Inorganic Nanocone Photovoltaic Solar Cells

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Outline

1. Background
2. Nanocone PV fundamental
3. Nanocone synthesis
4. Nanojunction
5. Functional nanocone PV

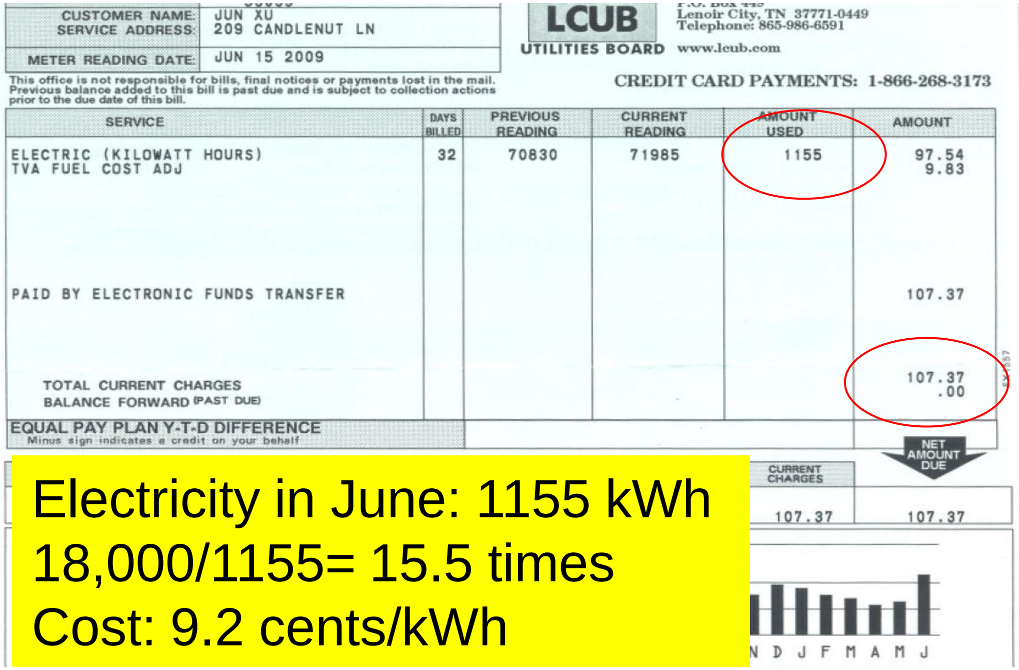
1. Background: Problems

Solar Energy

Knoxville: 6 kWh/day/m^2

If I cover 100 m^2 solar roof,
→18,000 kWh/month

Electricity Bill



CUSTOMER NAME: JUN XU
SERVICE ADDRESS: 209 CANDLENUT LN
METER READING DATE: JUN 15 2009

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SERVICE	DAYS BILLED	PREVIOUS READING	CURRENT READING	AMOUNT USED	AMOUNT
ELECTRIC (KILOWATT HOURS)	32	70830	71985	1155	97.54
TVA FUEL COST ADJ					9.83
PAID BY ELECTRONIC FUNDS TRANSFER					107.37
TOTAL CURRENT CHARGES					107.37
BALANCE FORWARD (PAST DUE)					.00
EQUAL PAY PLAN Y-T-D DIFFERENCE (Minus sign indicates a credit on your behalf)					

CURRENT CHARGES: 107.37
NET AMOUNT DUE: 107.37

N D J F M A M J

Electricity in June: 1155 kWh
18,000/1155= 15.5 times
Cost: 9.2 cents/kWh

Problems:

- Low efficiency (commercial): 7.5%
- High cost: ~30 cents/kWh

Background: Current Technologies

Conventional PV, crystalline silicon, CdTe and CIGS thin films, will continue to be a major part of the solar market.

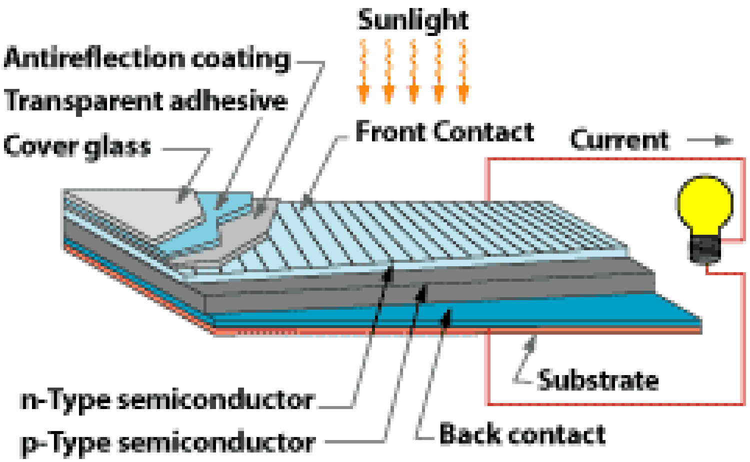
Next generation PV:
Simultaneously reduce cost yet also provide breakthrough performance:

→ Nanocone PV

2. Fundamentals: Why nanocones ?

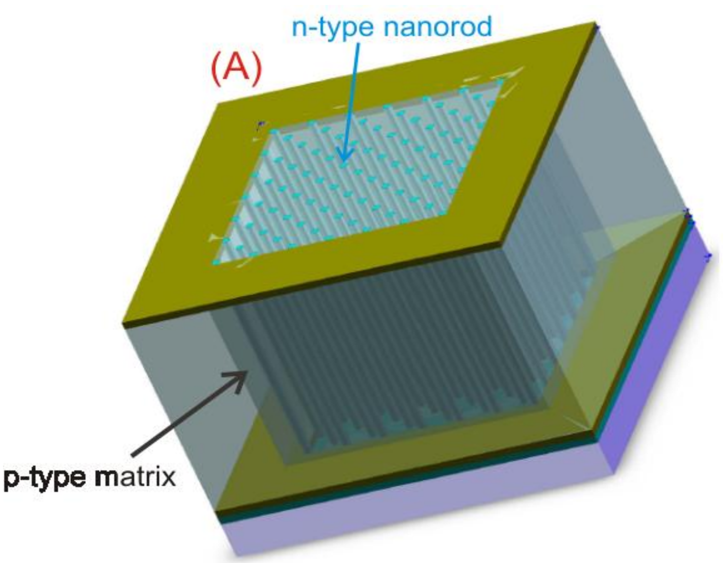
Conventional planar PV has conflicting requirements

- Large scale maximizes photon collection
- Small scale minimizes charge loss

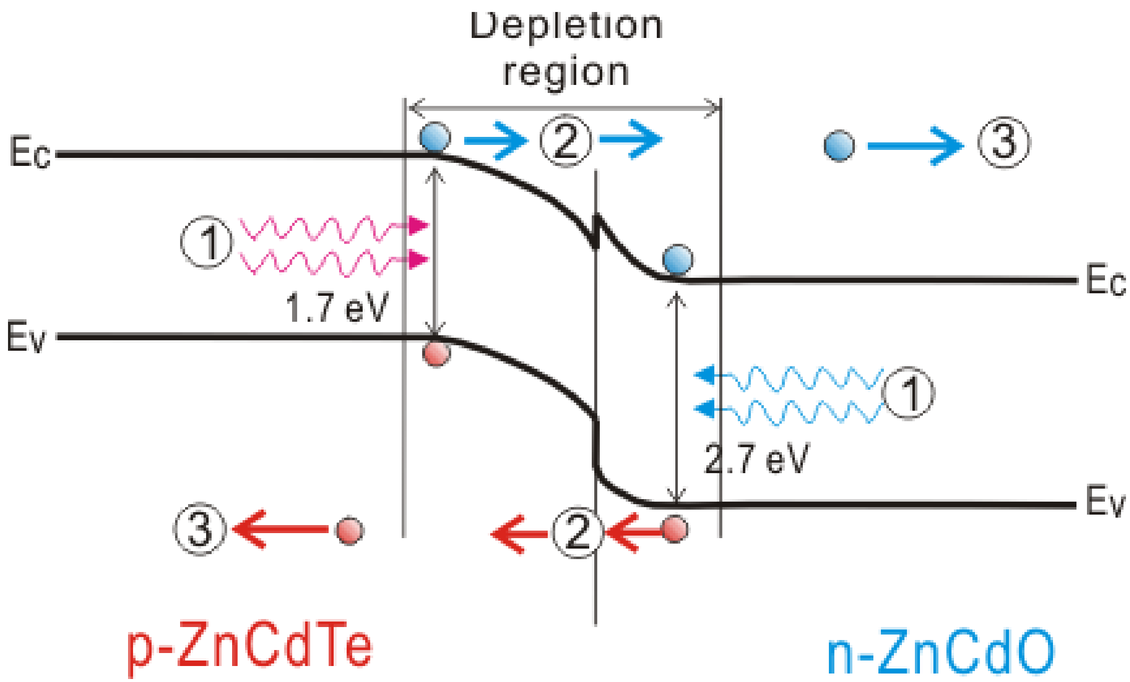


Nanocone PV: 3-D inter-digitated PV architecture

- Reduce charge loss
- Improvements in charge mobility and collection
- In-expensive fabrication

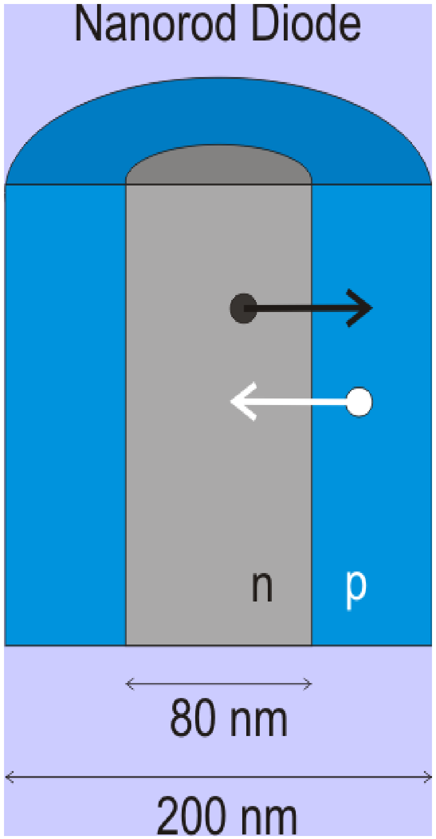


Fundamental: Advantageous absorption and transport

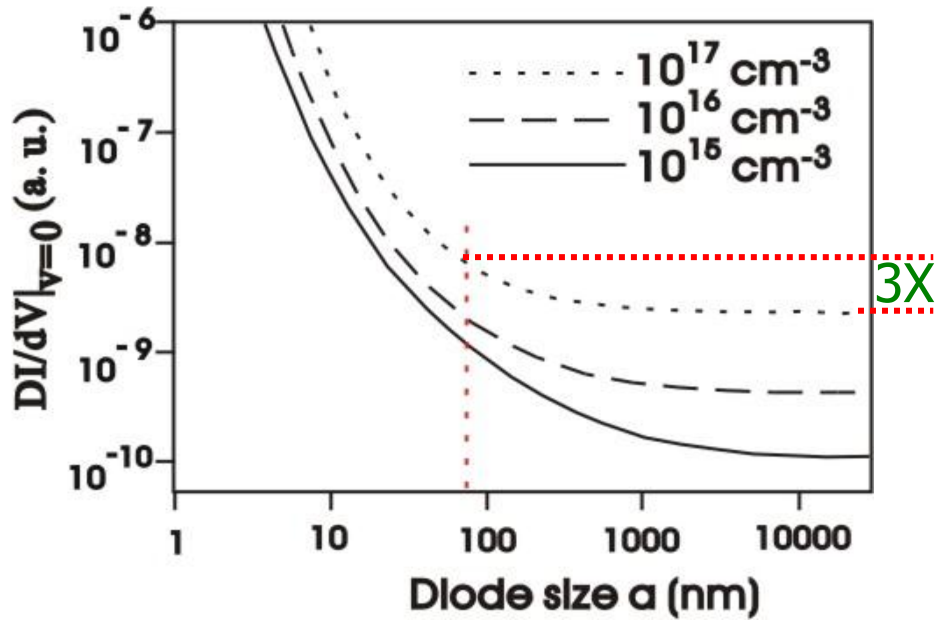


1. More charges produced because of favorable light absorption (bandgap and thickness)
2. Higher tunneling rate for charges crossing *p-n* junction because of nano-scale diodes
3. Higher rate of charge collection because nanocone junction can be made completely depleted

Efficient Charge Crossing p/n Nano-Junction



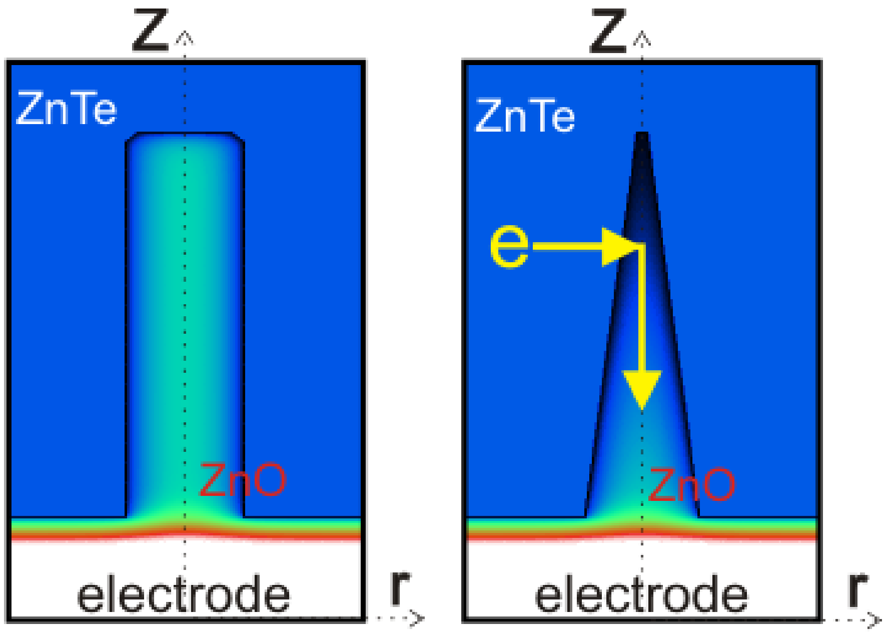
High tunneling rate for nanorod diode

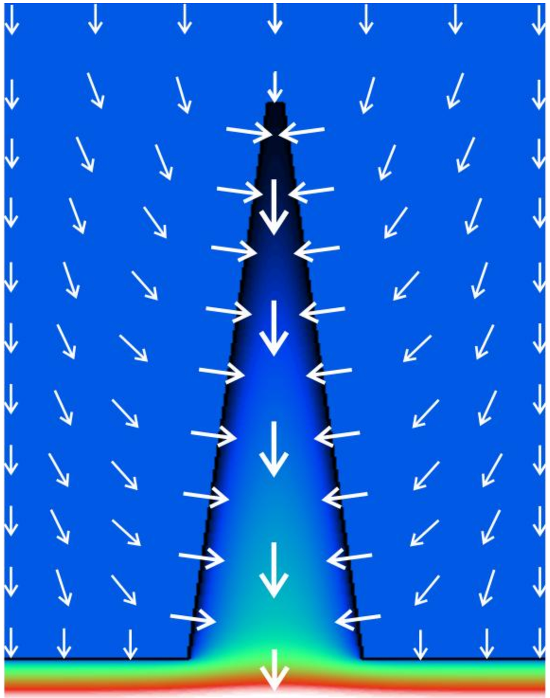


G. D. Smit, *Appl. Phys. Lett.* **80** (2002) 2568.

- 3X higher tunneling rate
  → Low surface recombination loss
- High junction surface → high efficiency
  (B. M. Kayes and H. A. Atwater, CalTech)

Modeling nanocone *p-n* junction
→ Completely depleted region



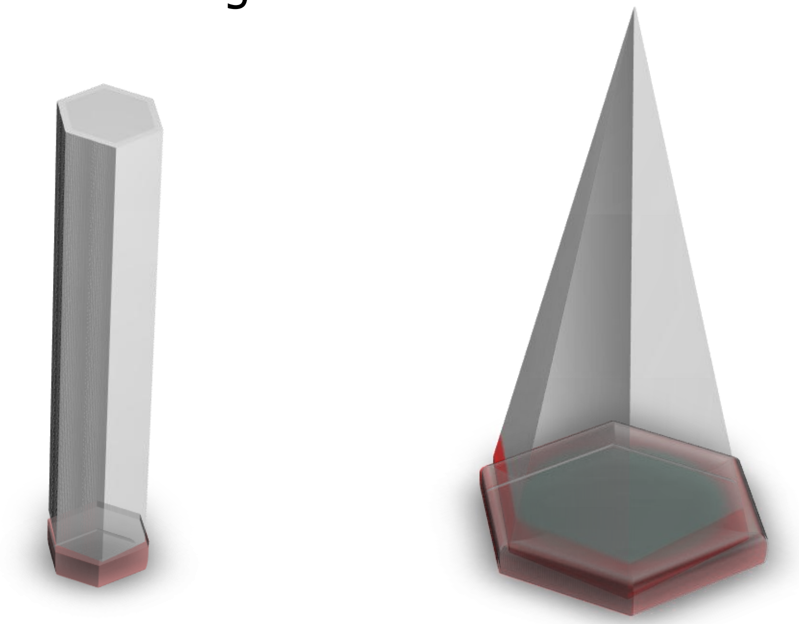


- Potential difference → Electric field→ Drives carriers

Nanocone is better than nanorod because the potential difference exists along Z. This potential will drive carriers into electrodes

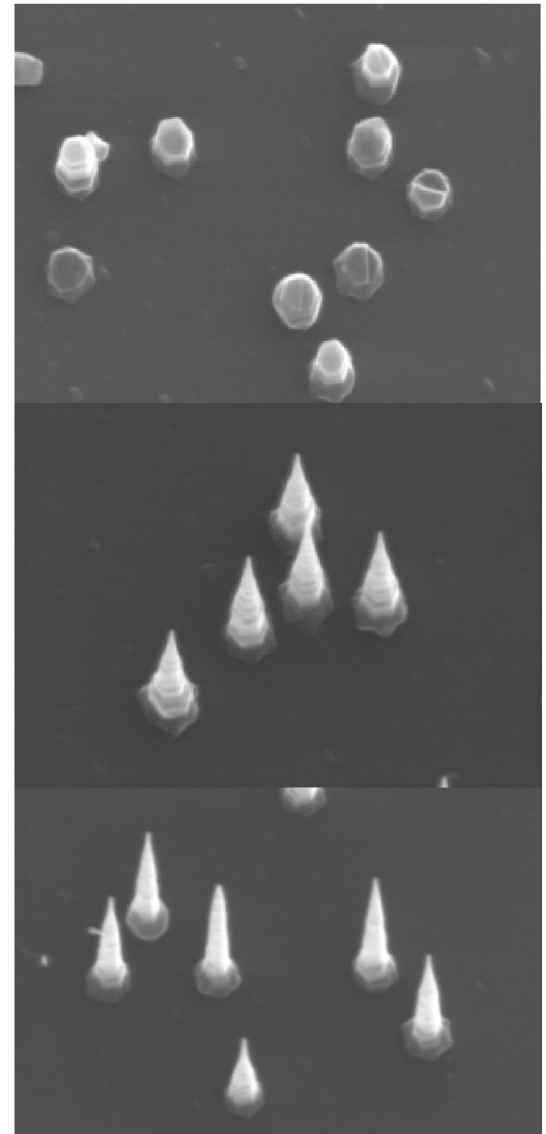
3. Synthesis of ZnO nanocones

- Start with large nucleation sites
- Use growth rate difference between terrace and edge sites to form nanocones



Terrace=edge

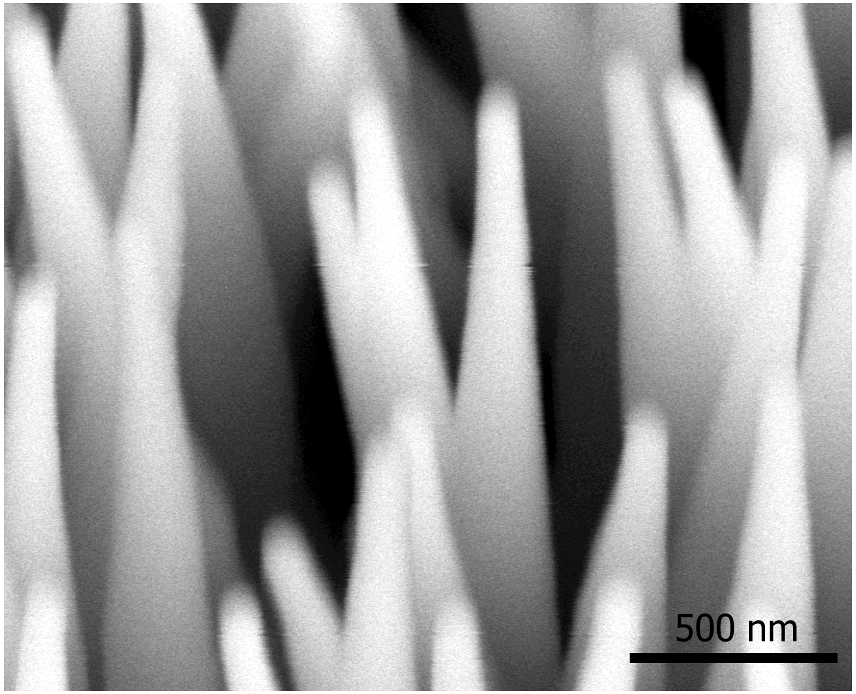
Terrace > edge



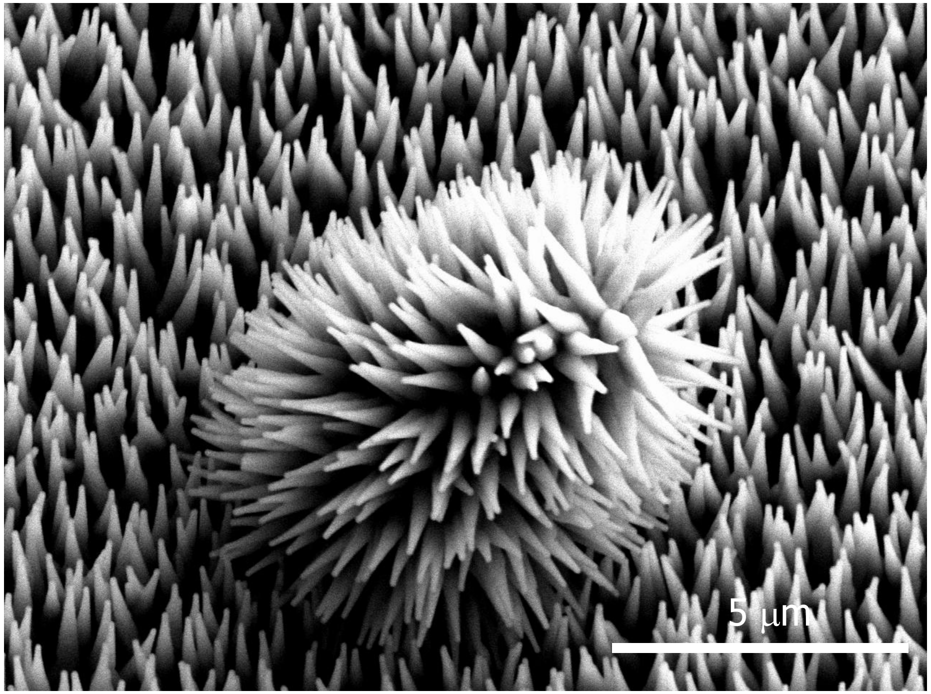
Challenge 1: High density
Challenge 2: PV compatible substrates

Achieved high density nanocones

$7\ \mu m^{-2}$ density



Nanocones on dust particulate



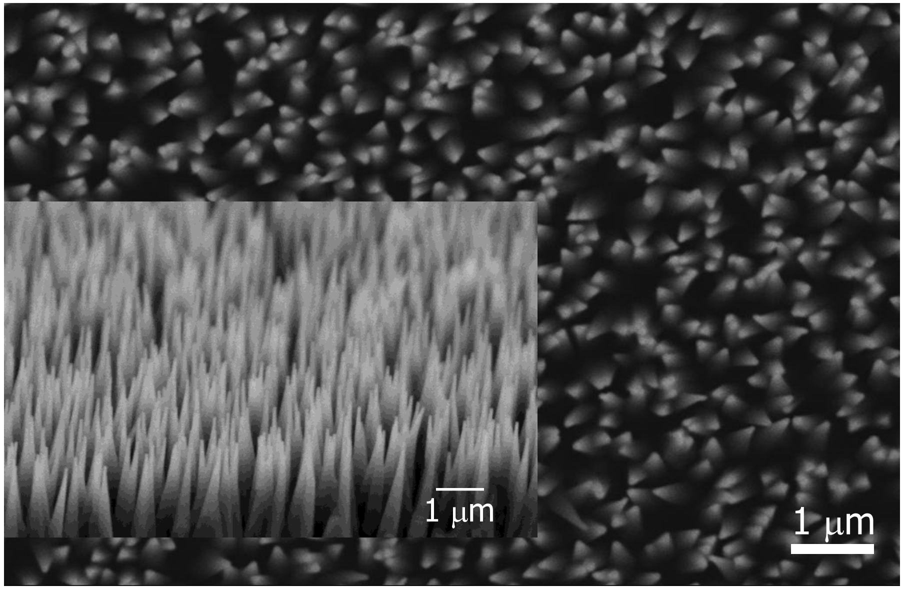
Nanocones grown on Si substrate: 5 μm long, 460 nm wide at the base, and 80 nm wide at the top

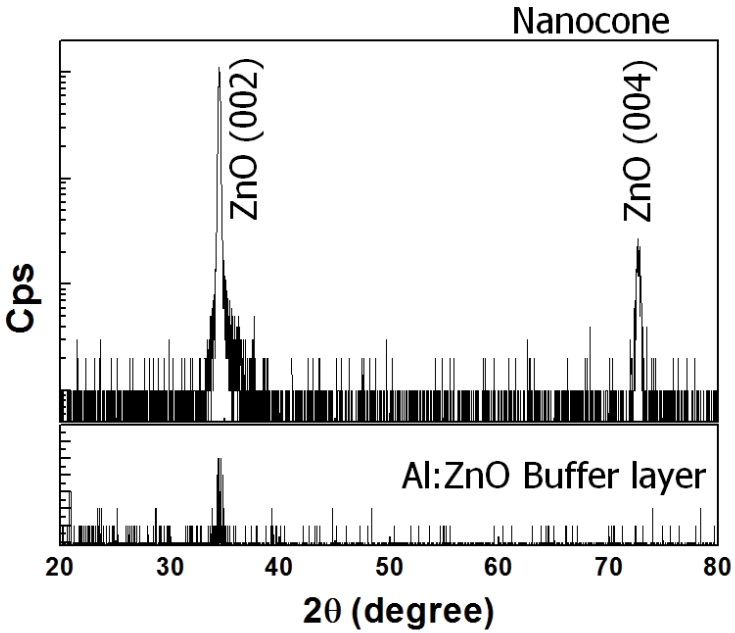
But not on PV substrates!

Synthesis of nanocones on ITO

Issue: Random orientation of nanocones on ITO substrate due to large mismatch in lattice spacing

Solution: Deposit a thin buffer layer by sputter or PLD

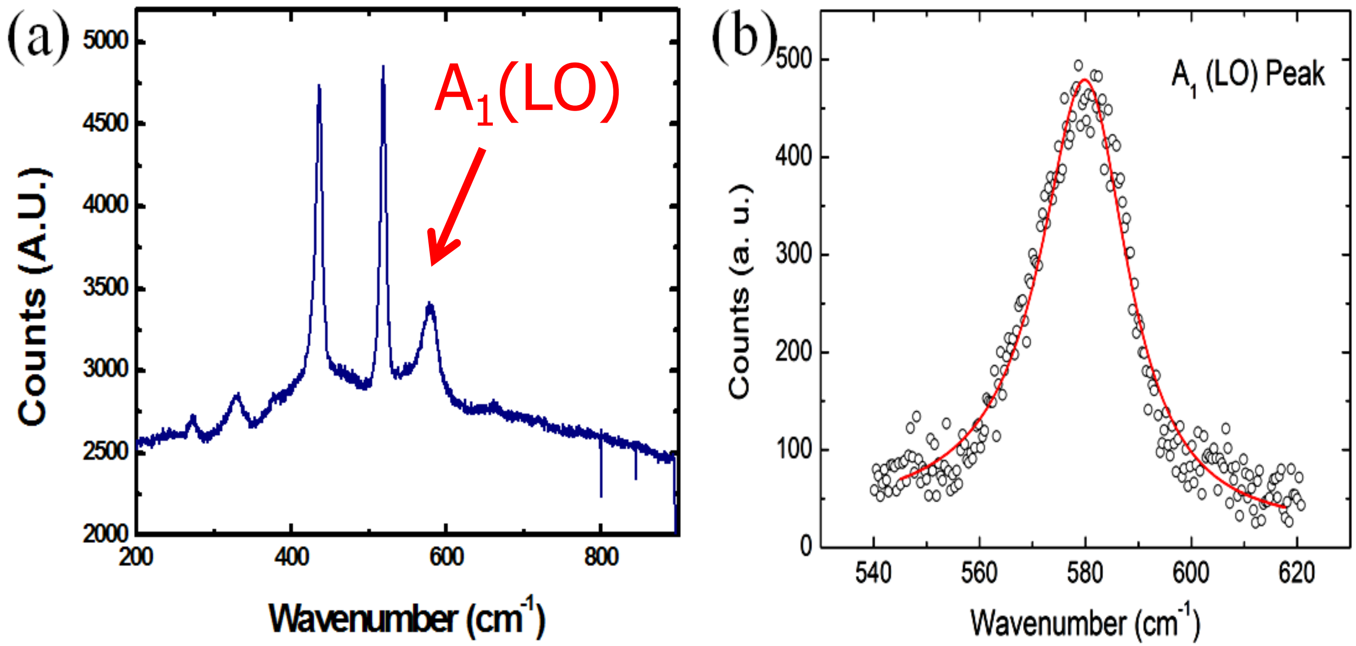




Able to grow ZnO nanocones on PV-compatible ITO/glass substrates

Raman spectroscopy: Carrier concentration and mobility for ZnO nanorods/nanocones

Sept 2010 paper: Jun Xu et al, Proc. of SPIE Vol. 7805 (2010) 78050Z-1

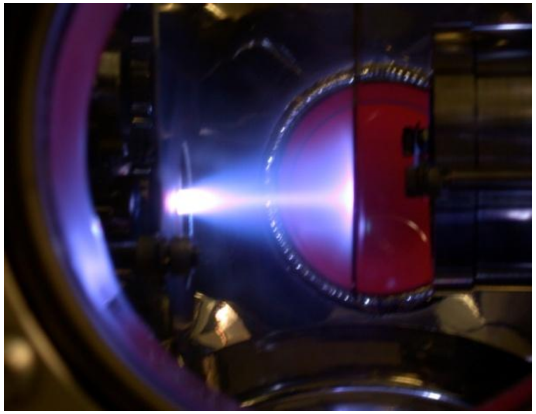


- No-contact measurements
- Carrier concentration: $3.7 \times 10^{17}/cm^3$
- Mobility: 54.1 $cm^2/V/s$

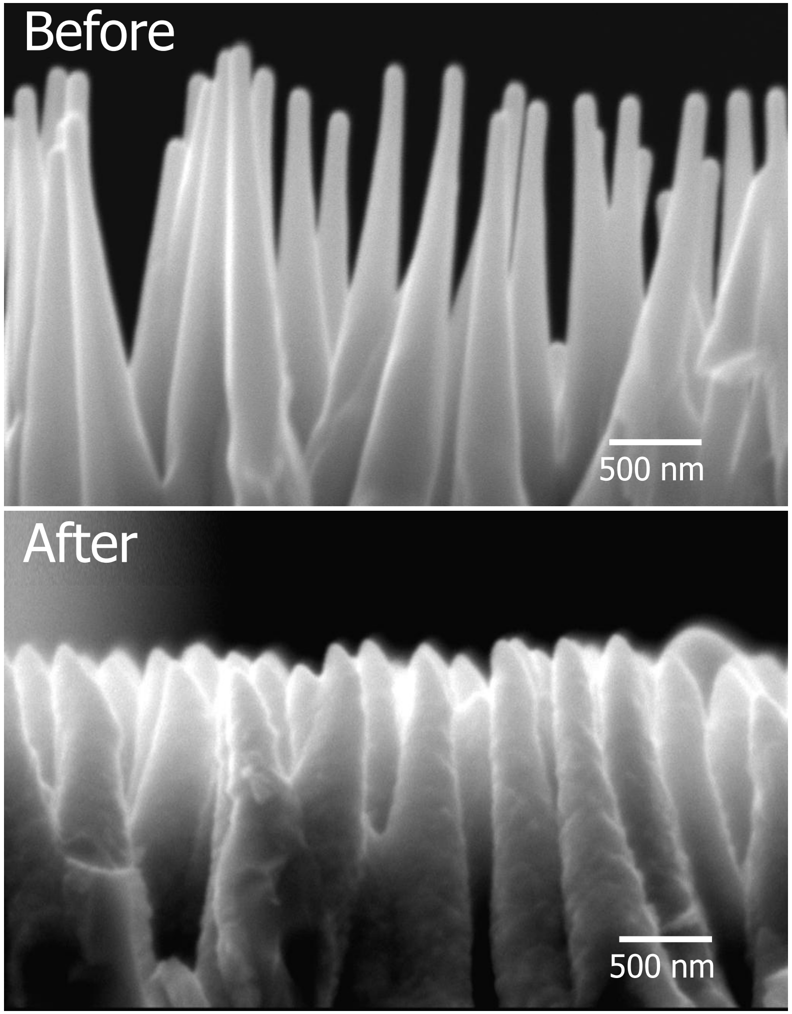
$$\omega_P = \sqrt{\frac{4\pi n e^2}{\varepsilon_\infty m^*}}$$

Carrier concentration in as-grown ZnO nanorod is already large enough for forming semiconductor junctions.

4. Nanojunction: Deposited ZnTe on nanocones using PLD



Pulsed laser deposition of ZnTe on ZnO nanocones

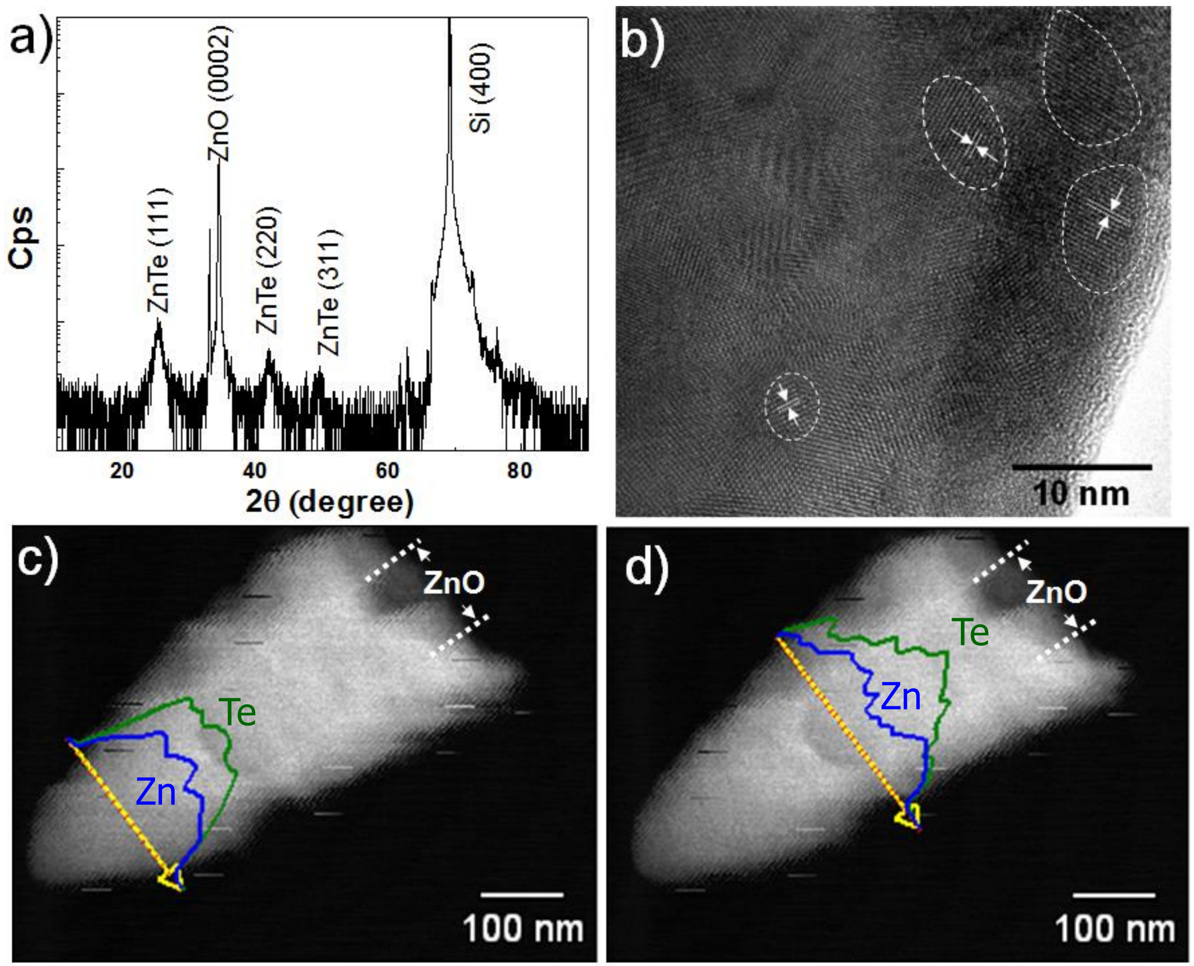


Results

- Base: 460 nm → 610 nm
- Top: 80 nm → ~210 nm
- Average increase in thickness was ~140 nm

We achieved uniform ZnTe coverage on ZnO nanocones

ZnTe-ZnO nanojunction characterization



Polycrystalline ZnTe

Grain sizes : 6-10 nm
Lattice spacing : 0.35 nm
→ ZnTe (111) planes

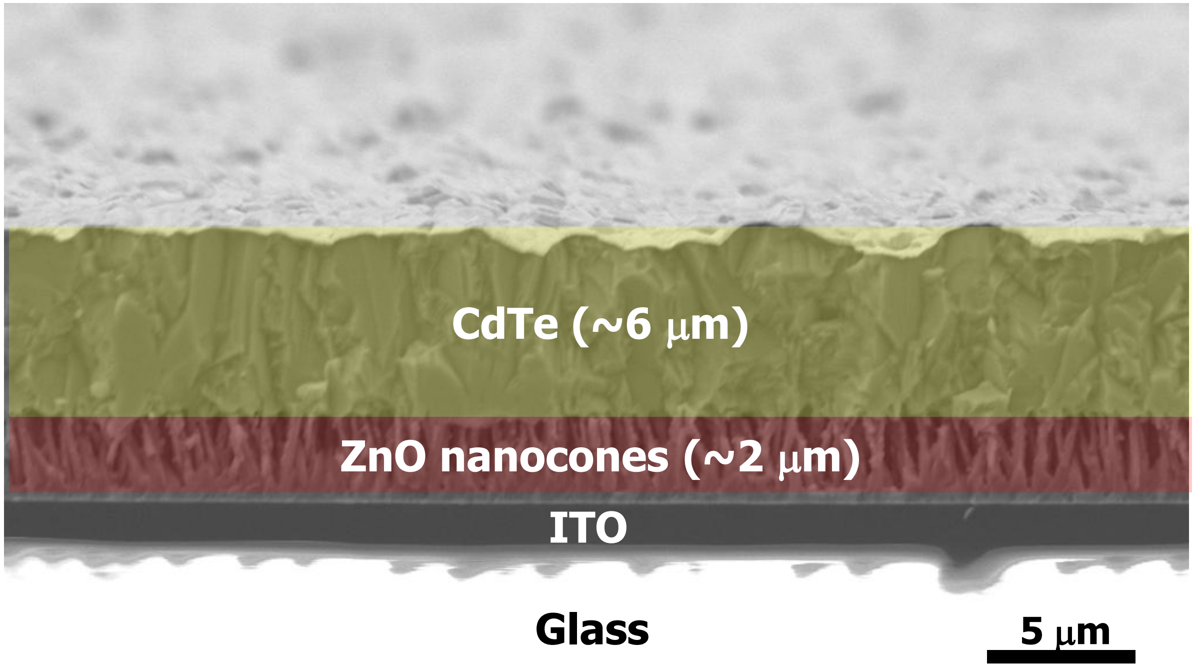
Confirmed ZnO core-ZnTe shell structure

May 2010 publication: S.H. Lee, X.–G. Zhang, B. Smith, S.S.A. Seo, Z.W. Bell, and J. Xu, "ZnO-ZnTe nanocone heterojunctions," Appl. Phys. Lett. 96, 193116 (2010).

CdTe-ZnO nanojuction

- PLD film deposition of ZnTe is slow, at present
- Bandgap in CdTe is better suited for conversion of sunlight

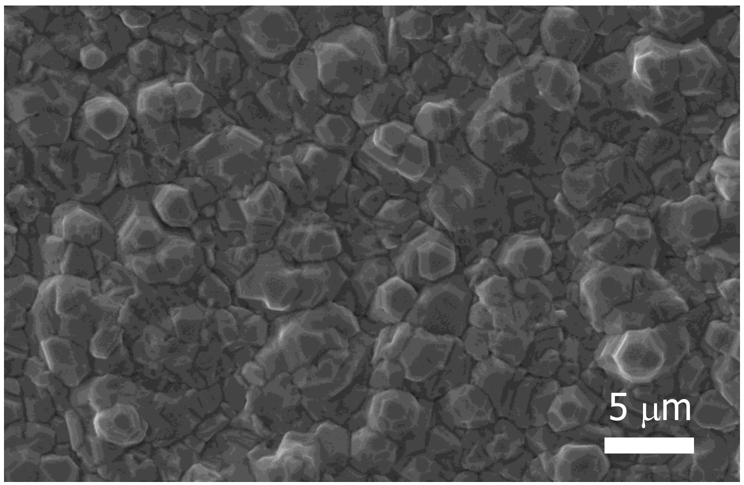
Used close spaced sublimation (CSS) to deposit CdTe



→ Incomplete CdTe coverage of nanocones using CSS

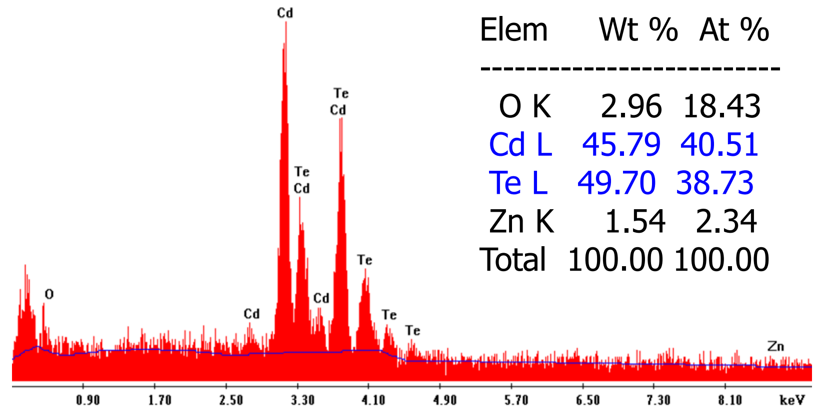
Characterization of CdTe deposition on ZnO nanocones

Grain sizes: 2-5 μm



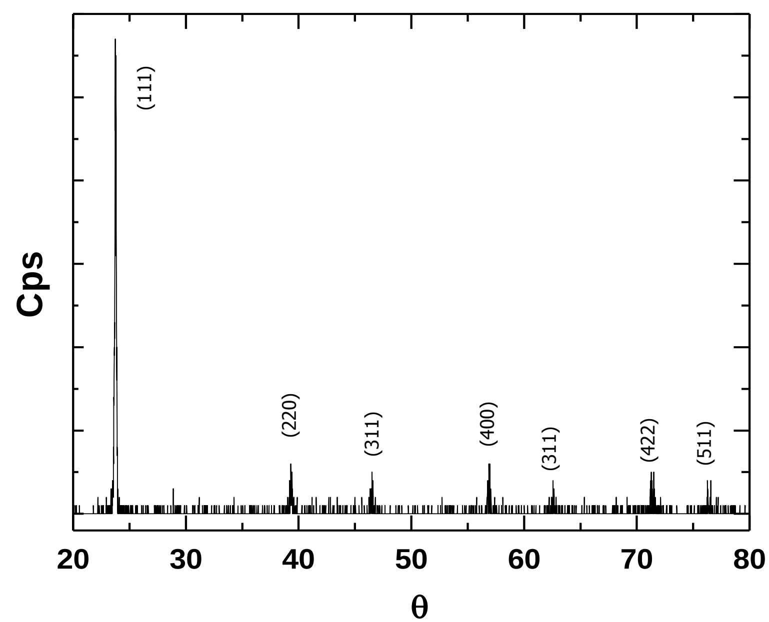
Deposited layer has CdTe stoichiometry (EDS → Cd:Te ~ 1:1) and CdTe crystalline structure (primary peak corresponds to major crystal direction) but large grains.

EDS



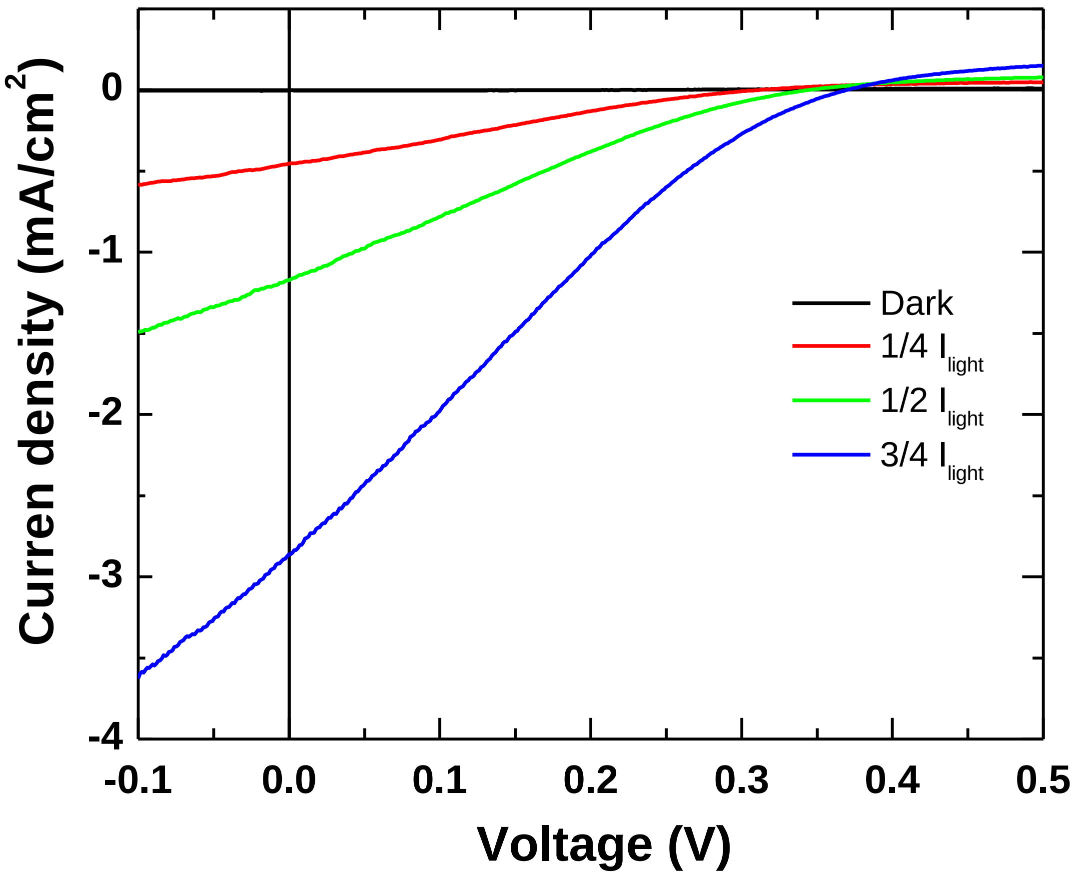
Elem	Wt %	At %
O K	2.96	18.43
Cd L	45.79	40.51
Te L	49.70	38.73
Zn K	1.54	2.34
Total	100.00	100.00

XRD

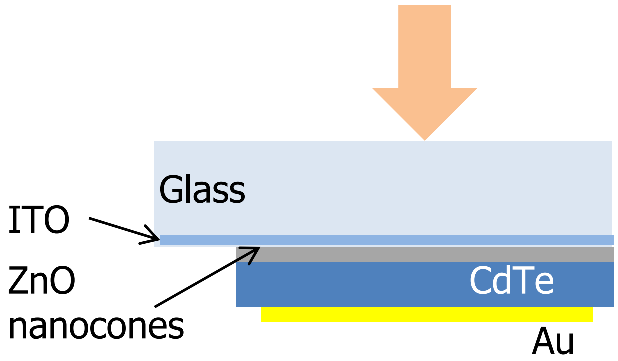


5. Functional nanocone PV:

I-V curve shift is dependent on light intensity



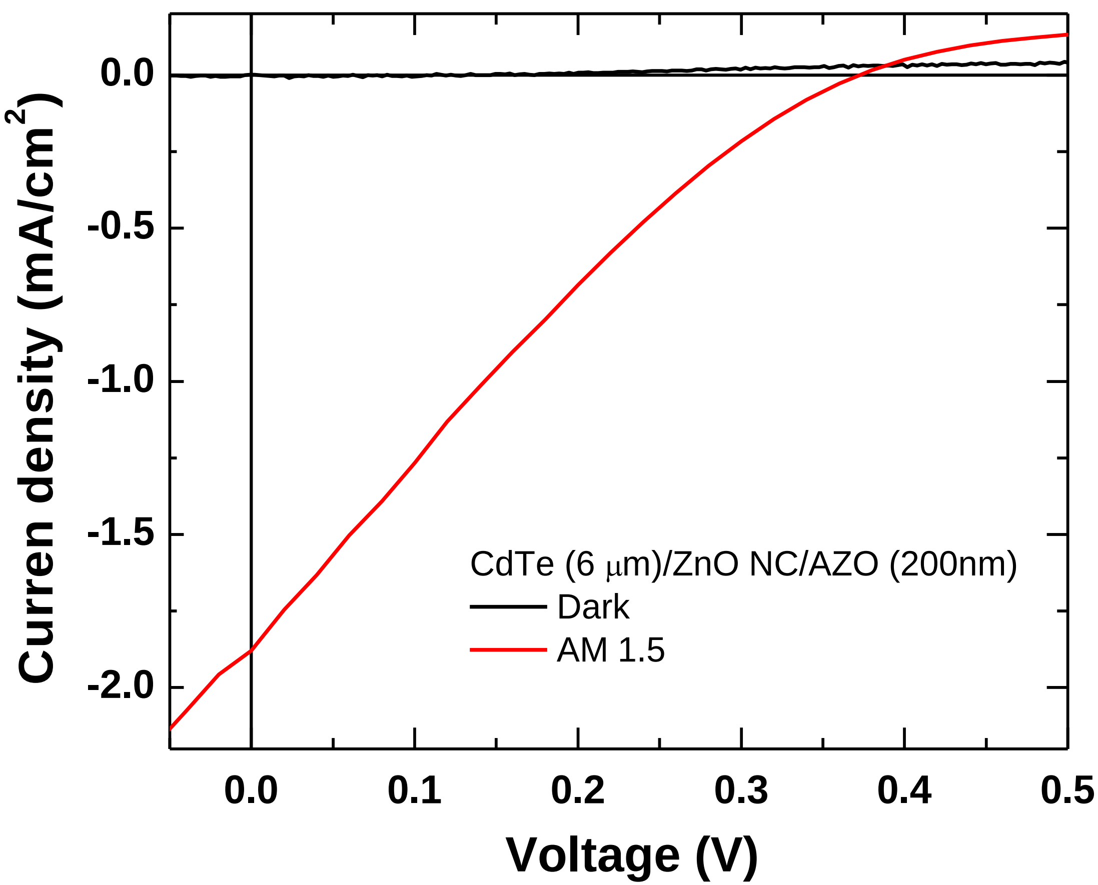
Light
(150 W halogen lamp)

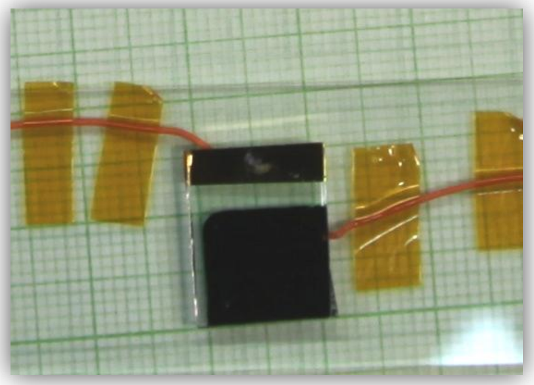


High series resistance:
→Low hall concentration of CdTe (~ 10^{-11} cm^{-3})
→ Contact barrier between CdTe and Au metal

ZnO nanocone/CdTe junction responds to light as expected → Functional PV!

I-V measurement under AM 1.5





V_{oc} (V)	0.38
J_{sc} (mA)	1.879
FF	0.2
Efficiency (%)	0.145

Efficiency measurement completed. Our proof-of-principle device is

- 50% more efficient than CdTe/AZO thin-film PV
- 2.7 times more efficient than ZnO nanorod device reported by LBNL

Theoretical Estimation: nanocone PV efficiency

AMPS-1D developed by Penn State Univ. and Electric Power Research Institute

Inputs: E_g, Carrier concentration, mobility, layer thickness

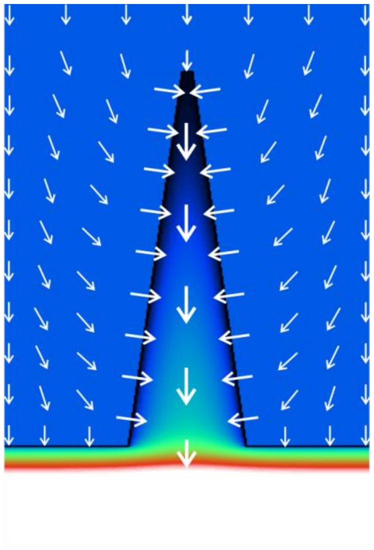
Outputs: Jsc, Voc, Fill Factor, and Efficiency

Improvement	Current EE	Target EE
Improve junction contacts	0.14%	0.7%
Optimize CdTe and ZnO layer thicknesses	0.7%	7.0%
Activate CdTe from $10^{11}/cm^3$ to $10^{14}/cm^3$	7%	25%

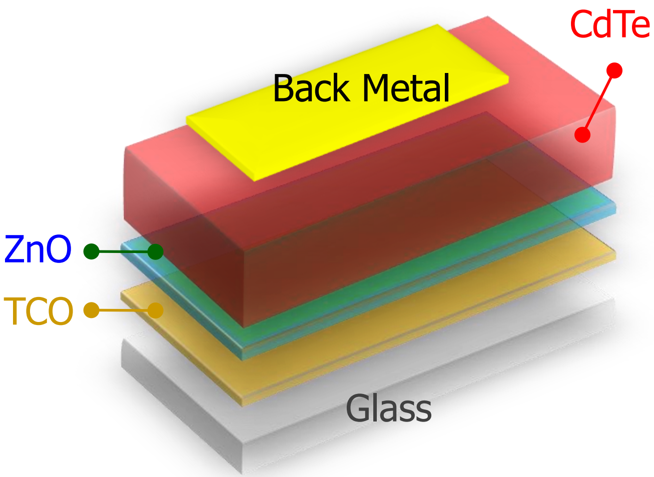
Caveats: Surface defects, stability, and non-Ohmic contacts

Conclusion & Remarks

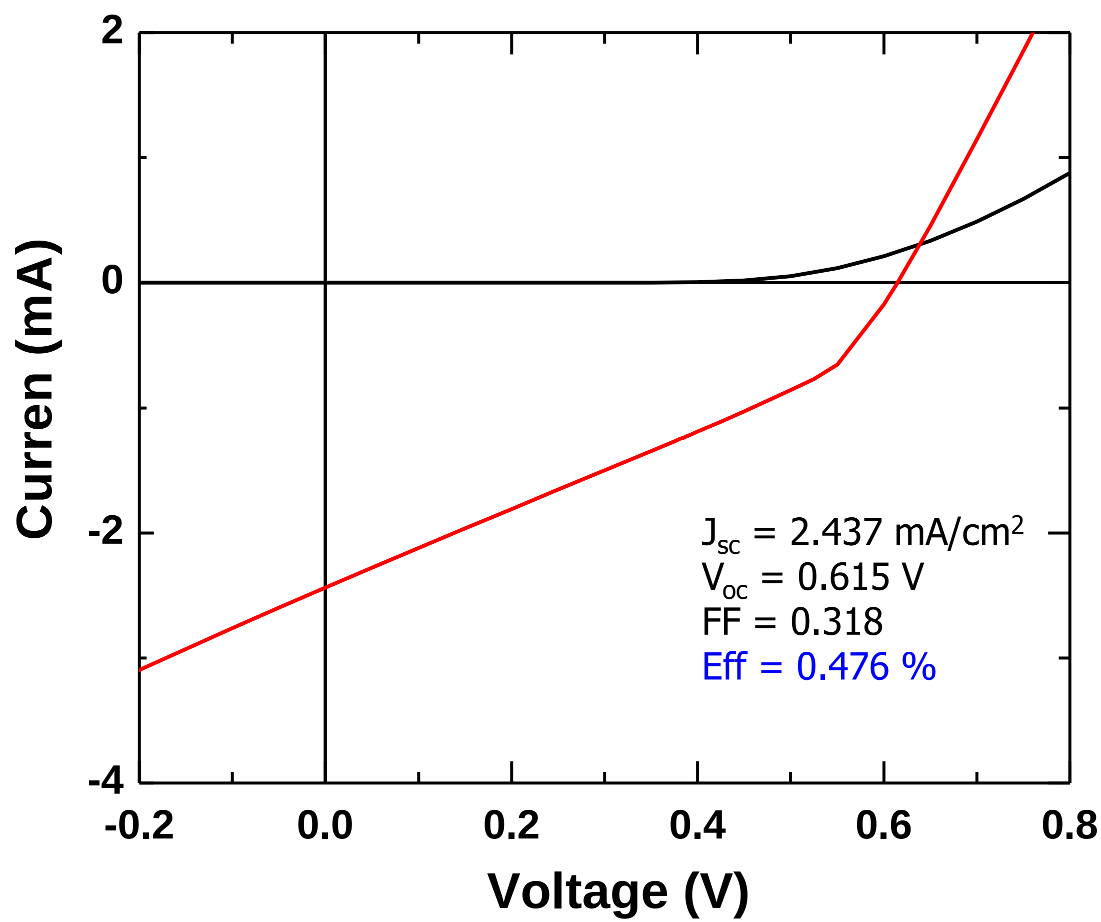
- Capability of synthesizing ZnO nanocones on solar light-compatible substrates
- Capability of fabricating nanojunctions, as characterized by SEM, EDX, TEM, XRD, and I-V curves.
- Demonstrate functional nanocone-based solar cells
  → A base for us to advance.
- Important objective: Build industrial partners and ORNL partners.



Theoretical estimation

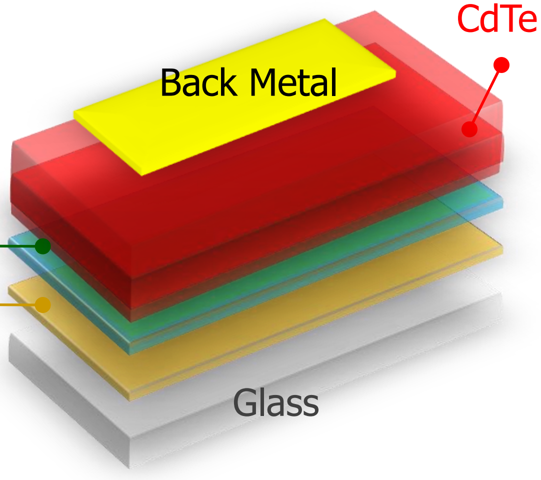


		Baseline
ZnO	Band gap (eV)	3.3
	thickness	500 nm
	Electron concentration (cm^{-3})	3.7×10^{17}
	Mobility (cm^2/Vs)	54
CdTe	Band gap (eV)	1.5
	CdTe thickness	6000 nm
	Hall concentration (cm^{-3})	5×10^{10}
	Mobility (cm^2/Vs)	~1



* AMPS-1D developed by Penn State Univ. and Electric Power Research Institute

Thickness effect calculations

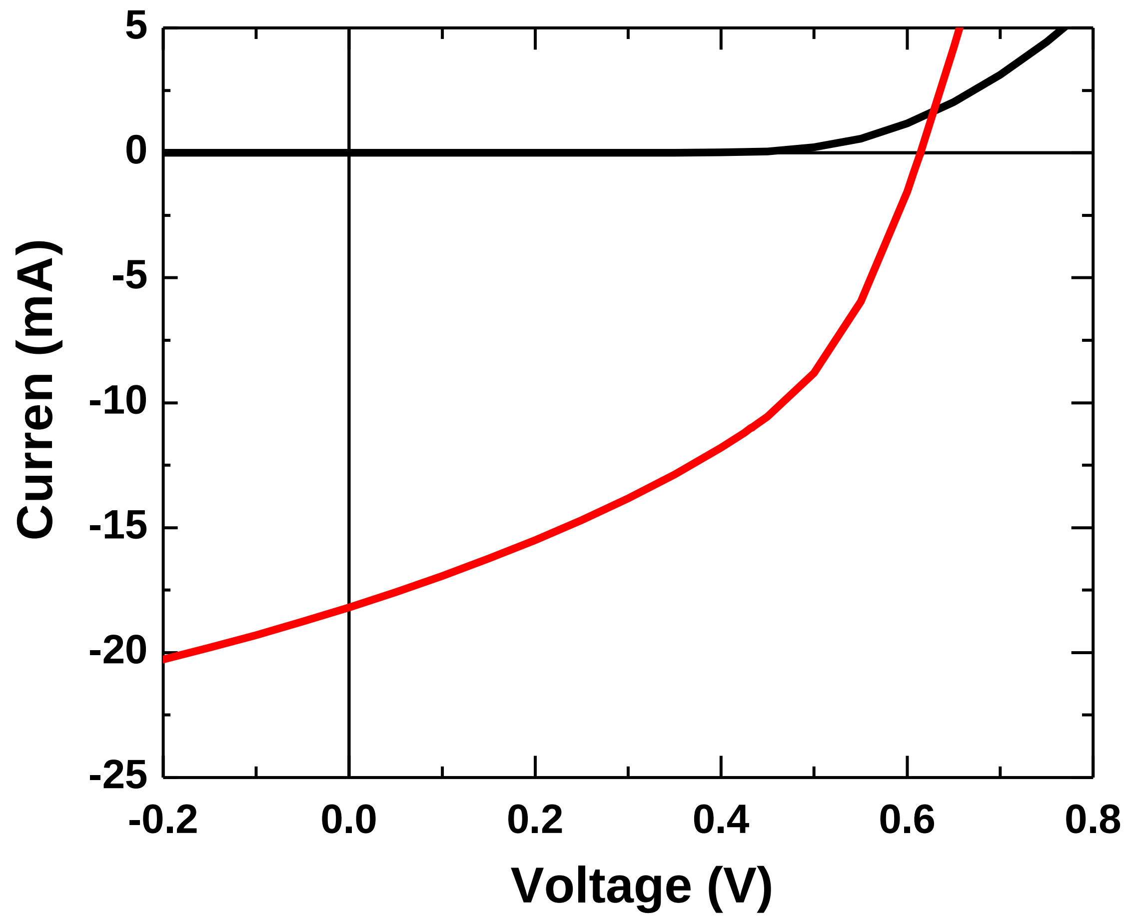


J_{sc} = 2.437 mA/cm^2
V_{oc} = 0.615 V
FF = 0.318
Eff = 0.476 %

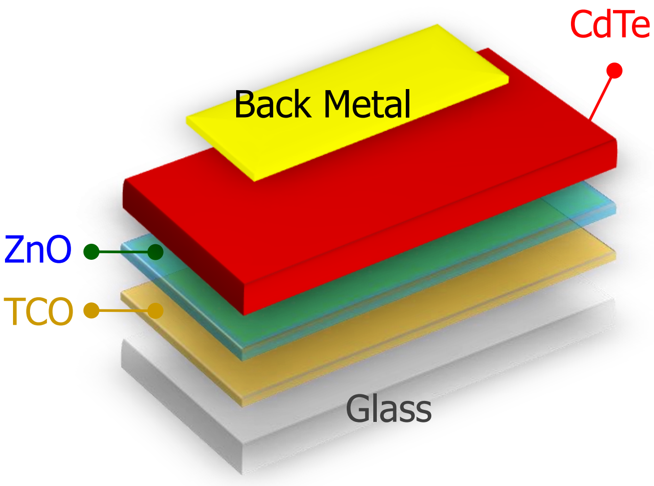
⬇

J_{sc} = 18.194 mA/cm^2
V_{oc} = 0.615 V
FF = 0.426
Eff = 4.761 %

Thickness of CdTe : 6 to 3 μm



Electric properties of CdTe

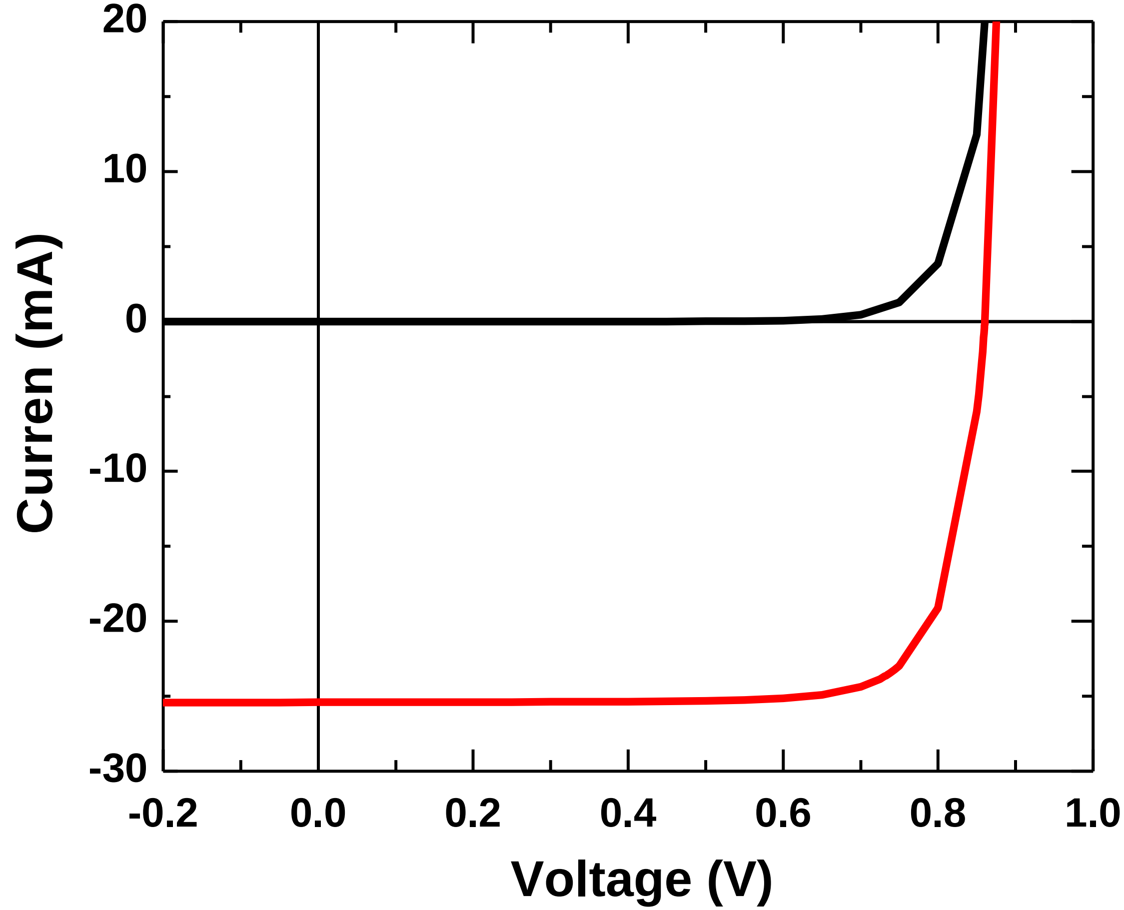


J_{sc} = 18.194 mA/cm^2
V_{oc} = 0.615 V
FF = 0.426
Eff = 4.761 %

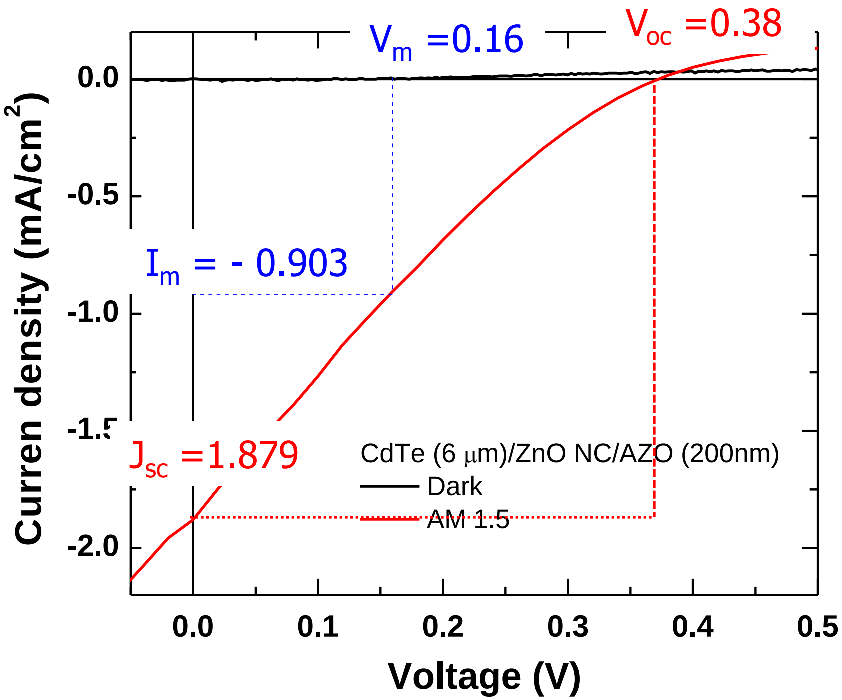
↓

J_{sc} = 25.409 mA/cm^2
V_{oc} = 0.86 V
FF = 0.792
Eff = 17.312 %

CdTe : Carrier concentration : 2 x 10^{14}cm^{-3}
Mobility : 320 cm^2/Vs



Fill factor and efficiency



$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} = \frac{0.16 \times 0.905}{0.38 \times 1.879} = 0.203$$

$$\eta = \frac{V_m I_m}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}} = \frac{0.16 \times 0.905}{100} = 0.001448 \rightarrow 0.145\%$$

V_{oc} (V)	0.38
J_{sc} (mA)	1.879
FF	0.2
Efficiency (%)	0.145