Metastability and Degradation of CdTe Solar Cells Investigated by nm-Scale Electrical Potential Imaging

C.-S. Jiang[1], D. Albin[1], M. Nardone[2], K.J. Howard[2], A. Danielson[3], A. Munshi[3], T. Shimpi[3], W. Sampath[3], C. Xiao[1], H.R. Moutinho[1], M.M. Al-Jassim[1], G. Teeter[1]

[1]National Renewable Energy Laboratory, Golden, Colorado, USA

[2]Bowling Green State University, Bowling Green, Ohio, USA

[3]Colorado State University, Fort Collins, Colorado, USA

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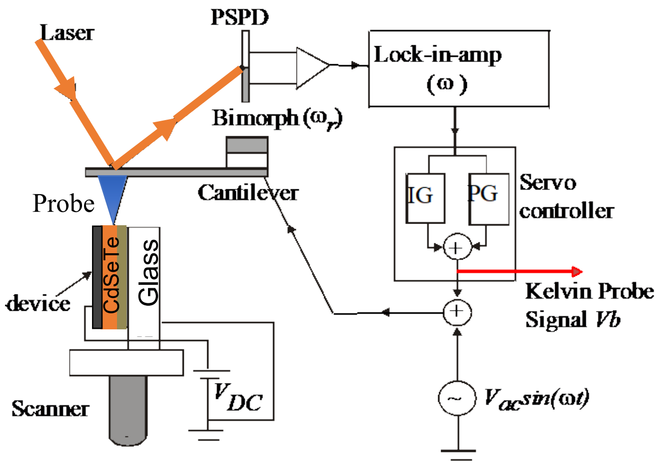
Outline

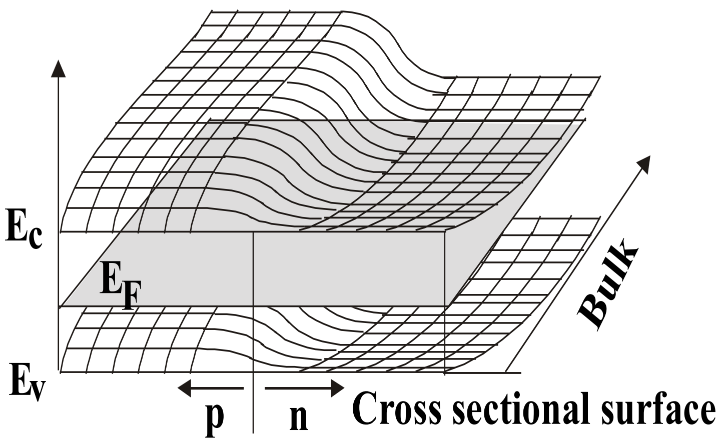
- Brief introduction to KPFM potential imaging across PV devices
- CdSeTe Device metastability and degradation
- KPFM potential imaging at Dark-soak, light-soak, and degradation states
- Device modeling on electric field and J-V
- Summary

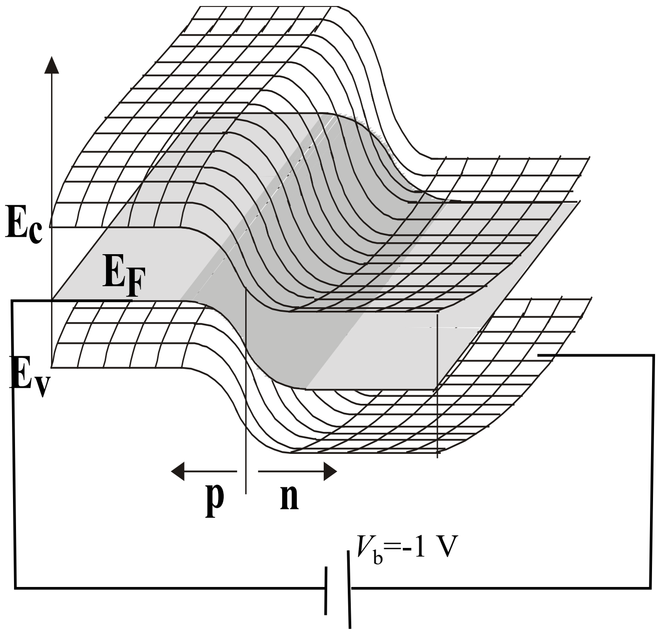
KPFM potential imaging for PV junction structures

Kelvin probe force microscopy (KPFM)
Potential imaging by probing Coulomb force



Junction location determined by surface potential profiling

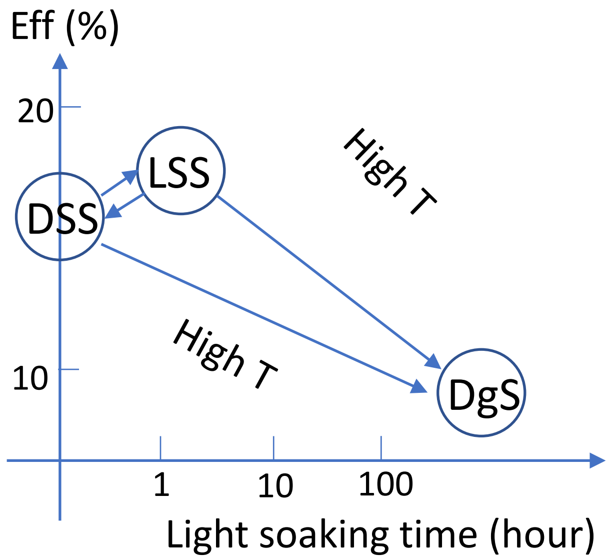


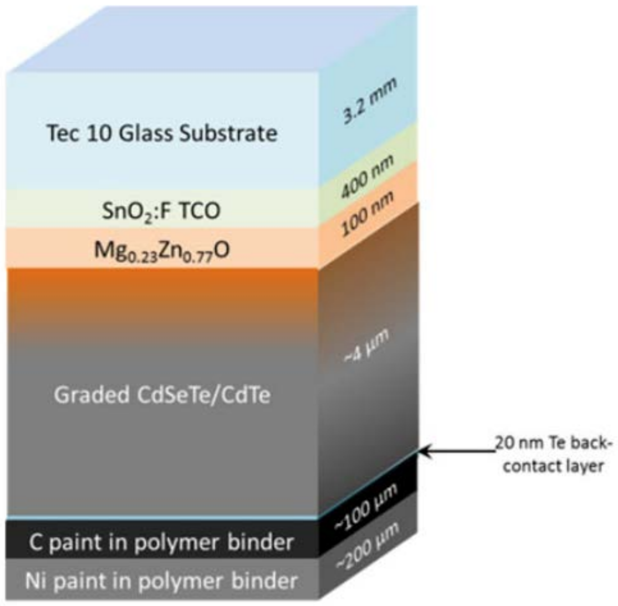


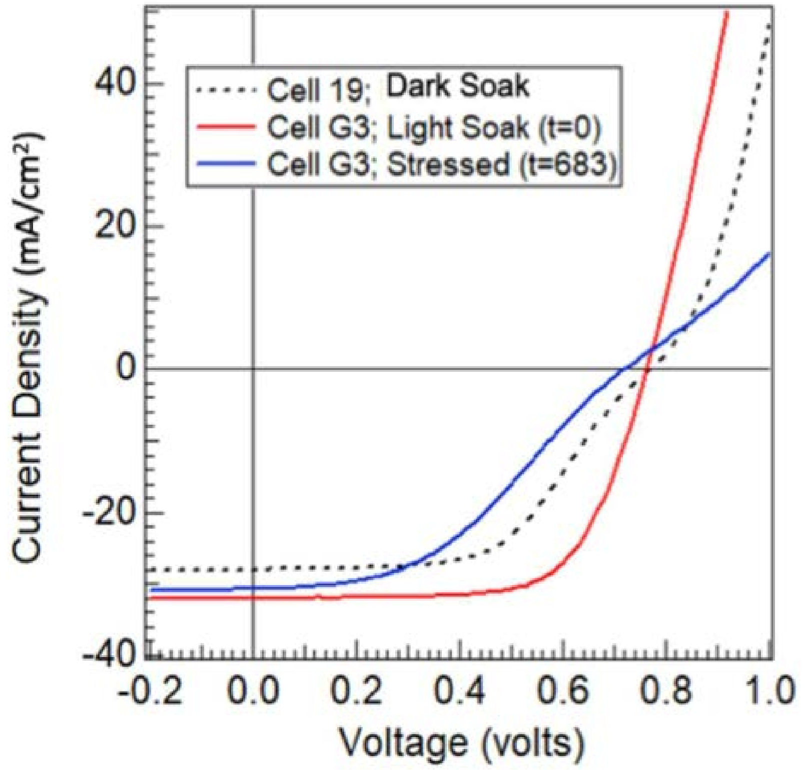
- KPFM: ***surface*** potential imaging in ~30 nm spatial and ~10 meV energy resolutions
- Revealing bulk potential change by measuring surface potential change by applying a bias voltage (Vb) to the device
- Junction location determination in a normal single junction device by applying Vb, where the junction locates at the electric field peak
- More complicated device structure: KPFM measures the locations where external voltage drops or external field is added---usually need device modeling to reveal the device junction/barrier structures and carrier concentrations

Metastability and degradation of CdTe devices

Device structure **A. Munshi et al., JPV 8, 310 (2018)**







Dark-soak and light-soak states

	Voc (V)	Jsc (mA/cm^2)	FF (%)	Efficiency (%)
Dark Soak	0.757 ± 0.021	28.3 ± 1.0	55.8 ± 7.9	12 ± 2.0
Light Soak	0.780 ± 0.012	30.4 ± 0.8	70.4 ± 3.6	16.7 ± 1.2

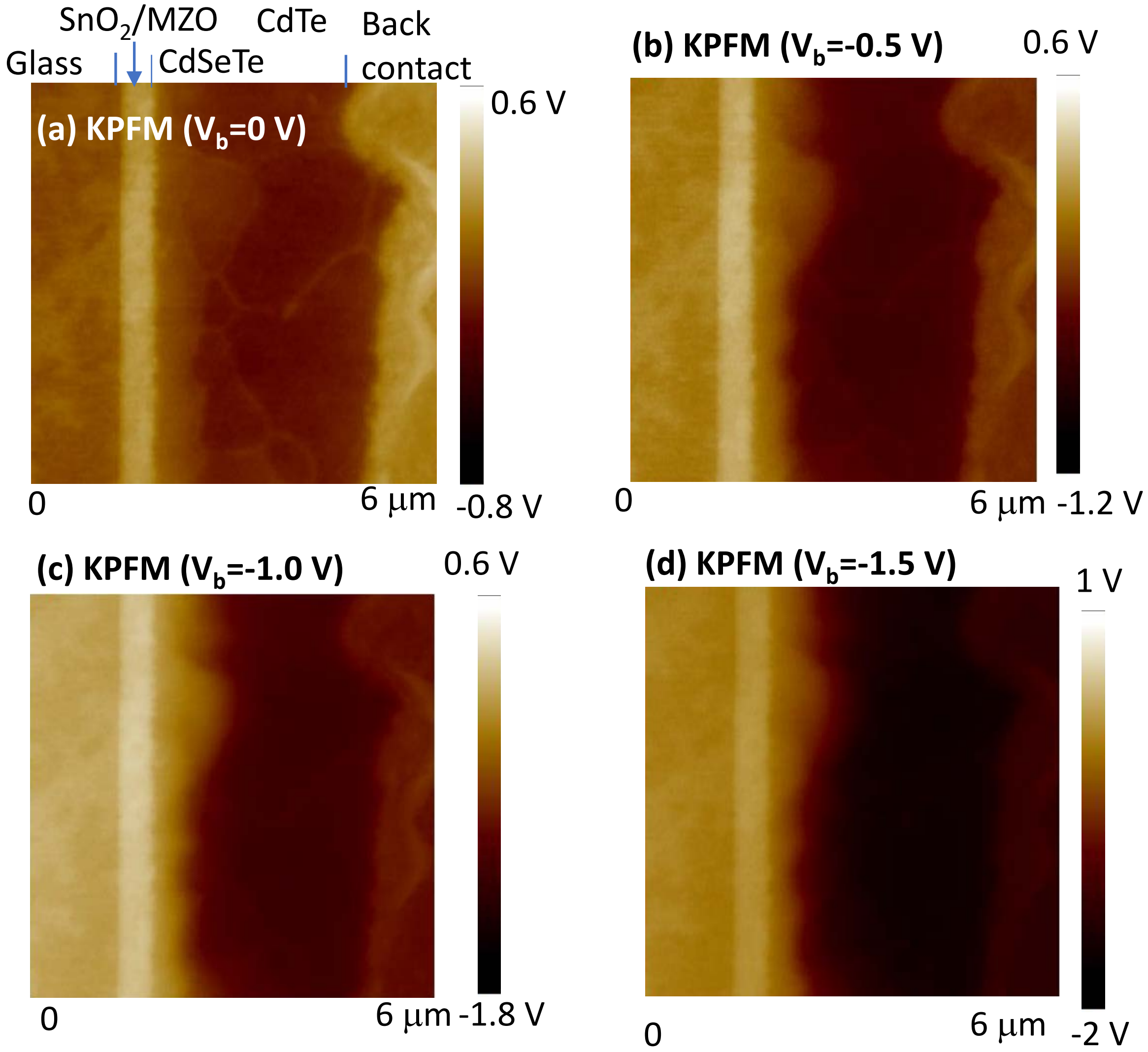
Light-soak and degradation states

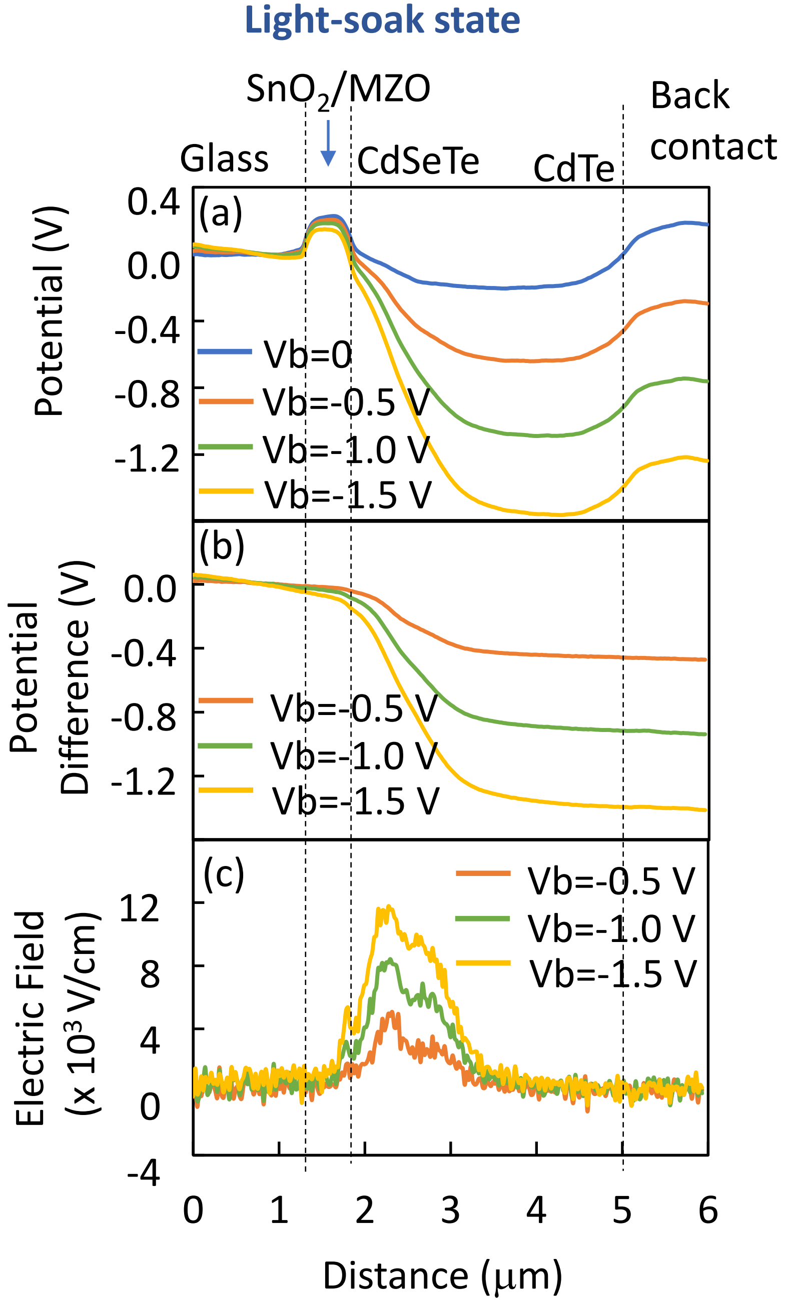
Device performance parameters at the DgS after light-soaking at one sun at 65 °C for 683 h.

Time (hrs)	Voc (V)	Jsc (mA/cm^2)	FF (%)	Efficiency (%)
0	0.756	30.3	66.3	15.2
683	0.722	29.7	44.3	9.5

- **FF degradation dominates the performance change in both dark-soak and degradation states**
- **The devices were with spray back metallization, devices with sputtered metallization show much less change with stressing**

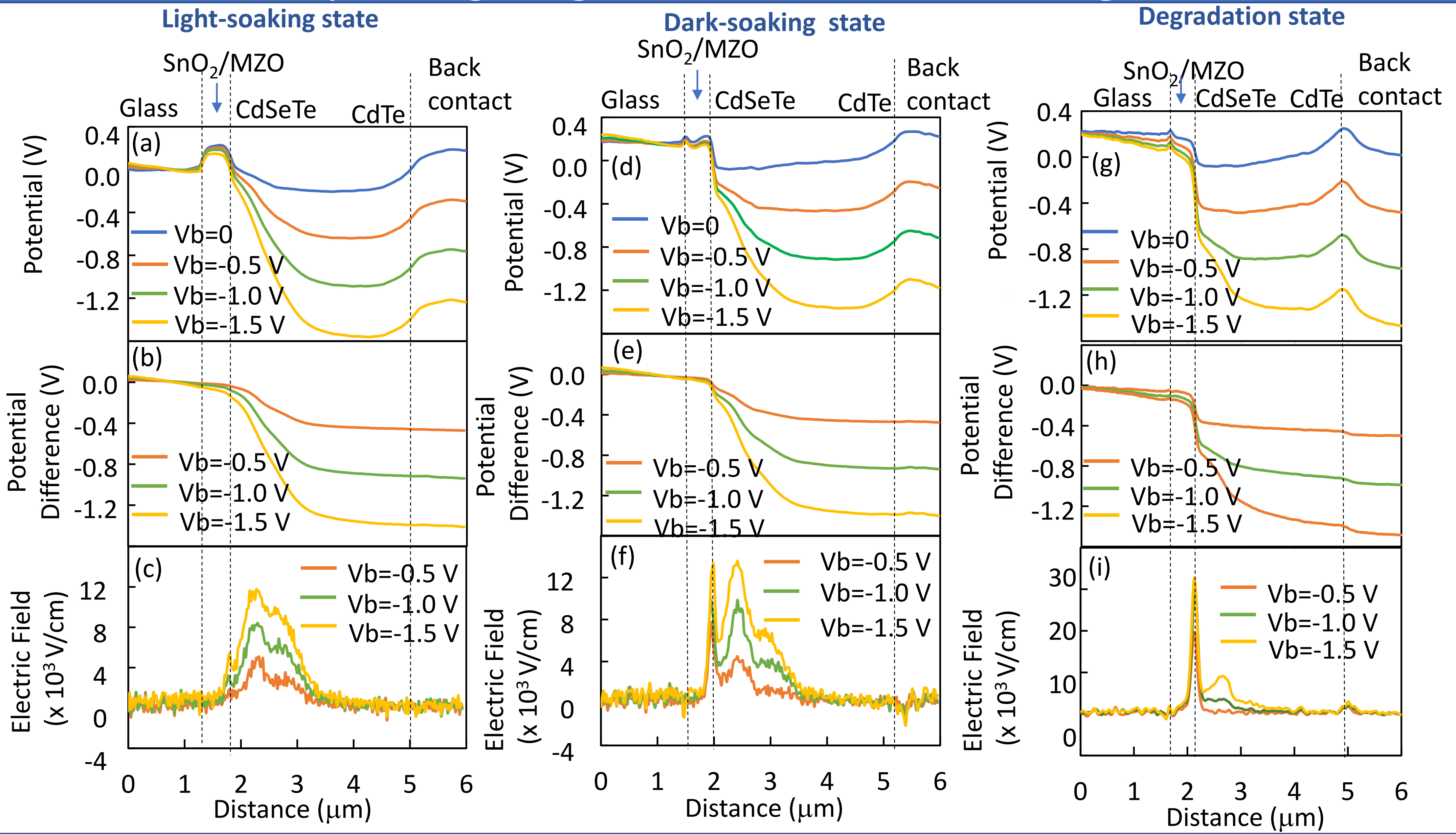
KPFM potential imaging at light-soak state with various Vb





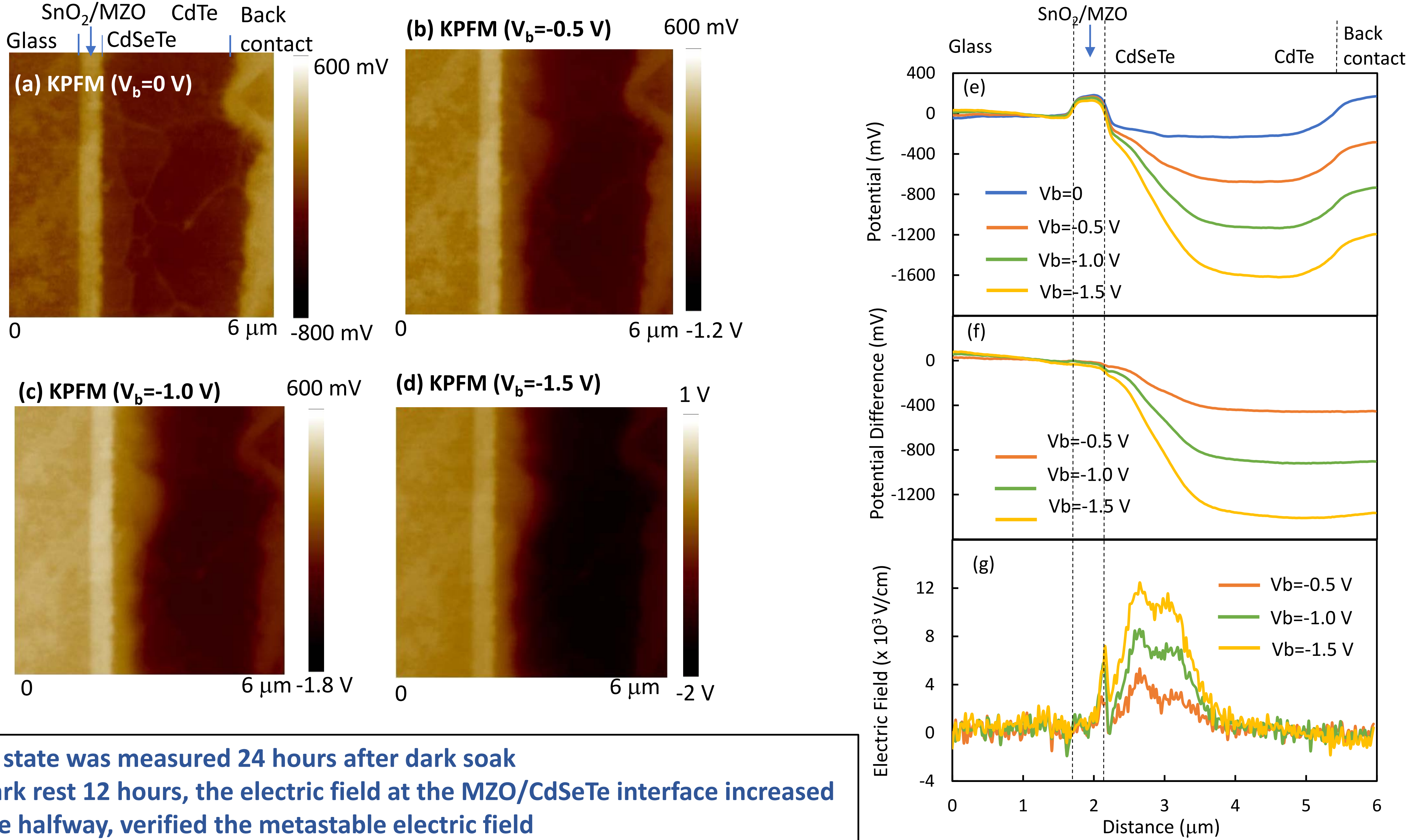
- **KPFM measurement at dark and room temperature**
- **The main electric field is within CdSeTe layer, not at the MZO/CdSeTe interface: a buried homo-junction (BHJ)**
- **There is a small electric field at the MZO/CdSeTe interface at the light-soak state**

Potential/field profiling at light-soak, dark soak, and degradation states



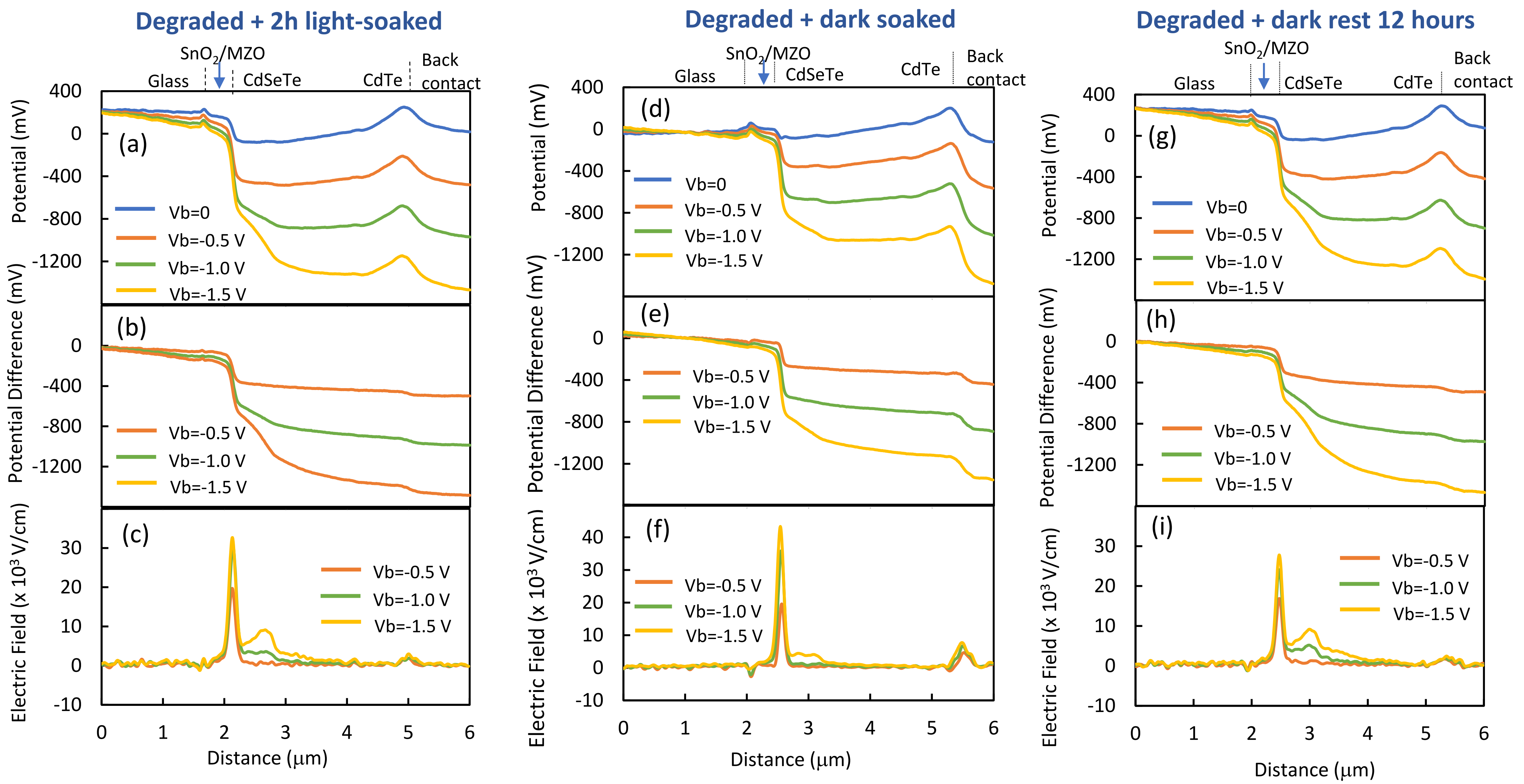
Double electric field peaks at dark-soak state; the peak at the interface further increased at degradation state and a small field at the back appeared

Electric field at intermediate dark rest state---metastable electric field



- **Dark state was measured 24 hours after dark soak**
- **At dark rest 12 hours, the electric field at the MZO/CdSeTe interface increased to the halfway, verified the metastable electric field**

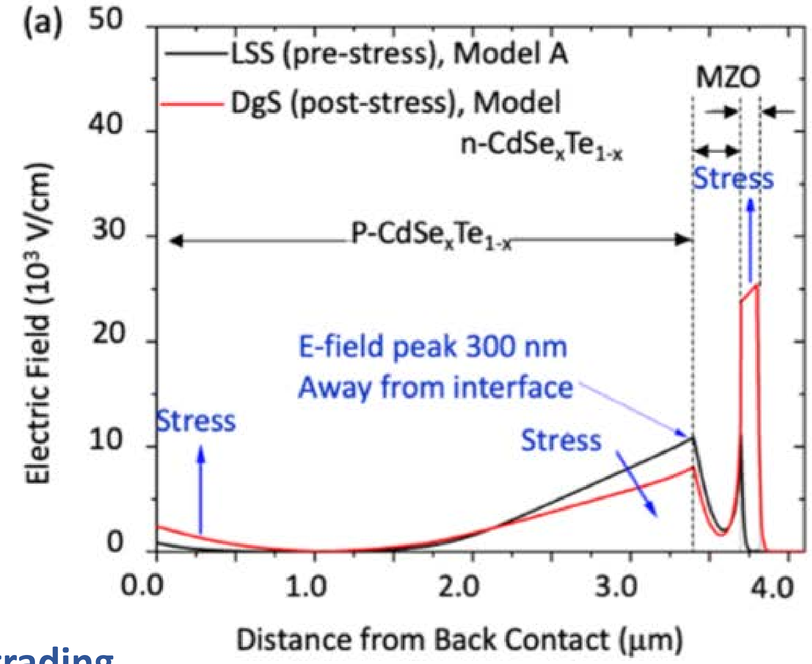
Electric field at degradation state with light-soak and dark soak---stable and irreversible degradation state



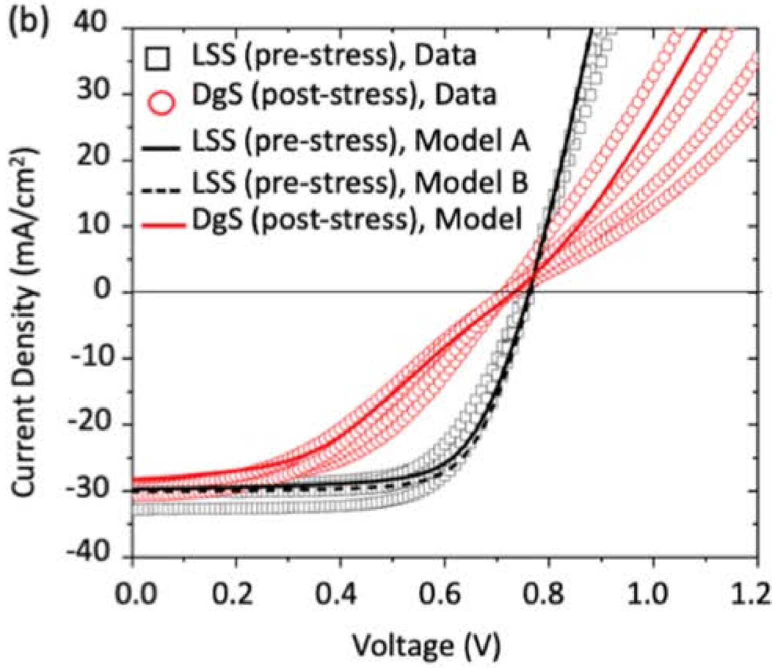
No significant change in electric field by light soaking, dark soaking, and dark rest--- the degradation state is stable and irreversible

Device modeling for light-soak and degradation states

Electric field



Experimental and modeled J-V



Bandgap grading

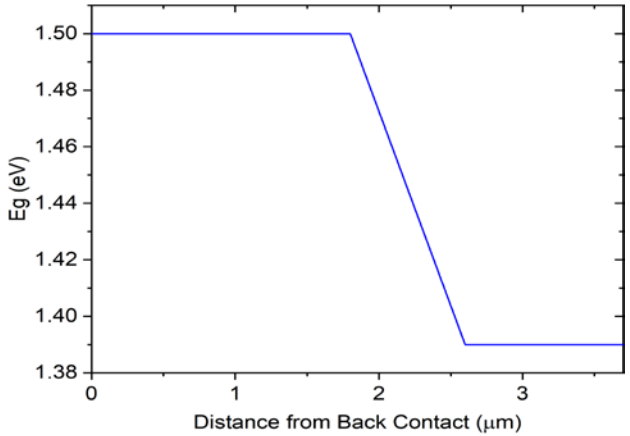


Table S1. Baseline device model parameters [1]-[4].

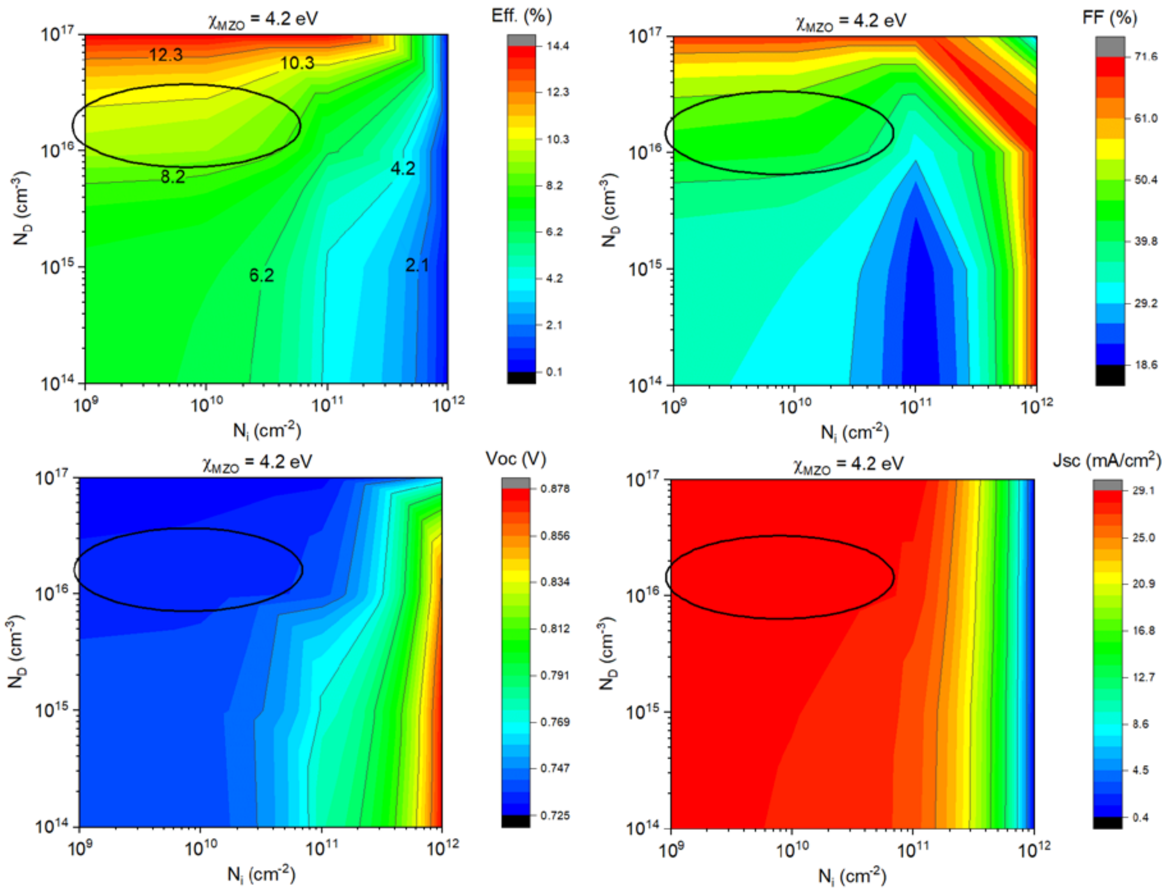
Parameter	Symbol	Unit	SnO_2:F	Mg(Zn,O)	p-Cd(Se,Te)	n-Cd(Se,Te)
Thickness	h	nm	400	100	3,400	300
Band Gap	E_g	eV	3.6	3.75	1.5–1.39*	1.39
Rel. Permittivity	ε		9.0	9.0	9.4	9.4
Electron Affinity	χ	eV	4.4	4.49	graded*	4.49
Mobility	μ_n, μ_p	cm^2/Vs	100, 25	1, 25	320, 40	320, 40
Lifetime	τ_n, τ_p	ns	0.1, 0.1	0.1, 0.1	2, 2	2, 2
Doping	N_A, N_D	cm^{-3}	n: 10^{17}	n: 10^{14}	p: $4x10^{14}$	n: $4x10^{15}$

Device modeling using COMSOL Multiphysics software in alignment with J-V and electric field
J-V: dominantly FF loss; Electric field: increasing around MZO

Device modeling for light-soak and degradation states

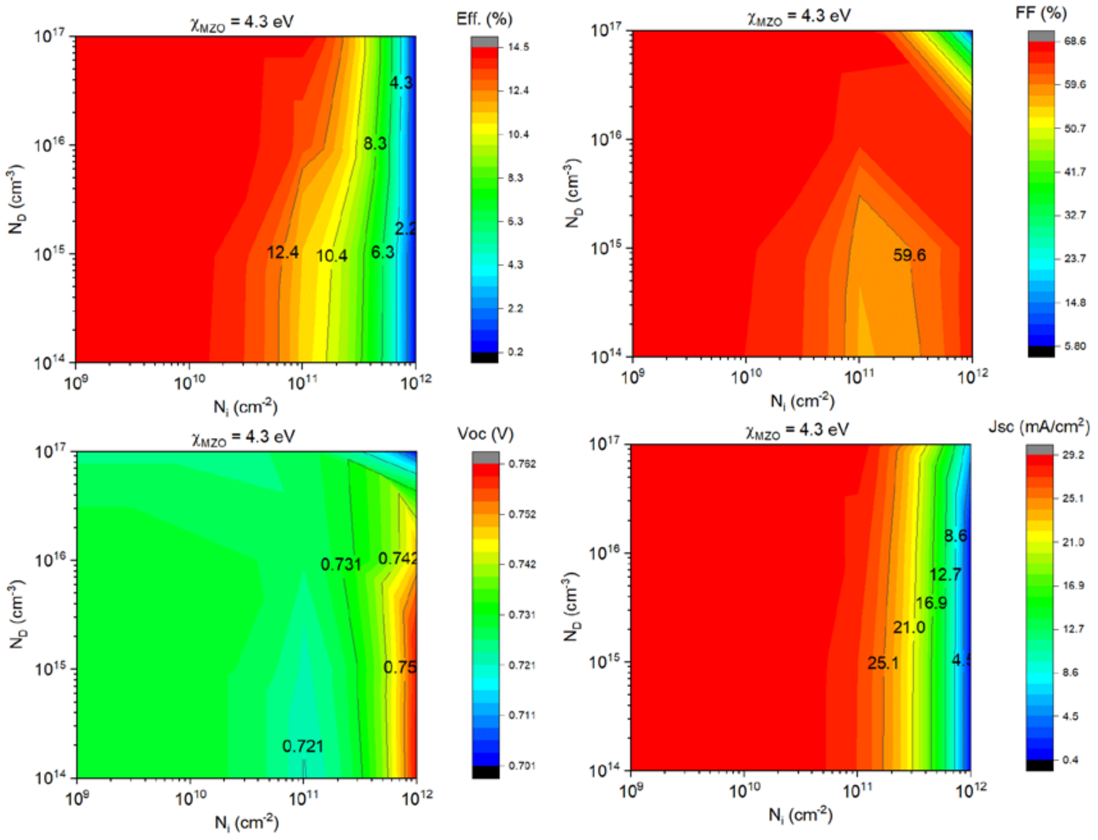
Spike=0.3 eV, X_{MZO}=4.2 eV

FF



Spike=0.2 eV, X_{MZO}=4.3 eV

FF



- **Parameter space: band offset, MZO doping, Interface defect density N_i**
- **Light soak state: either MZO doping is good (>10^{18}/cm^3) or small band alignment spike <0.3 eV (X_{MZO}>4.2 eV). Model A for LSS: spike=0.3 eV, N_{MZO}=10^{18}/cm^3, N_i=10^9/cm^2, Model B: spike=0, N_{MZO}=10^{14}/cm^3, N_i=10^9/cm^2**
- **Degradation state, both poor doping (<10^{16}/cm^3) and large band spike >0.2 eV, DSS in graph: spike=0.3 eV, N_{MZO}=10^{16}/cm^3, N_i=10^9/cm^2; based on literature (Pandy et al., SOLMAT 232 (2021), 111324), the doping decrease at a large spike is more plausible?**

Summary

- KPFM surface potential imaging: 30 nm spatial and and 10 meV energy resolutions
- KPFM potential profiling across devices: nm-resolution junction location determination (buried homojunction for the CdSeTe device), junction/barrier structure for more complicated device than normal single junction device etc.
- Metastability and degradation of CdSeTe devices: additional electric field at MZO/CdSeTe interface for both dark state and degradation state.
- Device modeling in alignment with both the electric field and J-V: The degradation can be induced either by MZO doping (D_{MZO}) decrease at a large MZO/CdSeTe band offset spike or an offset spike increase at low D_{MZO}.

Thank you

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Chun.sheng.jiang@nrel.gov
Phone: +1-720-984-6368
https://www.nrel.gov/research/chun-sheng-jiang.html

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