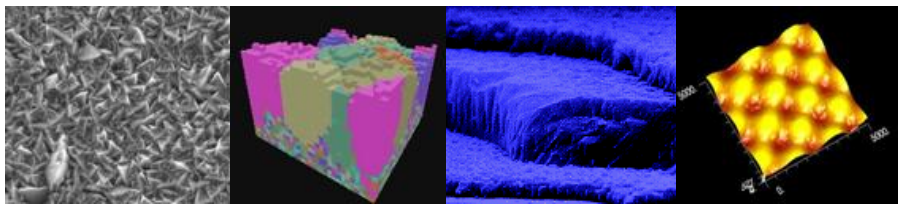
Periodic textures for enhanced current in thin film solar cells

MRS Spring meeting 2008

San Francisco



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Light scattering in solar cells

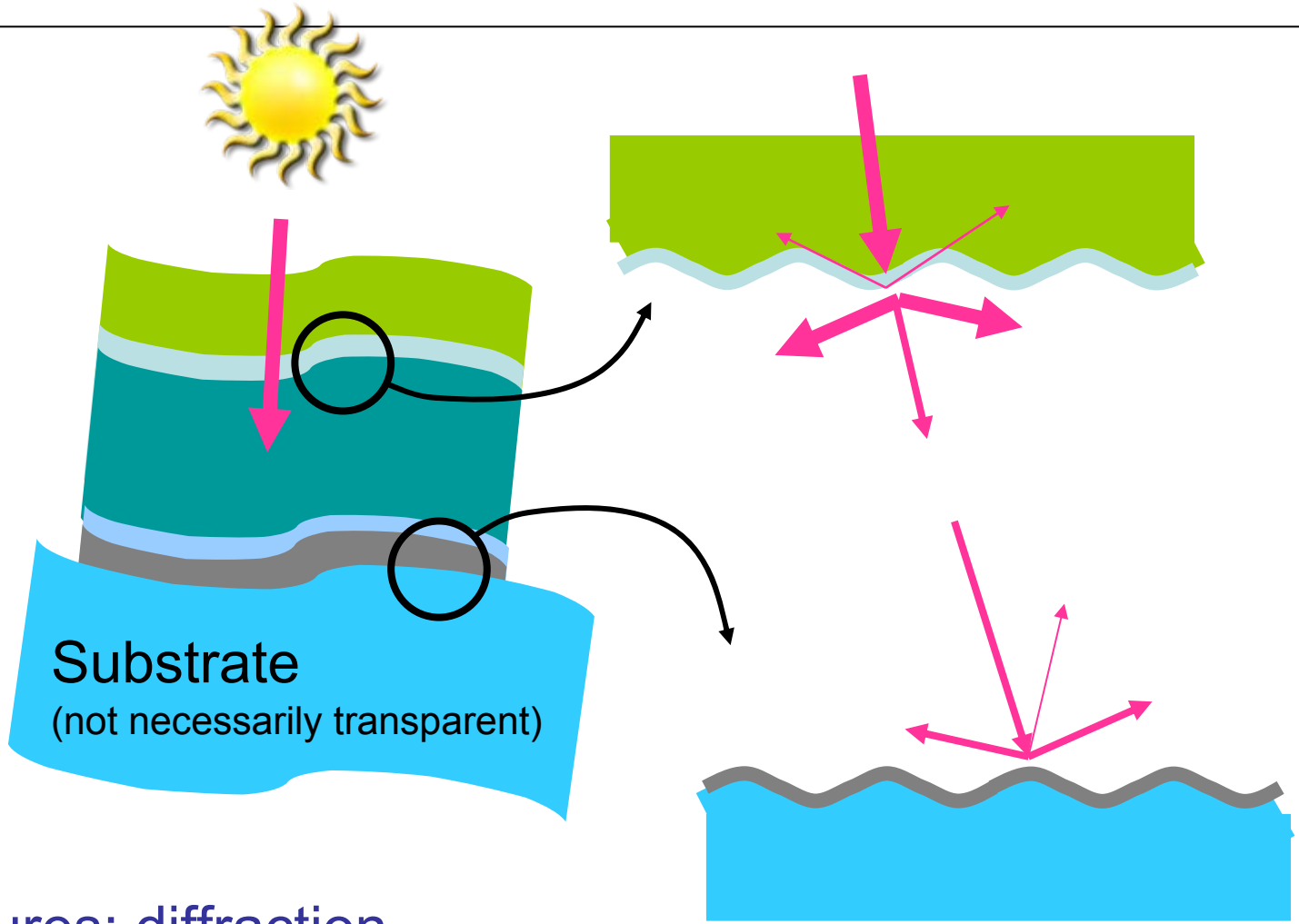
Front contact

p-layer

i-absorber

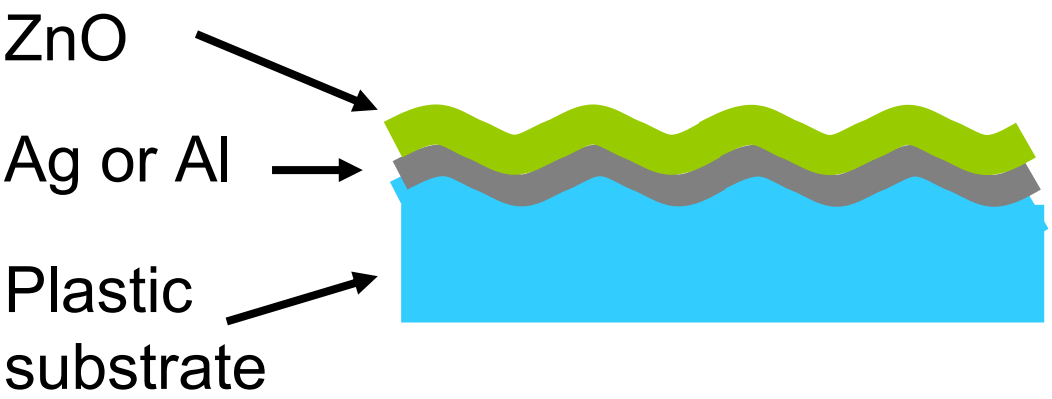
n-layer

Back contact



Periodic structures: diffraction

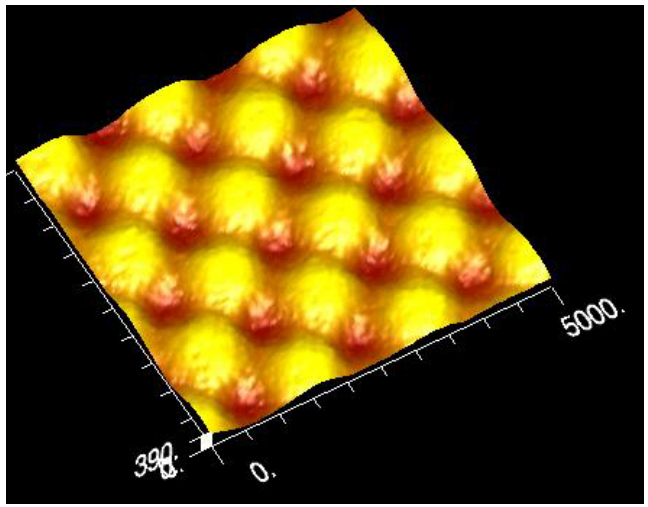
Approach to scattering: textured substrate



feasible for large area processing
conformity of coating carries texture into all interfaces

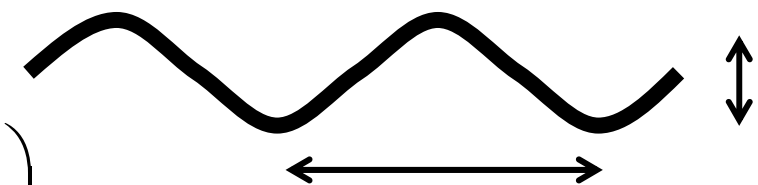
Periodic substrate texture

Substrate texturing by large area
roll to roll imprinting process on plastic (PEN or PET)



Sinusoidal bigrating (2D):

$$z = h \cdot \sin\left(\frac{2\pi}{L}x\right)\sin\left(\frac{2\pi}{L}y\right)$$

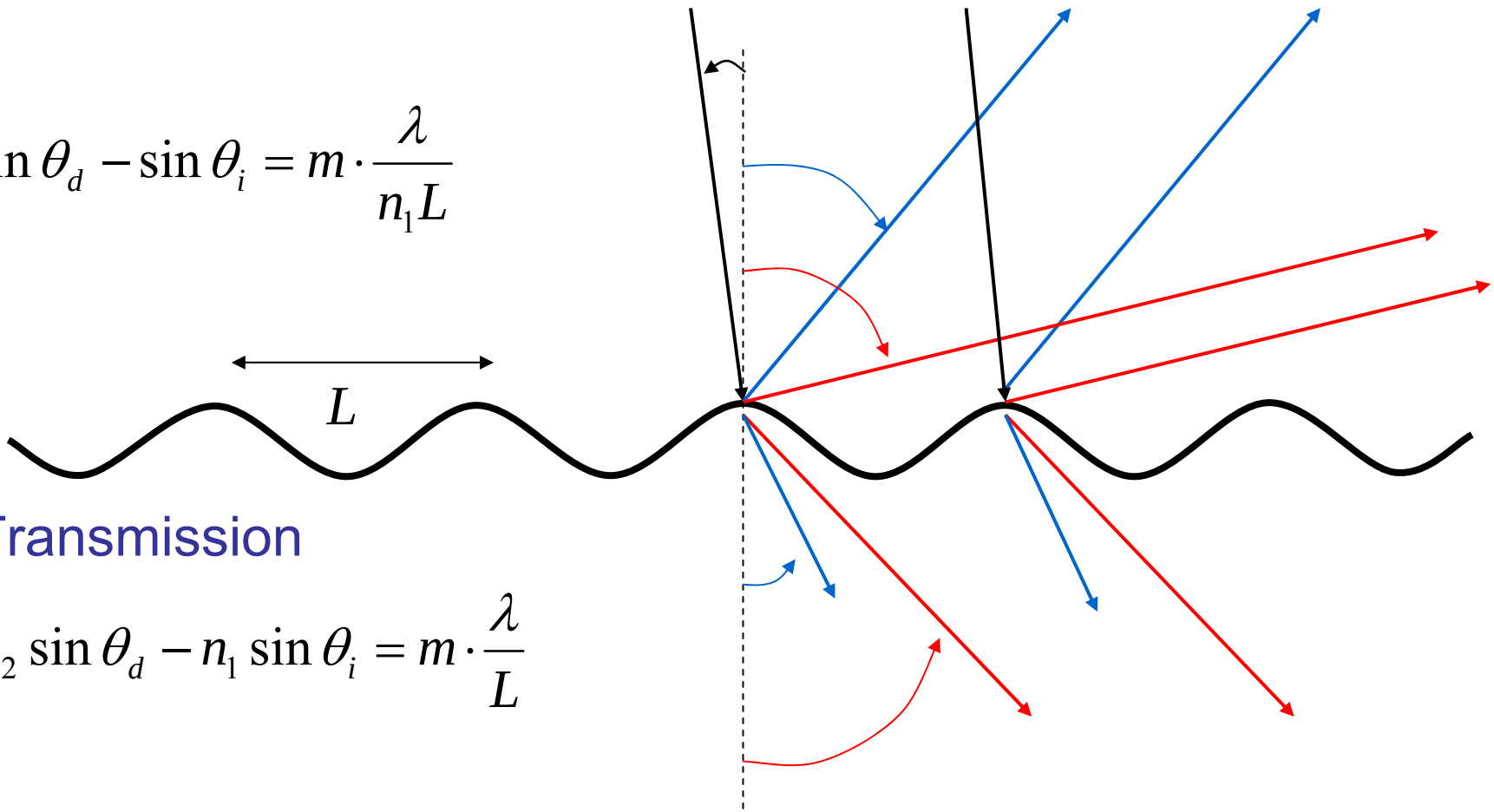


Period = L Depth = 2 h

Diffraction grating (e.g. sinusoidal)

Reflection

$$\sin\theta_d - \sin\theta_i = m \cdot \frac{\lambda}{n_1 L}$$

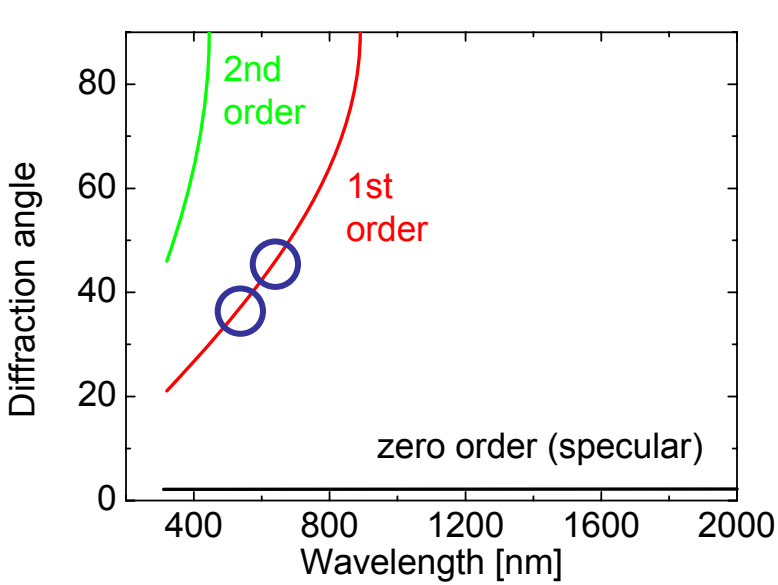


Transmission

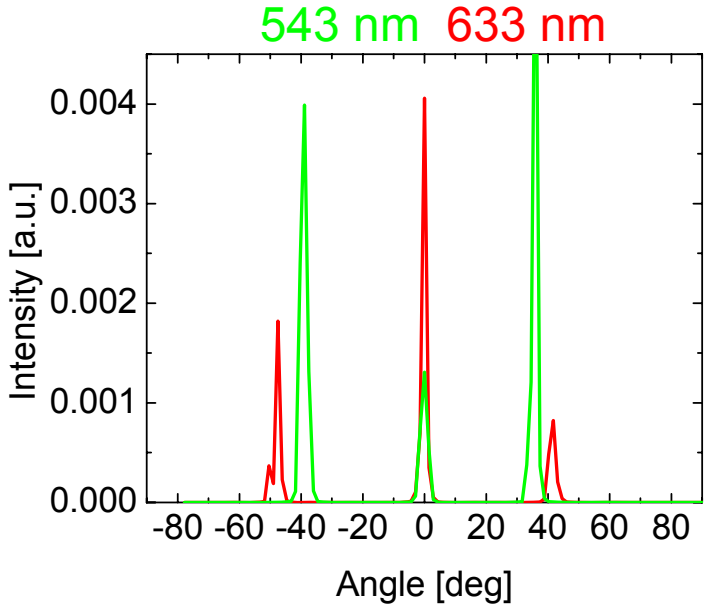
$$n_2 \sin\theta_d - n_1 \sin\theta_i = m \cdot \frac{\lambda}{L}$$

Grating period => angular properties

Model: line grating d=890 nm, h=70 nm, 0° incidence, in air



angle resolved reflection



$\lambda > d$: specular reflection, no diffraction, only zero order

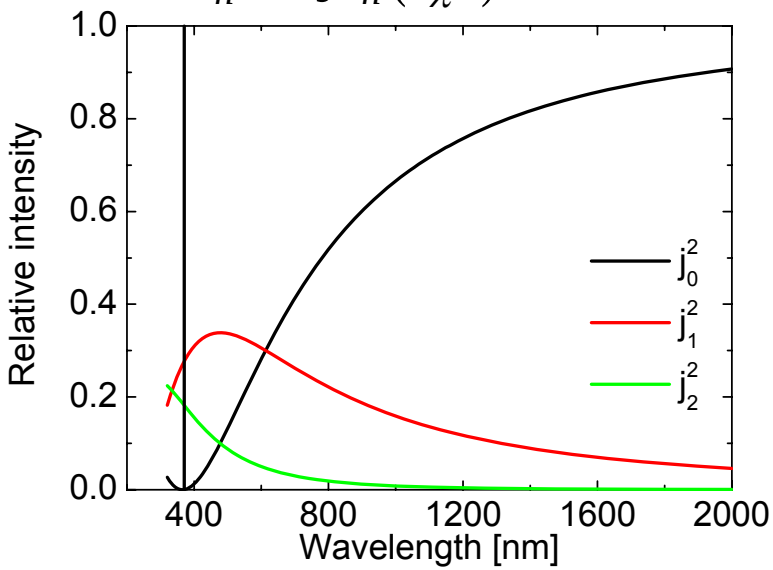
$\lambda \in [d/2 \ldots d]$: zero and first order

$\lambda \in [d/3 \ldots d/2]$: zero, first, and second order

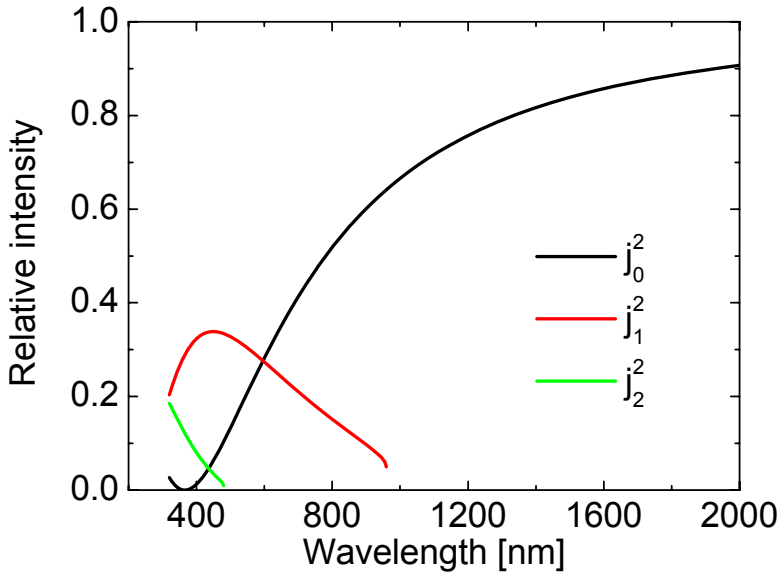
Grating shape and depth => mode intensity

Sinusoidal grating => Intensity given by Bessel functions

$$I_n \sim j_n^2\left(\frac{2\pi h}{\lambda}\right)$$



$$I_n \sim j_n^2\left(\frac{2\pi h(\cos\theta_1+\cos\theta_2)}{\lambda}\right)$$



Zero order suppression at $2\pi h/\lambda = 2.4048$

Non paraxial correction $h_{eff} = h(\cos\theta_1 + \cos\theta_2)$

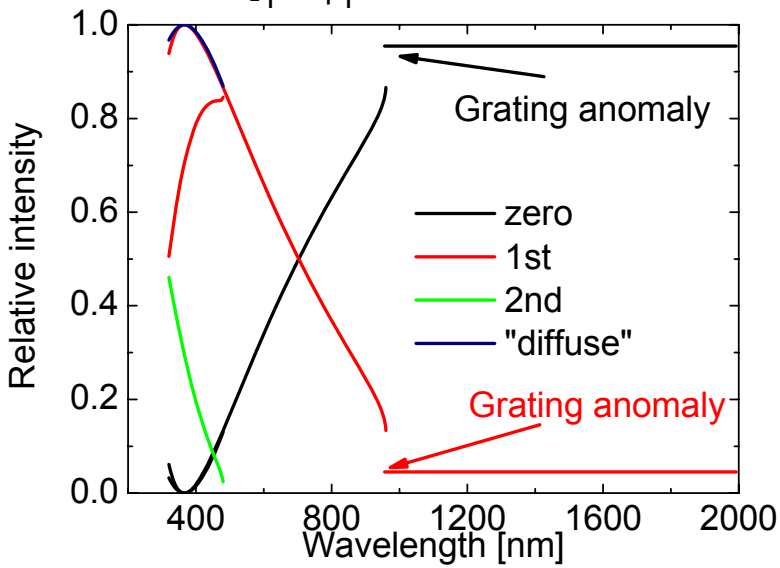
Problem: Normalization

see e.g.
Harvey,
Proc. SPIE AM100-26
Denver, 2004

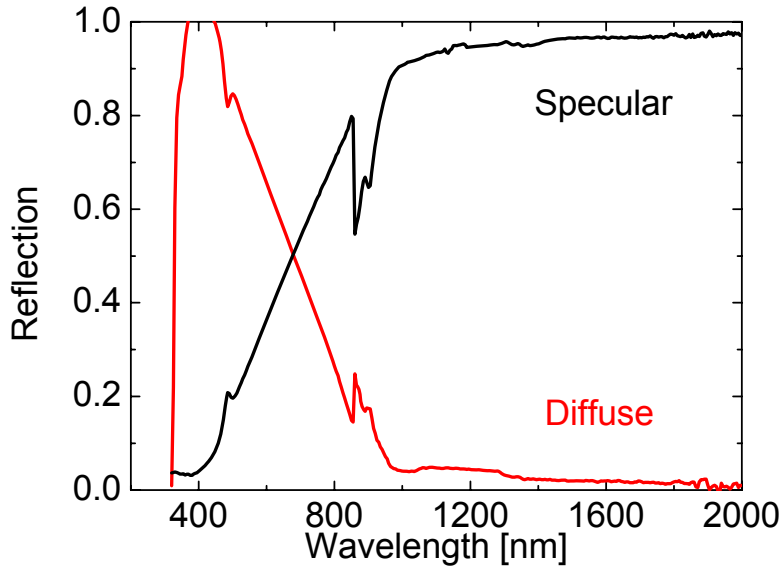
Sinusoidal grating

intensity normalized

"specular" = I_0
"diffuse" = $I_{-1}+I_{+1}$



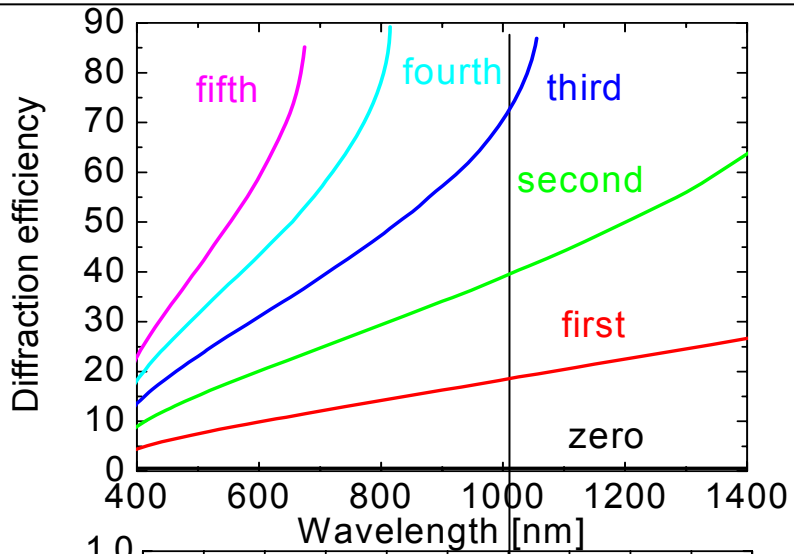
measurement

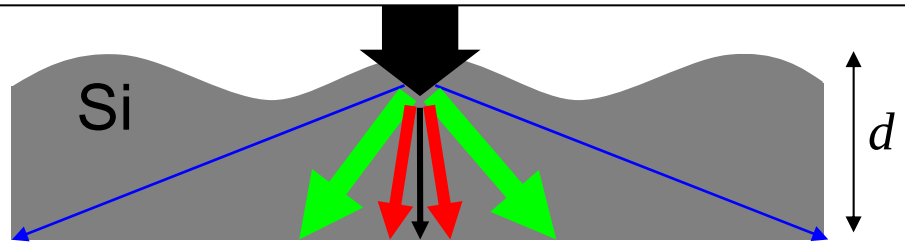


example: sinusoidal grating in air
reflection with 0° incidence
L=890 nm, h=70 nm
rms = $h/2\pi$ = 11 nm

Excitation of plasmon resonances

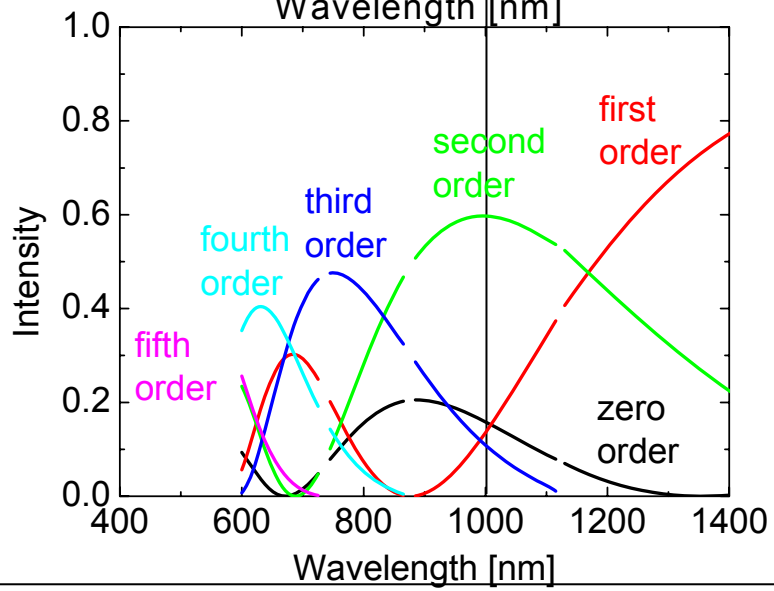
Diffraction in a dielectric (e.g. silicon)

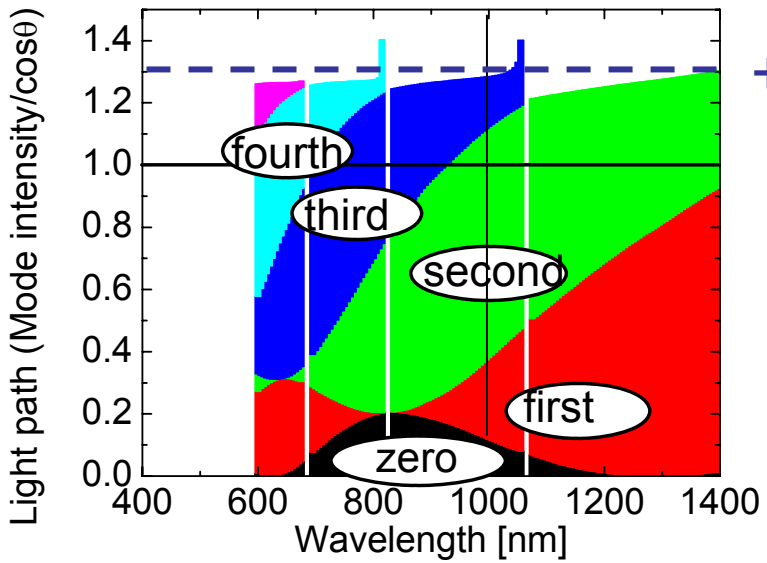




effective path L (one pass through d):

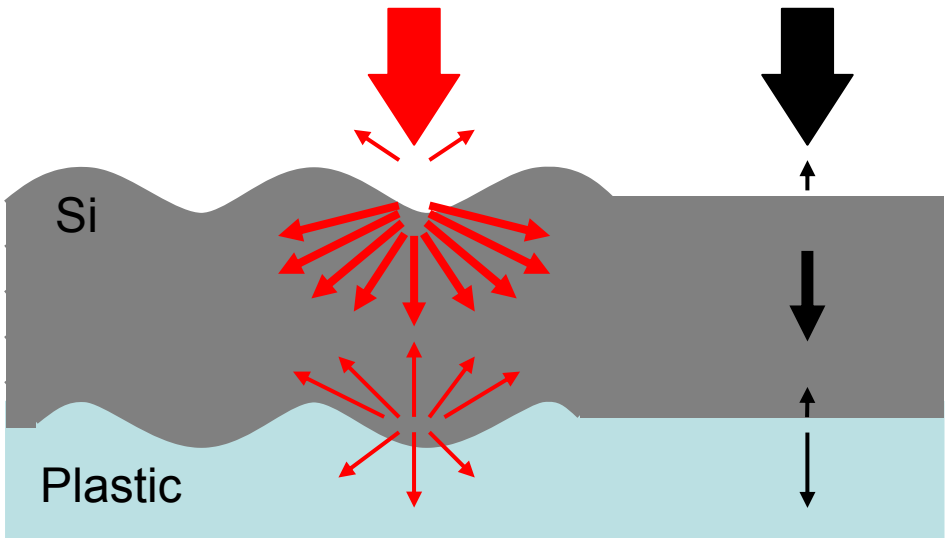
$$L = \sum I_n \cdot d / \cos\theta$$

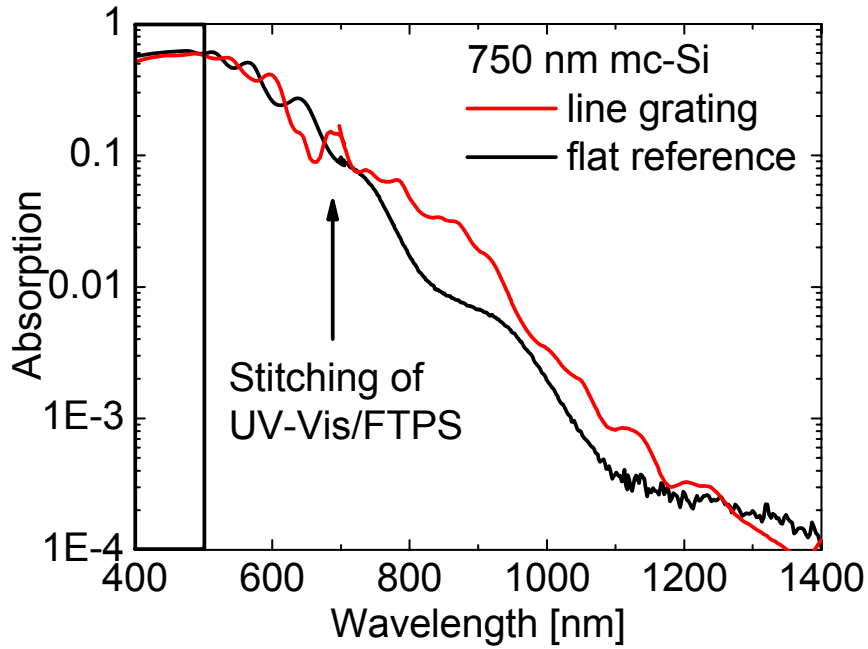




Grating enhanced absorption

Absorption in textured and flat film (co-deposition)



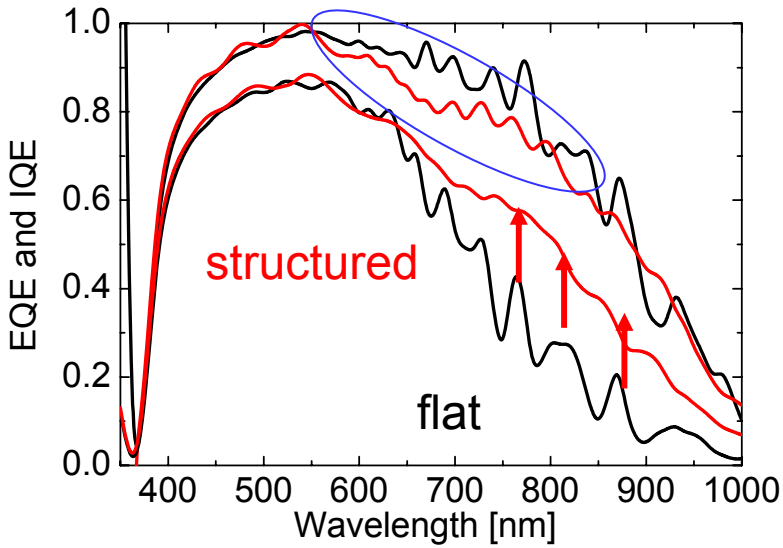


three to fivefold enhancement in absorption, relative to flat film

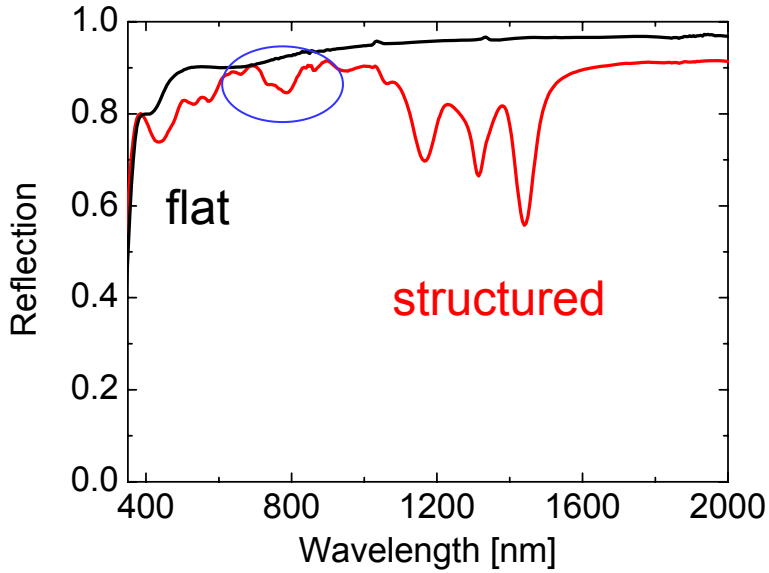
Surface plasmon excitation

µc-Si solar cells on 2D textured substrate

quantum efficiency



substrate reflection



Voc [mV]	515	491
Isc [mA/cm^2]	17.9	23.0
FF [%]	73	69
η [%]	6.7	7.8

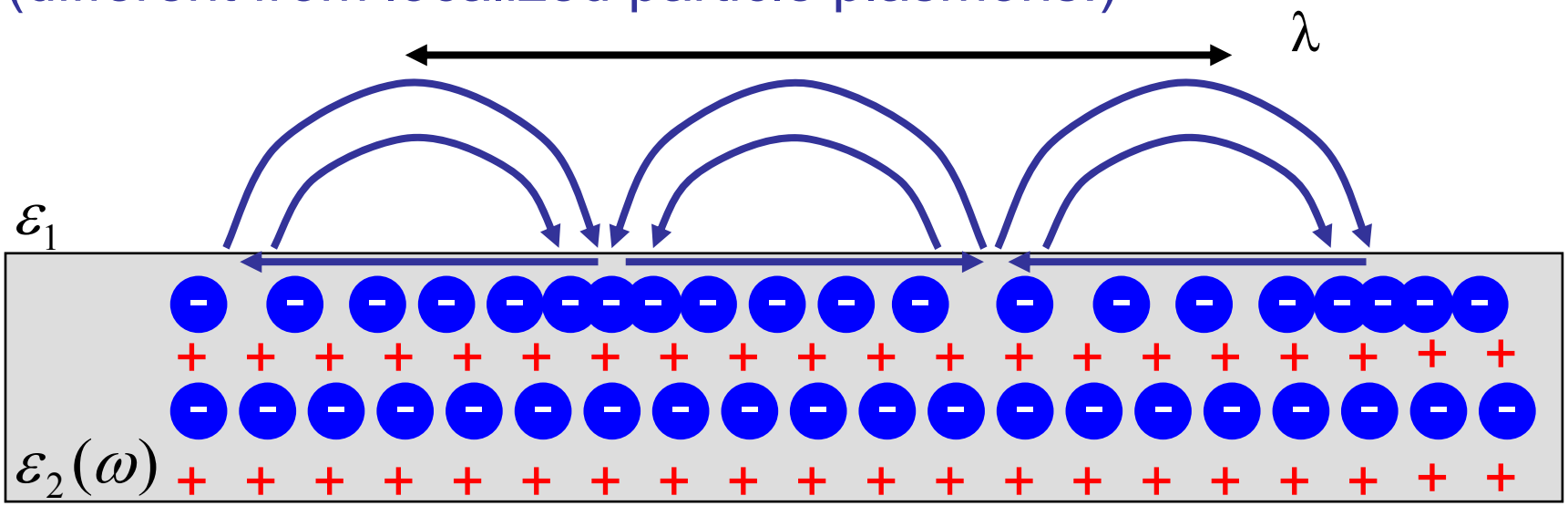
(~30% increase)

Observation: internal QE shows loss mechanism at 700 nm

- different n-layer absorption (=> co-deposition)
- plasmon absorption (possible, based on bare substrate reflection)

Surface plasmon polariton (SPP)

SPP: propagating wave of the surface charge density
(different from localized particle plasmons!)



Plasmon dispersion relation:

$$k(\omega) = \pm \frac{\omega}{c} \sqrt{\frac{\varepsilon_1 \varepsilon_2(\omega)}{\varepsilon_1 + \varepsilon_2(\omega)}}$$

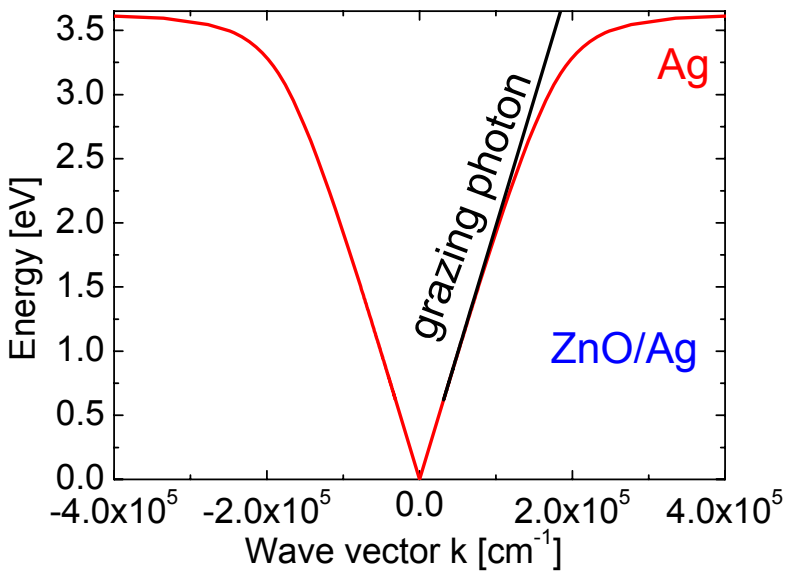
(metals: ε_2<0 in visible)

Photon dispersion relation :

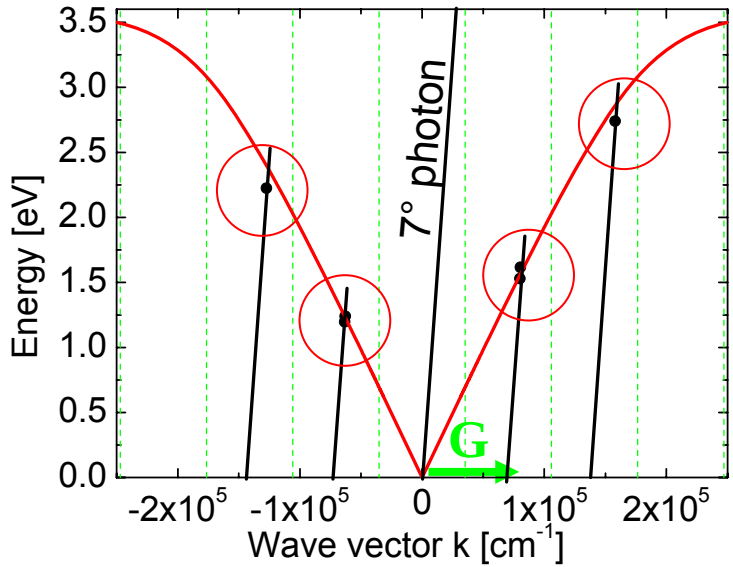
$$k(\omega) = \frac{\omega}{c}$$

Dispersion relation

Flat surface



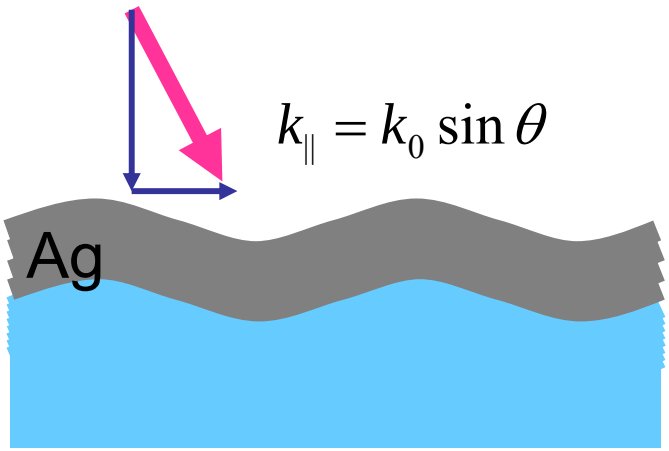
Periodicity L (not too rough)

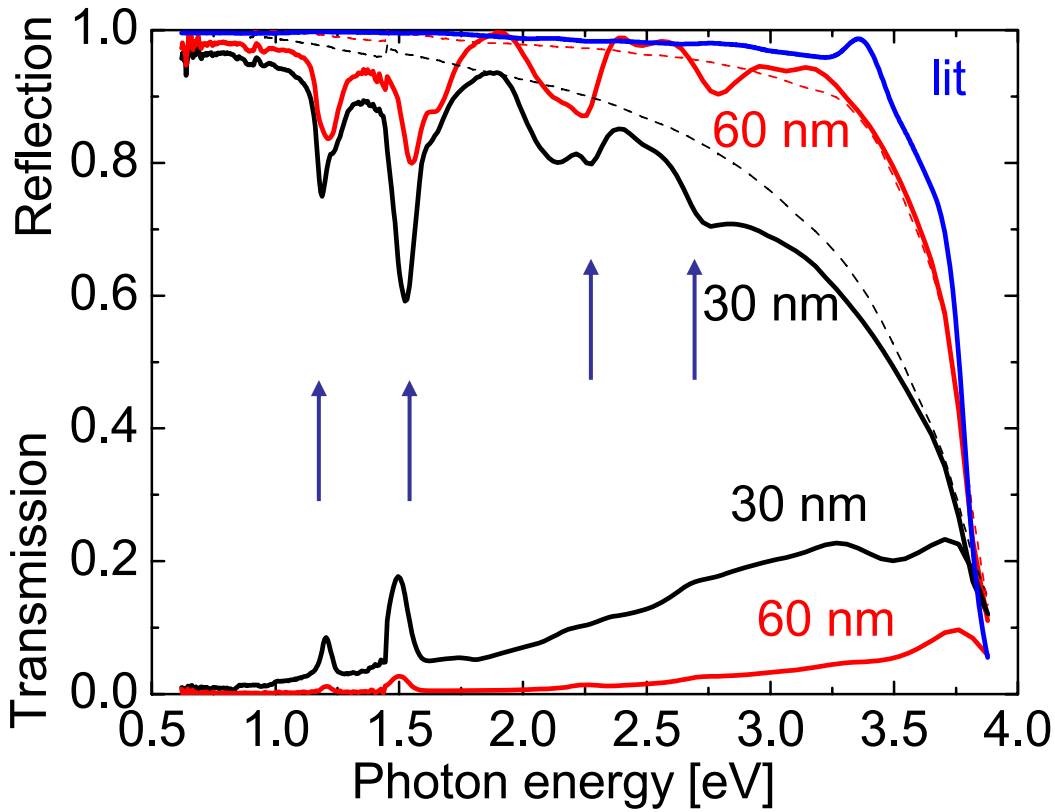


dispersion relations of photon and plasmon do not intersect
=> no excitation of plasmons by light

Grating coupling:
- pick in plane contribution
- shift by multiples of reciprocal grating vector $G=2\pi/L$

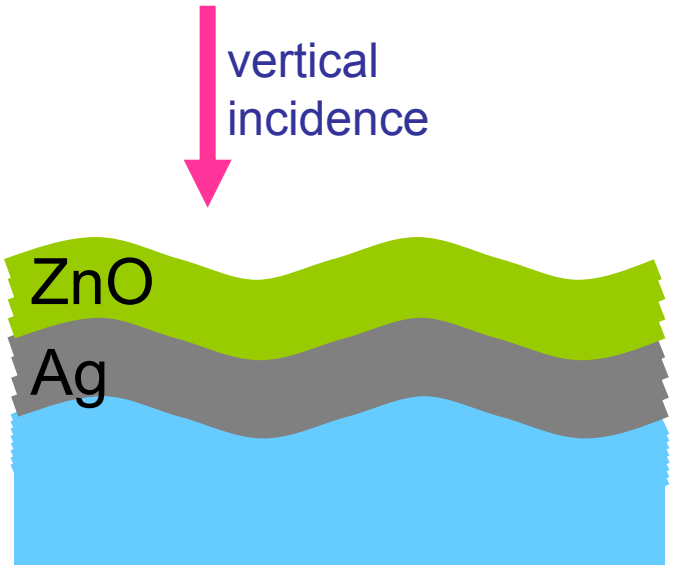
Surface plasmon excitation on gratings

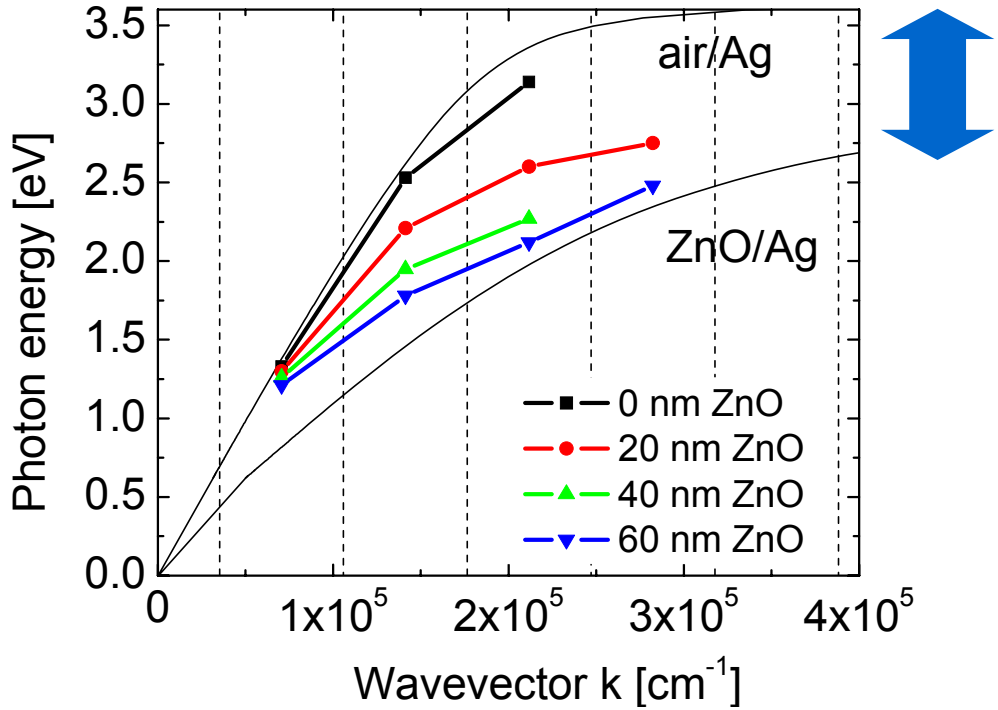




- excitation by periodicity is mediated at distinctive energies
- on known grating: reflection dips allow sampling of $k(\omega)$ (e.g. for mulitlayers)

Measurement of Ag-ZnO reflector

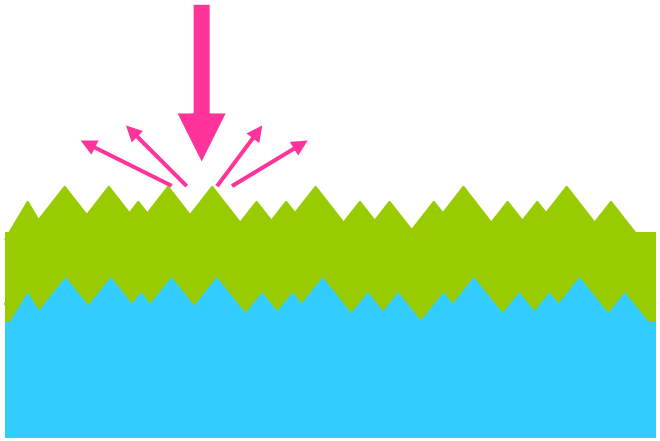


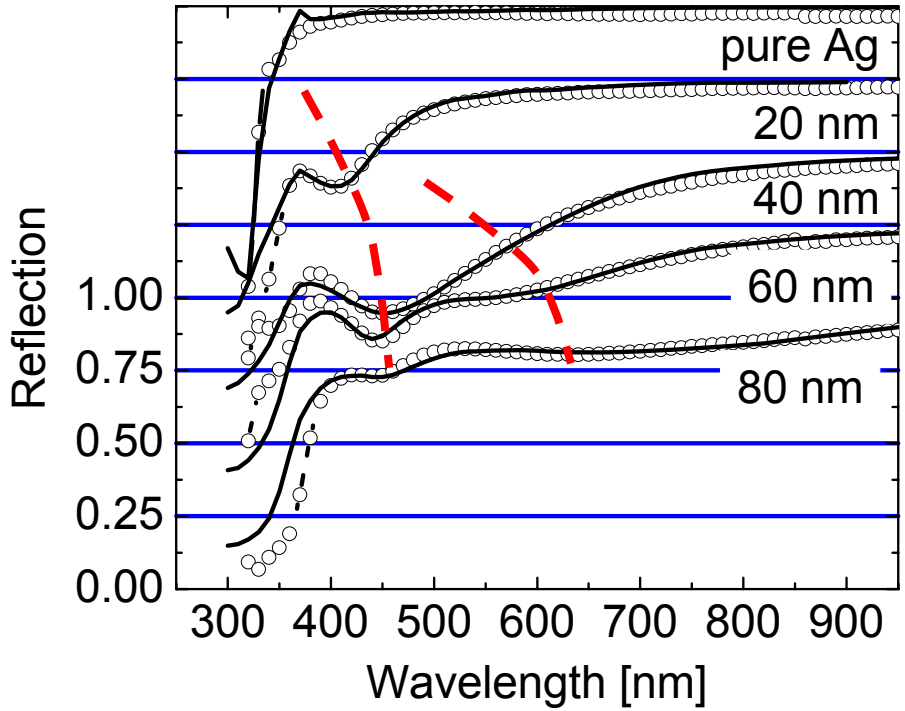


Coupling in the flat part of the dispersion relation:
dips fall into a small range of energies
$\Rightarrow$ absorption can take place for any value of k
$\Rightarrow$ this regime applies also to random textures

Relation to arbitrary texture

Two types of reflection dip





High E: 3.5 eV down to 2.8 eV:

=> flat part of characteristic

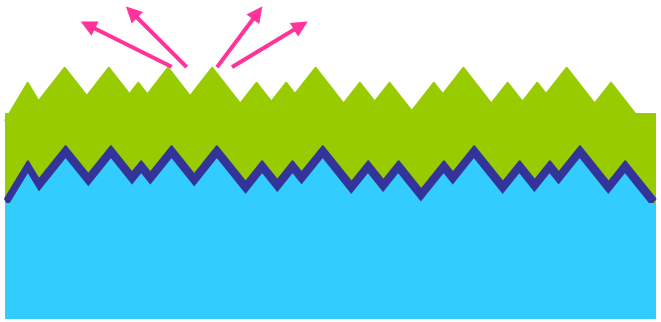
Low E: (3 eV) down to 1.8 eV:

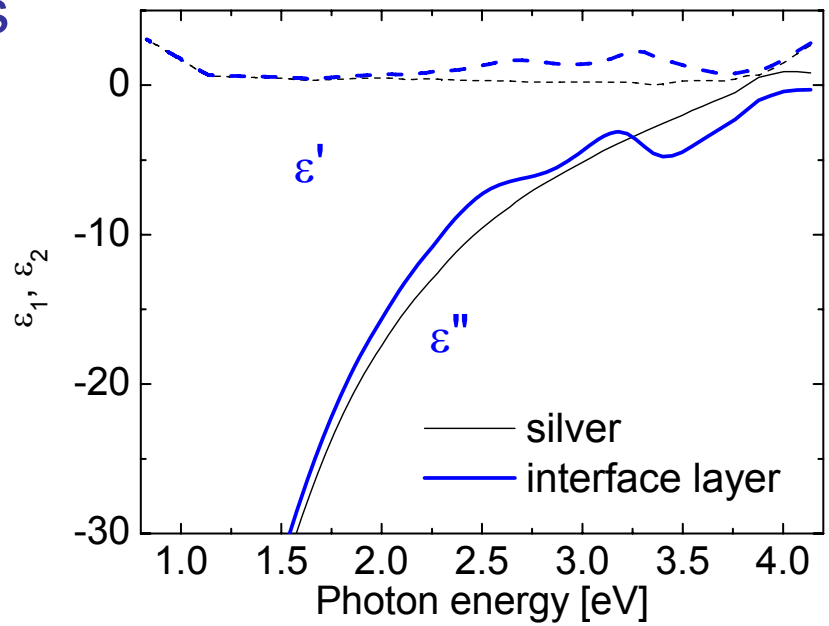
=> no periodicity, but distribution about correlation length

Lines: modelling results using SunShine software, (Uni Lubljana)

Modelling input

Assume interfacial layer:
thickness: 20 nm (plasmon penetration depth)
$\varepsilon(\omega)$: silver plus two Lorentzians

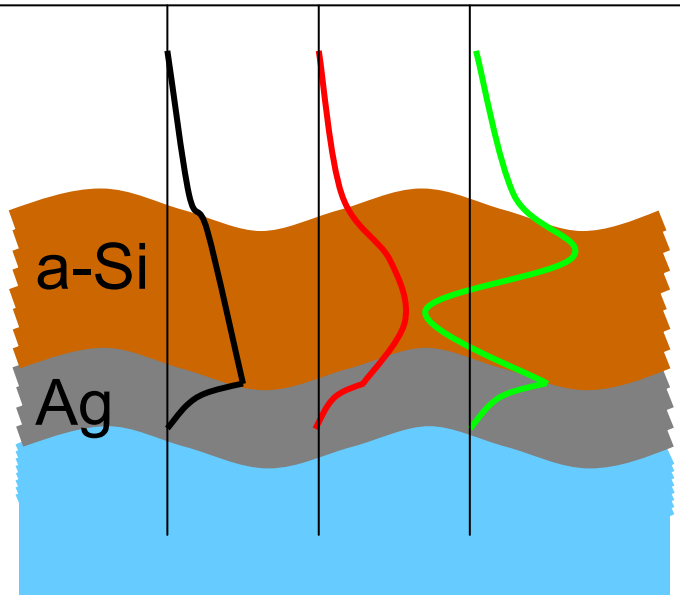


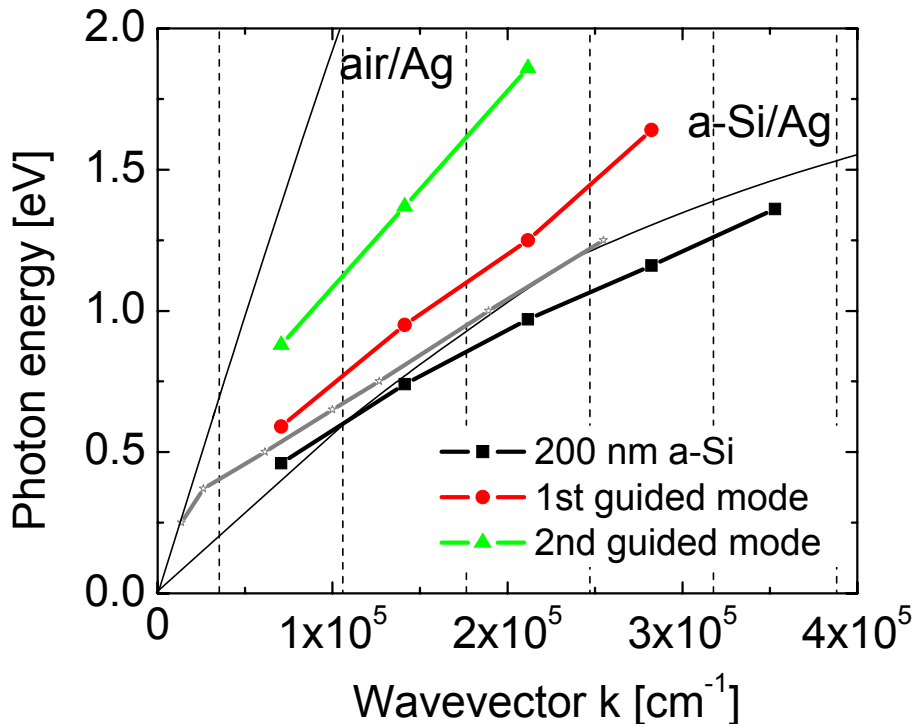


As yet:
fitting of reflection OK, but:
no prediction of intensity or fwhm

Sainju et.al.
Proc. 4th World PVSEC
Hawaii, (2006)

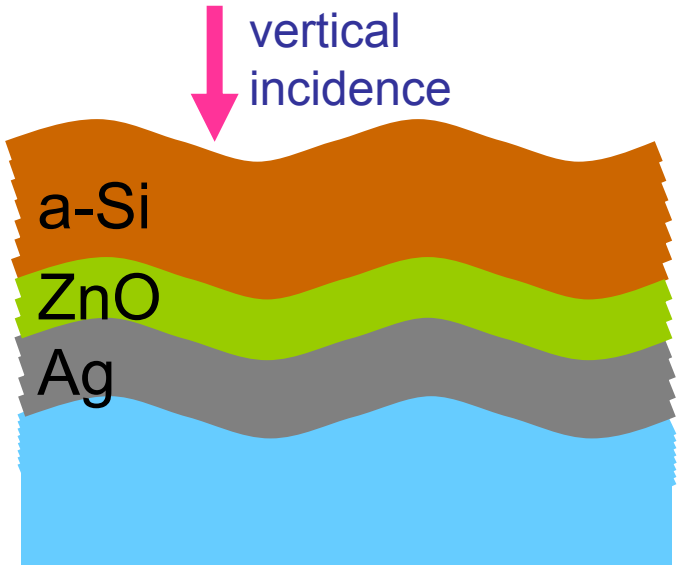
Waveguiding

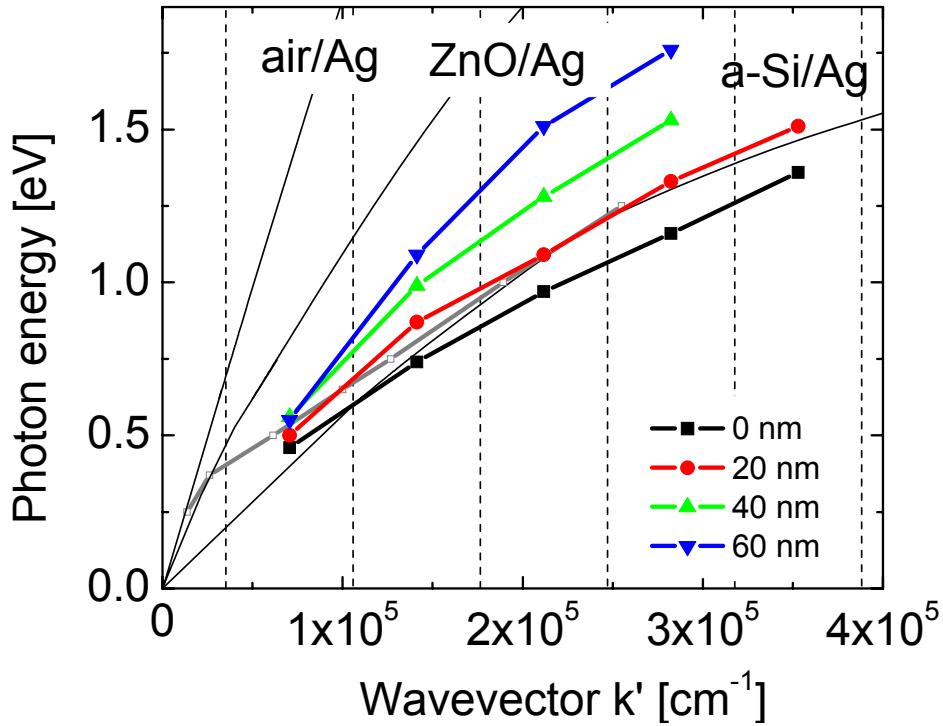




occurrence of guided modes in optically thick films
200 nm a-Si:H , sub gap

Solar cell back contact model





Without ZnO:

plateau at 1.9 eV, fwhm ~0.5 eV

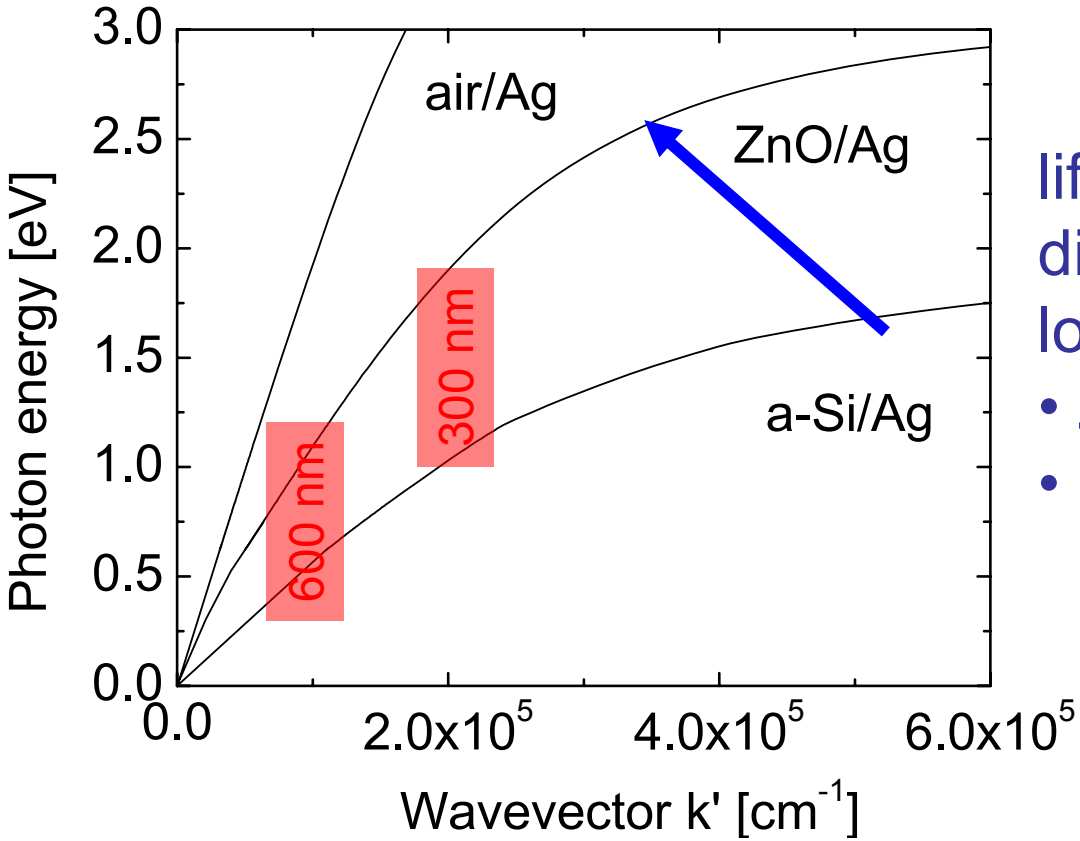
=> Plasmon absorption in a-Si:H light trapping region

Witn ZnO: plasmon curve raised towards higher energy

=> plasmon absorption in less critical energy range

Strategy for dielectric back reflector

correlation length Δ mediates interactions centred on $k = 2\pi/\Delta$



lift curve by dielectric; ε as low as possible

- ZnO
- SiO_x:P

For given dimension, shape and depth still define the intensities in the diffraction orders

Periodic textures for light trapping

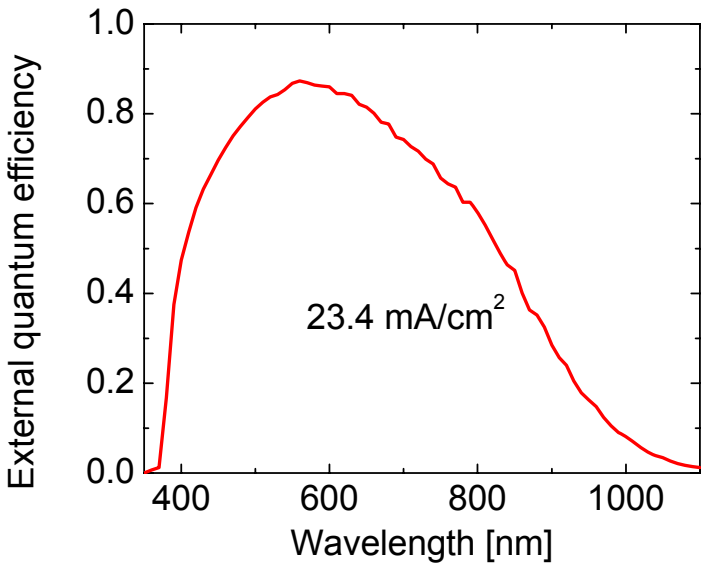
Current enhancement

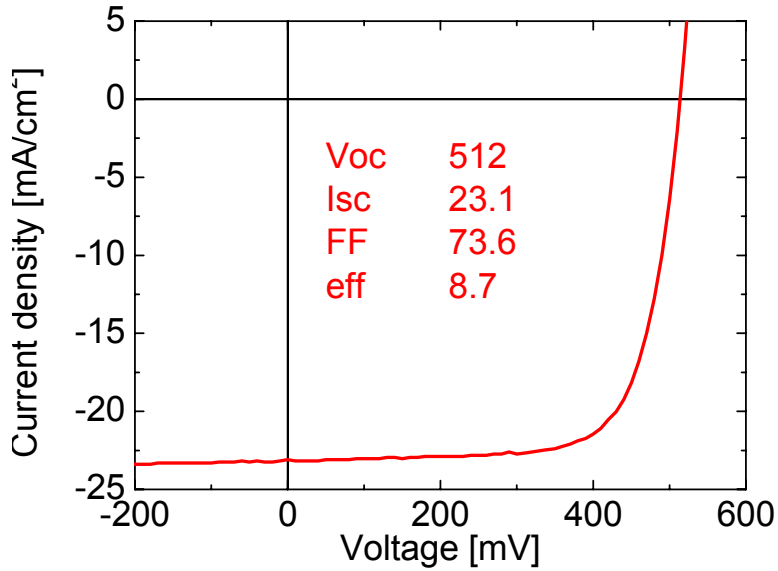
- excellent tool for understanding of light trapping
- importance of periodicity (lateral dimension)
  and depth (rms)
- large area fabrication of grating structures is feasible

Plasmon absorption losses

- Plasmon dispersion relation depends critically on dielectric environment
- dielectric layer ameliorates the reflector properties
- Periodic structure can be used for measuring of the dispersion relation

µc-Si solar cells on 2D grating



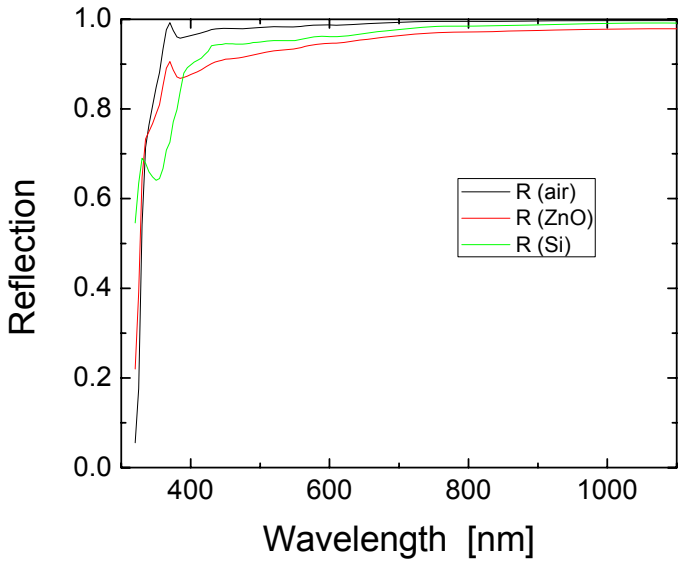
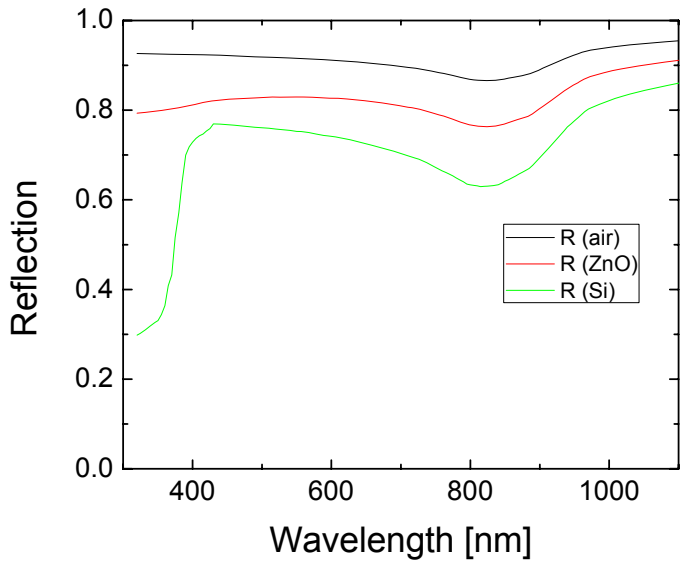


>23 mA/cm2 in 1.2 µm thick i-layer

8.7% efficiency, fully flexible on low cost plastic substrate

Acknowledgements:

nip group UniNe (Vanessa, Thomas, Xavier, Stephanie, Oscar)

European Union funding through FLEXCELLENCE

Metals and dielectrics