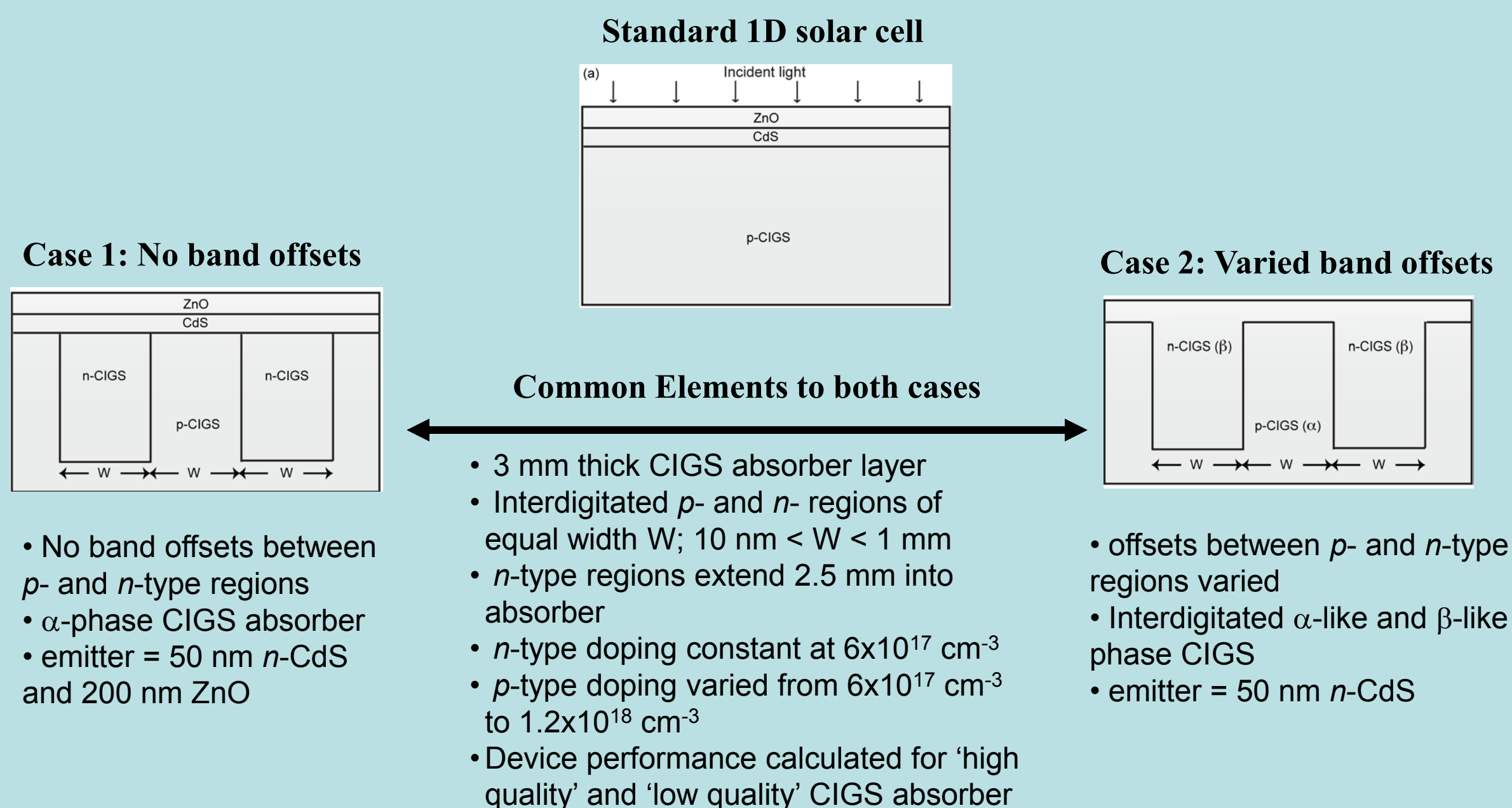


# Device Physics of Nanoscale Interdigitated Solar Cells

Wyatt Metzger and Dean Levi

National Renewable Energy Laboratory • Golden, CO 80401

## DEVICE MODELS: 2 cases of interdigitated cells



## MOTIVATION

- Nanoscale interdigitated solar cell device architectures are being investigated for organic and inorganic solar cell devices.
- Due to the inherent complexity of these device designs quantitative modeling is needed to understand the device physics.
- Theoretical concepts have been proposed that nanodomains of different phases may form in polycrystalline CIGS solar cells.
- These theories propose that the nanodomains may form complex 3D intertwined *p-n* networks that enhance device performance.
- Recent experimental evidence offers some support for the existence of nanodomains in CIGS thin films.
- This study utilizes CIGS solar cells to examine general and CIGS-specific concepts in nanoscale interdigitated solar cells.

## Material Parameters

Bulk Properties	ZnO	CdS	$\alpha$ -CIGS	$\beta$ -CIGS
$E_g$ (eV)	3.3	2.4	1.15	1.43
$\chi$ (eV)	4.6	4.6	4.6	4.62
$\mu_n$ (cm <sup>2</sup> /V-s)	100	100	100/10	100/10
$\mu_p$ (cm <sup>2</sup> /V-s)	25	25	12.5/1.25	12.5/1.25
$n, p$ (cm <sup>-3</sup> )	$n: 10^{18}$	$n: 6.0 \times 10^{17}$	varied	varied
$\alpha/\alpha_0$	9	10	13.6	13.6
$m_e/m_0$	0.2	0.2	0.09	0.09
$m_h/m_0$	1.2	0.8	0.72	0.72
Midgap state (cm <sup>-2</sup> )	$N_A: 10^{14}$	$N_A: 10^{14}$	$N_A: 1 \times 10^{15}$	$N_A: 1 \times 10^{15}$
$\sigma_n$ (cm <sup>2</sup> )	$10^{-13}$	$10^{-13}$	$2 \times 10^{-13}$	$2 \times 10^{-13}$
$\sigma_p$ (cm <sup>2</sup> )	$10^{-11}$	$10^{-11}$	$2 \times 10^{-13}$	$2 \times 10^{-13}$
Surface Properties	Front	Back		
$S_n$ (cm/s)	$10^7$	$10^7$		
$S_p$ (cm/s)	$10^7$	$10^7$		
Reflectivity	0.05	0		

## COMPUTATIONAL APPROACH

- Device performance was calculated by solving the Poisson and electron-hole continuity equations using the drift-diffusion model and by solving current and energy density boundary equations at heterointerfaces described by the Anderson model.
- Programming was done within the Sentaurus Device simulation environment.

## CASE 1: *n* and *p* regions both $\alpha$ -phase CIGS

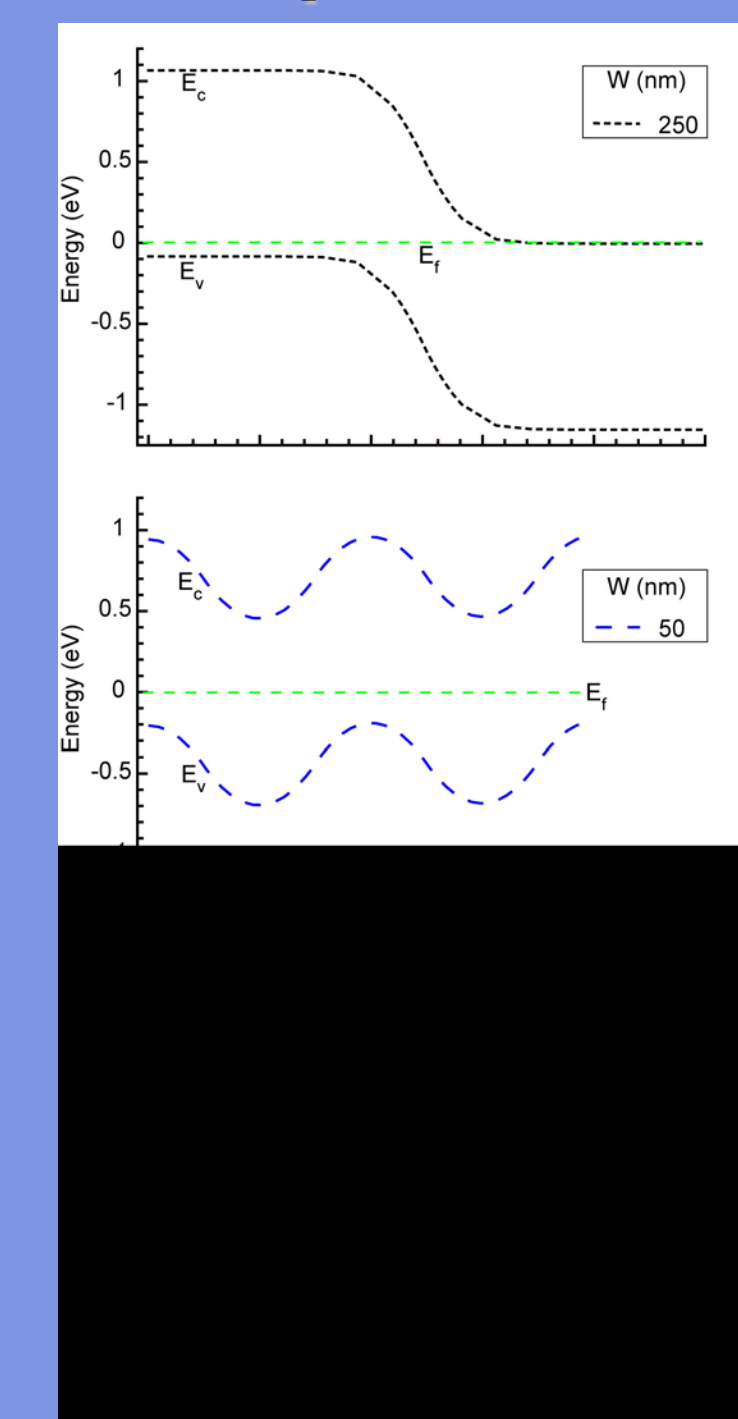
*p*-doping varies, *W* varies

$$E_g(n) = E_g(p) = 1.15 \text{ eV}$$

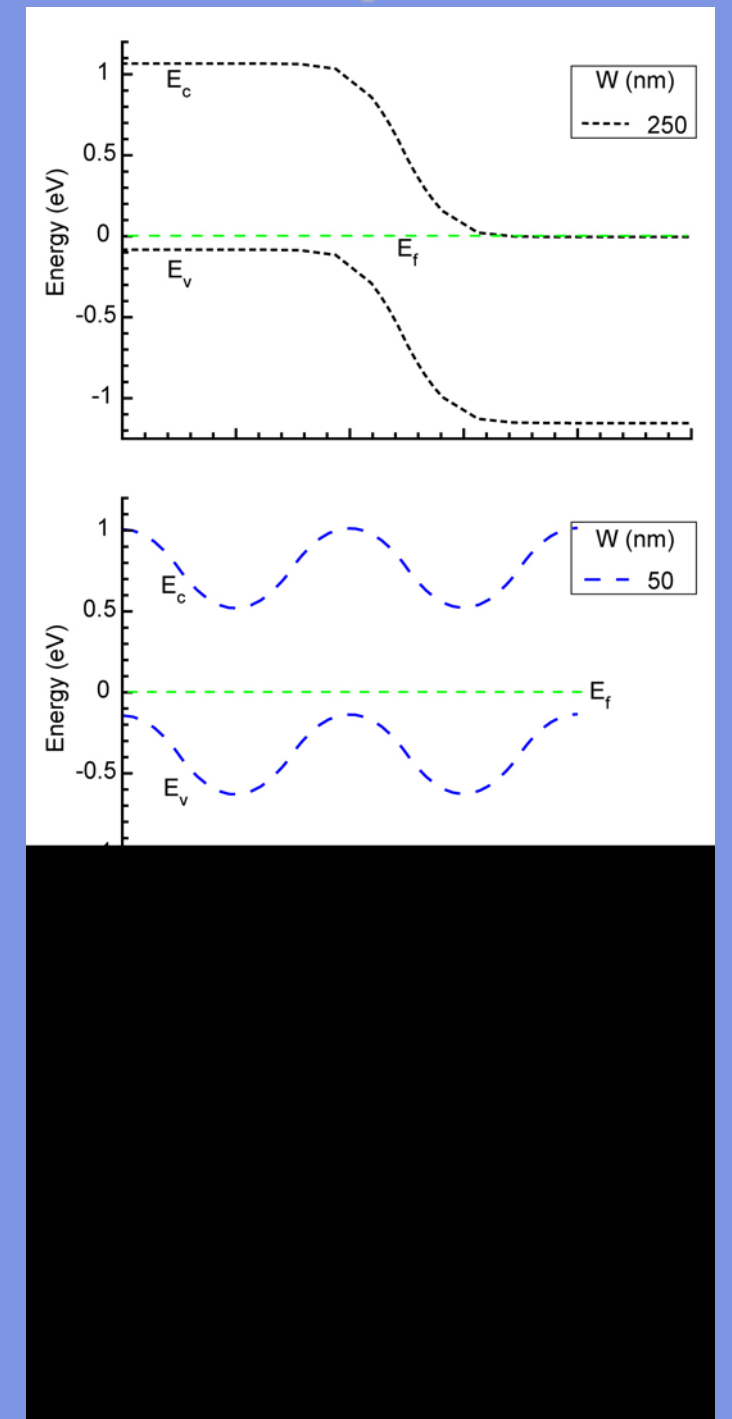
$$n = 6.0 \times 10^{17}, 6.2 \times 10^{17} \text{ cm}^{-3}$$

$$p = 6.0 \times 10^{17}, 6.2 \times 10^{17} \text{ cm}^{-3}$$

Band bending vs *W* for equal doping  
 $n = p = 6 \times 10^{17} \text{ cm}^{-3}$

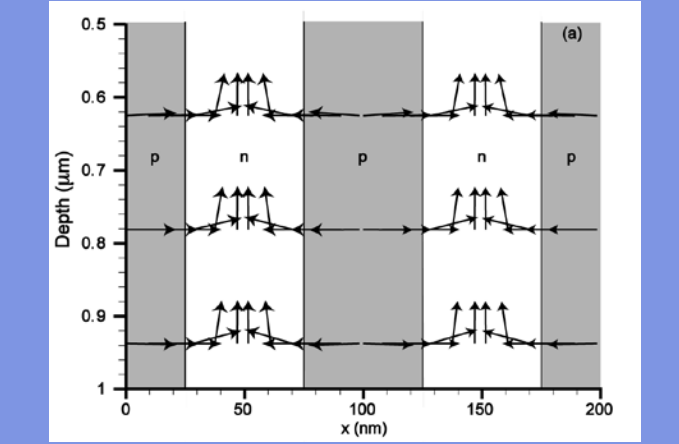


Band bending vs *W* for unequal doping  
 $n = 6 \times 10^{17} \text{ cm}^{-3}, p = 6.2 \times 10^{17} \text{ cm}^{-3}$

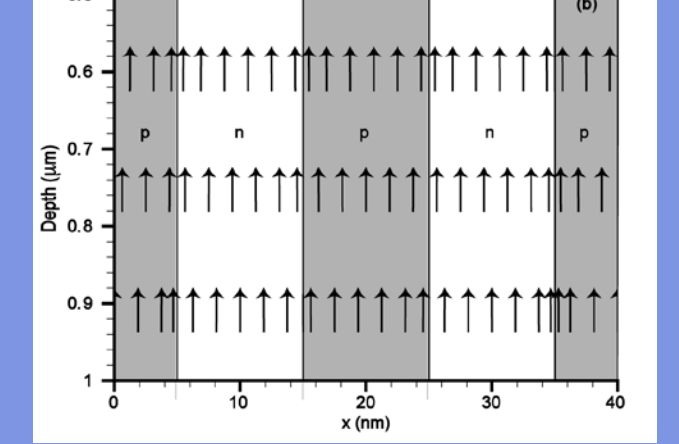


Current flow pathways

*W* = 50 nm



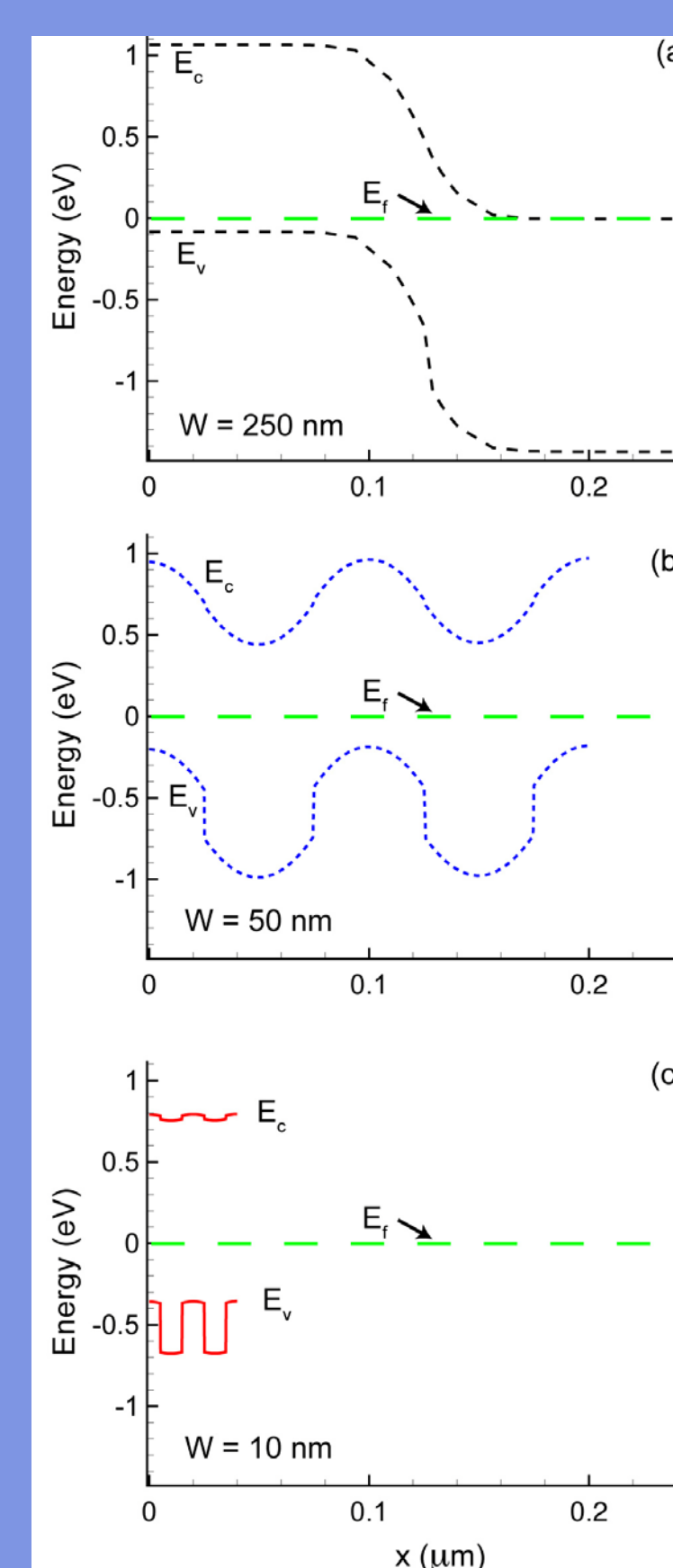
*W* = 10 nm



As *W* decreases less charge is available to create band bending, the built-in field at the vertical *p-n* junction decreases, and the device becomes a 1D solar cell with average properties of the *n* and *p* regions.

As *W* decreases less charge is available to create band bending, the built-in field at the vertical *p-n* junction decreases, and the device becomes a 1D solar cell with average properties of the *n* and *p* regions.

Band bending when  $D_c = 0$   
 $n = p = 6 \times 10^{17} \text{ cm}^{-3}$

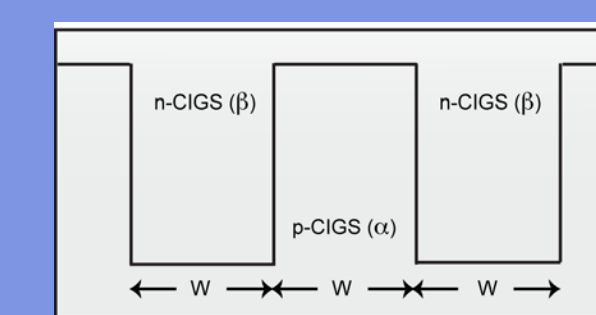


## CASE 2: *n* regions $\alpha$ -phase, *p* regions $\beta$ -phase

Band offset varies, *W* varies

$$\Delta\chi = -0.3, 0.0, 0.3 \text{ eV}$$

$$E_g(\alpha) = 1.15 \text{ eV}, E_g(\beta) = 1.45 \text{ eV}$$



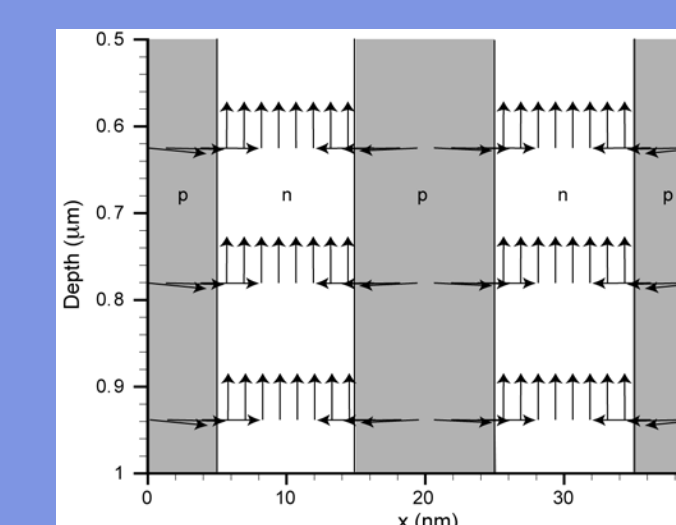
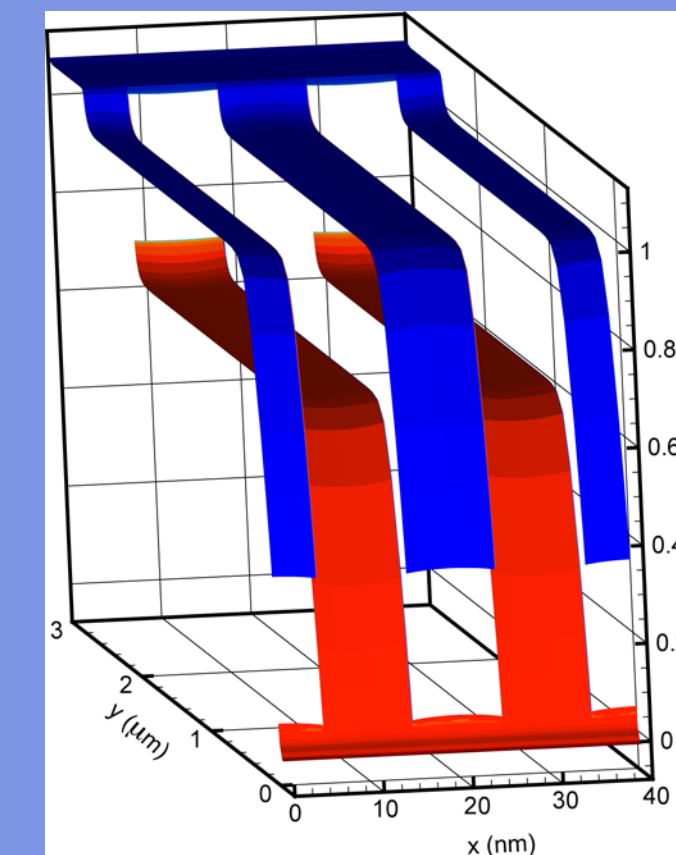
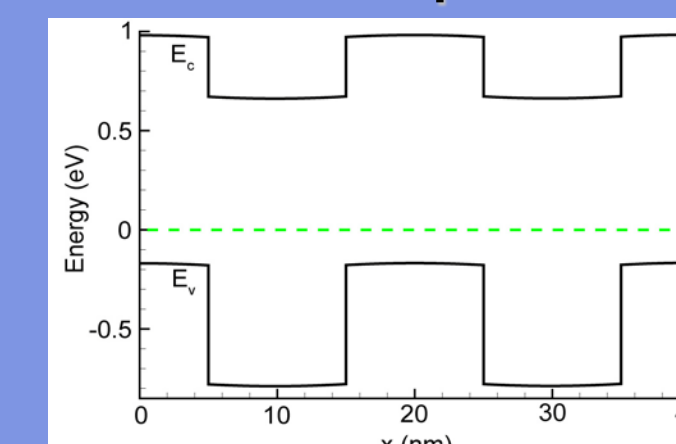
For large *W* (e.g. 250 nm), the lateral band alignment is determined by charge transfer and band bending (upper left figure).

For intermediate *W* (e.g. 50 nm), the lateral band alignment is determined both by band bending and band offsets (middle left figure).

For small *W* (e.g. 10 nm), the lateral band alignment is determined by the bandgap and conduction and valence band offsets and not by band bending (bottom left figure).

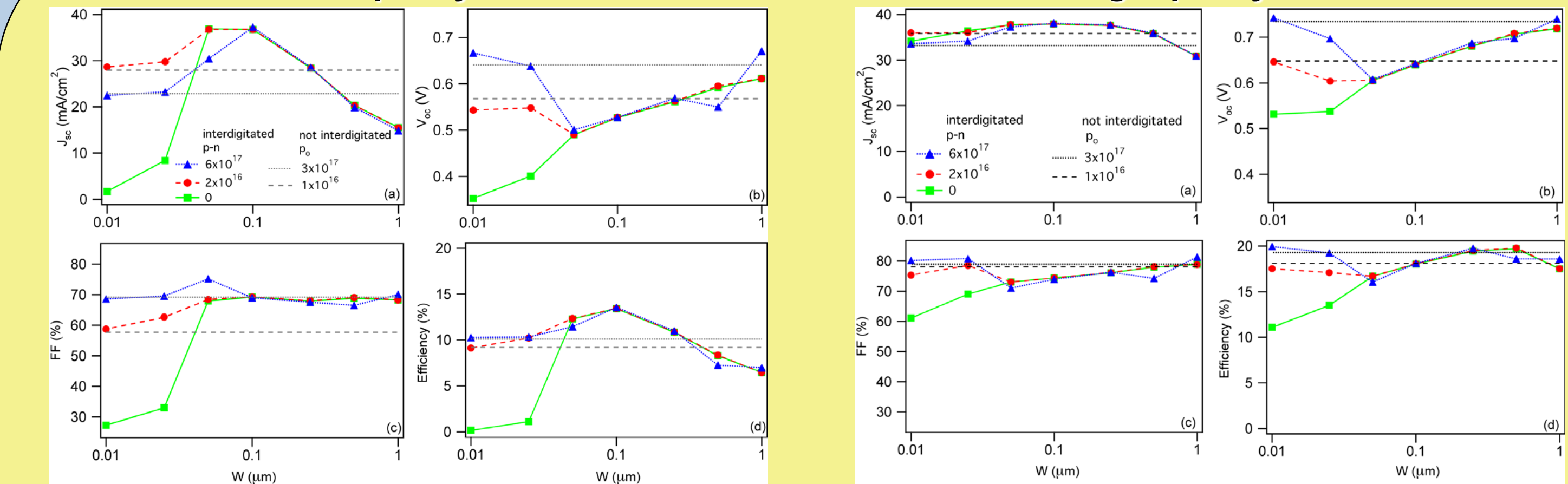
If the bandgap and offsets form a robust type II interface (e.g.  $\Delta\chi = -0.3$ , middle and upper right), charge separation occurs even when *W* = 10 nm (lower right).

$\Delta\chi = -0.3 \text{ eV}$   
Type II band alignment  
Effective carrier localization  
Enhanced device performance



## "Low quality CIGS"

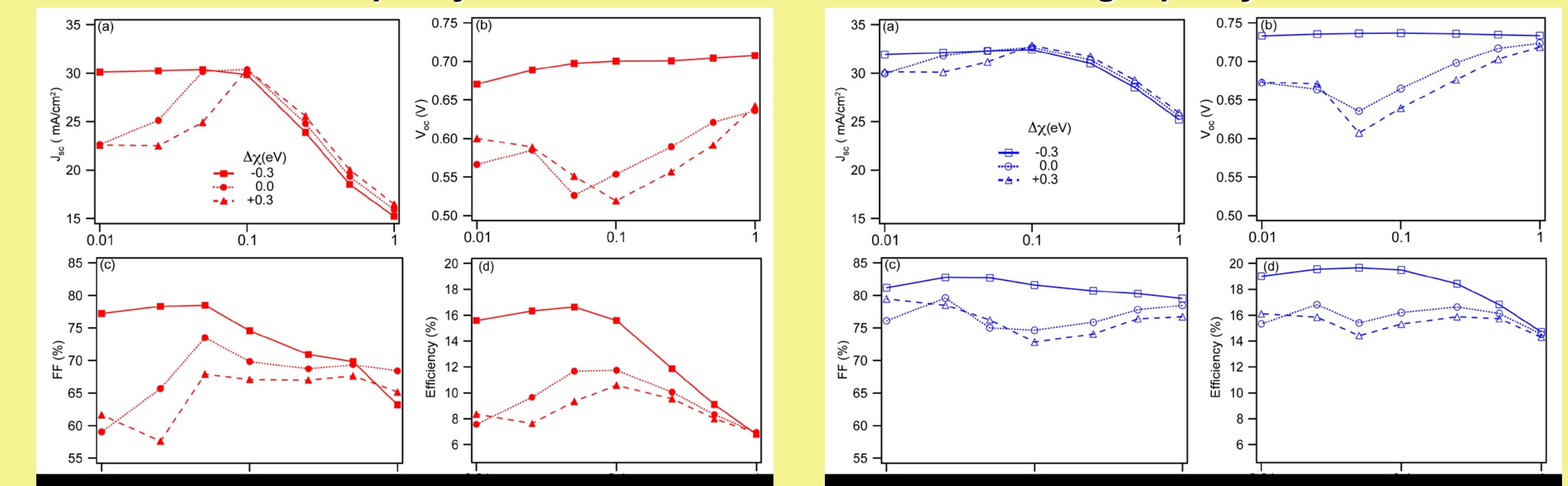
## "High quality CIGS"



- W* = 1 μm**  $V_{oc}$  is optimum when there is maximal band bending and minimal dark current, which occurs at large *W*. But the geometry is not ideal for current collection and  $J_{sc}$  is inferior to a comparable planar junction device.
- W* > 50 nm** As *W* decreases towards 50 nm, current is collected more efficiently, but increasing dark current and reduced band bending lower  $V_{oc}$ . PV designs that increase photocurrent collection generally increase dark current too.
- W* < 50 nm** The strength of the lateral fields diminish and no longer effectively separate charge. Transport and performance becomes identical to a planar junction device with a uniform doping equivalent to half of *p-n* in the CIGS layer.

## "Low quality CIGS"

## "High quality CIGS"



- $\Delta\chi = 0.0$  or  $+0.3$  For *W* greater than 50 nm, the lateral fields and device performance are similar to the case with no offsets. For *W* less than 50 nm, either the valence or conduction band is flat. Hence one carrier is not separated laterally and recombination is not effectively reduced. The results are again similar to the case with no offsets.
- $\Delta\chi = -0.3$  For large *W*, the lateral fields and device performance are similar to the case with no offsets. However as *W* is reduced, the offsets form a robust type II junction which effectively separates charge and reduces recombination even for *W* = 10 nm. This structure improves device performance relative to a planar junction device, and attains efficiencies greater than 15% even for "low quality" material with a diffusion length of 100 nm.

## CONCLUSIONS

- Interdigitated thin-film solar cells can give good device performance commensurate with comparable planar junction devices.
- Interdigitated *p* and *n* regions increase efficiency relative to a comparable planar junction device for low-quality material when *W* is about 50 or 100 nm in this study.
- In most cases, device performance is generally not significantly increased relative to a planar junction.
- Performance can be increased for low and high quality material when the band offsets between *n* and *p*-type material form a robust type-II band alignment that effectively separates electrons and holes even when *W* is small.