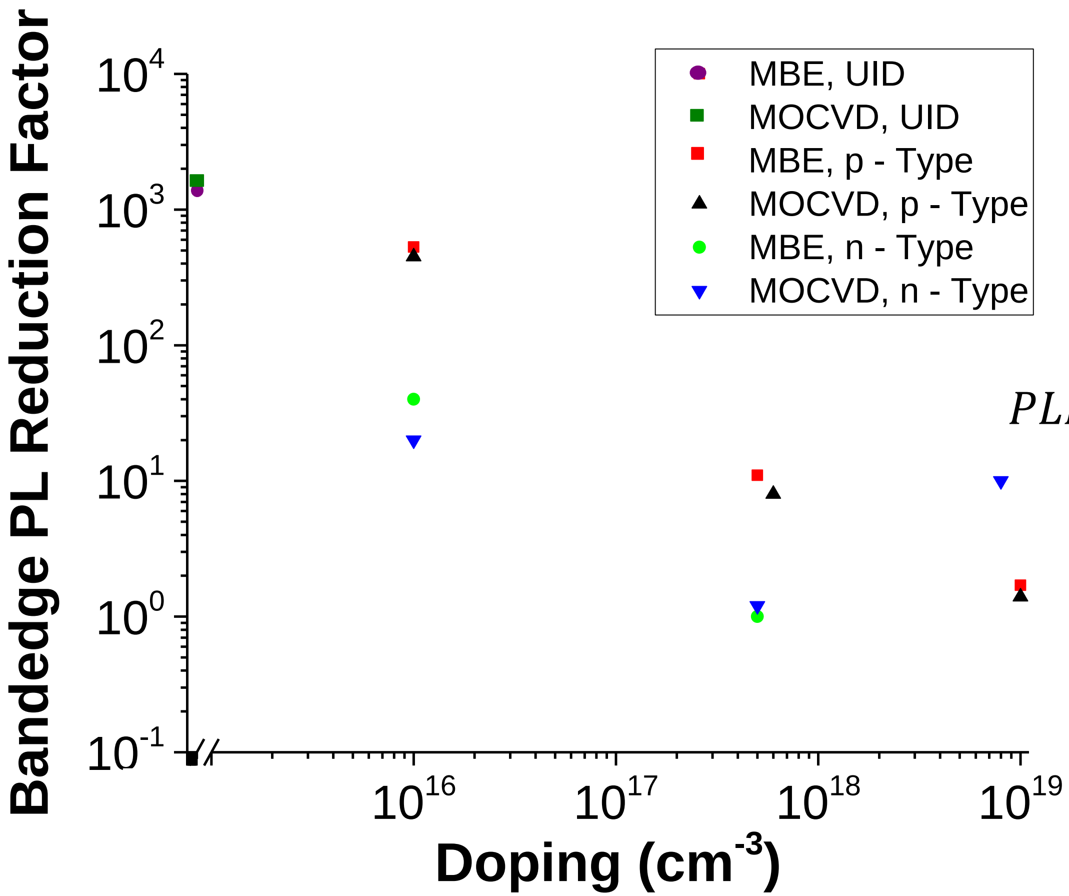




Hydrogen ions passivate shallow donor states in GaAs possibly by direct bonding to donor[4]. No resolvable evidence for proton induced trap state formation or state passivation in n-type samples. For these, majority of carrier recombinations could occur at the bandedge or at shallow donor states, unaffected by trap formation.

Electron Radiation Induced Bandedge PL Reduction

Comparison between lowest and highest doses



$$PLRF = \frac{I(Dose = 1x10^{12}\ e^{-}/_{cm^2})}{I(Dose = 5x10^{14}\ e^{-}/_{cm^2})}$$

n-type samples appear to be more radiation hard for both growth methods. p-type sample resilience increases with doping density.

SSPL Summary

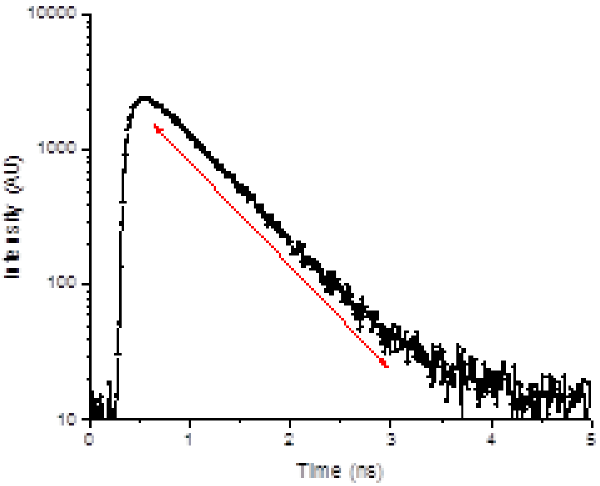
- Low temperature SSPL reveals defect states potentially associated with dopants and impacted by radiation exposure.
- Possible proton radiation induced trap formation for *p*-type samples. No evidence of donor state passivation.
- Greater radiation induced bandedge PL reduction for *p*-type than for *n*-type samples. *p*-type sample resilience increases with doping density.
- Radiation induced hole trap formation not as rigorously examined for *p*-type GaAs as for *n*-type[4,5]. More analysis of radiation effects in *p*-type GaAs warranted.

[4] J. Appl. Phys., 100(034503), pp. 1-7 (2006).
[5] J. Appl. Phys., 53(2), pp. 8691-8696 (1982).

Radiation Effects on Recombination Coefficients

Rate Equation at Low Carrier Injection

- Rate equation: $$\frac{\partial \rho}{\partial t} = -(BN + k_{nr})\rho - B\rho^2$$
- Low injection condition: $$\frac{\rho}{N} \ll 1; \quad B\rho^2 \ll BN\rho$$
- Modified rate equation: $$\frac{\partial \rho}{\partial t} \cong -(BN + k_{nr})\rho$$
- Mono-exponential decay lifetime: $$\tau_o^{-1} = (BN + k_{nr})$$
- Linear fit of decay lifetime inverse as a function of doping level to estimate B and k_{nr}.



Pulse energy ~ 1 nJ, pump angle of incidence to cryostat = 32^o, CaF_2 cryostat window, GaAs sample cap, spot size radius of ~ 250 μm, and e^{-1} attenuation length in GaAs of 1 μm → a peak carrier density of < <u>1x10^{15} cm^{-3}</u> (ignores losses at optics).
1x10^{15} cm^{-3} <lowest doping = 1x10^{16} cm^{-3} (low injection approximation valid).

Non-Radiative Coefficient

Radiation Effects

- Definition of lifetime damage coefficient[6] (k_τ):

$$\tau^{-1} = \tau_o^{-1} + k_\tau \phi; \qquad \phi = \text{radiation fluence}$$

$$\tau^{-1} = (BN + k_{nr}) + k_\tau \phi$$

- Radiation modified non-radiative coefficient:

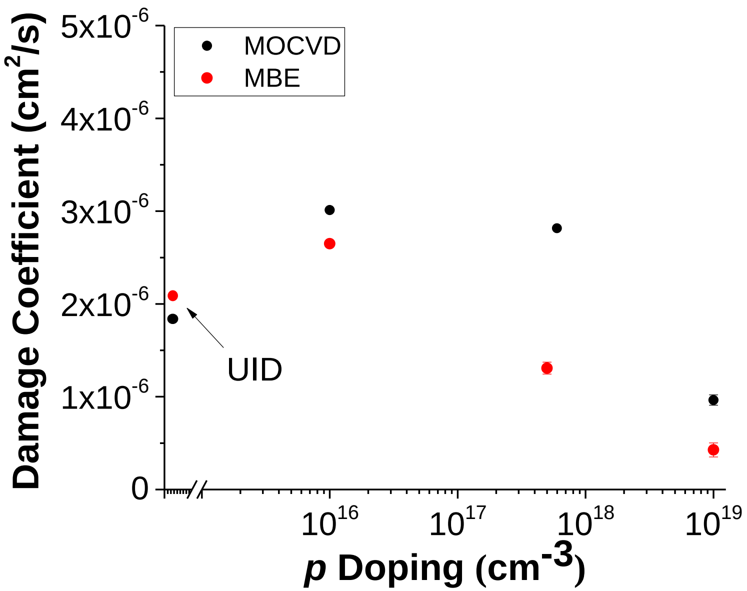
$$k_{nr}(modified) = k_{nr} + k_\tau \phi$$

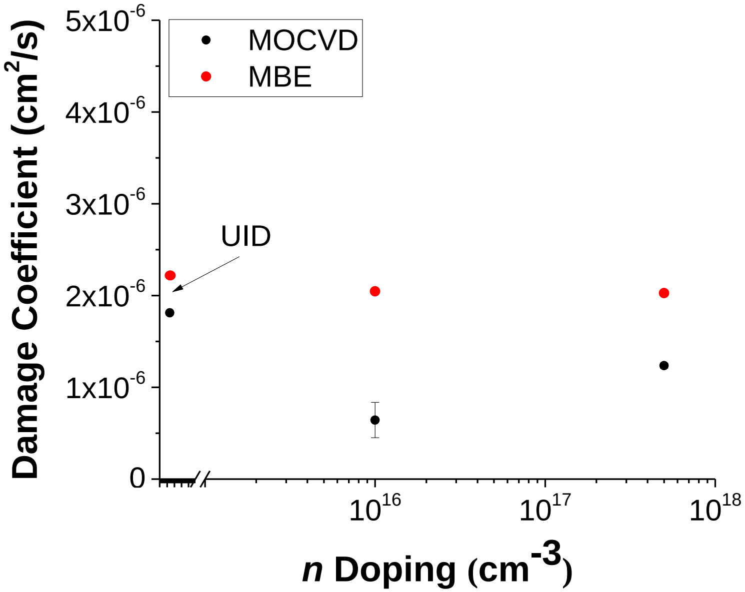
Radiation damage to the bulk increases the rate of non-radiative carrier recombination.

[6] IEEE Trans. on Nuc. Sci., 43(6), pp. 2601-2608 (1996).

Lifetime Damage Coefficients

Electron exposure





Possible damage reduction for p-type samples at higher doping levels. No apparent correlation for n-type materials.

Proton Effects on Non-Radiative Coefficients

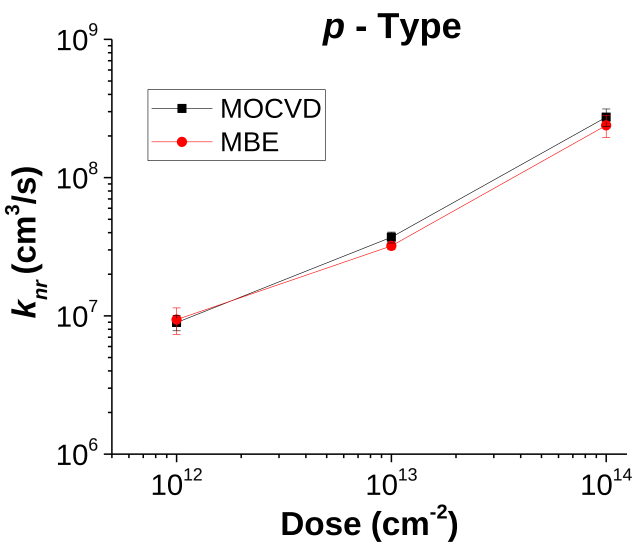
MBE

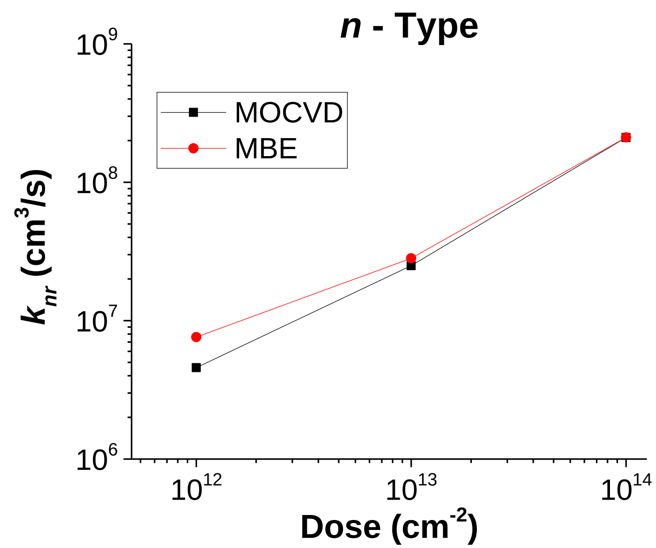
Dose (cm^{-2})	k_{nr} (cm^3/s)
0	5.5×10^6, 7×10^6 +/- 4.5×10^6
1×10^{10}	6.2×10^8, 8.6×10^8 +/- 0.2×10^8

- Two order of magnitude increase in non-radiative coefficient between no exposure and lowest dose. Percent increase comparable for both material types.
- Coefficients not computed for higher doses: lifetimes approaching detector IRF limit.
- No uncertainty estimates for *n*-type samples: no TRPL collected for doping concentration of 1×10^{19} cm^{-3}. No resolvable bandstructure at room temperature. Only two data points available for coefficient estimates.

Blue: p-type samples.
Red: n-type samples.

Electron Effects on Non-Radiative Coefficients



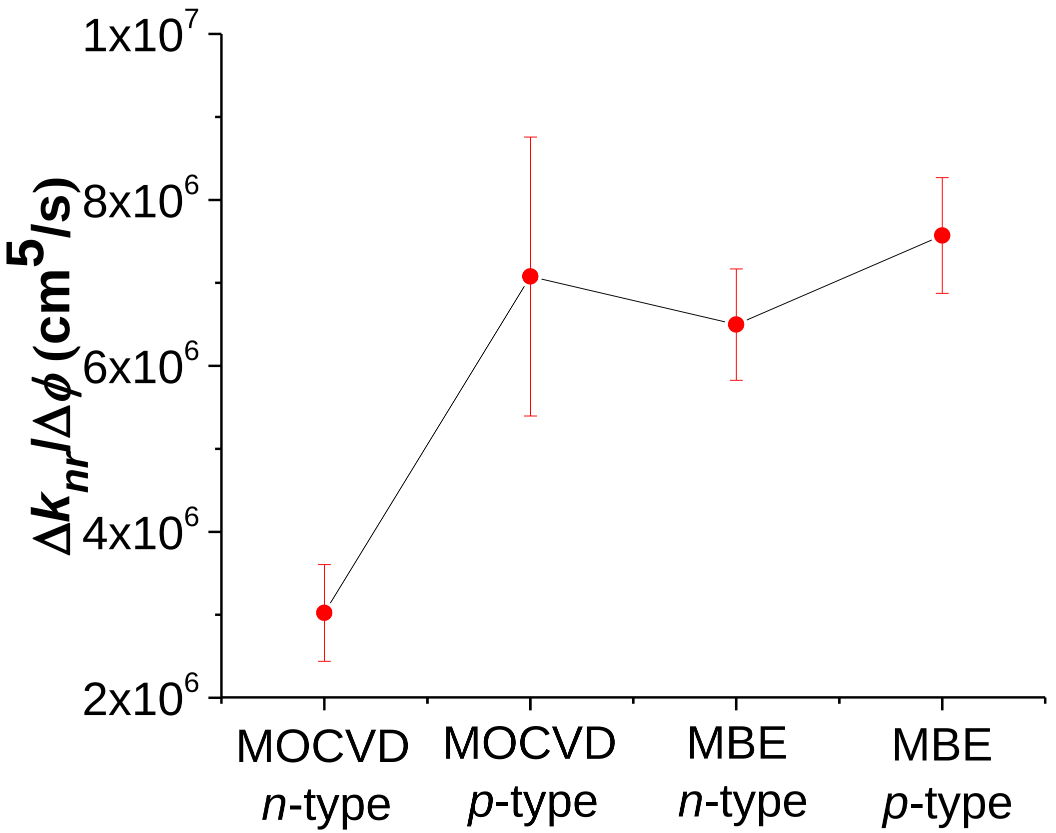


- Nearly two order of magnitude increase in non-radiative coefficient.
- Coefficients not computed for highest dose: lifetimes approaching detector IRF limit.
- No uncertainty estimates for *n*-type samples: no TRPL collected for doping concentration of 1×10^{19} cm^{-3}. No resolvable bandstructure at room temperature. Only two data points available for coefficient estimates.

No significant difference between growth techniques.

Change in Non-Radiative Coefficient per Unit Dose

Electron exposure, from linear fits to data in Slide 23



Smallest for n-type MOCVD samples, almost distinct to 1-σ. Could suggest that the n-type specimens are more radiation hard to 1 MeV electron effects than the p-type ones.

Summary

- Proton implantation appears to generate trap states in *p*-type material.
- Radiation induced bandedge PL reduction suggests that *p*-type samples are more prone to electron induced degradation. Effect mitigated by increased doping concentration.
- Non-radiative coefficients for *p*-type material appear to increase more as a function of exposure dose in comparison to those for *n*-type.
- Radiation mitigation efforts should address bulk changes in the *p*-type region of a photovoltaic junction device.
- Analysis of radiation effects in *p*-type GaAs under represented in the literature. Further study is warranted, especially if *p*-type GaAs is more vulnerable than *n*-type to radiation induced carrier dynamic degradation effects.

Acknowledgements

We would like to thank Mr. Colin Mann of The Aerospace Corporation for performing the proton exposures. We would also like to thank Dr. Brandon Wall of the Boeing Effects Radiation Laboratory for executing the electron exposures.

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