Epitaxial lift-off monocrystalline CdTe/MgCdTe double heterostructures and proton radiation study for space applications

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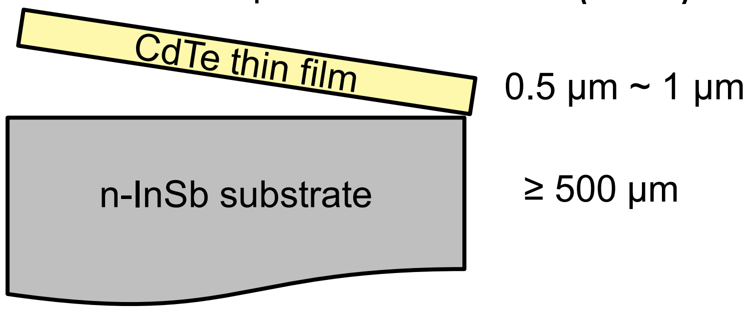
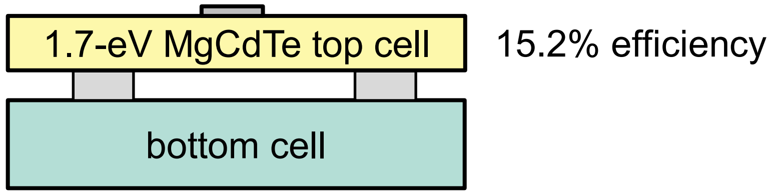
CdTe Thin-Film Solar Cells for Space Applications

Light-weight & high-power-density

Epitaxial lift-off (ELO)

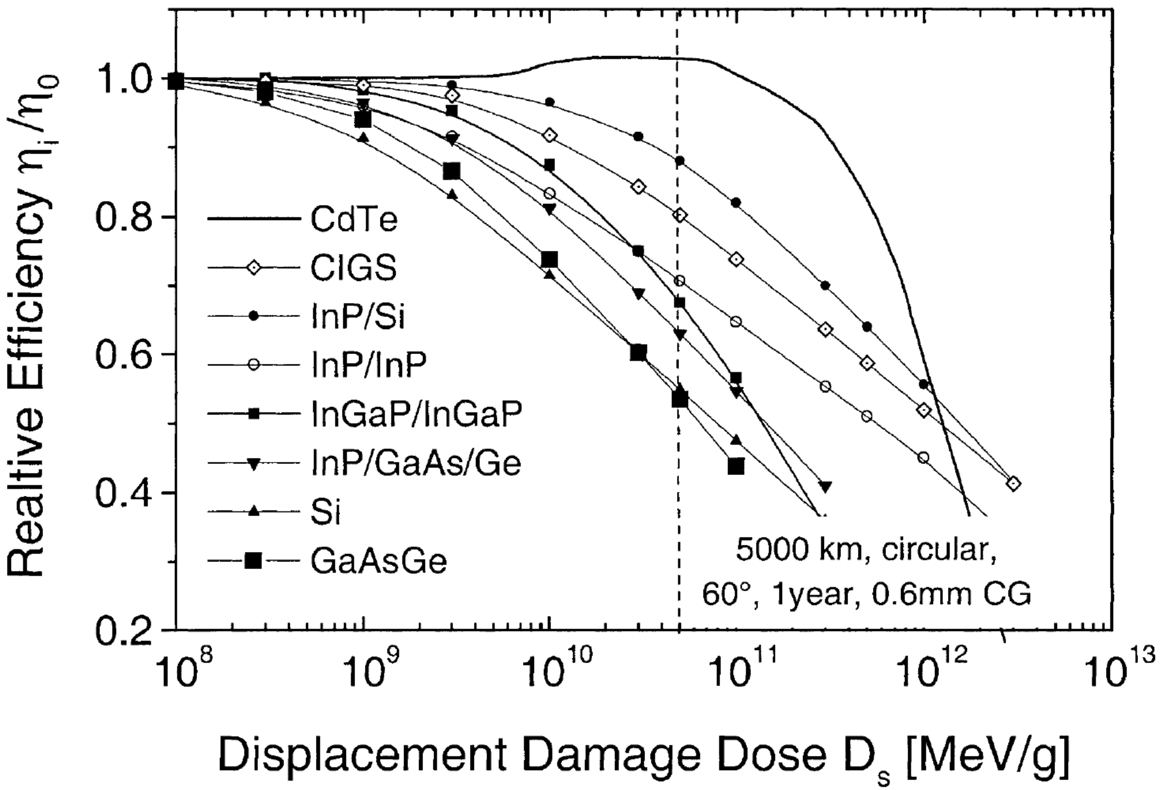


Tandem solar cells



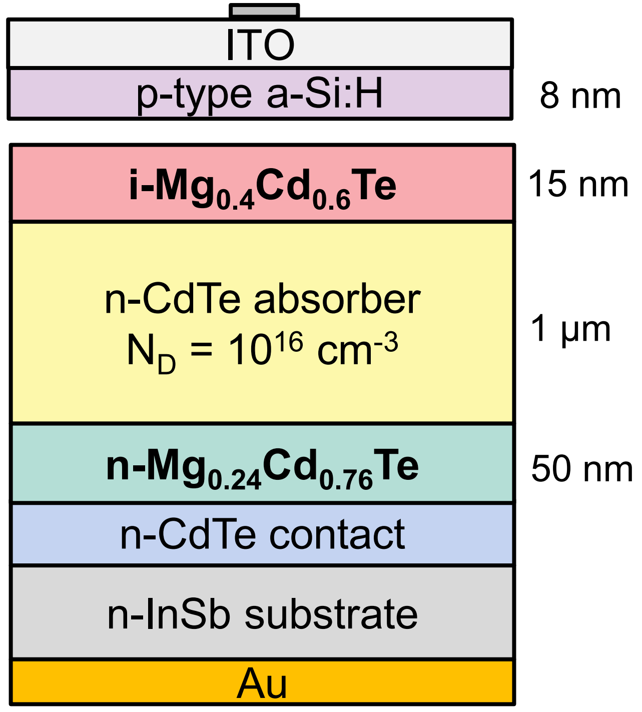
J. Ding, J.J. Becker, C.M. Campbell, C.-Y. Tsai and Y.-H. Zhang, *PVSEC 2019*

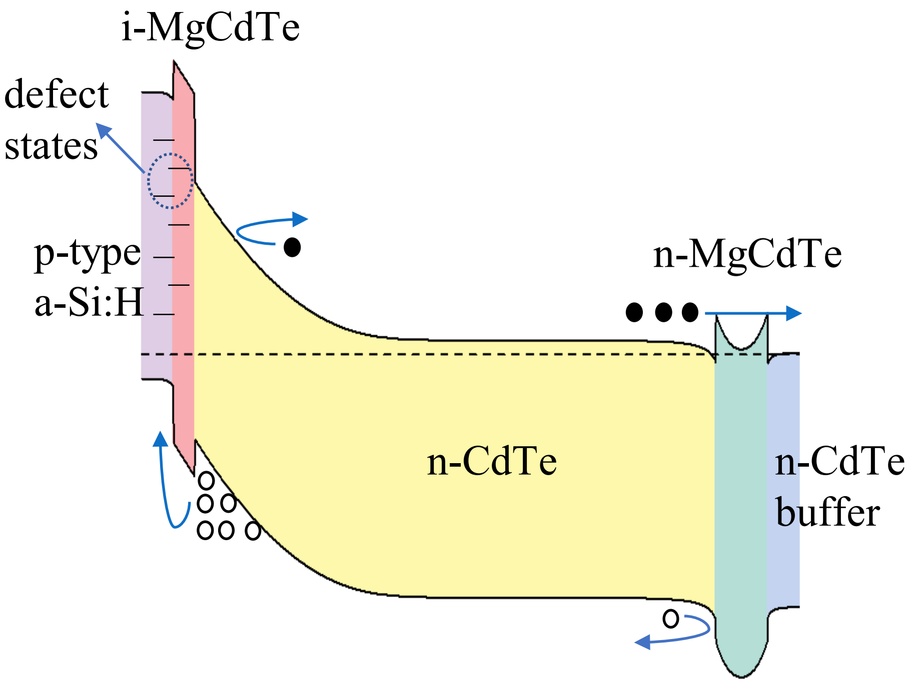
Radiation-hard

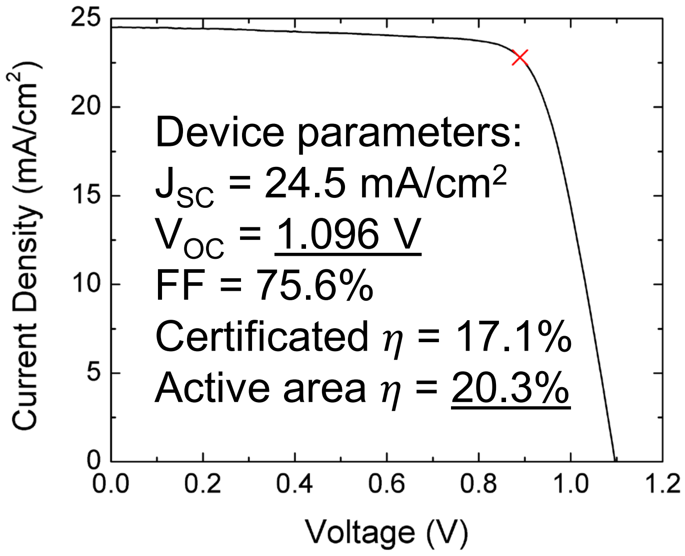


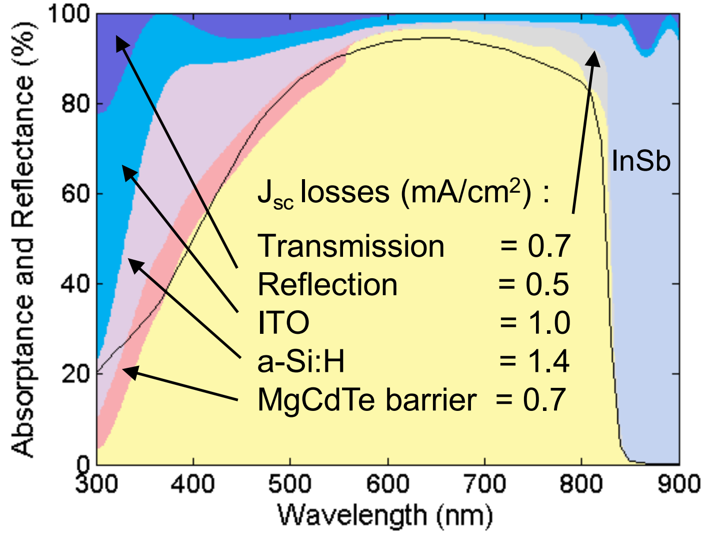
D.L.Batzner *et al*, *Thin Solid Films* 451-452 (2004) 536-543

CdTe Double Heterostructure (DH)







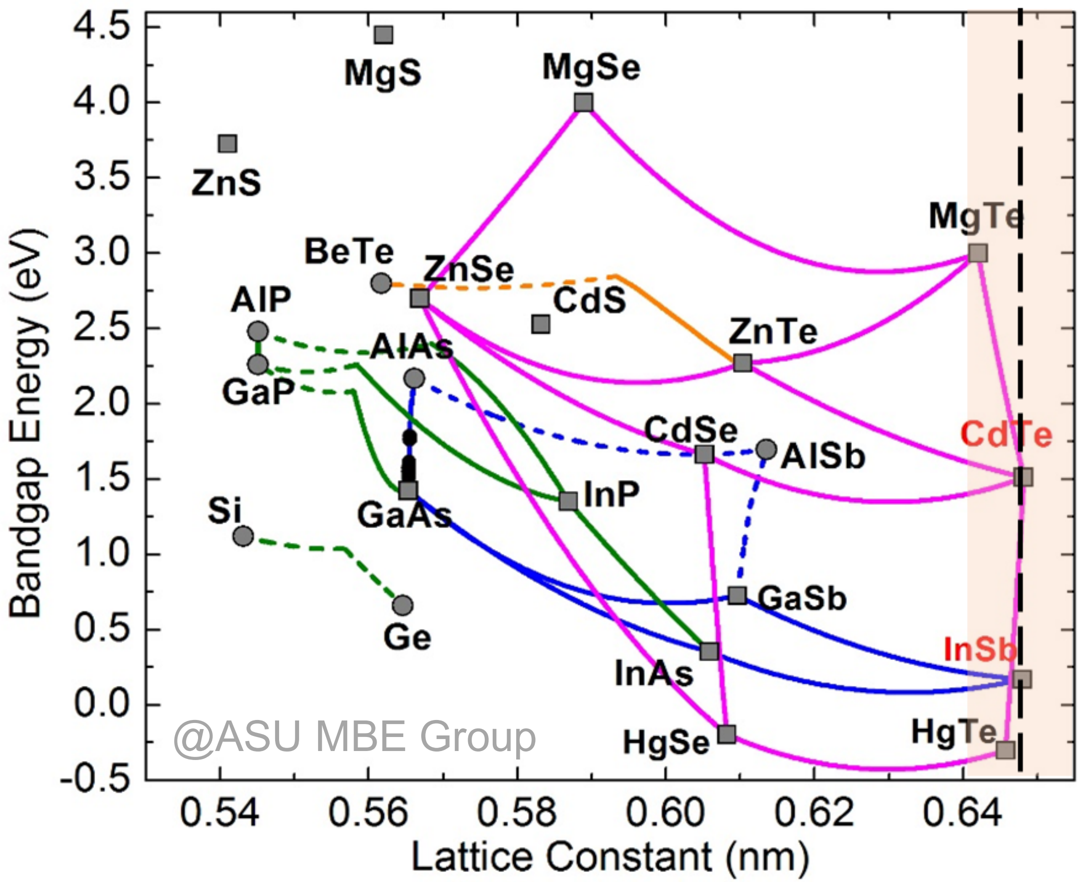


Y. Zhao, M. Boccard, S. Liu, J. J. Becker, X.-H. Zhao, C. M. Campbell, E Suarez, M. B. Lassise, Z. Holman, Y.-H. Zhang, *Nature Energy* **1**, 16067 (2016)
J. J. Becker, M. Boccard, C. M. Campbell, Y. Zhao, M. B. Lassise, Z. Holman, Y.-H. Zhang, *IEEE J. Photovoltaics* **7**, 900 (2017)

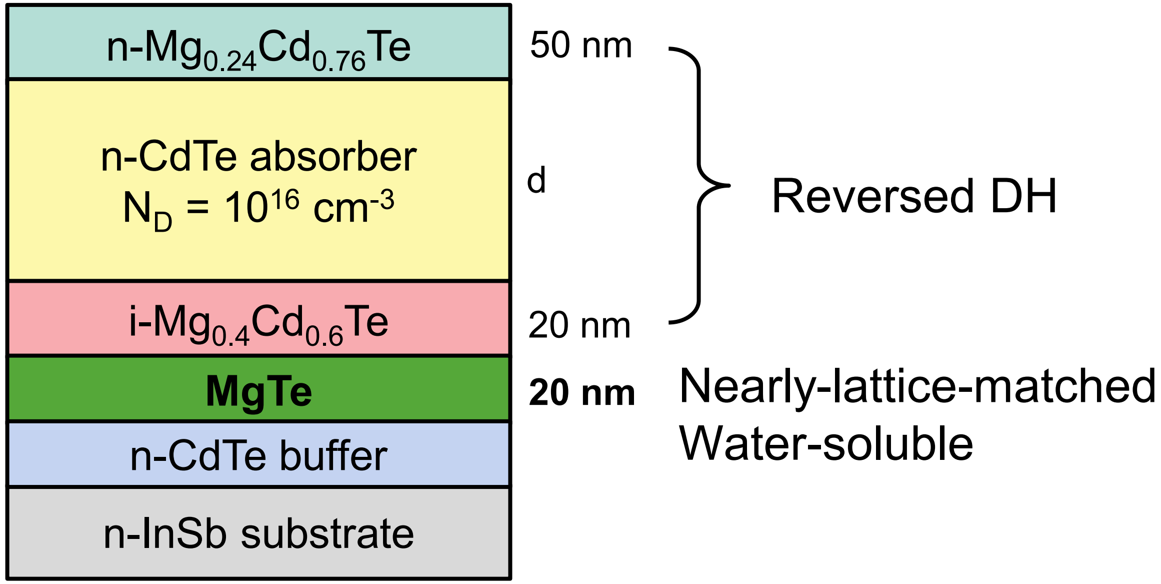
I. Epitaxial Lift-Off Technology

ELO Using MgTe Sacrificial Layer

Lattice-Matched 6.5 Å-Family

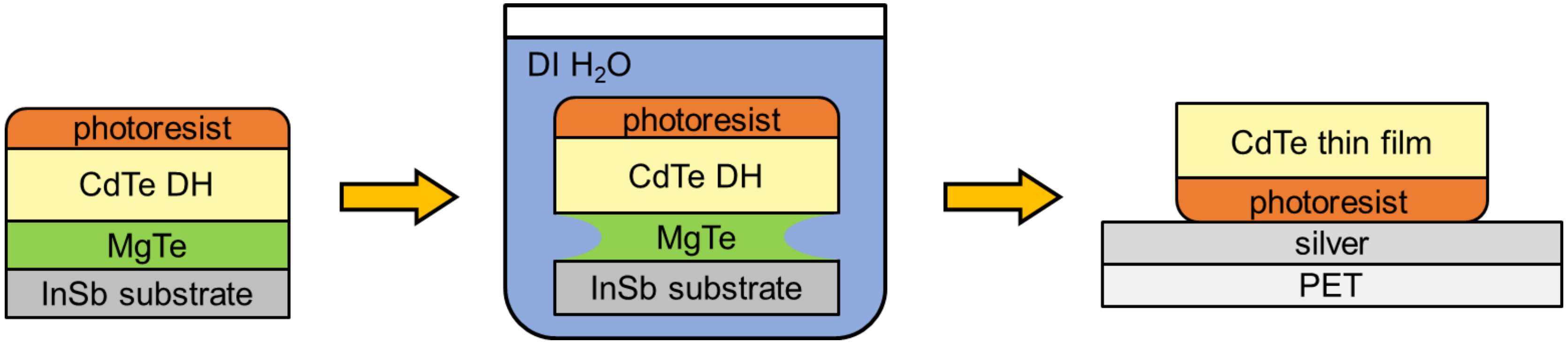


Sample	Absorber thickness (d)
A	0.5 μm
B	1 μm

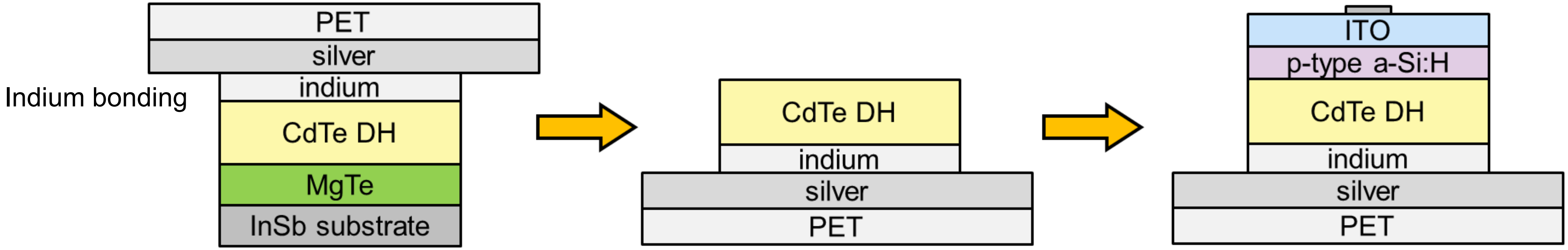


ELO process of CdTe DH thin films / Devices

- **ELO process in this study**



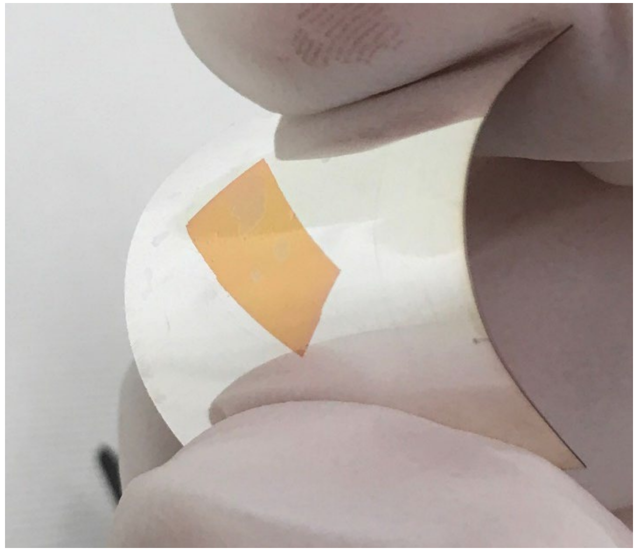
- **Next step**

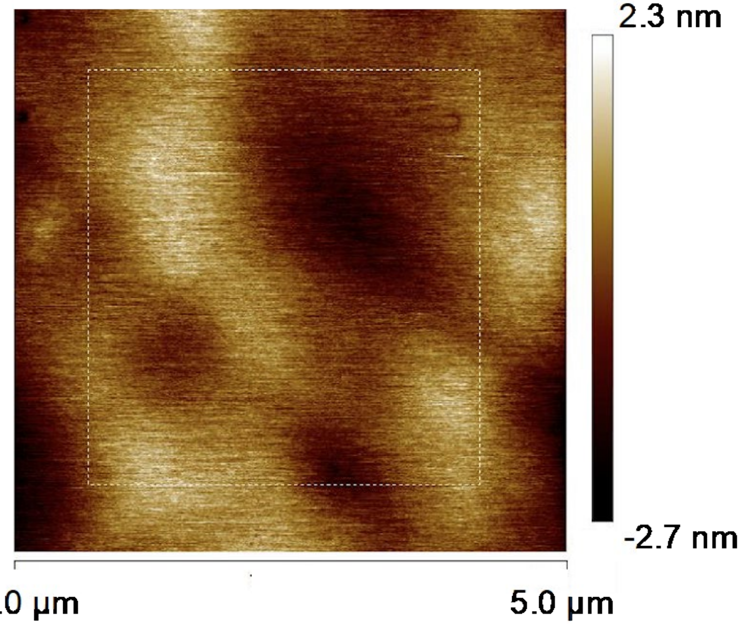


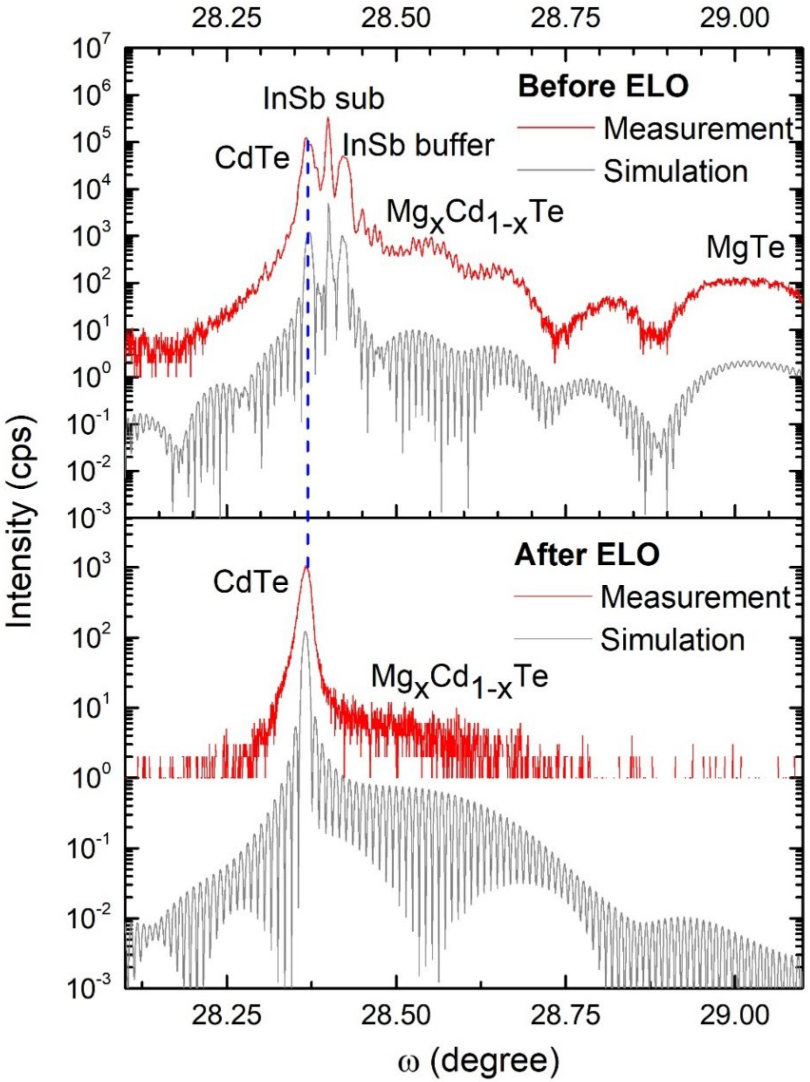
W. Yang *et al*, "Ultra-thin GaAs single-junction solar cells integrated with a reflective back scattering layer", J. Appl Phys, **115**, 203105 (2014)

Thin Film Characterizations

AFM: RMS roughness of 0.67 nm



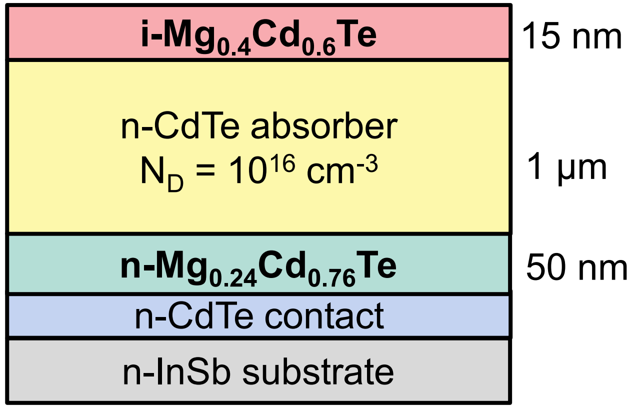




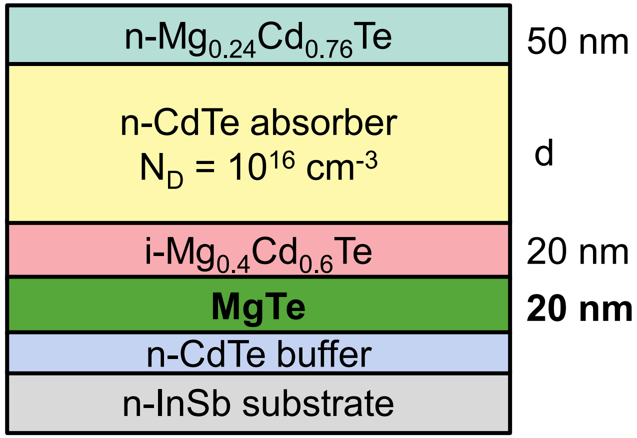
- Smooth and intact lift-off surface revealed by AFM image.
- CdTe/MgCdTe DH survives the ELO.
- Highly selective etching of MgTe vs. CdTe using DI water.

Photoluminescence Before/After ELO

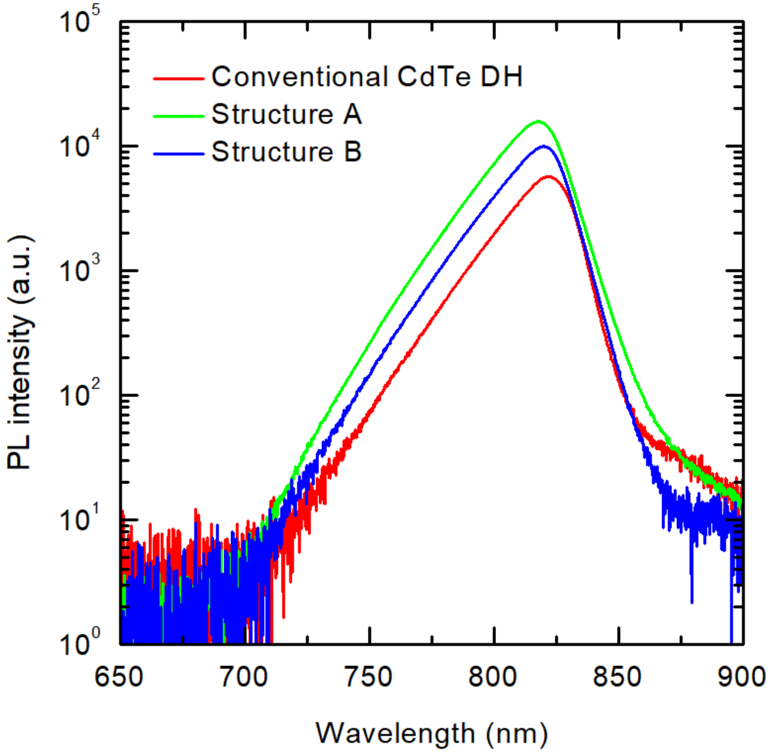
Conventional CdTe DH



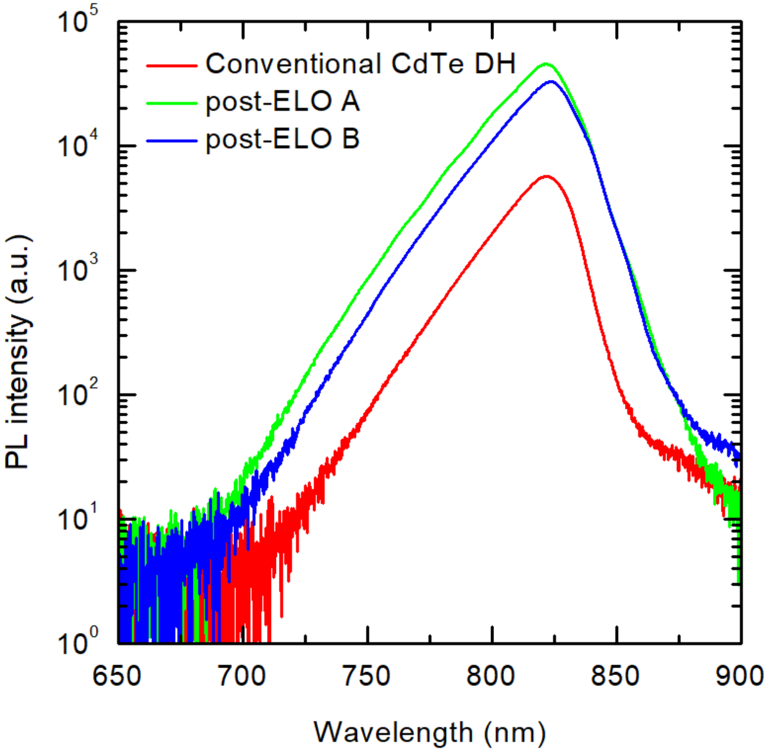
Structure A: d = 0.5 μm
Structure B: d = 1 μm



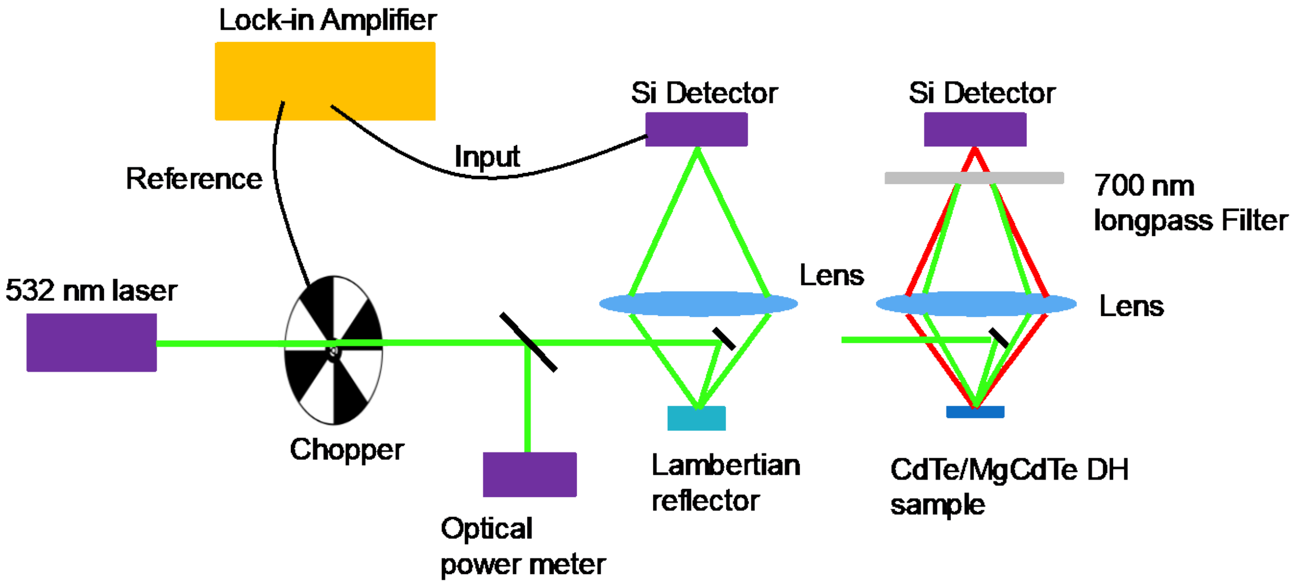
As-grown samples
before ELO



Lift-off thin films
after ELO



Photoluminescence Quantum Efficiency & iV_{OC}



The implied open-circuit voltage (iV_{OC}) of a solar cell, or the quasi-fermi-level splitting (ΔE_F) in the absorber region, can be estimated through

$$iV_{OC} = V_{OC,ideal} - \frac{kT}{q}|\ln(\eta_{ext})|$$

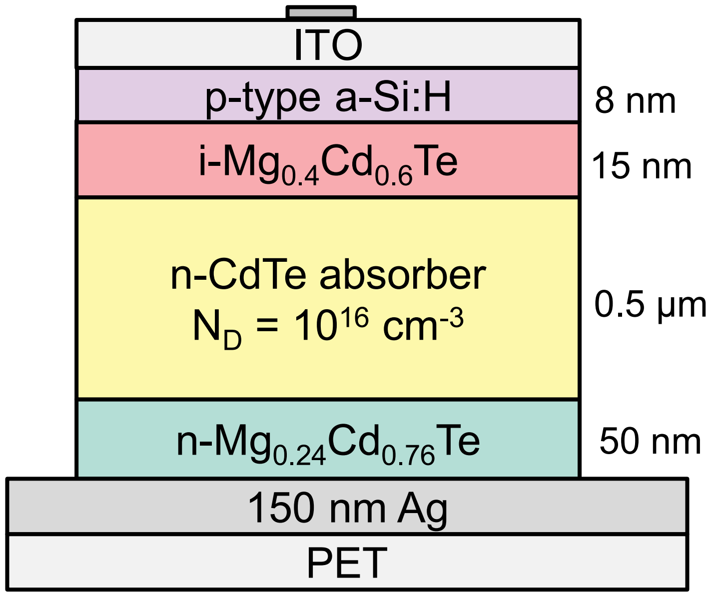
U. Rau, 2007, *Phys. Rev. B* **76**, 085303.
O. D. Miller *et al*, *IEEE Journal of Photovoltaics*, **2,** 303-311, 2012

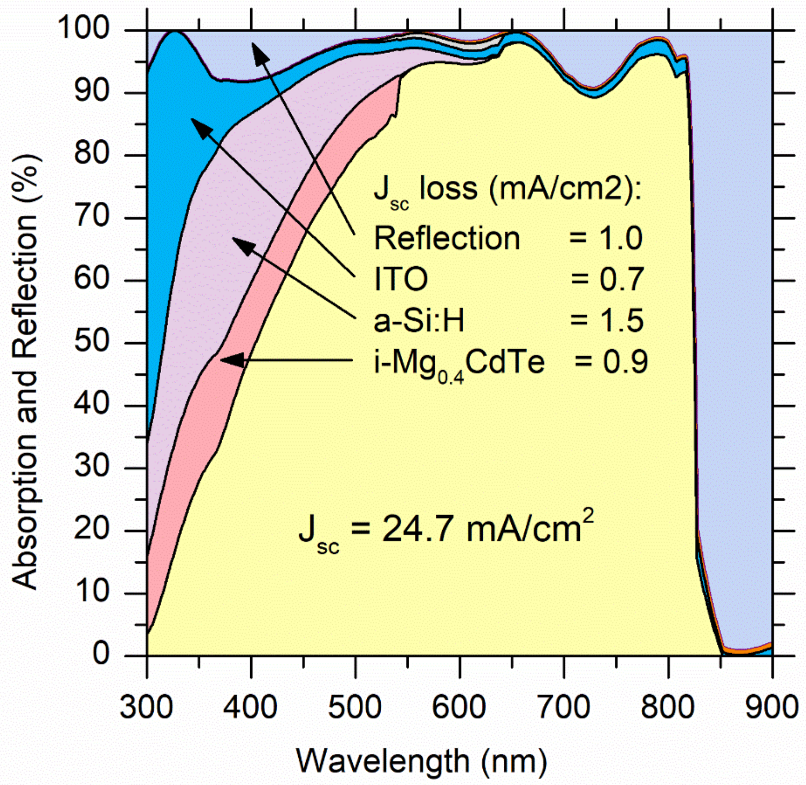
Sample	CdTe DH	Structure A	Structure B	post-ELO A	post-ELO B
η_{ext} (@ 1 sun)	1.54%	3.65%	1.80%	5.35%	3.39%
Implied V_{OC} (V)	1.119	1.141	1.123	1.152	1.139
V_{OC} (V)	1.11*				

*certificated by NREL

Absorption spectrum simulation

Based on n & k of each layer, absorption spectrum is calculated using transfer matrix method. The short-circuit current (J_{sc}) is **24.7 mA/cm²** according to the simulation.





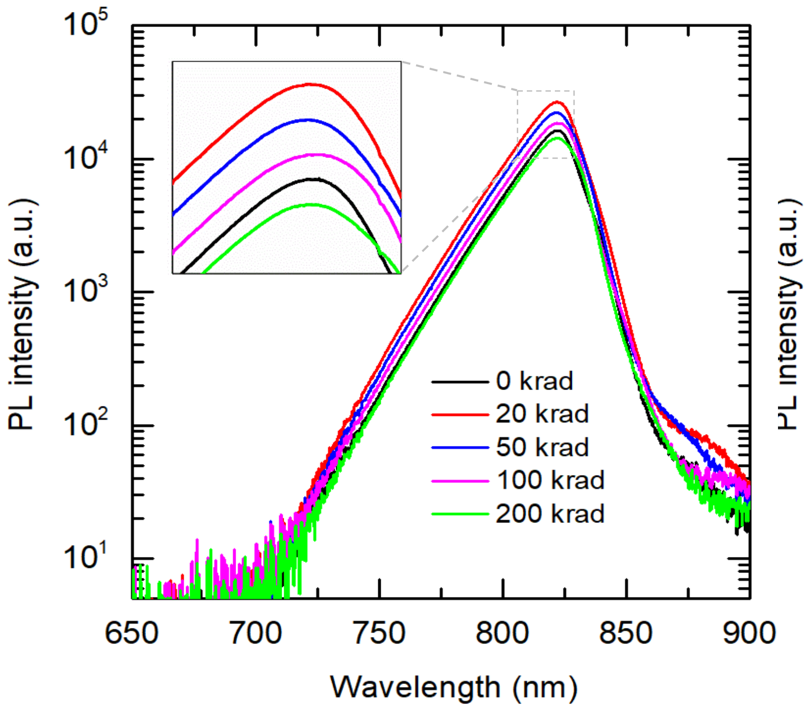
Recap of Section I

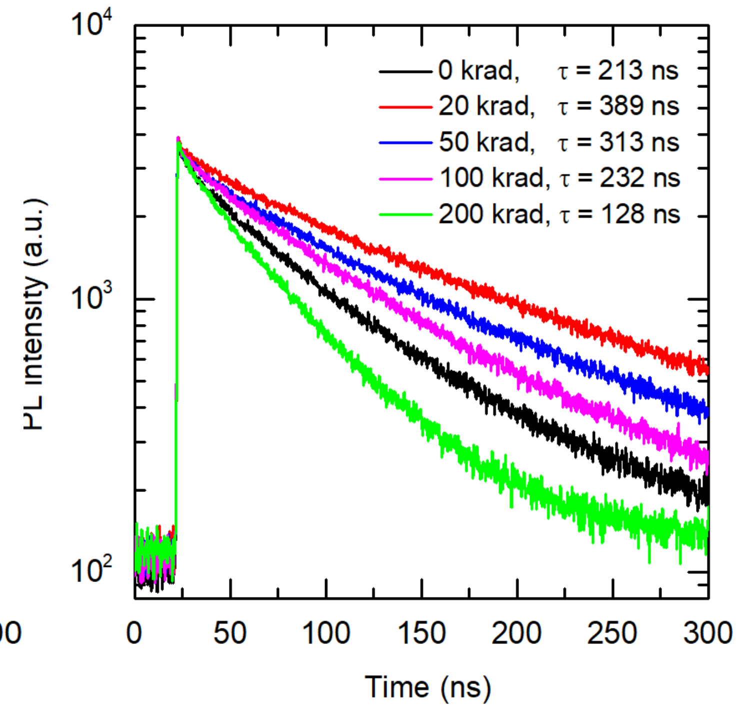
- Using nearly-lattice-matched, water-soluble MgTe as a sacrificial layer. High-quality CdTe DH can be grown on MgTe layer by using MBE.
- Smooth and intact lift-off surface.
- Enhanced optical performance of the lift-off thin films.
- CdTe lift-off thin-film solar cell performance
    - iV_{OC} = 1.152 V
    - J_{sc} = 24.7 mA/cm^2 based on simulation

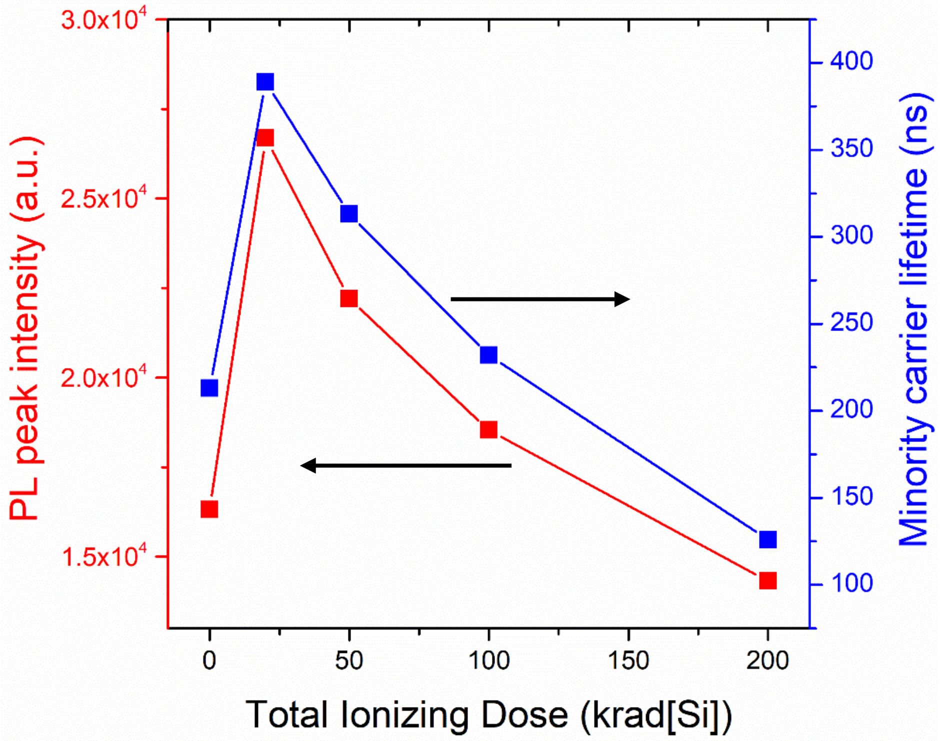
II. Proton Radiation Study

Steady-state PL and Time-resolved PL

The CdTe DH samples are under stepwise **63-MeV** proton irradiation to total ionizing dose (TID) of **0, 20, 50, 100, 200 krad[Si].**
* 1 TID is equivalent to proton fluence (Φ_p) of **7.5×10^9 p/cm²**.







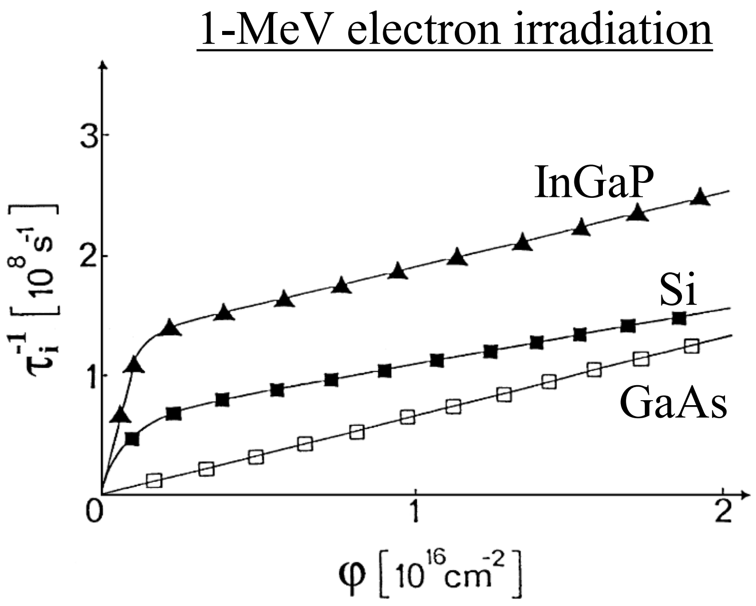
Current Radiation Effect Theory

The concentration of defects per unit volume (N_R) generated by radiation

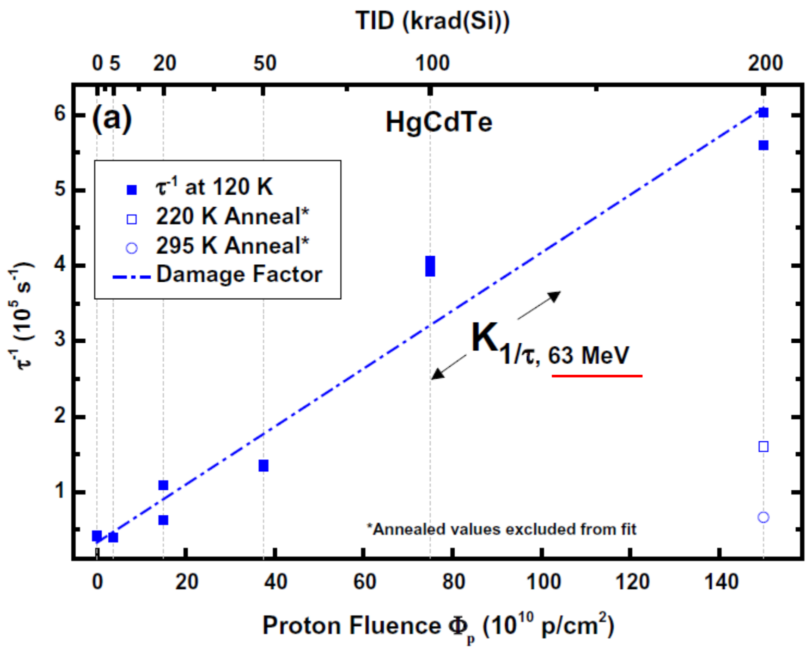
$$N_R(\Phi_p) = N_R(0) + k \cdot \Phi_p$$

The minority carrier lifetime, dominated by radiation induced defects, can be derived

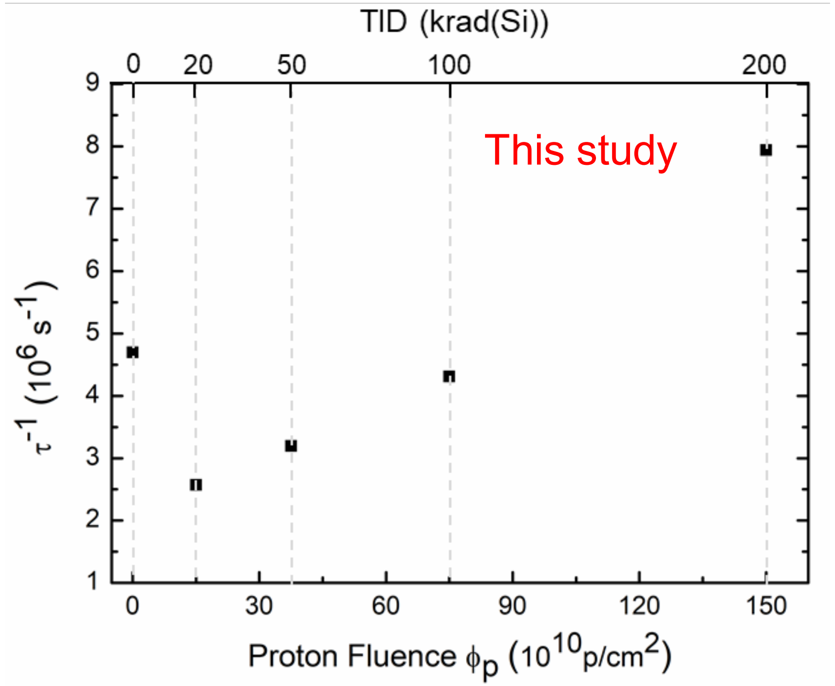
$$\frac{1}{\tau(\Phi_p)} = \sigma v_{th} N_R(\Phi_p)$$



N. De Angelis, et al. *Sol. Energy Mater Sol. Cells* 66.1-4 (2001): 495-500

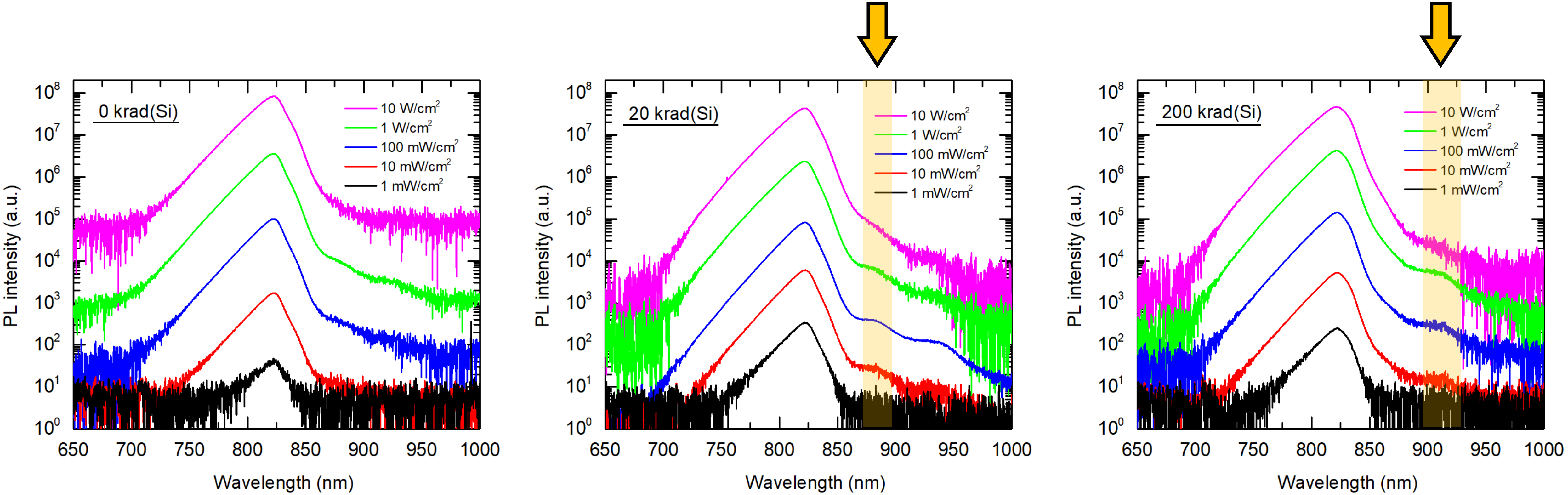


G. D. Jenkins, et al. *J. Electron. Mater,* Vol. 46, No. 9, 2017



Radiation Defect Study

- Some sub-bandgap peaks are observed in the proton-irradiated samples, while these peaks are not significant in the sample without proton irradiation.
- The sub-bandgap peaks gradually saturate with the increased excitation density.
- The sub-bandgap peaks move towards a longer wavelength with the increased irradiation dose.



Recap of Section II

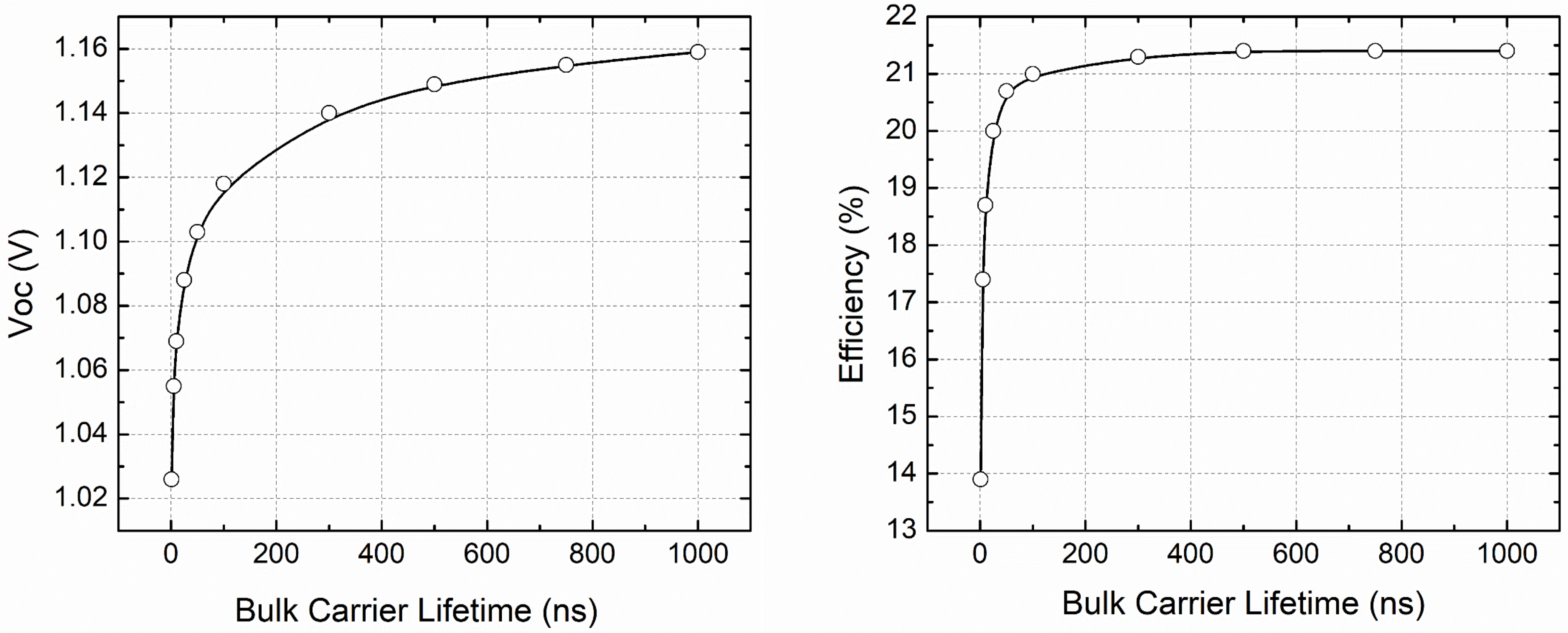
- The sample after 200 kRad(Si) radiation shows ***decreased*** PL intensity and PL decay time of 12% and 40%, respectively.
- Compared with the reference sample without irradiation, the samples after proton irradiation at 20, 50 and 100 kRad(Si) show ***increased*** PL intensity and PL decay time.
- This interesting finding is attributed to the effect of the additional defects generated by proton radiation:
    - When the radiation defect density is relatively low, the increased localization and reduced mobility of photogenerated carriers would hinder the carriers from reaching to Shockley-Read-Hall (SRH) centers to recombine non-radiatively.

Summary

- The ELO technology enables the fabrication of monocrystalline CdTe thin-film solar cells with light wight, high power density and high specific power.
- The radiation study shows the CdTe DH solar cells are expected to be radiation robust and are suitable for space applications.

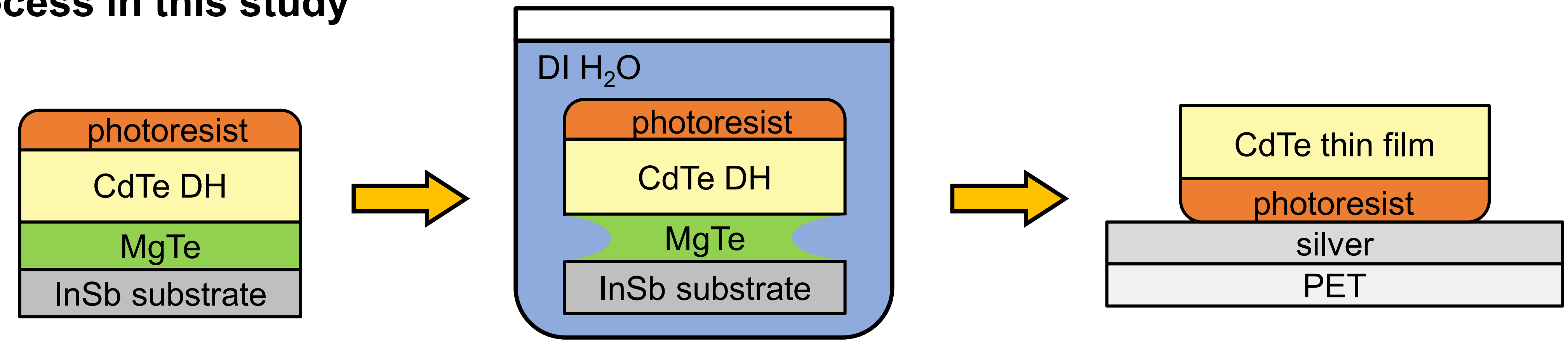
The work is partly supported by AFRL, Space Vehicles Directorate RVSWS with an award number: FA9453-20-2-0011, managed by Dr. Preston T. Webster. The authors acknowledge Dr. Webster for the assistance with proton irradiation experiments.

Backup: PC1D Simulation



ELO process of CdTe DH thin films / Devices

- **ELO process in this study**



- **Next step**

W. Yang *et al*, "Ultra-thin GaAs single-junction solar cells integrated with a reflective back scattering layer", J. Appl Phys, **115**, 203105 (2014)

Indium bonding