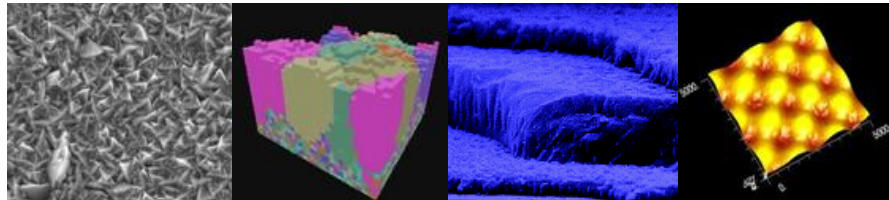


Periodic textures for enhanced current in thin film solar cells

MRS Spring meeting 2008
San Francisco



F.-J. Haug, T. Söderström, V. Terrazzono-Daudrix,
X. Niquille, S. Perregaux, C. Ballif

Institute of Microtechnology, University of Neuchâtel, Switzerland

Light scattering in solar cells

Front contact

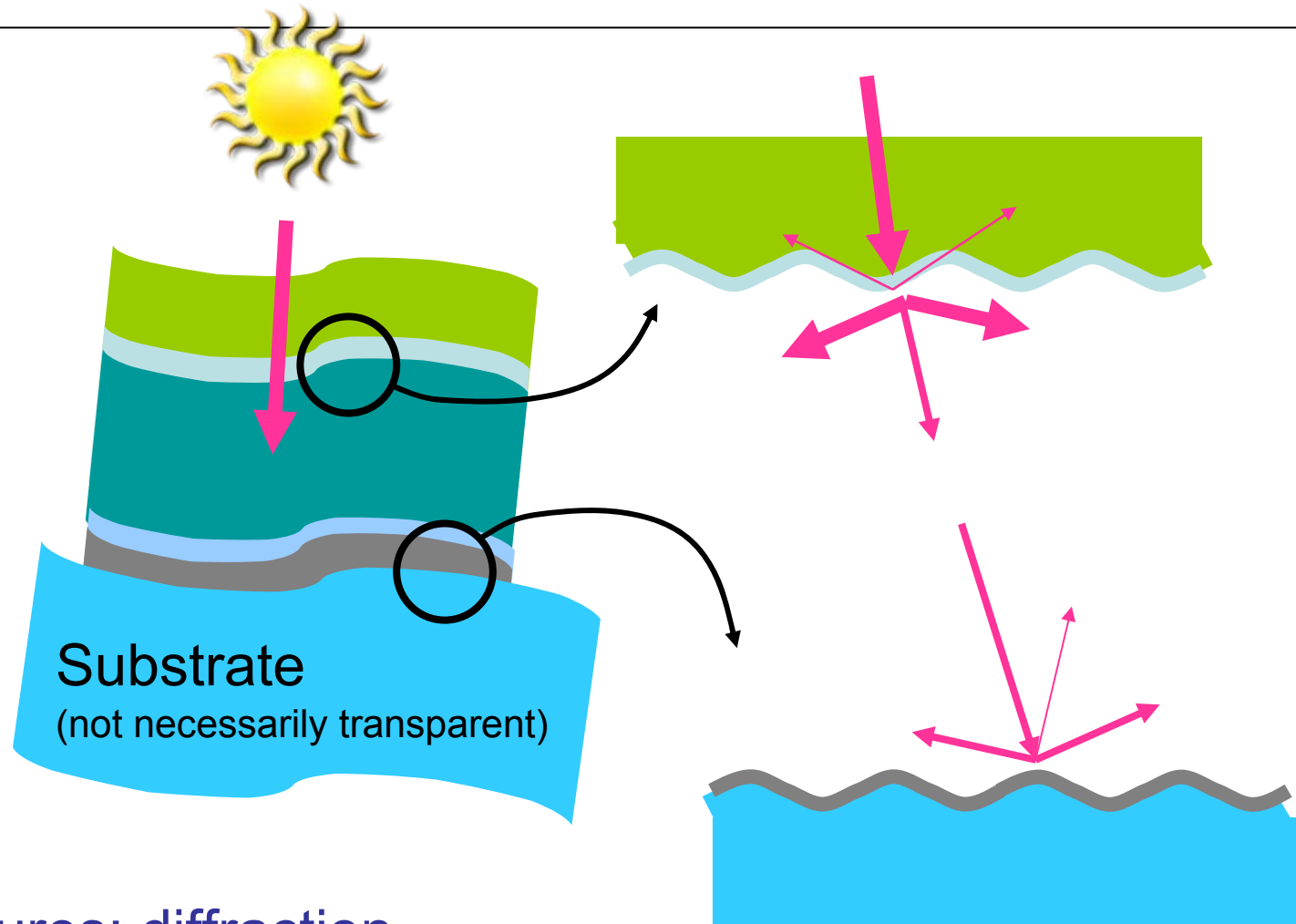
p-layer

i-absorber

n-layer

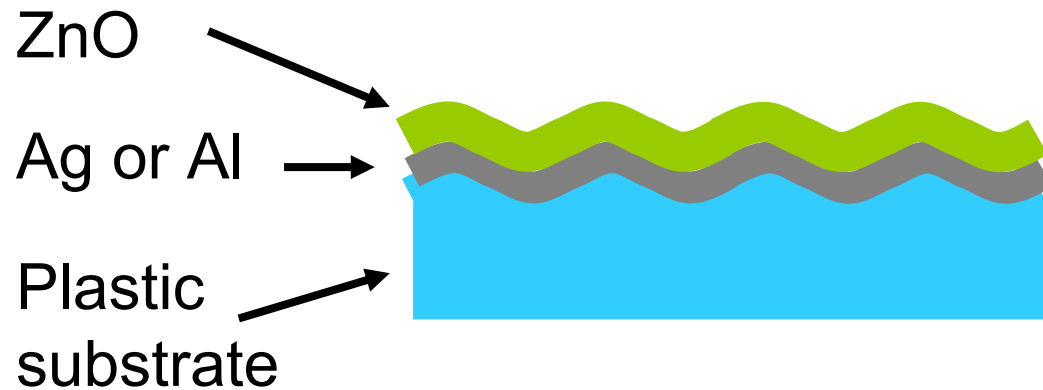
Back contact

Substrate
(not necessarily transparent)



Periodic structures: diffraction

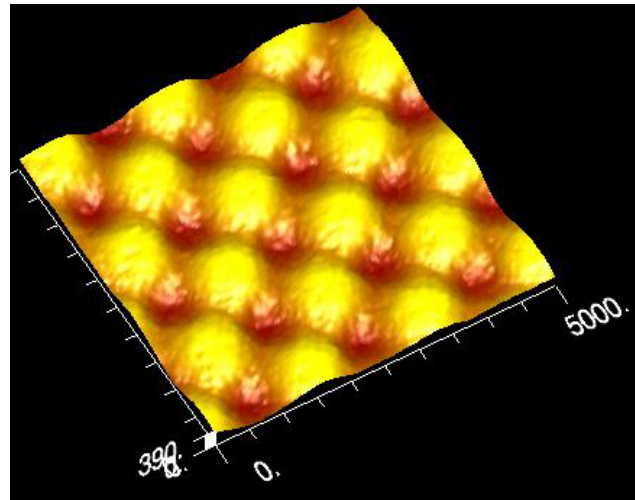
Approach to scattering: textured substrate



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

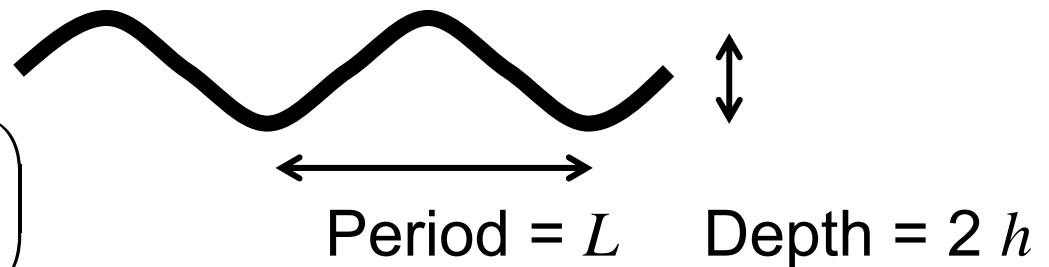
Periodic substrate texture

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



Sinusoidal bigrating (2D):

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



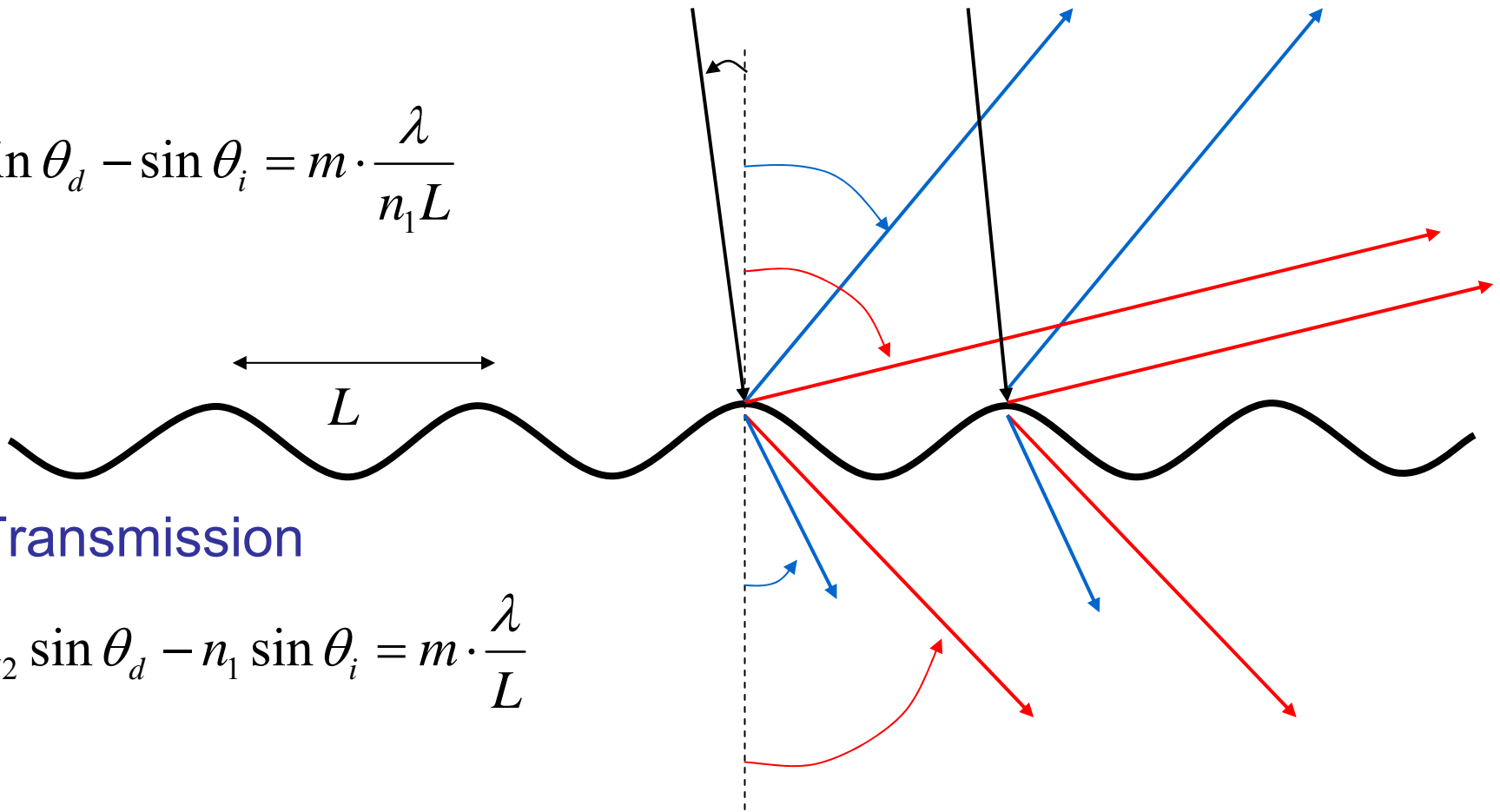
Diffraction grating (e.g. sinusoidal)

Reflection

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

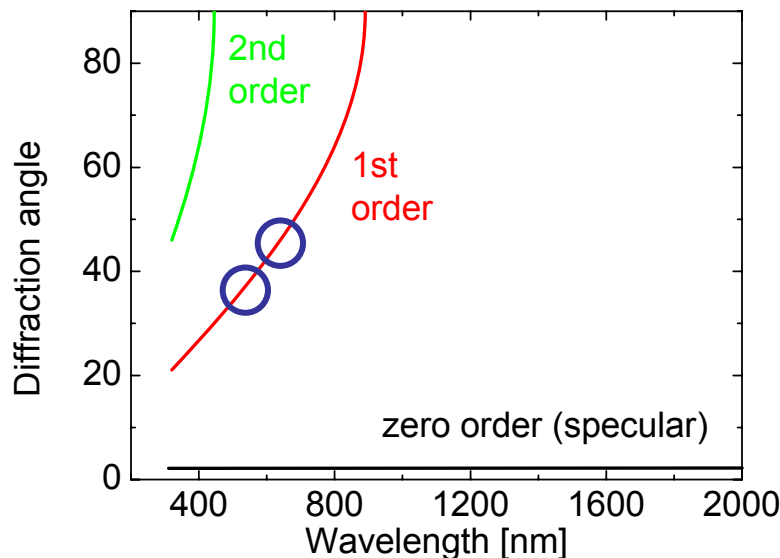
Transmission

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

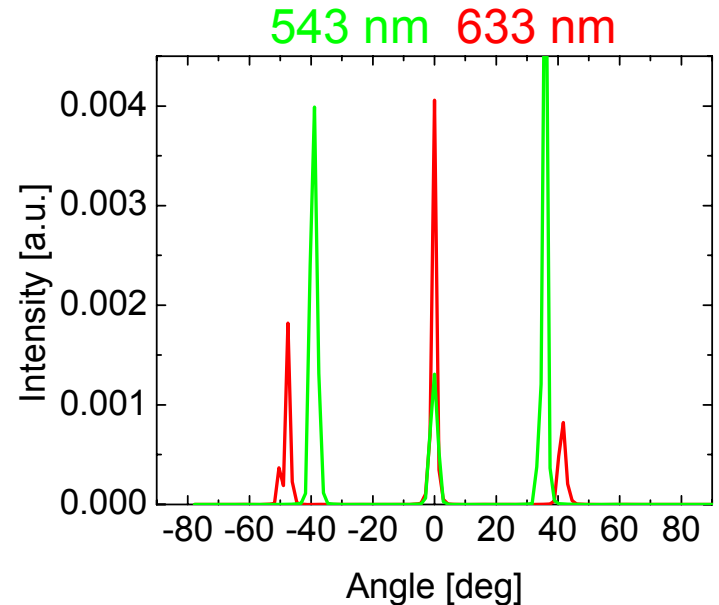


Grating period => angular properties

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



angle
resolved
reflection



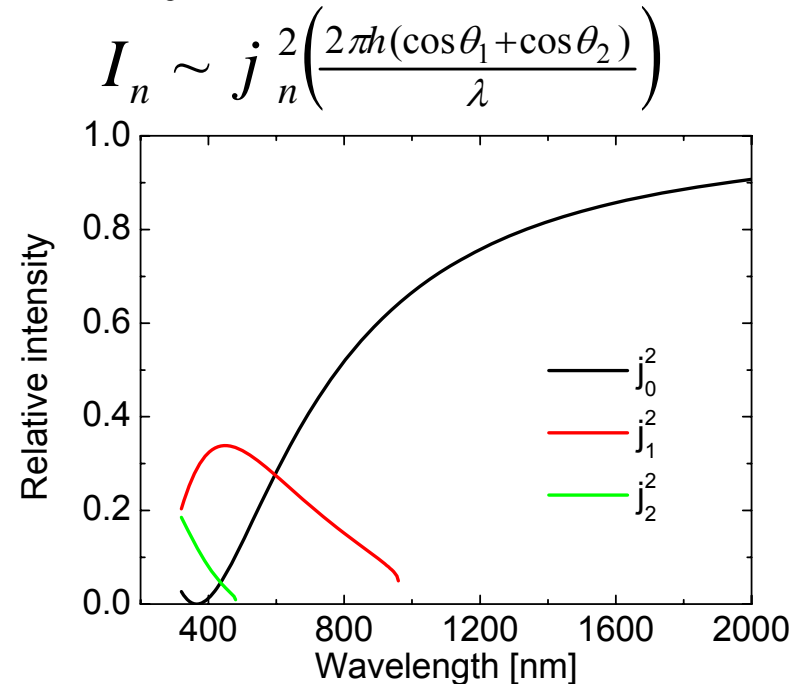
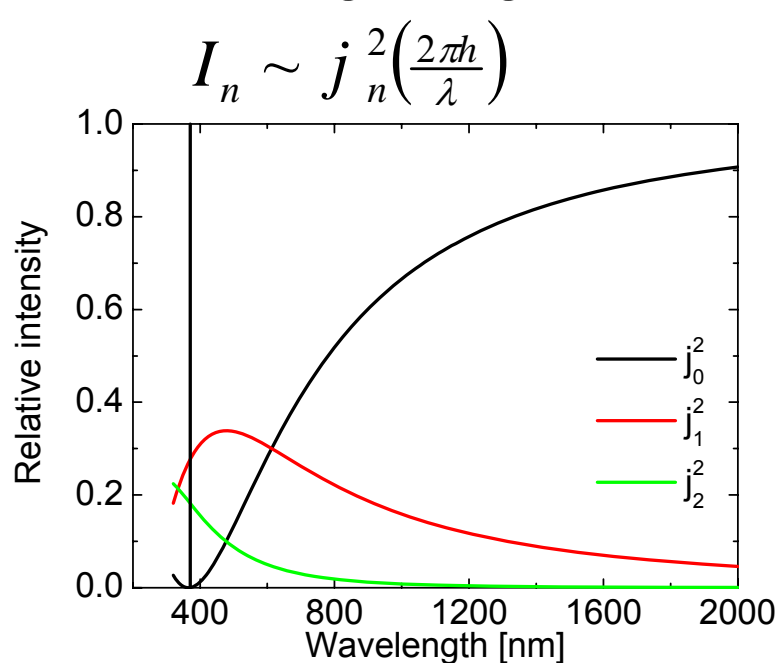
$\lambda > d$: specular reflection, no diffraction, only zero order

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

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

Grating shape and depth => mode intensity

Sinusoidal grating => Intensity given by Bessel functions



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

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

Problem: Normalization

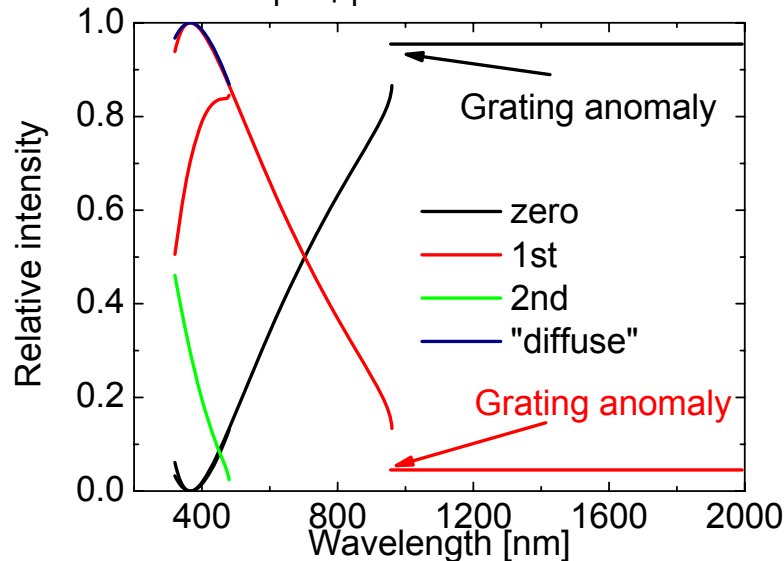
see e.g.
Harvey,
Proc. SPIE AM100-26
Denver, 2004

Sinusoidal grating

intensity normalized

“specular” = I_0

“diffuse” = $I_{-1} + I_{+1}$

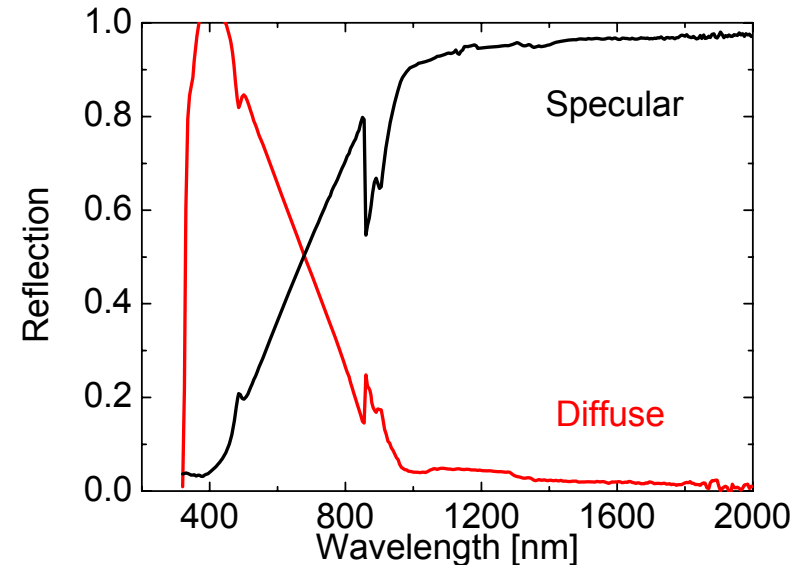


example: sinusoidal grating in air
reflection with 0° incidence

$L=890$ nm, $h=70$ nm

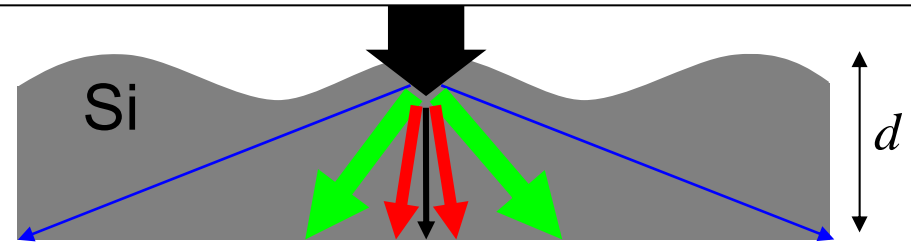
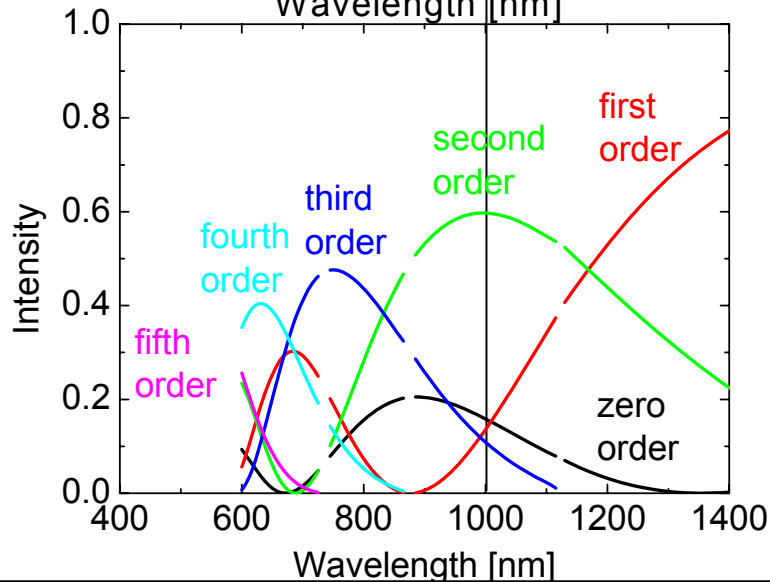
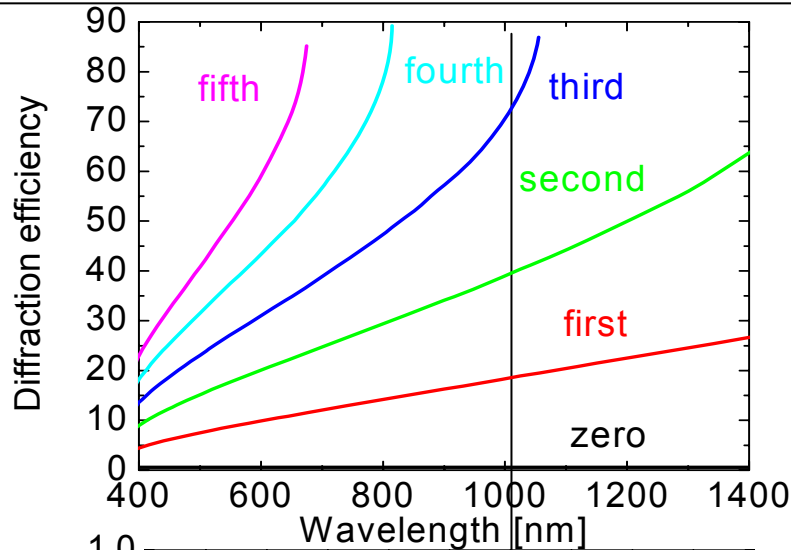
$\text{rms} = h/2\pi = 11$ nm

measurement



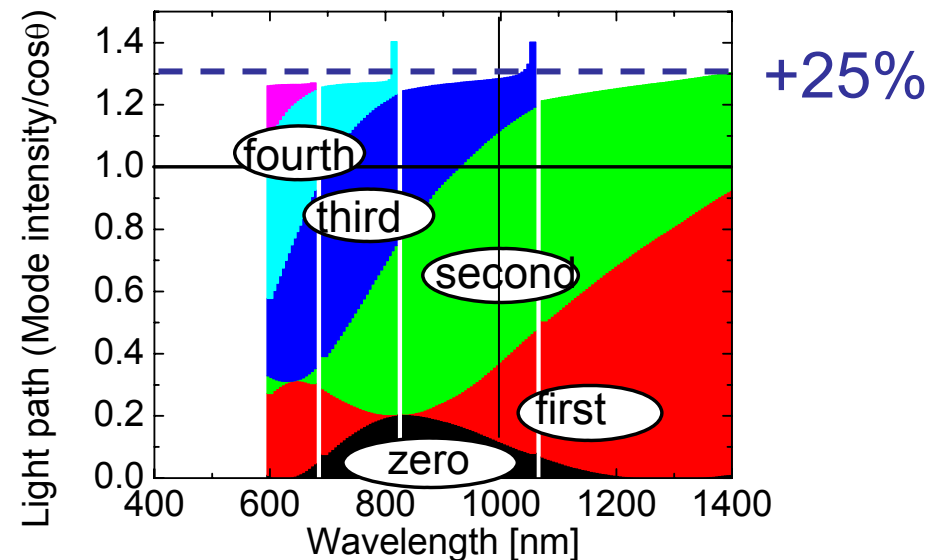
Excitation of plasmon resonances

Diffraction in a dielectric (e.g. silicon)



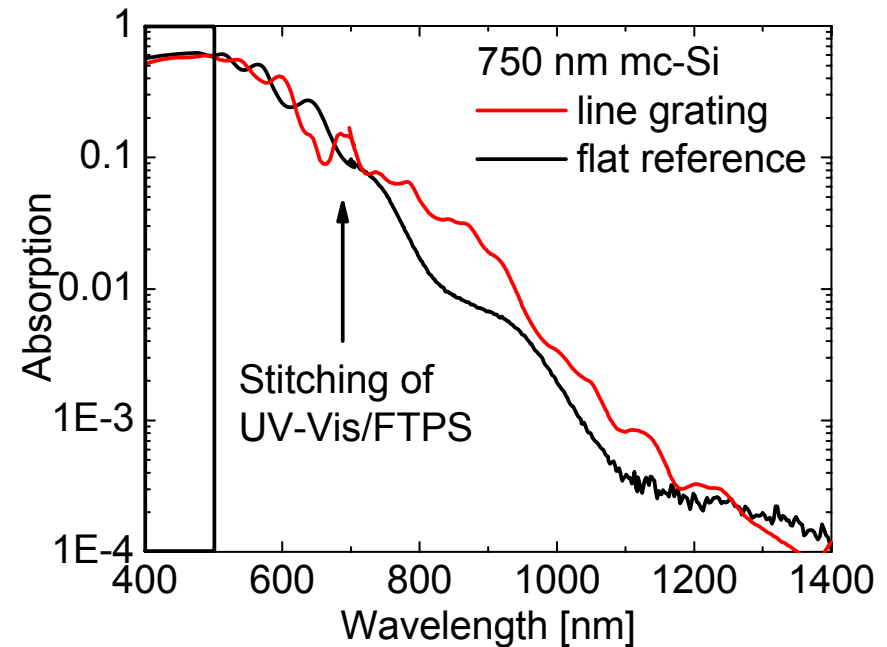
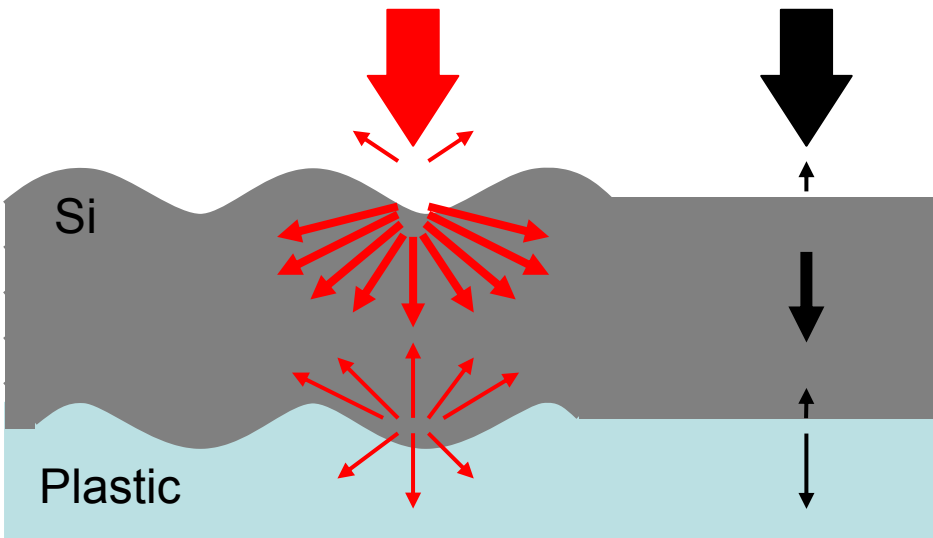
effective path L (one pass through d):

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



Grating enhanced absorption

Absorption in textured and flat film (co-deposition)

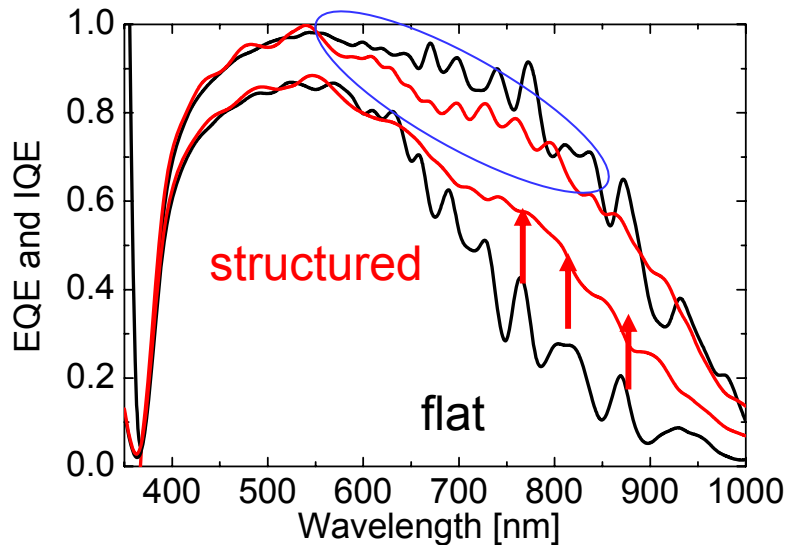


three to fivefold enhancement in absorption, relative to flat film

Surface plasmon excitation

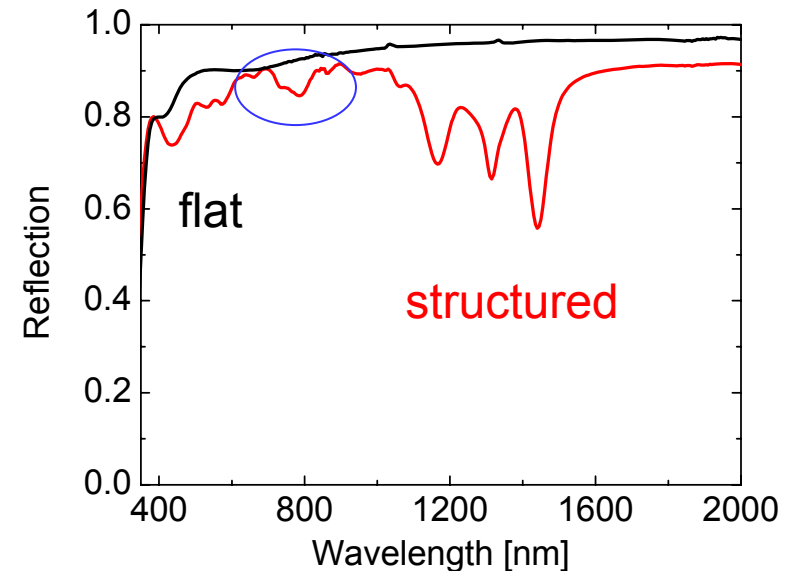
$\mu\text{c-Si}$ solar cells on 2D textured substrate

quantum efficiency



Voc [mV]	515	491	
Isc [mA/cm ²]	17.9	23.0	(~30% increase)
FF [%]	73	69	
η [%]	6.7	7.8	

substrate reflection

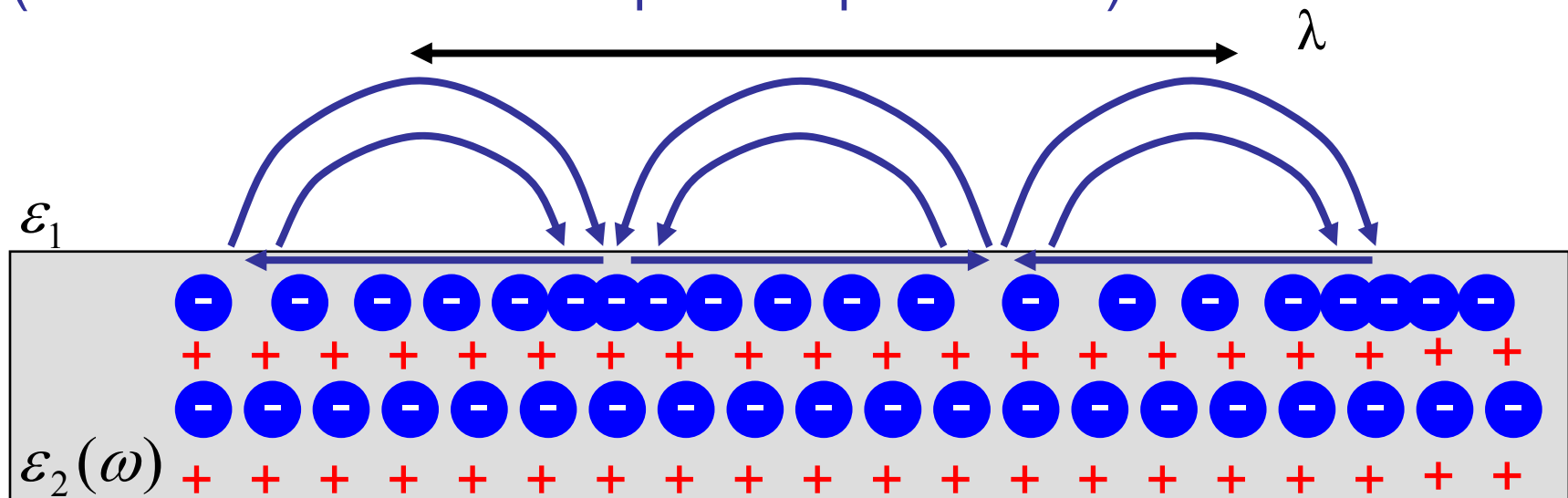


Observation: internal QE shows loss mechanism at 700 nm

- different n-layer absorption (\Rightarrow 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:
(metals: $\epsilon_2 < 0$ in visible)

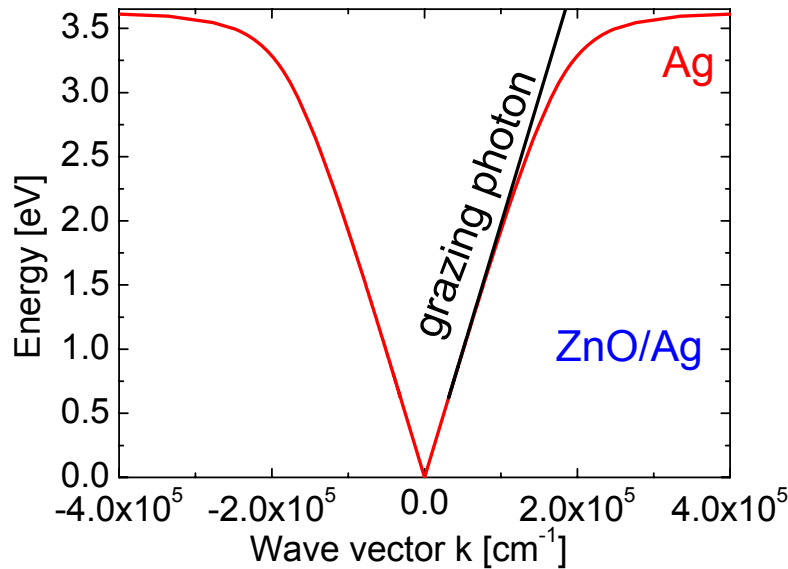
$$k(\omega) = \pm \frac{\omega}{c} \sqrt{\frac{\epsilon_1 \epsilon_2(\omega)}{\epsilon_1 + \epsilon_2(\omega)}}$$

Photon dispersion relation :

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

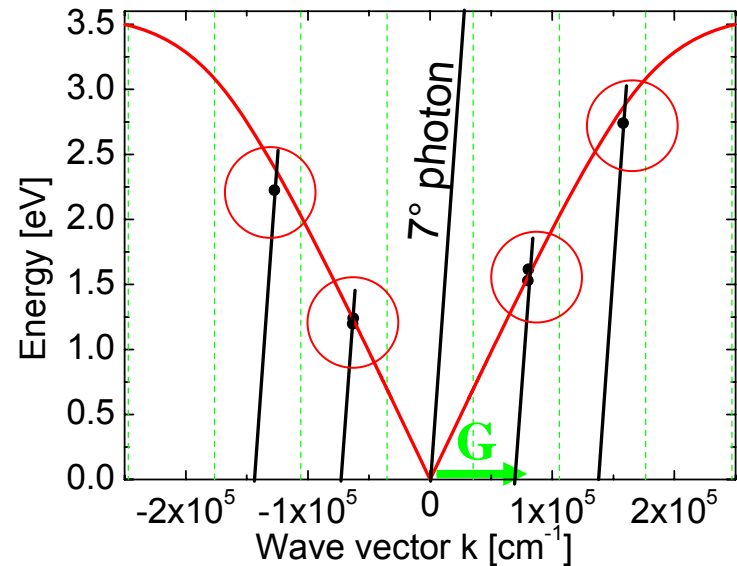
Dispersion relation

Flat surface



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

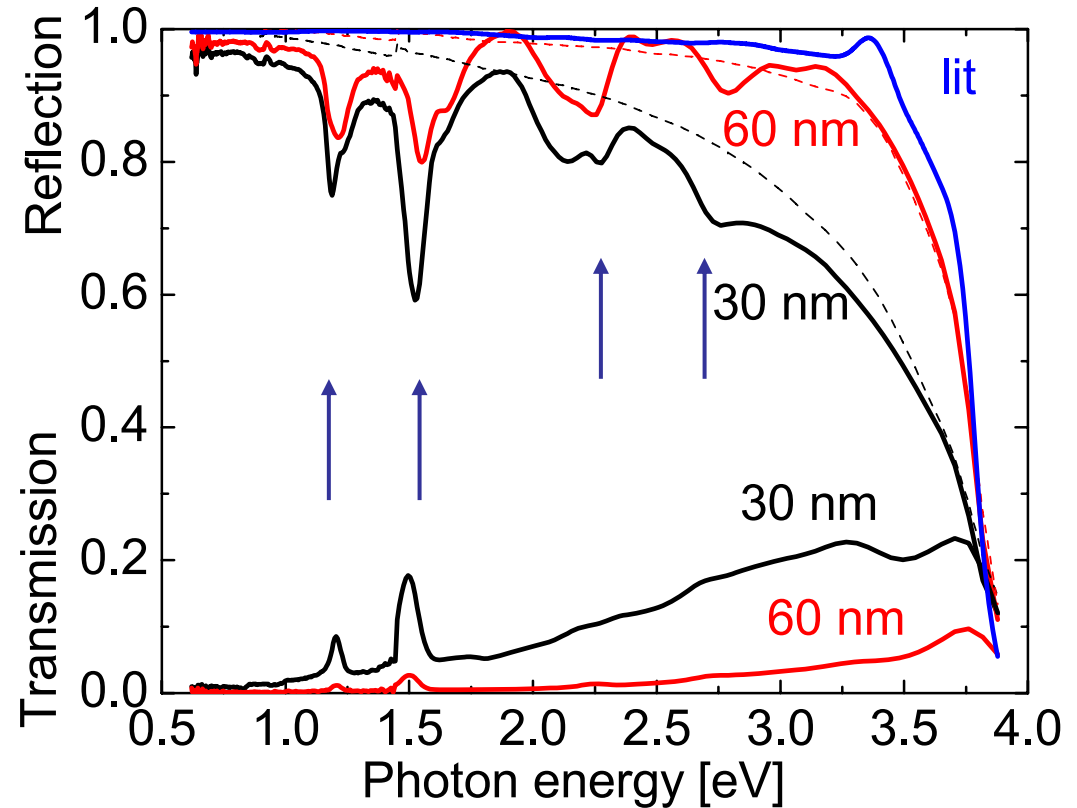
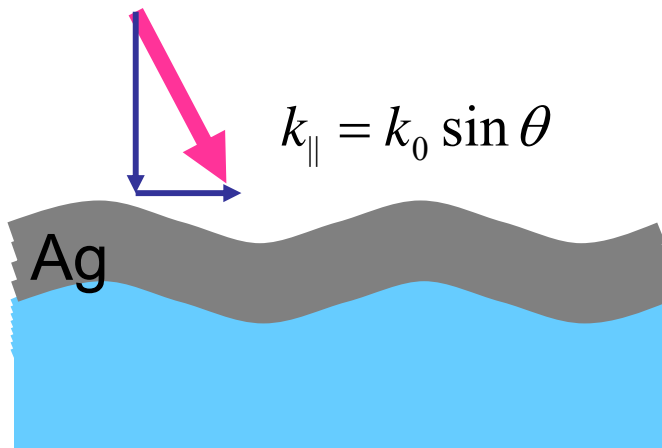
Periodicity L (not too rough)



Grating coupling:

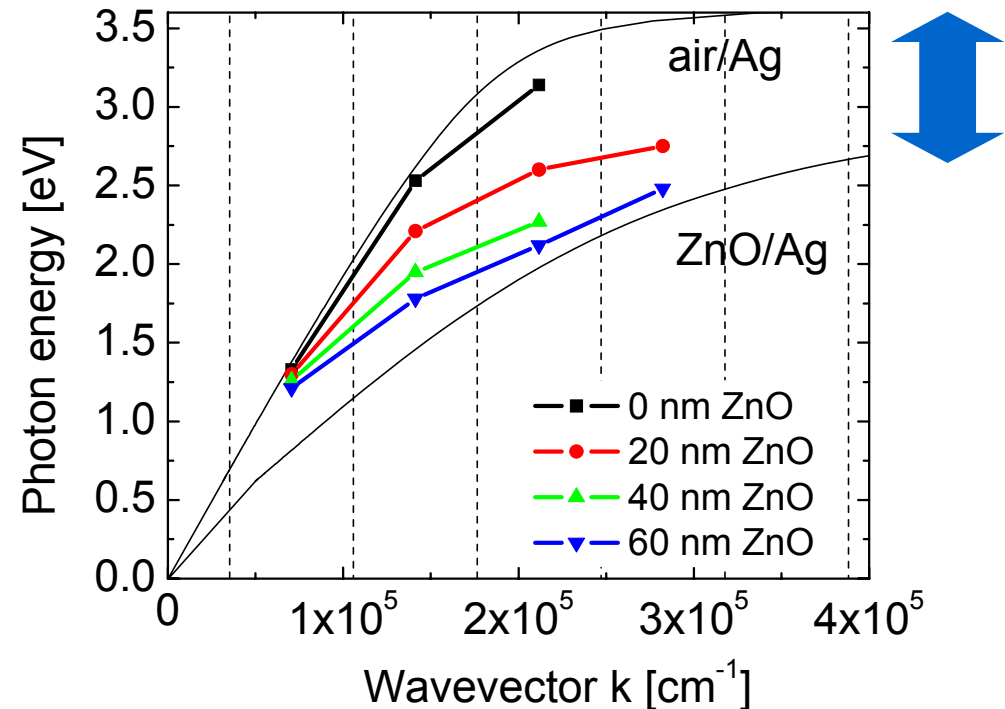
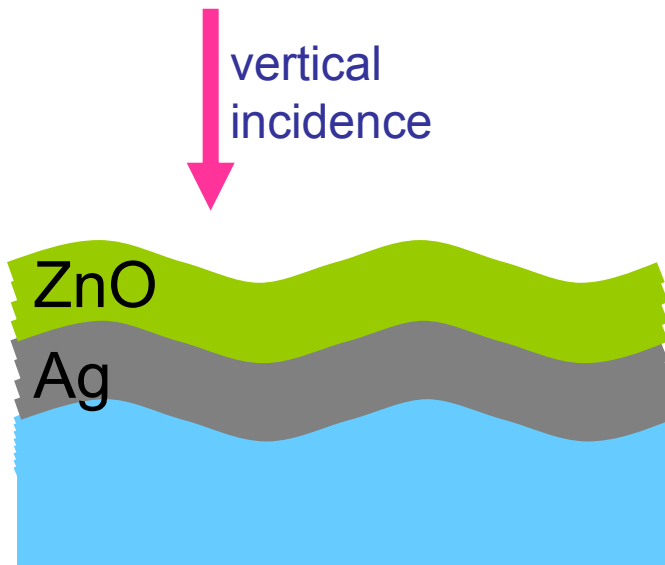
- pick in plane contribution
- shift by multiples of reciprocal grating vector $G=2\pi/L$

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 multilayers)

Measurement of Ag-ZnO reflector



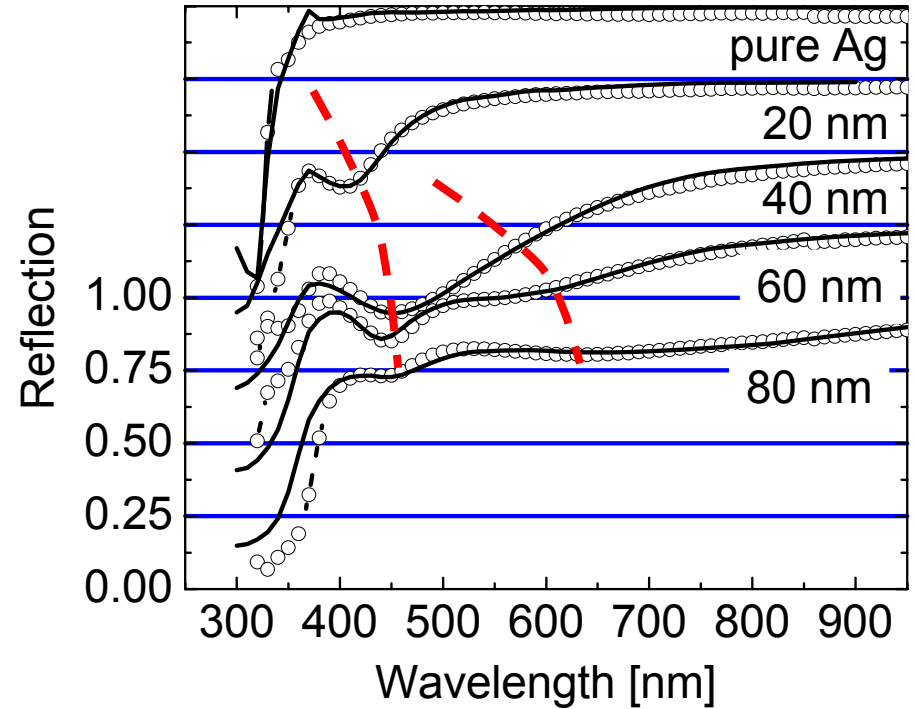
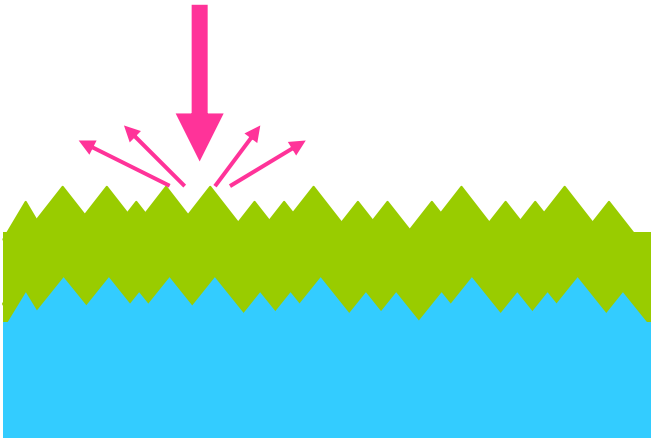
Coupling in the flat part of the dispersion relation:
dips fall into a small range of energies

⇒ absorption can take place for any value of k

⇒ 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

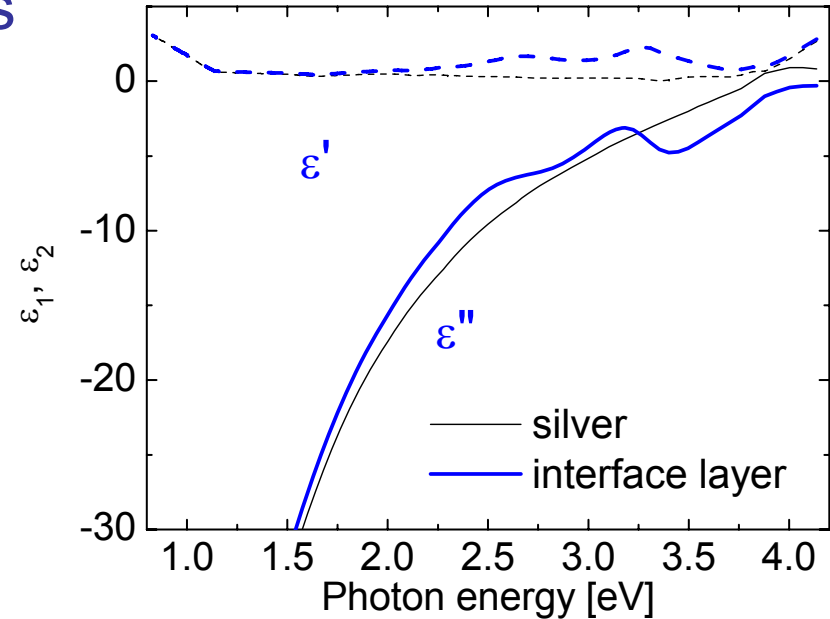
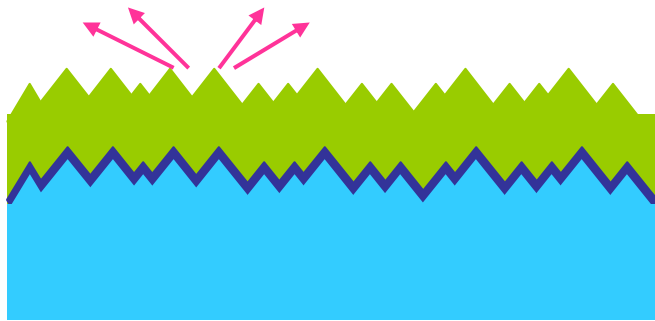
Low E: (3 eV) down to 1.8 eV:

=> no periodicity, but distribution about correlation length

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

Modelling input

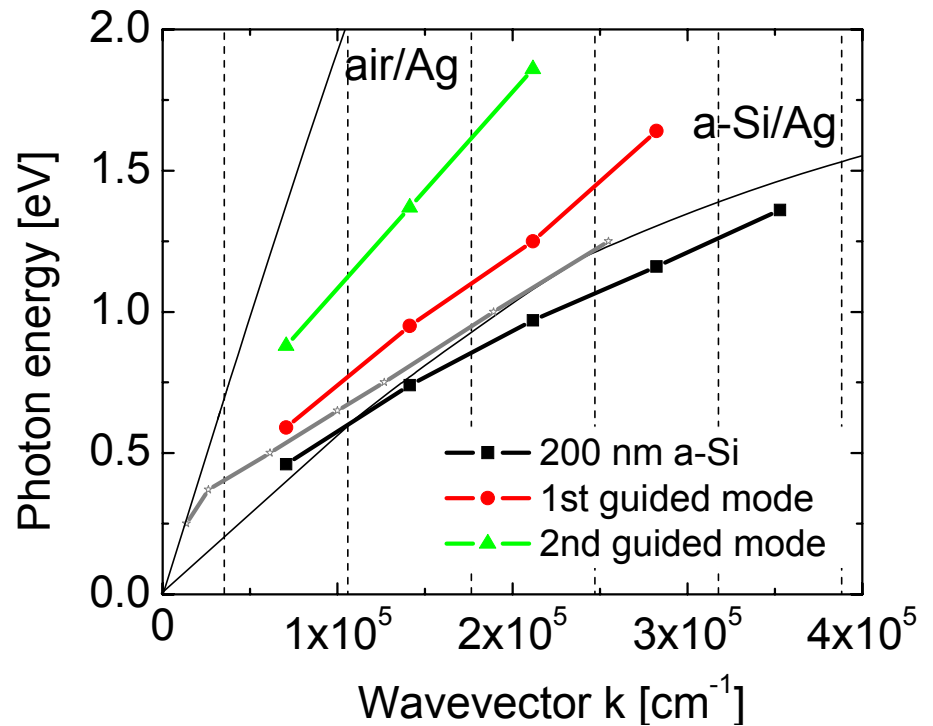
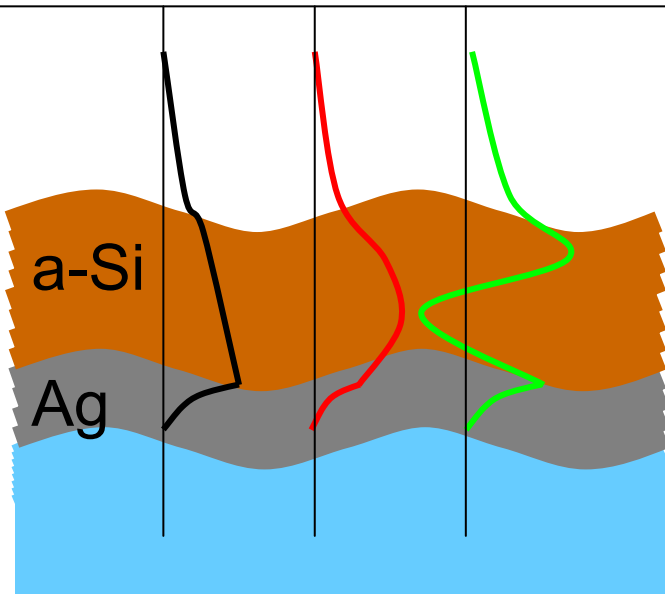
Assume interfacial layer:
thickness: 20 nm (plasmon penetration depth)
 $\epsilon(\omega)$: silver plus two Lorentzians



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

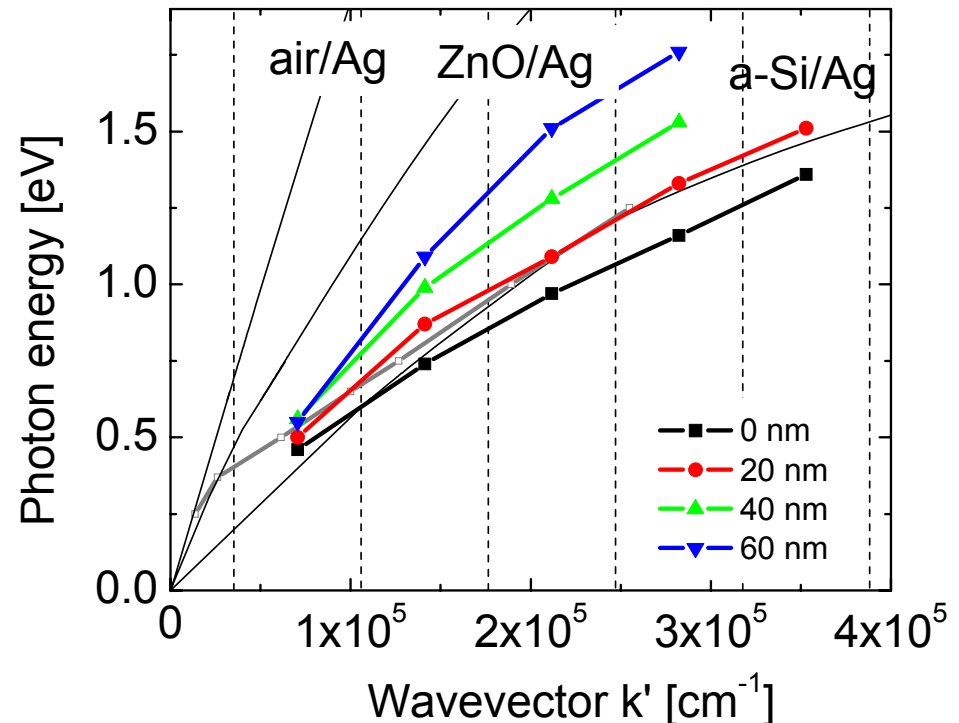
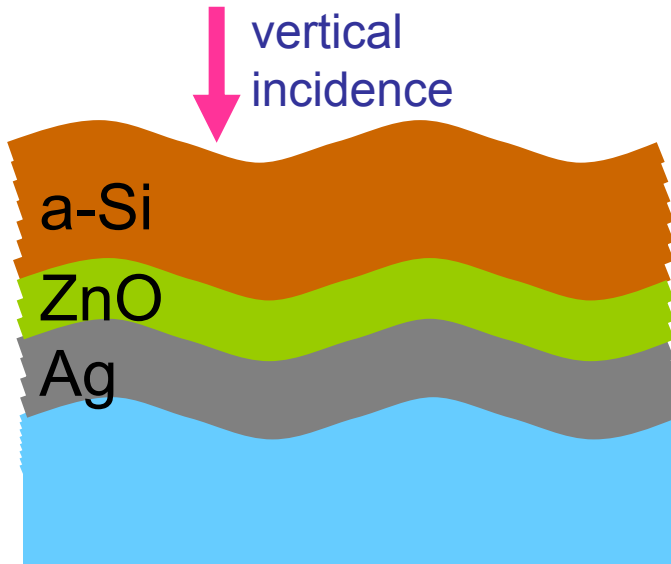
Sainju et.al.
Proc. 4th World PVSEC
Hawaii, (2006)

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

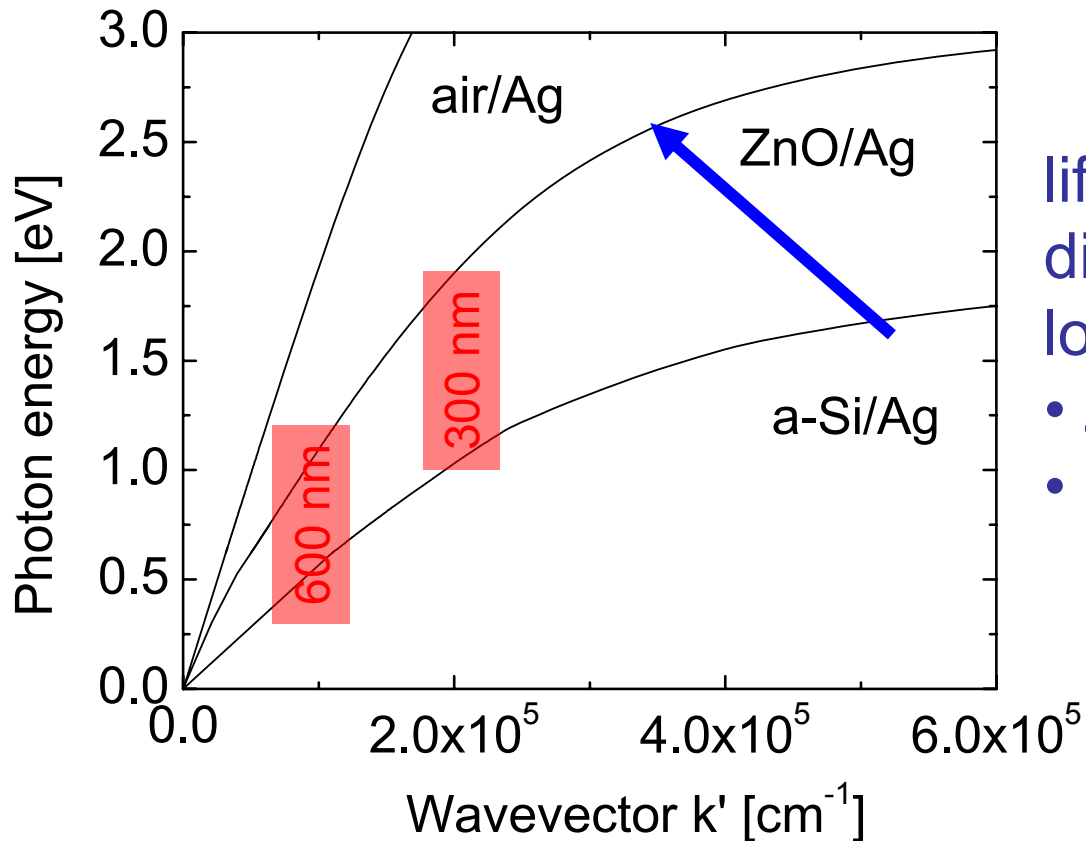
With ZnO:

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

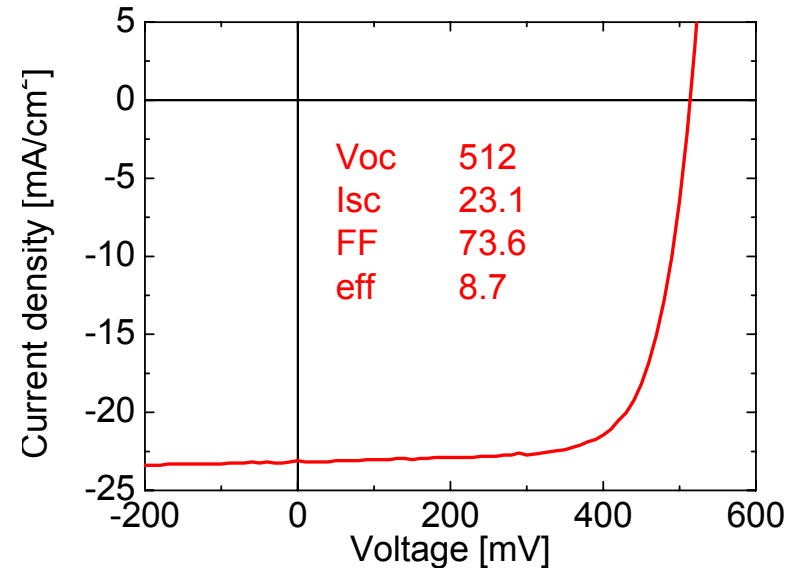
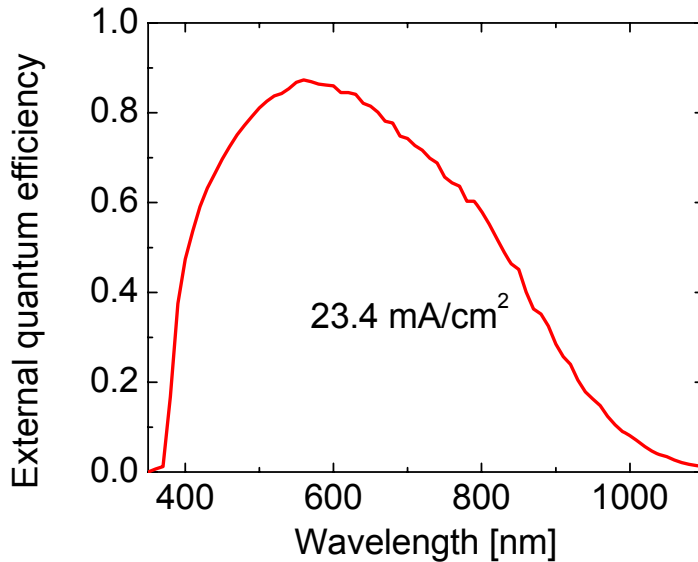
Current enhancement

- 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

μ c-Si solar cells on 2D grating



>23 mA/cm² in 1.2 μ m thick i-layer

8.7% efficiency, fully flexible on low cost plastic substrate

Acknowledgements:

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

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Metals and dielectrics

