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Influence of defect and polarization on efficiency of InGaN-based double-junction solar cell



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Summary

A detailed investigation on the performance of an InGaN-based double-junction solar cell was carried out. We have globally simulated the solar cell using empirical InGaN material parameters, to avoid any overestimation in the solar cell performances. In order to take into account the interdependence of the solar cell physical and geometrical parameters, ensuring the absoluteness of the optimized photovoltaic performances, the cell was optimized using a multivariate optimization algorithm that simultaneously optimizes eleven physical and geometrical parameters. We obtained an optimal efficiency of 24.4%, with a short circuit current $J_{SC} = 12.92 \text{ mA/cm}^2$, an open circuit voltage $V_{OC} = 2.287 \text{ V}$ and a fill factor $FF = 82.55\%$. We then quantitatively investigated the impact on the solar cell performances of the internal polarization and structural defects in InGaN. We have shown that the internal polarization reduces the performance of the cell by inducing an electric field which does not favor an efficient collection of photo-generated carriers. We have also investigated the impact of structural defects in InGaN, including disorder and deep defects, and correlated their effect to the InGaN doping concentration.

Solar Cell Structure

InGaN-based double-junction solar cell

- Structure composed of **two p-n junctions**
- Two subcell vertically stacked having different **bandgaps**

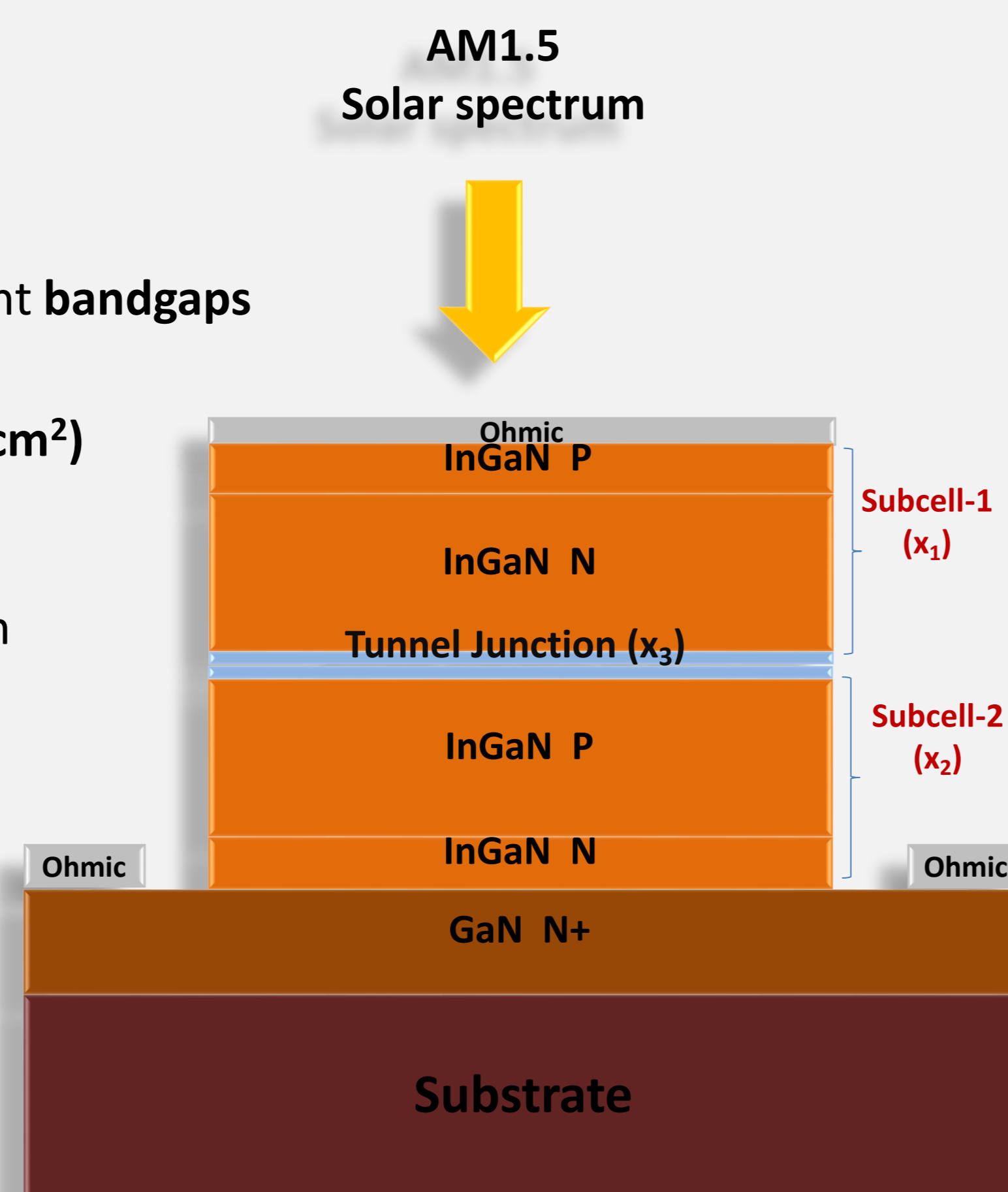
Structure under AM1.5 illumination (100 mW/cm^2)

- Subcell-1, absorbs **high-energy** photons
- Subcell-2, absorbs **lower energies** photons
- The Solar cell absorbs a larger solar spectrum than a single junction cell

Tunnel junction

- The two subcells are connected by a tunnel junction to enhance current matching between the subcells

- X_1 , X_2 and X_3 Indium composition of subcell-1, subcell-2 and tunnel junction respectively



Numerical Simulation and Optimization

Multivariate Optimization

- Simultaneously optimizing of several physical and geometrical parameters
- Much more rigorous than single parametric analysis
- Suitable for next generation solar cell
- Optimum efficiency as a function of several optimization parameters

Sage/Scipy

- We use the Sage software interface to the Scipy optimizers
- Open source free software
- Coded and optimized by computer experts

Simulation

Drift-Diffusion Model

- Current equations
- Poisson's equation

Using ATLAS

(Silvaco company software)

Physical modeling using Experimental data to tune well known models:

- Carrier Mobility
- Carrier Recombination
- Index of refraction
- Absorption coefficient

Optimal Results

11 Parameters of solar cell are optimized simultaneously

- Obviously the optimization problem becomes more complex with so many variables
- Optimization method with a higher-order convergence
- Ensure the overall convergence of the optimization method

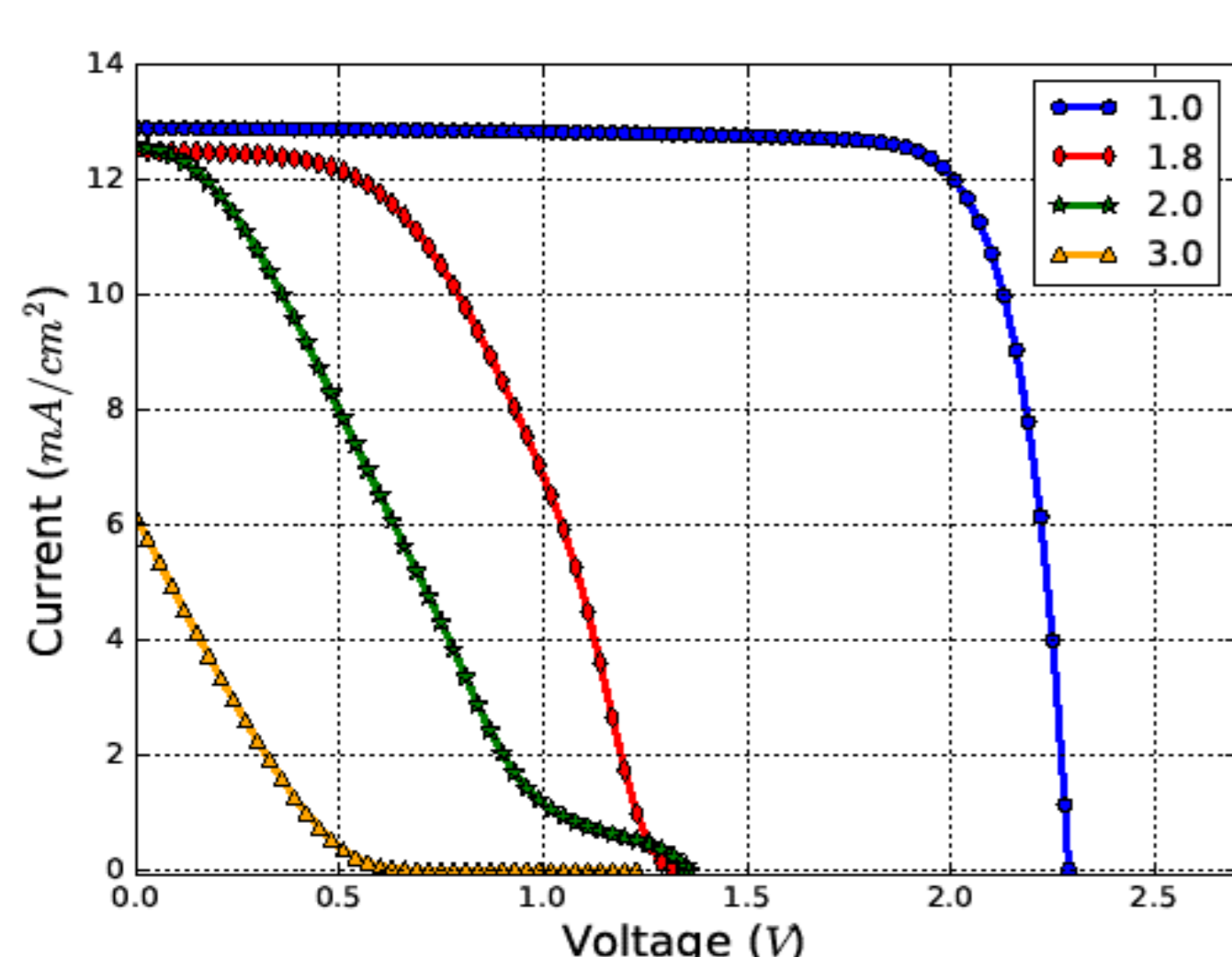
11 Optimization parameters concerns the **dopings** and the **thicknesses** of the **2 subcells** and the different **indium compositions** (x_1 , x_2 , x_3).

Optimal efficiency and the significant parameters of the solar cell

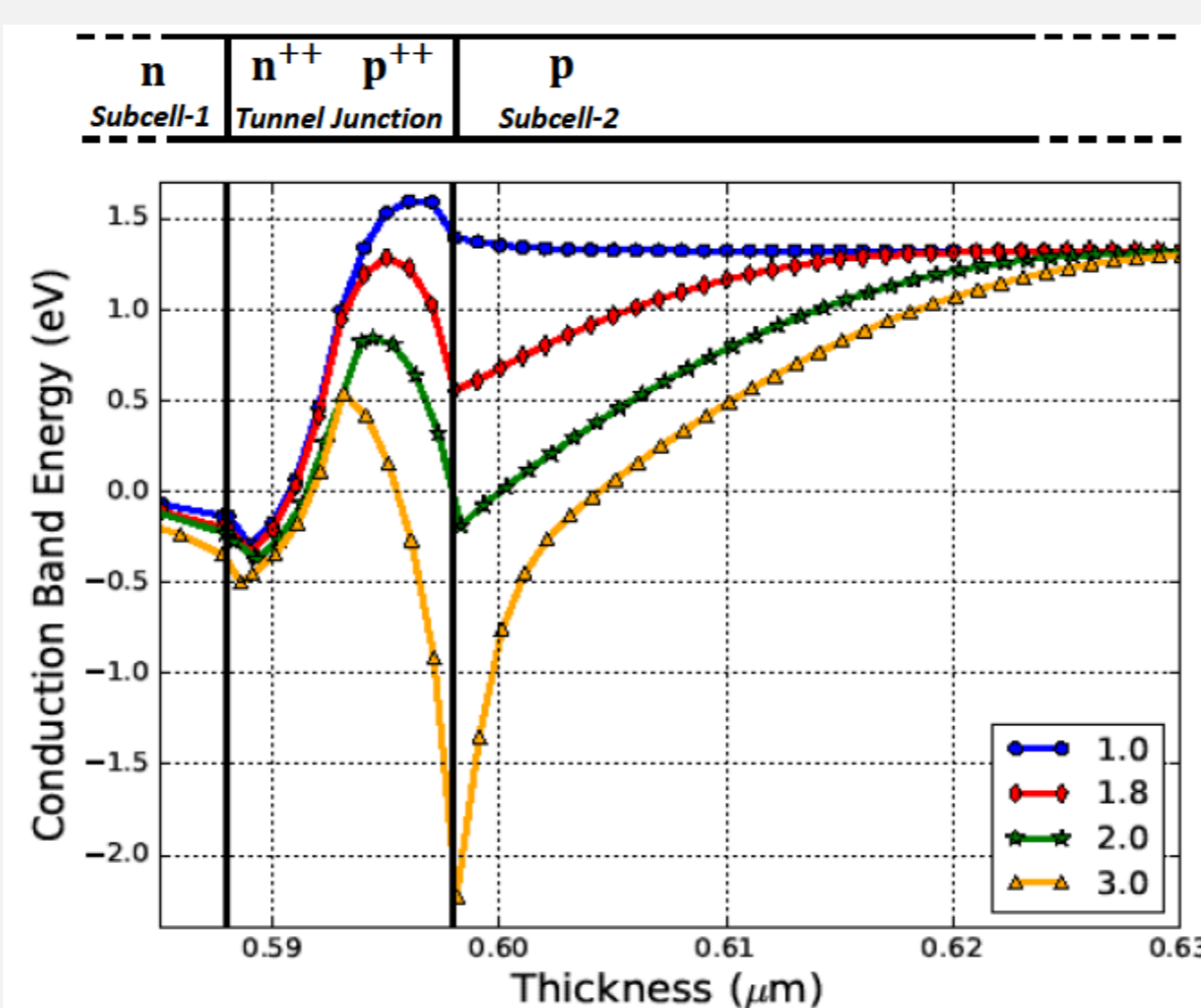
$\eta = 24.4\%$

The short-circuit current, $J_{SC} = 12.92 \text{ mA/cm}^2$
 The open-circuit voltage, $V_{OC} = 2.287 \text{ V}$
 Fill factor, $FF = 82.55$

Spontaneous and Piezoelectric polarization



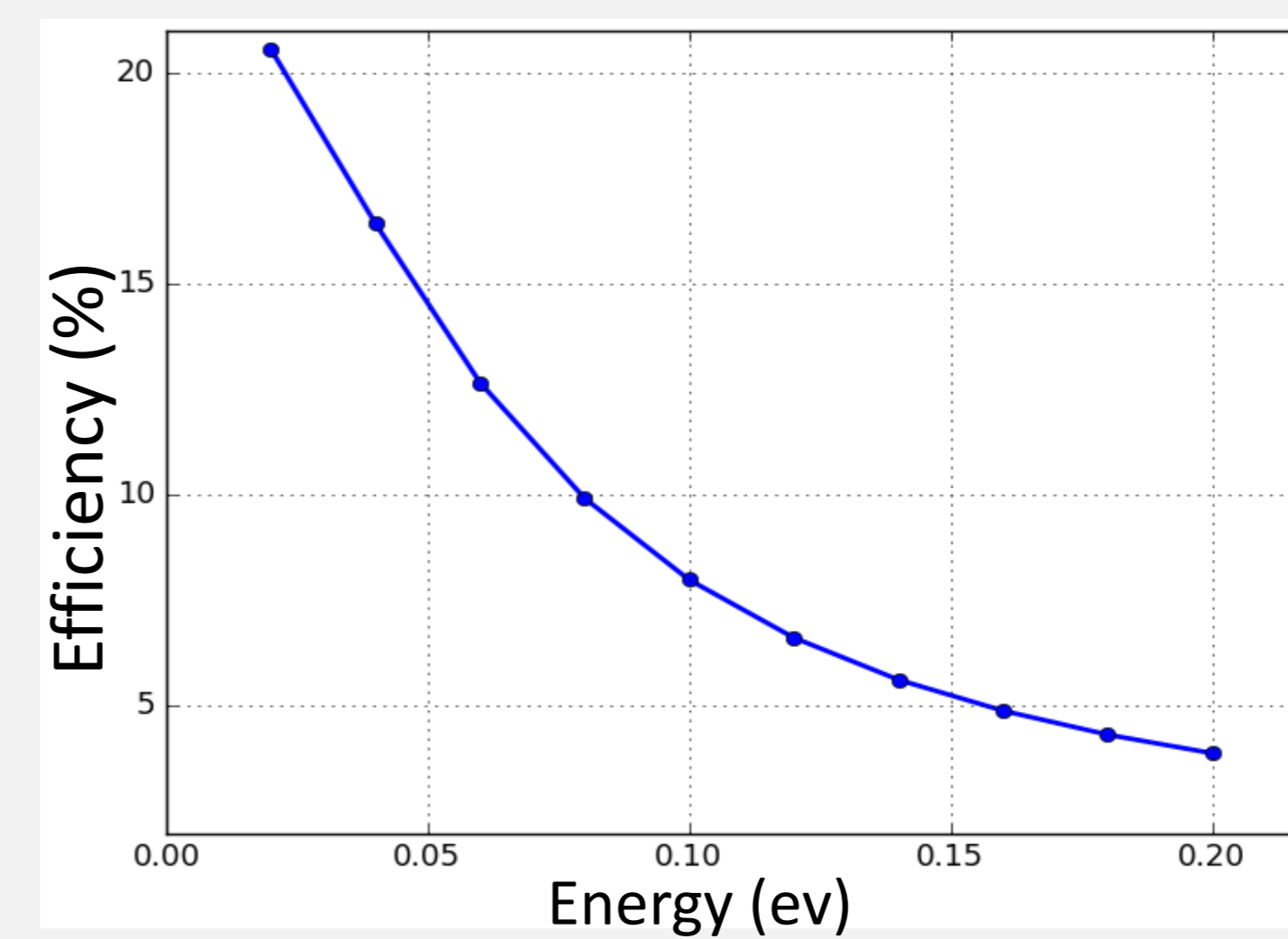
Current-voltage characteristics with different polarization charges.



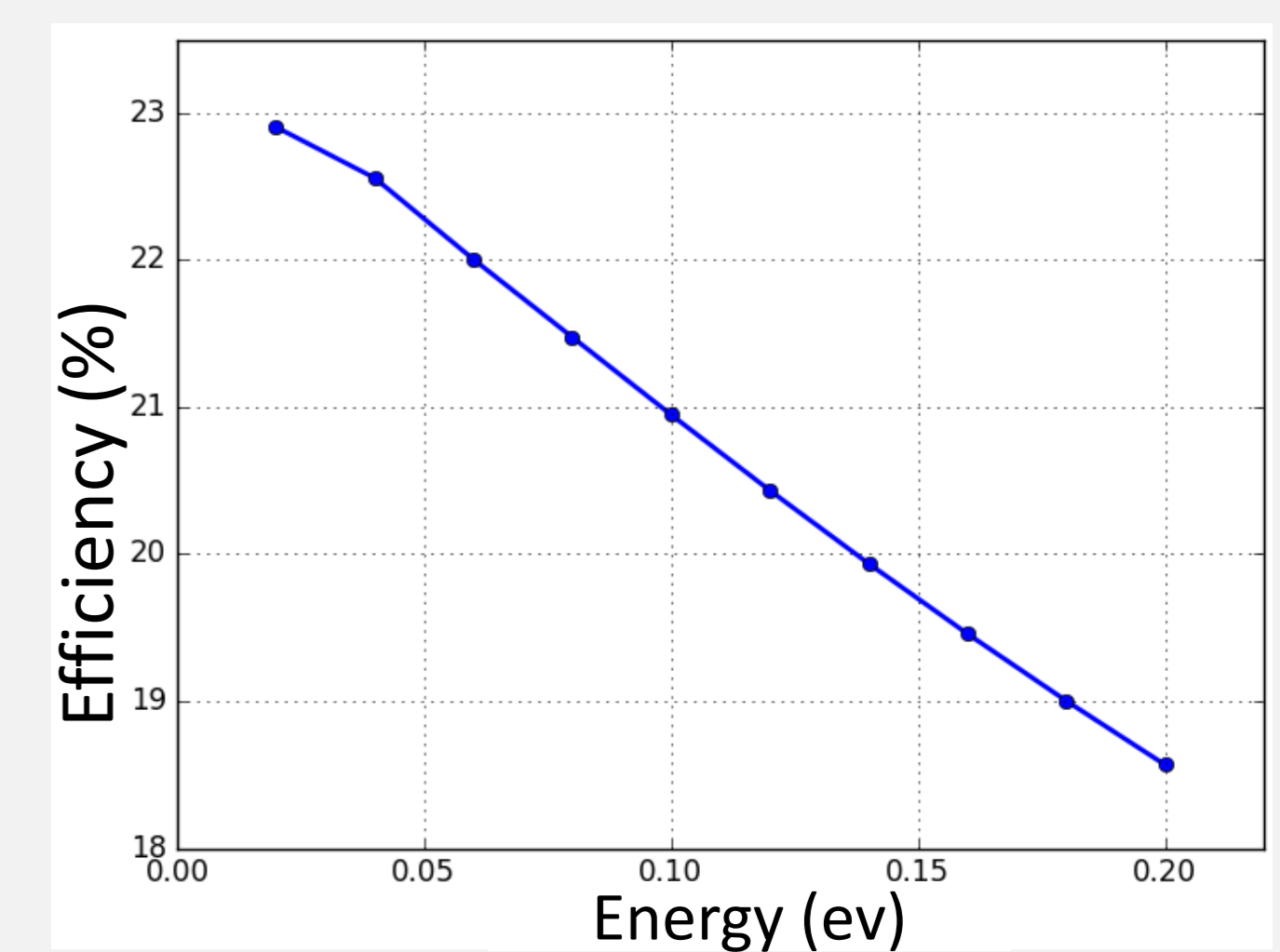
Conduction band diagrams in the tunnel junction with different polarization charges.

The polarization charges in the solar cell bend the conduction band at the interface between the tunnel junction and subcell-2; the bend curvature increasing with the polarization. This causes charges to accumulate at this interface, which in turn create an electric field. This field, induced by the polarization, is in the opposite direction to that of the PN junction internal field. It thus tends to lower the total integrated electric field in the cell, which explains the decrease in the performances of the solar cell.

Deep and band tail defects



Variation of efficiency as a function of the Urbach energy of the band tail.



Variation of efficiency as a function of the decay energy of the Gaussian distribution.

The increase of the Urbach energy implies a reduction in the optical gap owing to the presence of states in the InGaN bandgap, leading to a higher probability of carrier recombination. In the same way, for the deep states, the increase of the decay energy also leads to an increase of the state density in the bandgap and therefore to a higher probability of recombination of the carriers. Both these effects thus result in the decrease of the short circuit current (J_{SC}) and therefore a decrease in the efficiency of the solar cell.

It can be noted that an increase in the disorder in the Urbach energy degrades the solar cell performances much more than a deep states decay energy increase. Thus, in InGaN solar cells, material disorder is therefore more detrimental to the performances of the solar cell than deep defects states.