# Optical modeling and simulation of thin-film $Cu(In,Ga)Se_2$ solar cells

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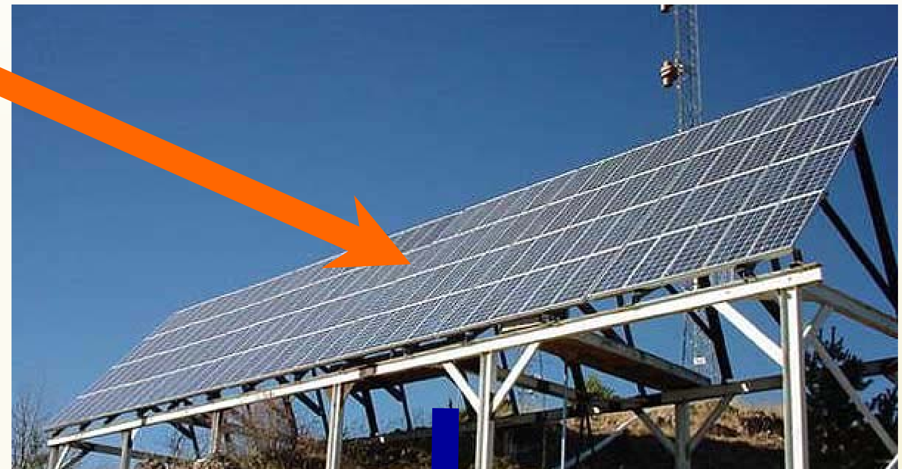
# Outline

- **Introduction**
- **Optical modeling of thin-film solar cells**
- **Optical simulator Sun*Shine***
- **Results**
  - Optical simulation of thin Cu(In,Ga)$Se_2$ solar cells
- **Conclusions**

# Introduction

Solar energy

Solar cell (PV modules)

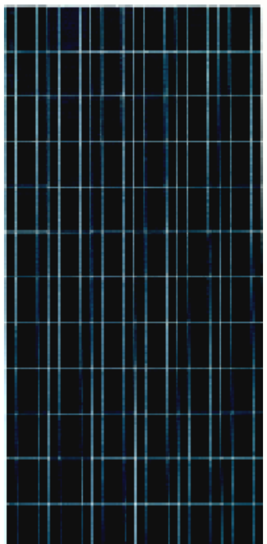


Electrical energy

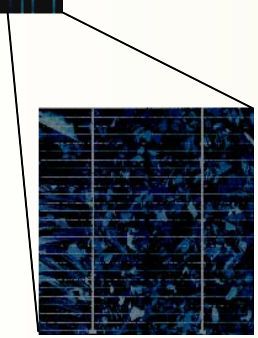
> 30 % growth in module production per year

# Introduction

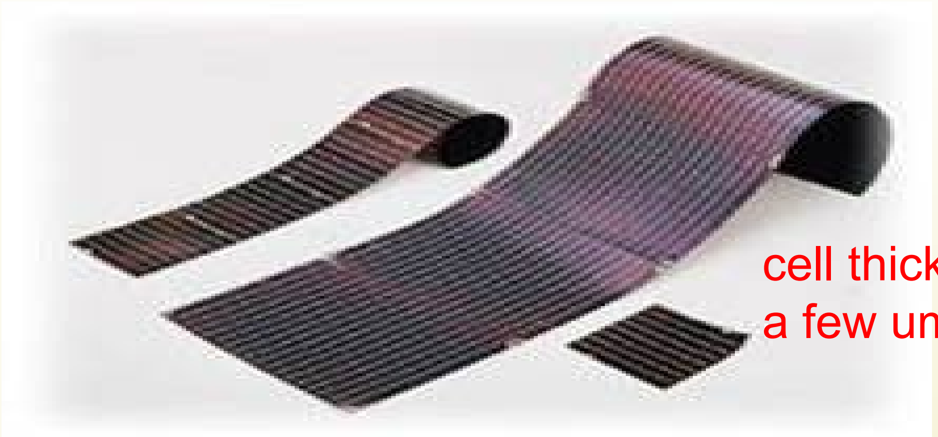
**conventional**
**wafer-based solar cells**



cell thickness:
a few 100 um



**thin-film (TF) solar cells**

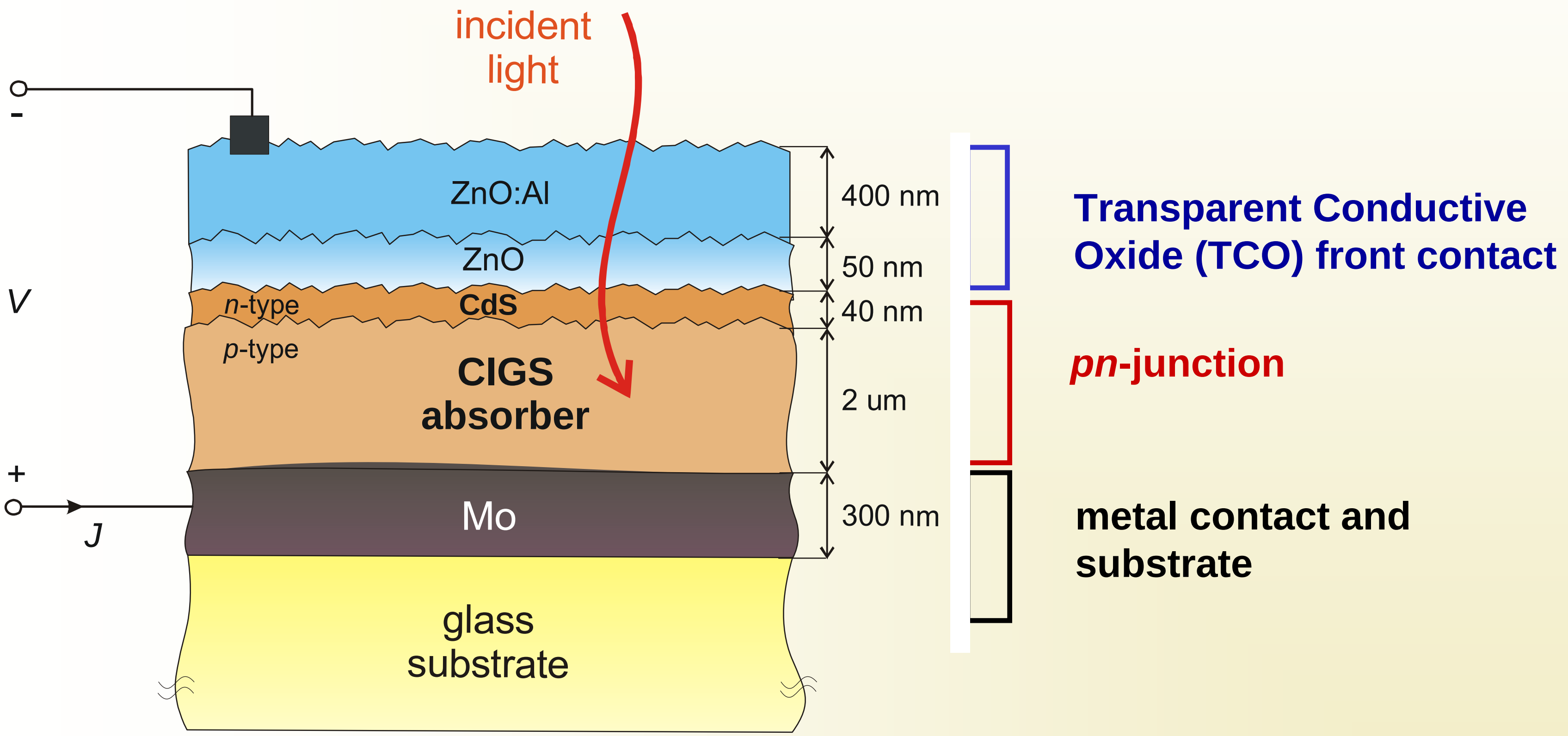


cell thickness:
a few um or less

- **lower material consumption**
- **low temperature processes**
- **possibility of being flexible**

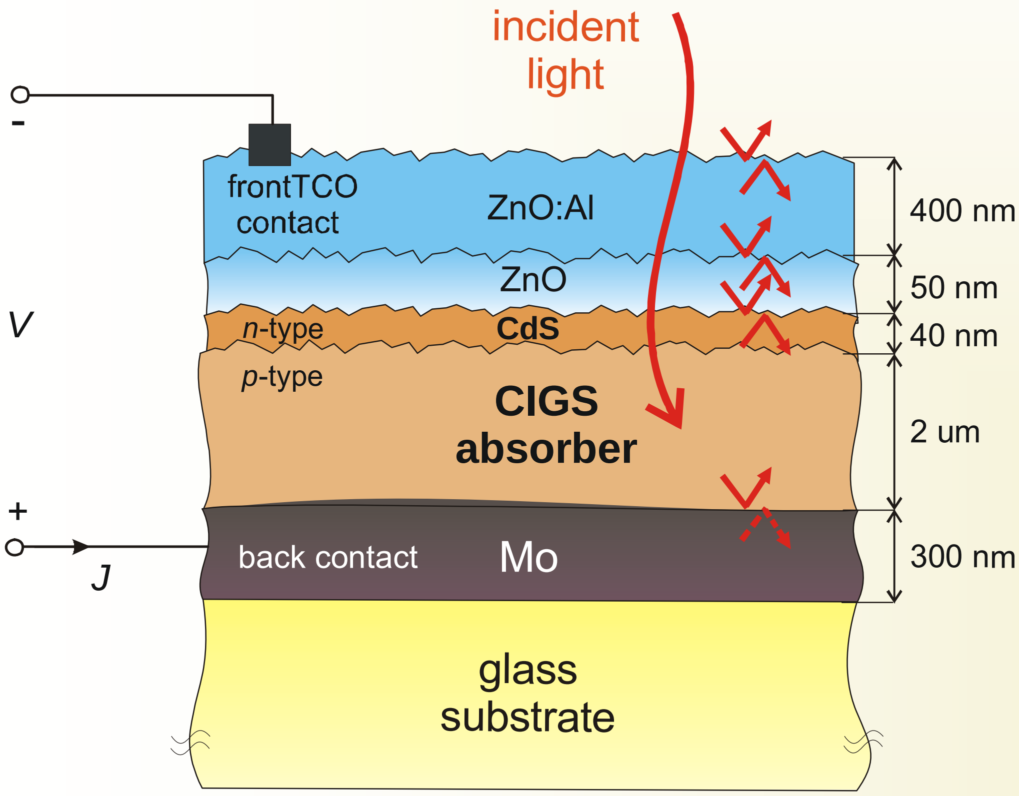
# Introduction

Cu(In,Ga)$Se_2$ (CIGS) thin-film solar cell:



# Introduction

TF solar cell as an optical system:



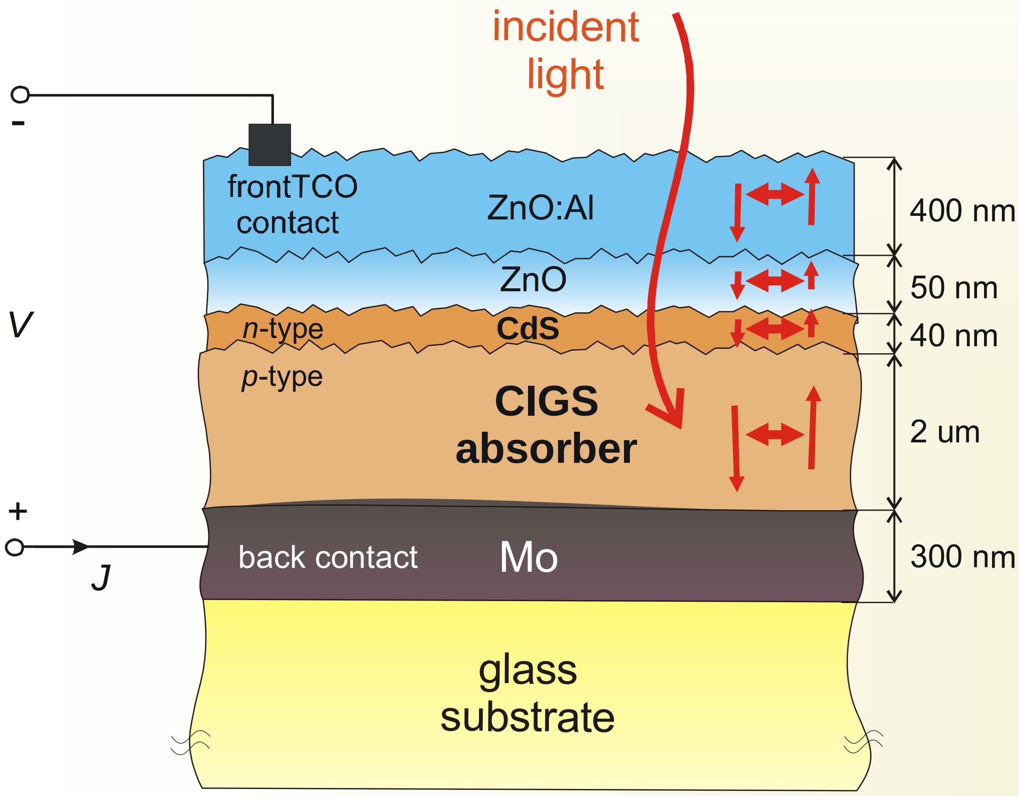

## Optical features:

- multilayer structure

**multiple *R* and *T*!**

# Introduction

TF solar cell as an optical system:




## Optical features:

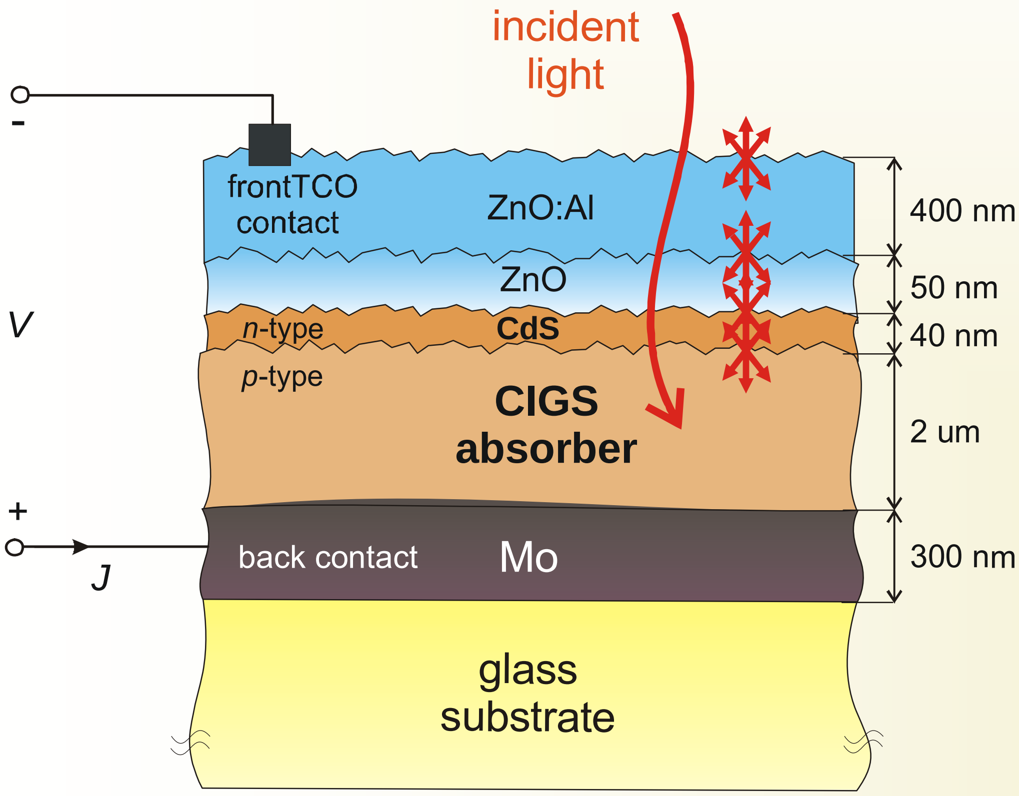
- multilayer structure
- layers in nm range

⬇

**interferences!**

# Introduction

TF solar cell as an optical system:




<u>Optical features:</u>

- multilayer structure
- layers in nm range
- textured interfaces

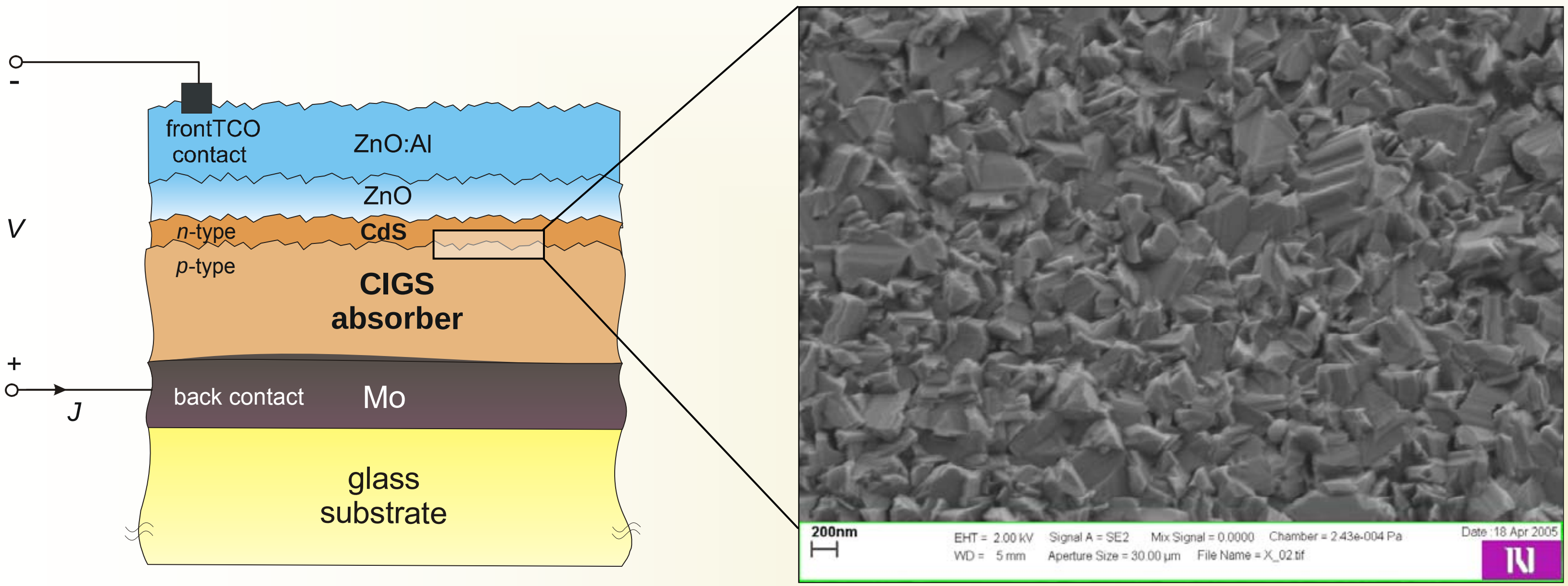
⬇

**light scattering!**

# Optical modeling of TF solar cells

# Optical modeling of light scattering

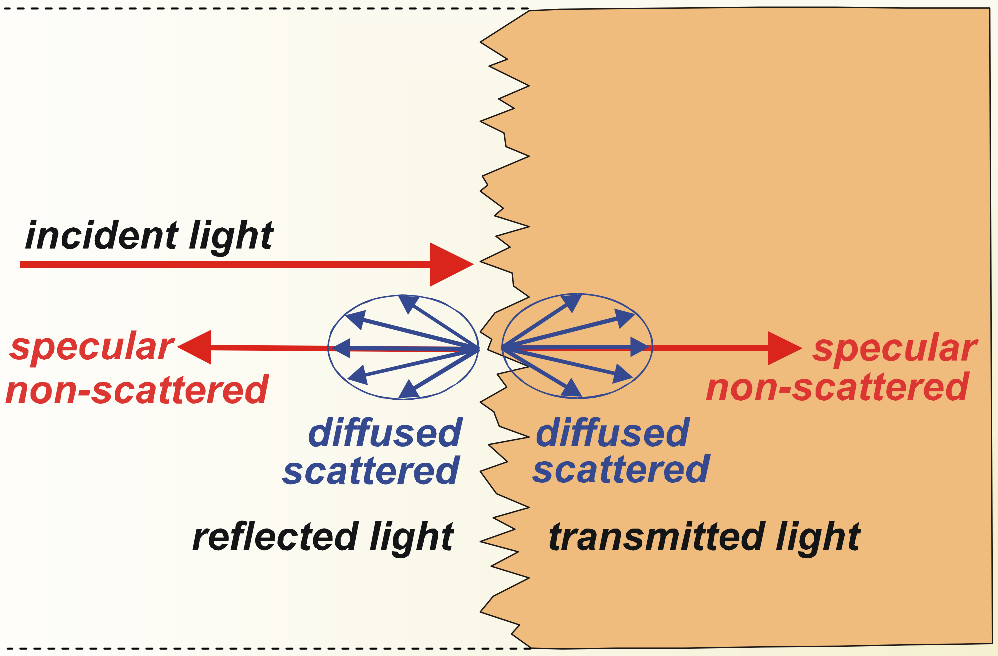
nano-textured surface of CIGS layer



# Optical modeling of light scattering

Light scattering at nano-textured interfaces:

- Specular (non-scattered) light
- Scattered (diffused) light



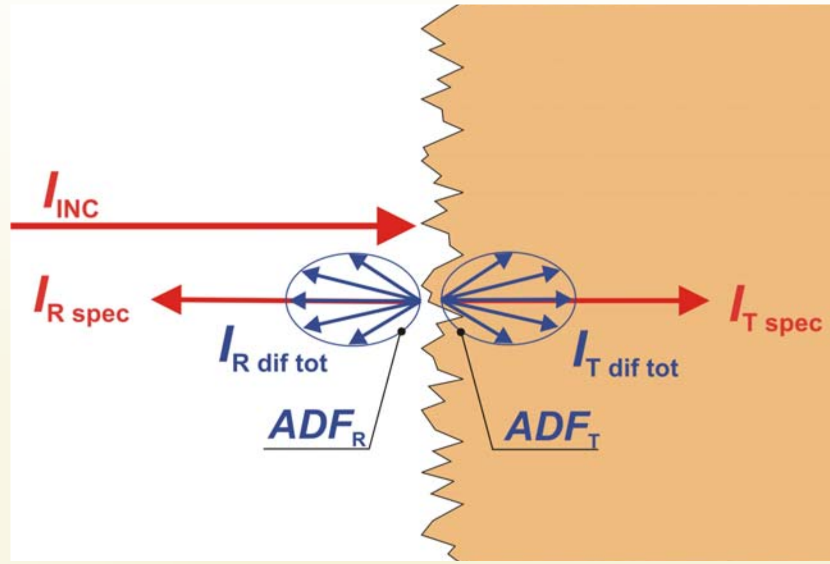
# Optical modeling of light scattering

Descriptive scattering parameters:

## 1. Haze (scattering level)

$$H_R = \frac{I_{R\ dif\ tot}}{I_{R\ dif\ tot} + I_{R\ spec}}$$

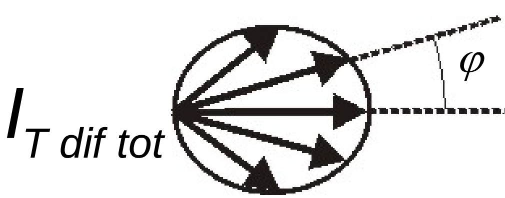
$$H_T = \frac{I_{T\ dif\ tot}}{I_{T\ dif\ tot} + I_{T\ spec}}$$




## 2. Angular distribution functions (directions)

$$ADF_R(\varphi_{scatt})$$

$$ADF_T(\varphi_{scatt})$$




$$I_{T\ dif}(\varphi) = ADF_T(\varphi) \cdot I_{T\ dif\ tot}$$

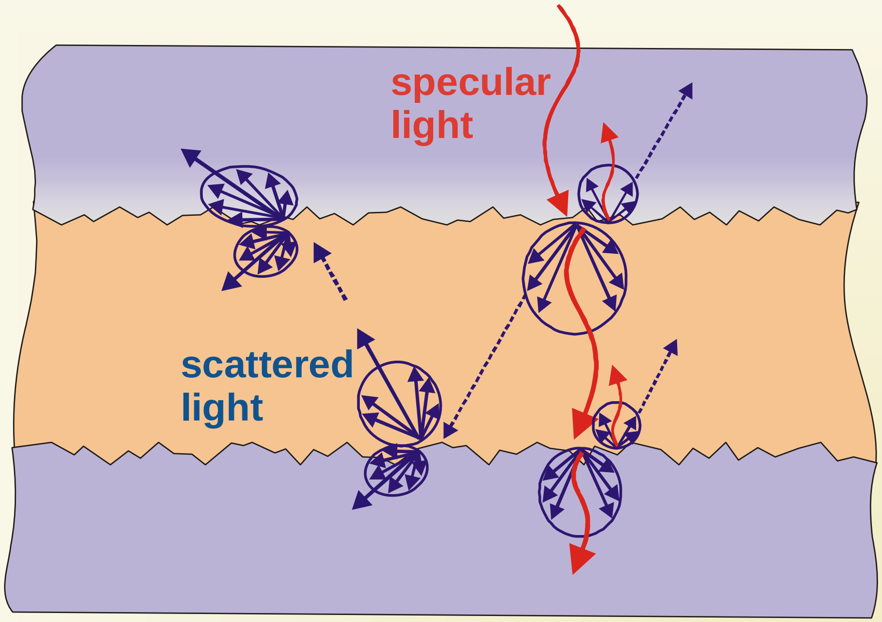
# Optical simulator Sun*Shine*

# Optical simulator Sun*Shine*

- 1-D semi-coherent optical model [J. Krc et al., Progress in Photovoltaics 11 (2003) 15.]

- specular light -
  electromagnetic waves (coherent)

- scattered light -
  light rays (incoherent)



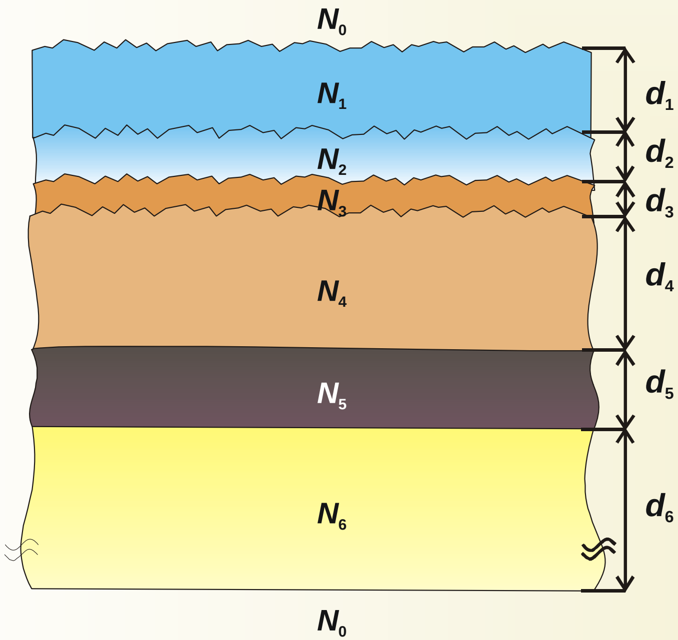
# Optical simulator Sun*Shine*

- 1-D semi-coherent optical model [J. Krc et al., Progress in Photovoltaics 11 (2003) 15.]

<u>Main input parameters (structure description)</u>:

- Complex refractive indexes and thicknesses of layers

$$N(\lambda) = n(\lambda) - jk(\lambda)$$

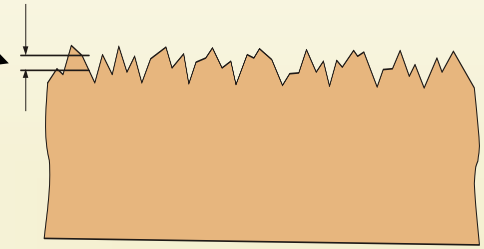


# Optical simulator Sun*Shine*

- 1-D semi-coherent optical model [J. Krc et al., Progress in Photovoltaics 11 (2003) 15.]

Main input parameters (structure description):

- Complex refractive indexes and thicknesses of layers
- *Haze* and *ADF* of textured interfaces and root-mean-square rougness, $\sigma_{rms}$, of interfaces



Calibrated equations of scalar scattering theory (for details refer to our NUSOD paper)

$\sigma_{rms}$, $n$, $\lambda$ → $H_R$, $H_T$ for internal interfaces

# Optical simulator Sun*Shine*

- 1-D semi-coherent optical model [J. Krc et al., Progress in Photovoltaics 11 (2003) 15.]

Main input parameters (structure description):

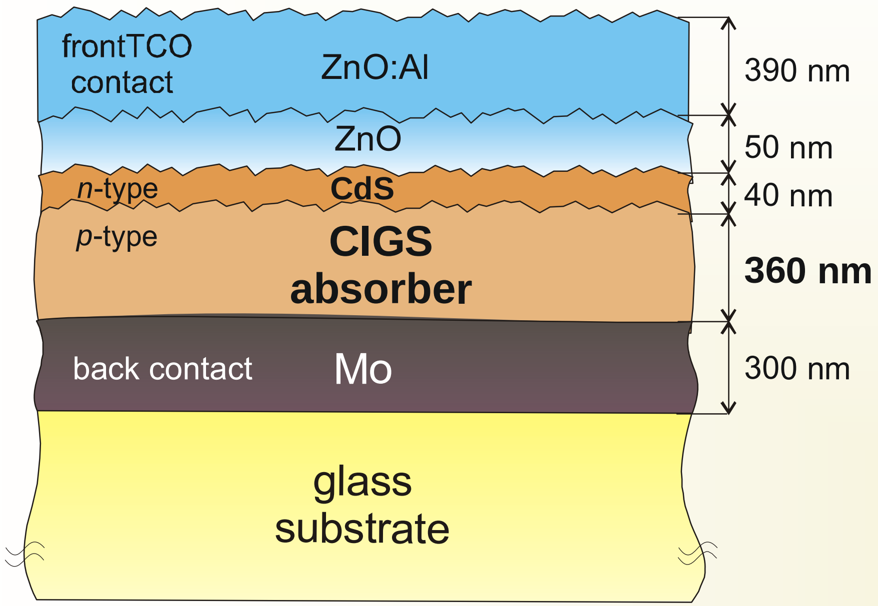
- Complex refractive indexes and thicknesses of layers
- *H* and *ADF* of textured substrates
  and measured root-mean square rougness of interfaces

Main ourput results:

- Optical reflectance from the structure
- Absorptances in individual layers
- Charge-carrier generation-rate profile

# Simulations

Simulated structure:




Extremely thin CIGS absorber

- Thinning down CIGS absorber below 1 um
  (lower material consumption, shorther deposition times)
- To analyse and optimise optical and electrical properties

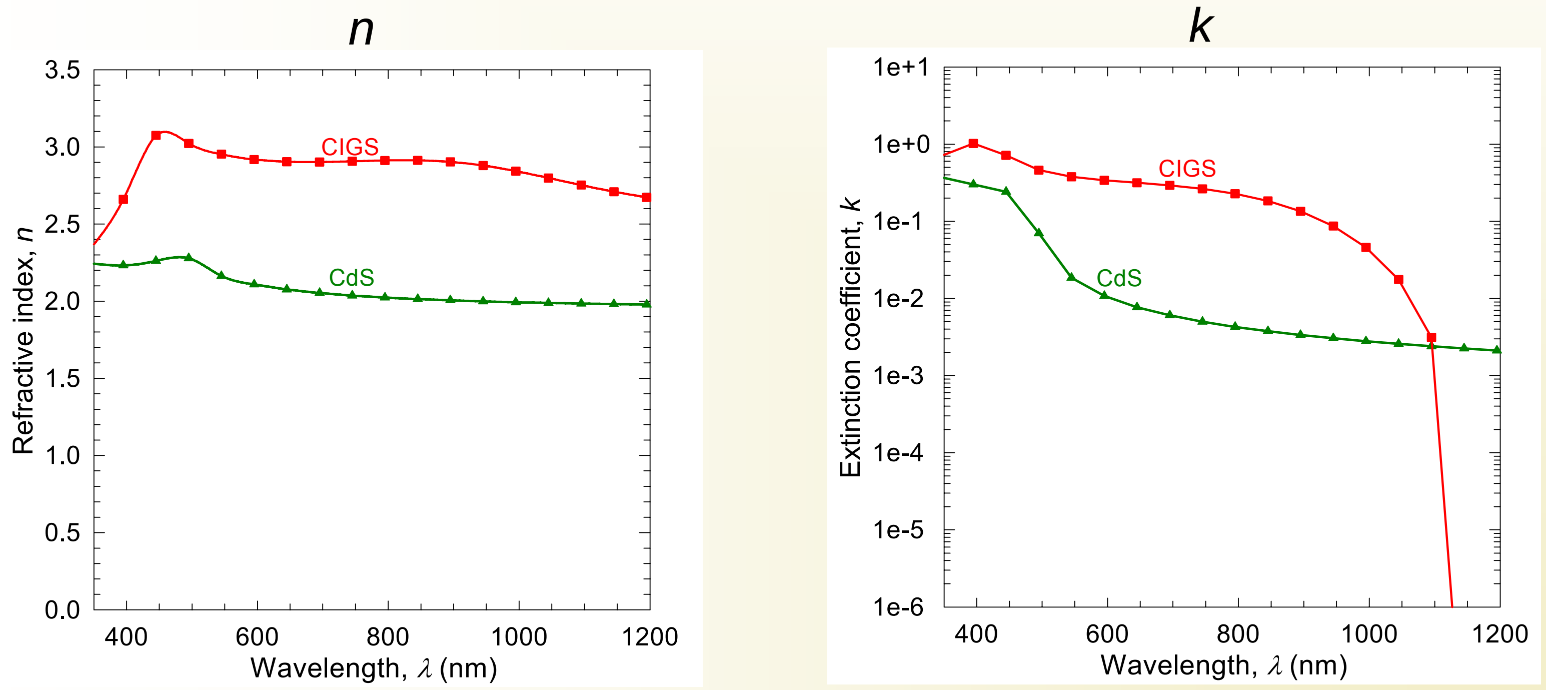
  **Numerical modeling&simulation an important tool!**

# Simulations

Included in simulations:

- Experimentally obtained complex refractive indexes of layers

  [ O. Lundberg, PhD. Thesis, Uppsala University, 2003]



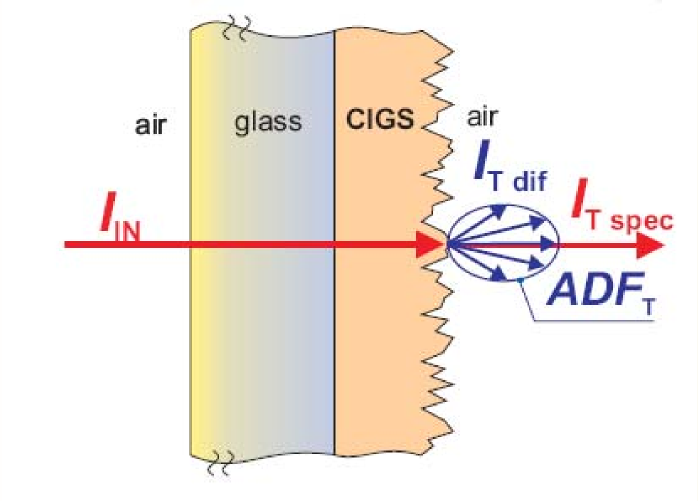
# Simulations

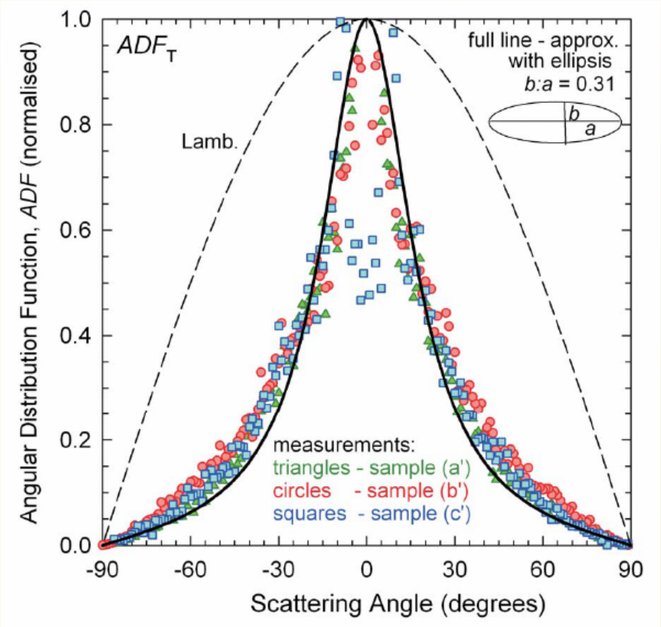
Included in simulations:

- Experimentally obtained complex refractive indexes of layers
  [ O. Lundberg, PhD. Thesis, Uppsala University, 2003]

- Measured *H* and *ADF* [ J. Krc et al., Proc. of E-PVSEC, Barcelona, 2005, p. 1831.]

Example of $ADF_T$ measurement:

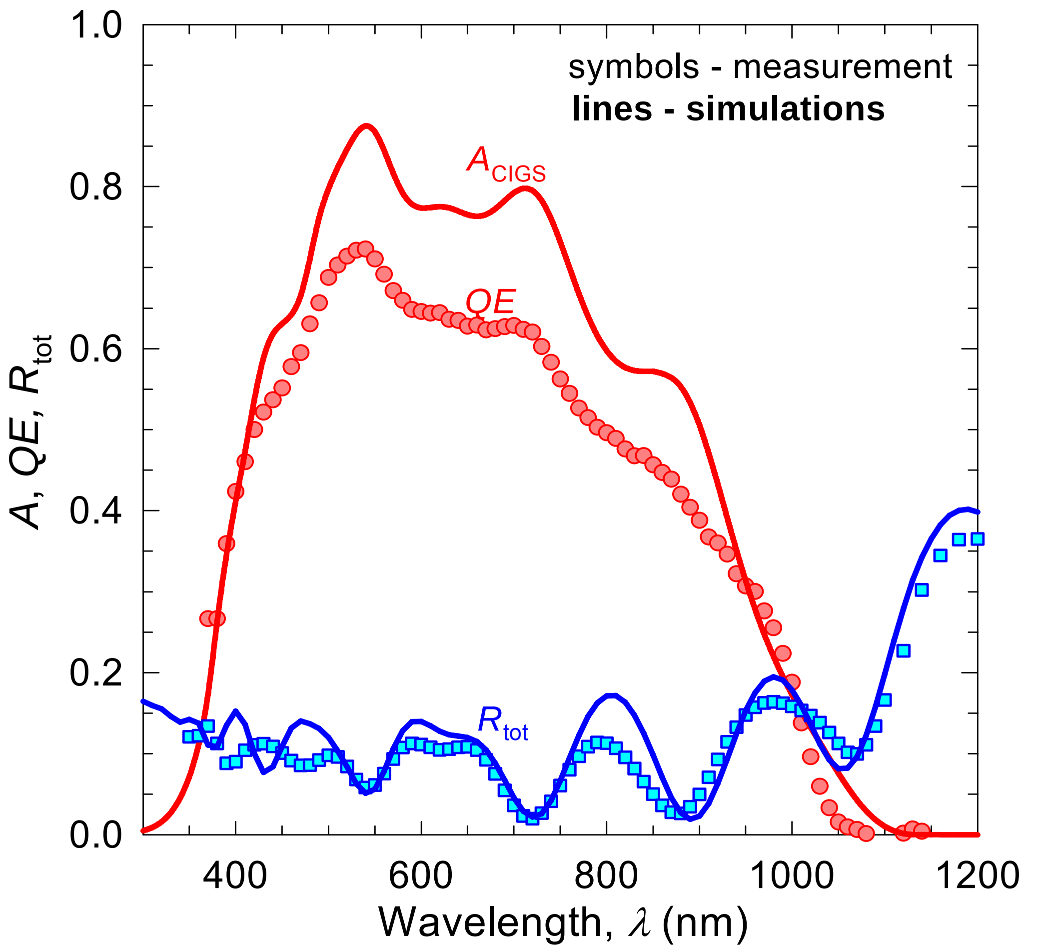


# Simulation results

# Simulation results

Total reflectance and quantum efficiency

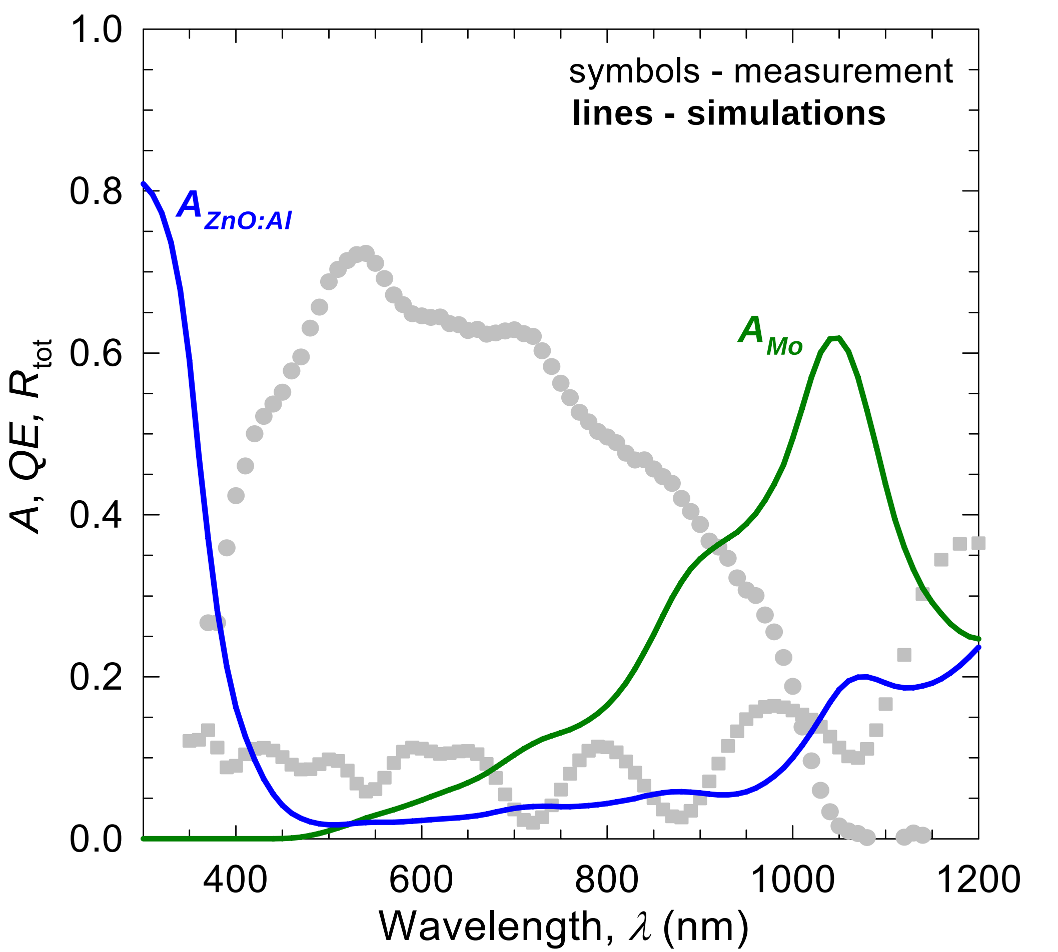



$A_{CIGS} \rightarrow QE$

*if ideal extraction of charge carriers from CIGS*

# Simulation results

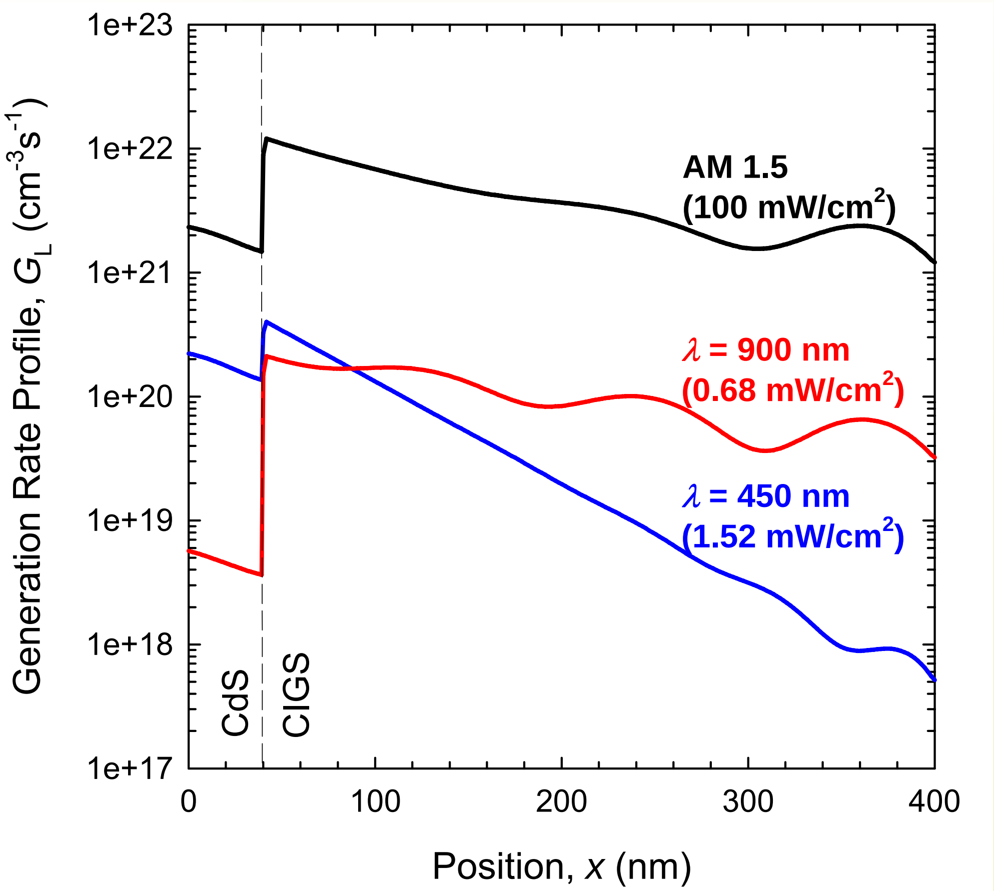
Absorptances in non-active layers




*determination of optical losses in the structure*

# Simulation results

Charge-carrier generation-rate profile




*for further electrical analysis of the structure*

# Conclusions

- good agreement in sim. and meas. total reflectance of thin CIGS solar cell

- calibration of the simulator with realistic optical parameters (refractive indexes, scattering and others) is important

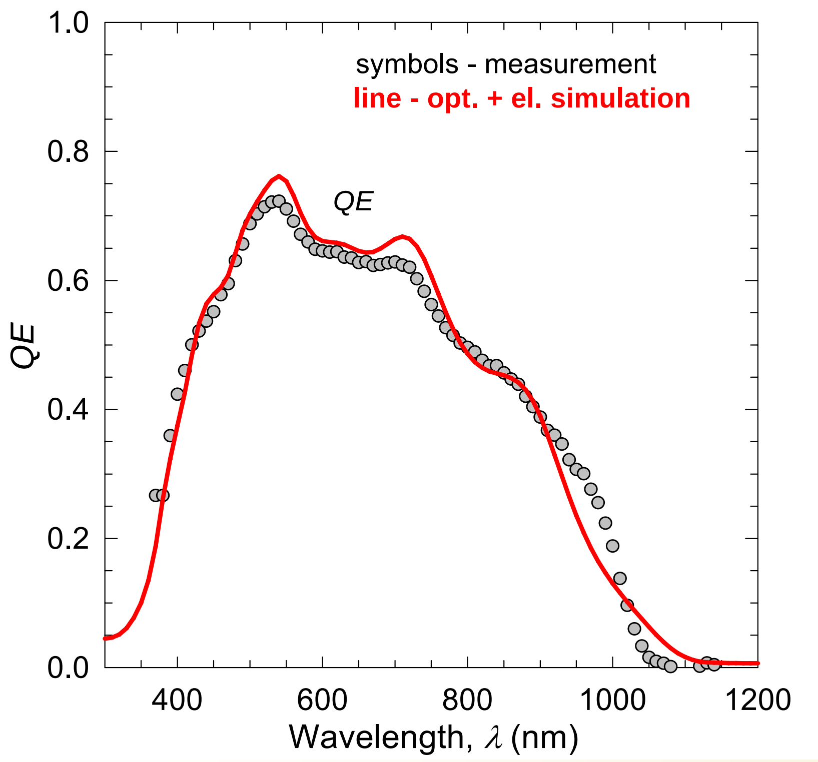
- starting point for optical optimisation and electrical analysis of the structure

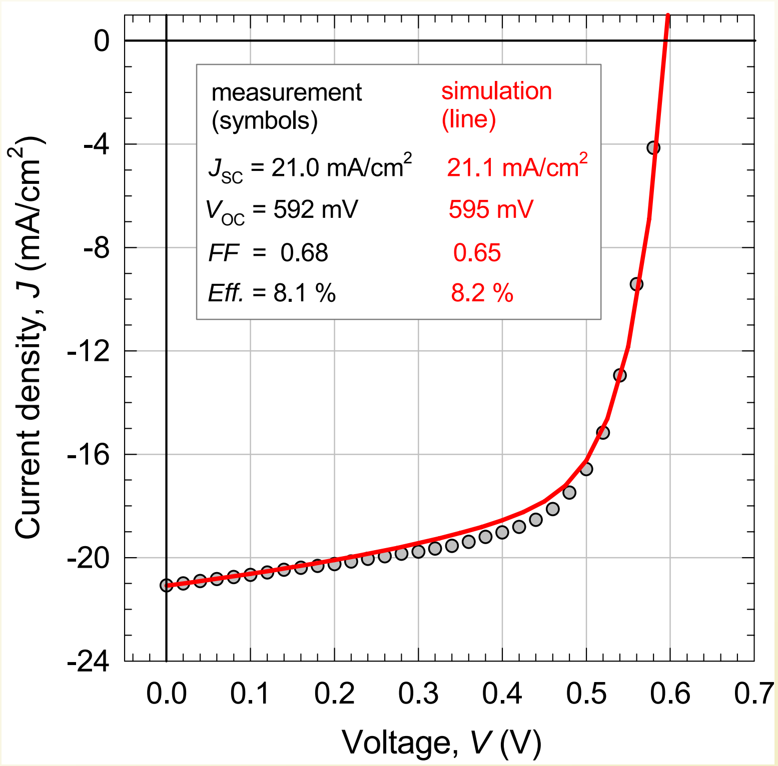
# Further work

*combined optical + electrical analysis of the structure*

***SunShine&Aspin*** *simulators*

*External characteristics and parameters of the solar cell:*



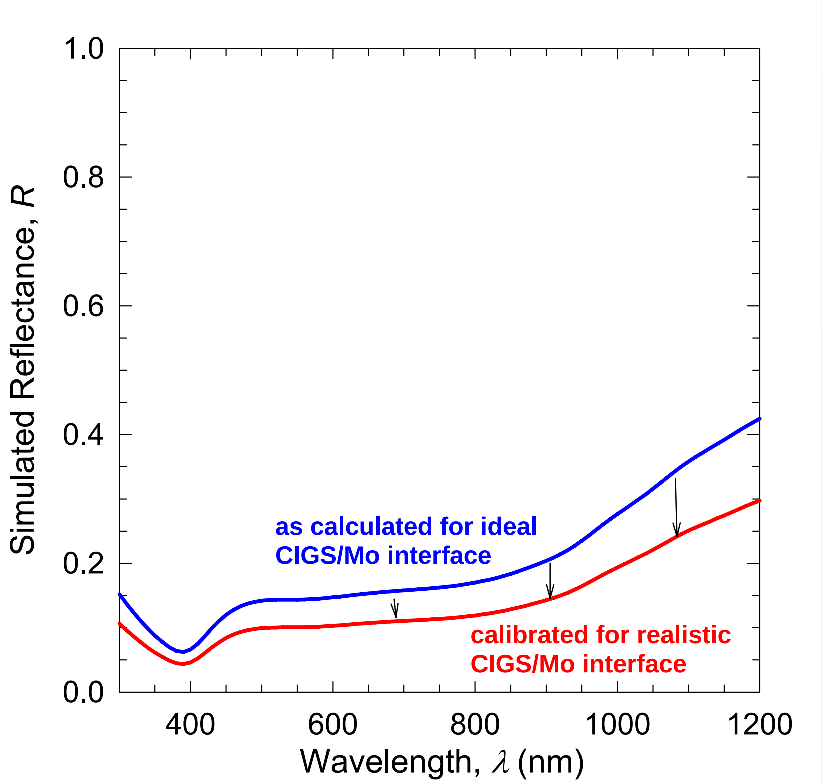

*see extended NUSOD paper submitted to OQE*

# Simulation

Included in simulations:

• Reduced reflectance of CIGS/Mo interface by 30 %

(formation of $MoSe_2$ interfacial layer) [ J. Krc et al., Proc. of E-PVSEC, Barcelona, 2005, p. 1831.]



# Simulation

## Haze of internal interfaces

Modified equations of scalar scattering theory:

$$H_R = 1 - e^{-\left(\frac{4\pi\sigma_{rms} \cdot c_R(\sigma_{rms}, \lambda)\, n_1 \cos\varphi_{inc}}{\lambda}\right)^2}$$

$$H_T = 1 - e^{-\left(\frac{4\pi\sigma_{rms} \cdot c_T(\sigma_{rms}, \lambda)\, \left|n_1 \cos\varphi_{inc} - n_2 \cos\varphi_{out}\right|}{\lambda}\right)^{2...3}}$$

**$c_R$, $c_T$ calibration functions**

***initial values:***

**$c_R = 1$**

**$c_T = 0.5$**

P. Beckmann, A. Spizzichino, Pergamon Press (1963)
C.K. Carniglia, Optical Engineering 18/2 (1979)
M. Zeman et. al. JAP 88 (2000)

*basic theory*

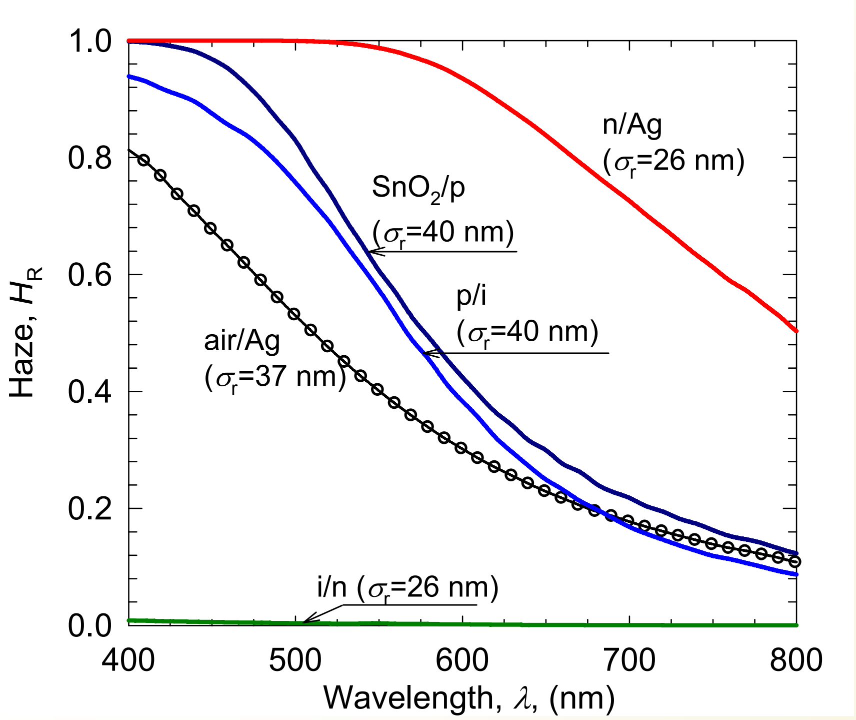
J. Krc et al. J. Appl. Phys. 92/2 (2002) 749-755.
J. Krc et al. Thin Solid Films 426/1-2 (2003) 296-304

*calibration introduced*

# Simulation

Application of the calibrated theory to internal interfaces

## $H_R$




## $H_T$