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IEK5 - Photovoltaics

Nanophotonic Light Management for Solar Cells – Fundamentals, Limitations and Opportunities

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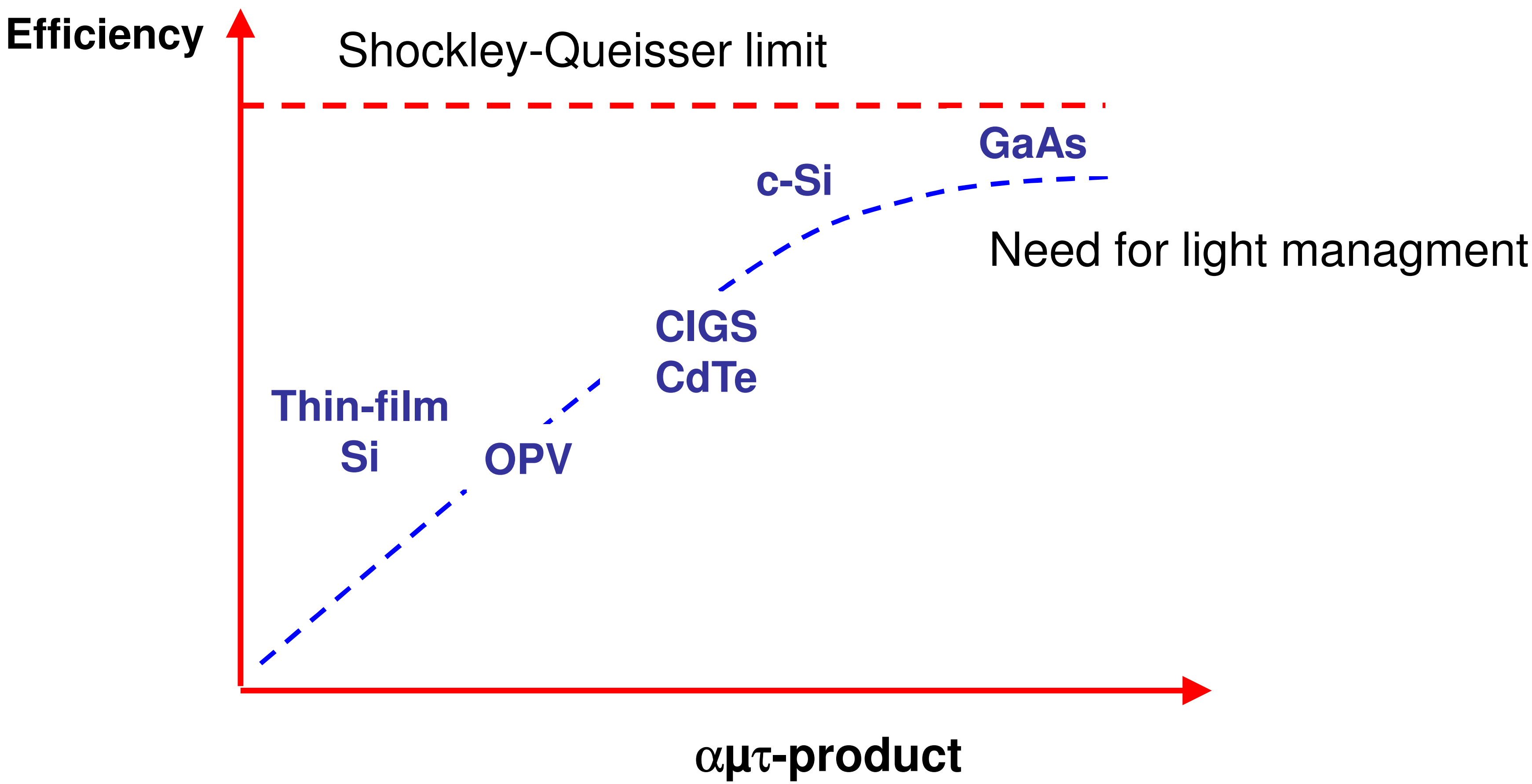
Nanophotonic Light Management for Solar Cells – Fundamentals, Limitations and Opportunities

Outline

1. Fundamentals
2. Limitations
3. Opportunities

There is no deal with SQ (w/o changing basic assumptions)

There are materials requirements (μ,τ,α) to come close to SQ



J. Mattheis, J. Werner, UR, Phys. Rev. B (2008)

Optics for photovoltaic energy conversion

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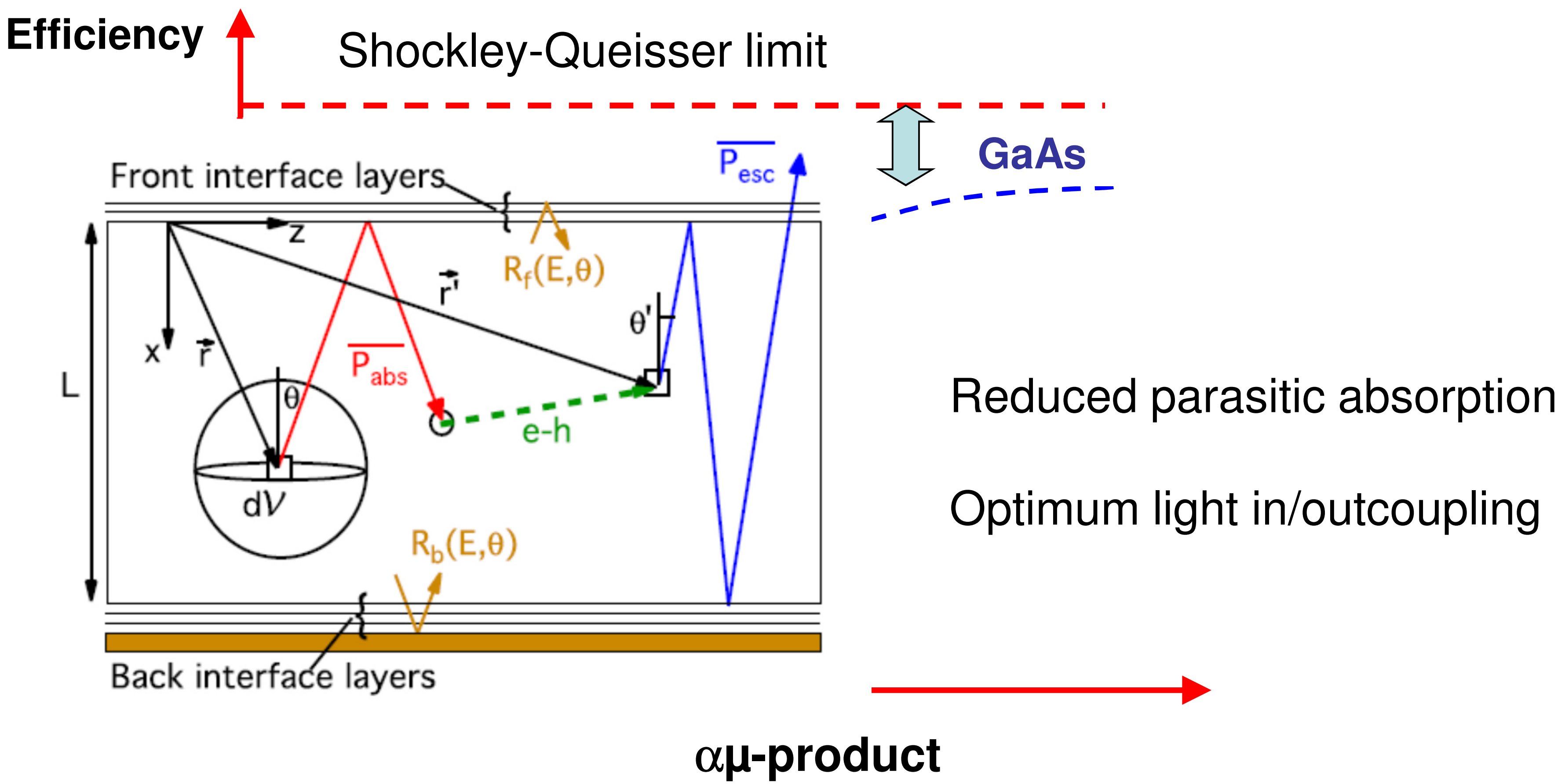
There are also optical requirements close to SQ !



M. A. Steiner et al., J. Appl. Phys. (2013)

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Limitations:

Thermodynamics of light trapping

Entropy generation

$$V_{OC} = V_{OC}^{rad} + \frac{kT}{q}\log\left(EQE_{LED}\right)$$

external

R. T. Ross, J Chem Phys **46,** 4590 (1967).
G. Smestad and H. Ries, Sol Energ Mat Sol C **25,** 51 (1992).
U. Rau, Phys Rev B **76,** 085303 (2007).

Entropy generation

$$V_{OC} = V_{OC}^{rad} + \frac{kT}{q}\log\left(EQE_{LED}\right)$$

external

3) emission /reabsorption

1) photon cooling

2) étendue expansion

4) non-rad. recombination

internal

$$qV_{oc} = kT\ln\left(\frac{\int A\phi_{sun}dE}{\int A\phi_{bb}dE}\times\frac{\varepsilon_{in}}{\varepsilon_{out}}\times\frac{\varepsilon_{out}\int A\phi_{bb}dE}{S_{cell}w4n^2\pi\int\alpha\phi_{bb}dE}\times\frac{QE}{1-QE+(1-p_r)QE}\right)$$

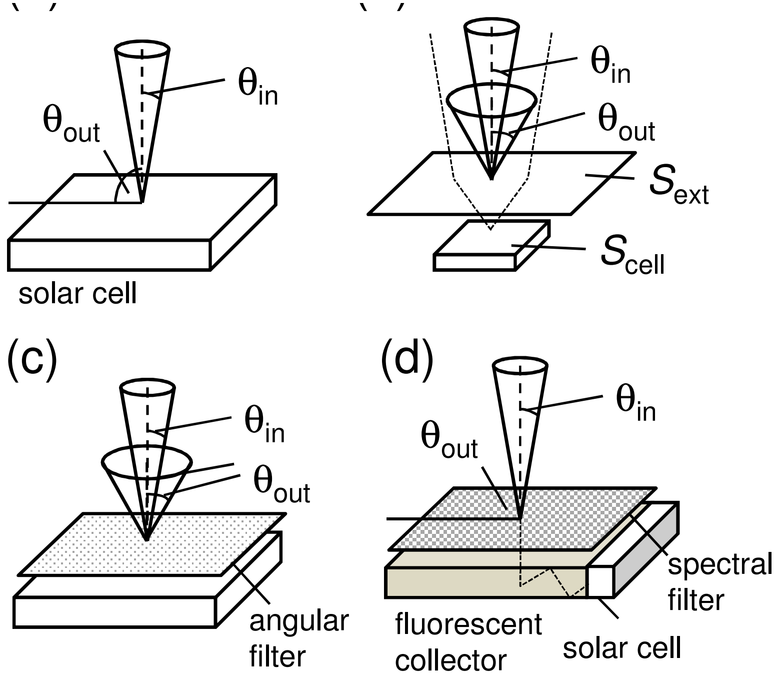
photon recycling

UR and T. Kirchartz, Nature Mat. (2014),

UR, U. W. Paetzold, T. Kirchartz, Phys. Rev. B (2014)

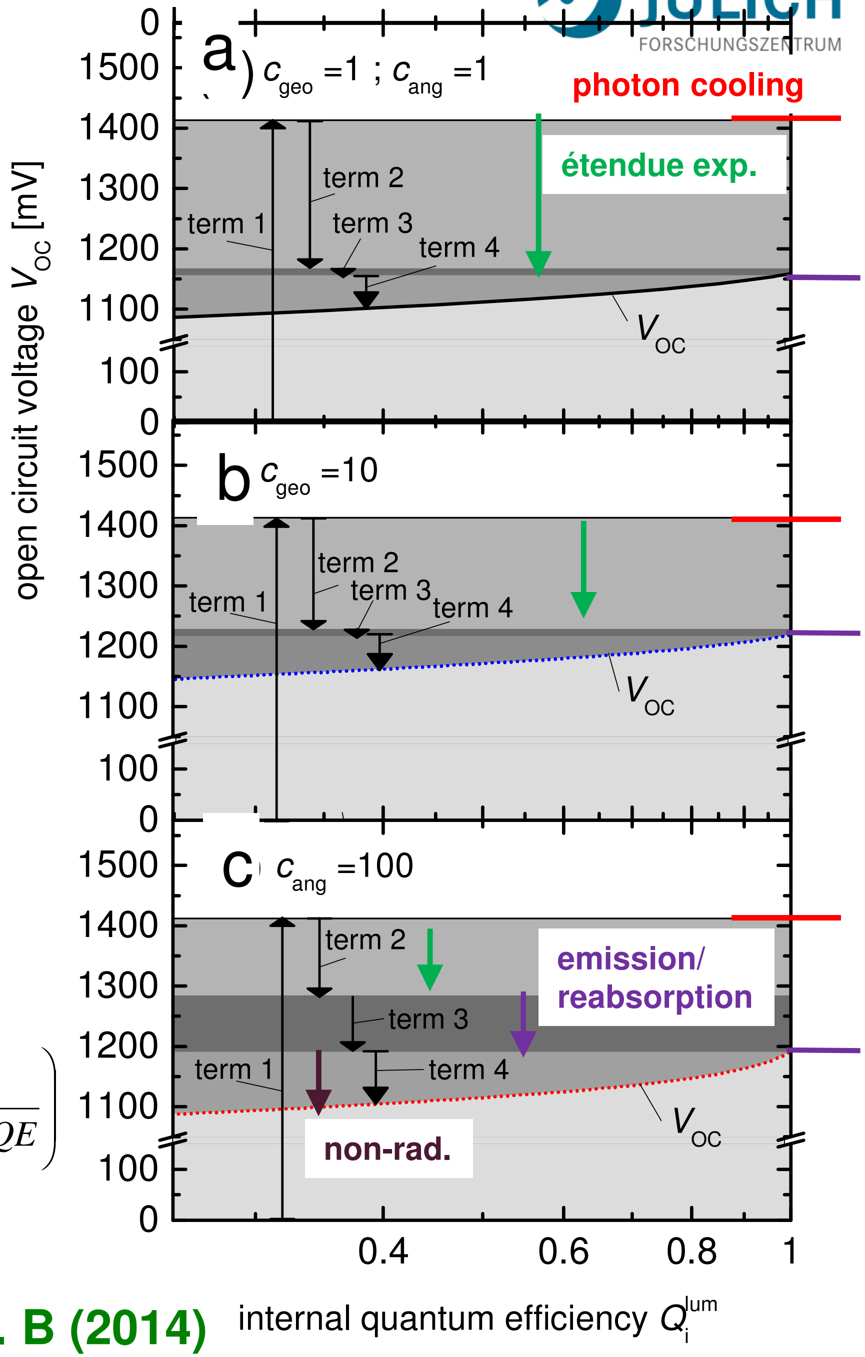
Prototypical optical settings

a) normal cell   b) concentrator



c) angular restriction   d) fluorescent concentrator

$$qV_{oc} = kT \ln\left(\frac{\int A\phi_{sun} dE}{\int A\phi_{bb} dE} \times \frac{\varepsilon_{in}}{\varepsilon_{out}} \times \frac{\varepsilon_{out} \int A\phi_{bb} dE}{S_{cell} w 4n^2 \pi \int \alpha\phi_{bb} dE} \times \frac{QE}{1 - QE + (1 - p_r) QE} \right)$$



UR, U. W. Paetzold, T. Kirchartz, Phys. Rev. B (2014)

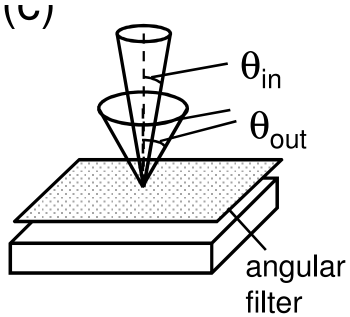
Opportunities:

What does nanophotonics add?

Directional selectivity

top

Concept:
M.A. Green (1987)
J. C. Miñano et al., Appl. Optics (1992),
V. Badescu, J. Phys. D (2006)



up

A. Braun et al., En. & Env. Sci. (2013)
'External Photon Recycling'

E. D. Kosten et al., Light Sci. Appl. (2013)
'Photon Recycling'

M. Peters et al., SEMSC (2010)
'Combination with concentration'

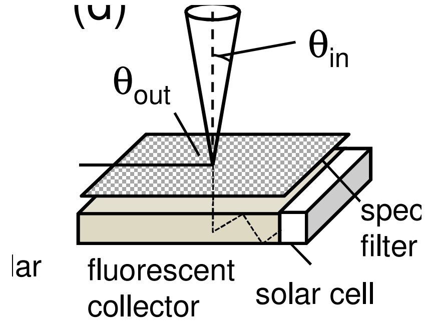
C. Ulbrich et al., Opt. Expr. (2010)
'Improved light trapping'

C. Ulbrich et al., PSSA (2008)
'Mixed balance w/o tracking'

down

bottom

Fluorescent collectors



<u>Concept:</u>
Götzberger et al., Appl. Phys. (1977)
E. Yablonovitch et al., JOSA (1982)
G. Smestat et al., SEMSC (1990)

UR et al., APL (2005), T. Markvart, JAP (2006)
'Fluco and SQ limit, spectral filtering'

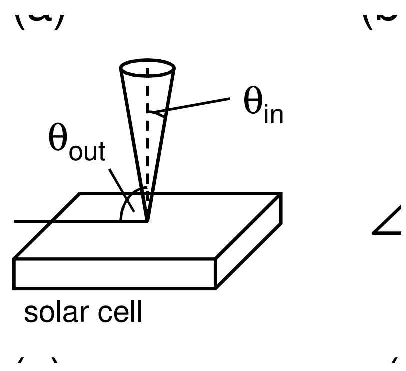
J. C. Goldschmidt et al., PSSA (2008),
SEMSC (2009), JAP (2009)
'Experimental proof of concept'

J. H. Sloff et al., PSS-RRL (2008)
'η > 7 %'

R. Reisfeld et al., (1980-)
many papers

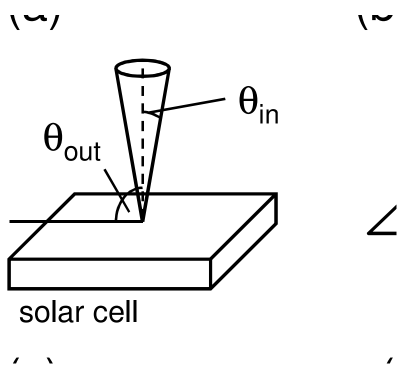
V. Wittwer et al., J. Lum. (1981);
SEMSC (1984)
'Loss analysis'

Light trapping (single junction)



<u>Concept:</u>
Redfield, APL (1974)
E. Yablonovitch et al., JOSA (1982)
M. A. Green, PIP (2002)

Plasmonic light trapping



<u>Concept:</u>
Redfield, APL (1974)
E. Yablonovitch et al., JOSA (1982)
M. A. Green, PIP (2002)

H.A. Atwater, A. Polman, Nat. Mat. (2010)

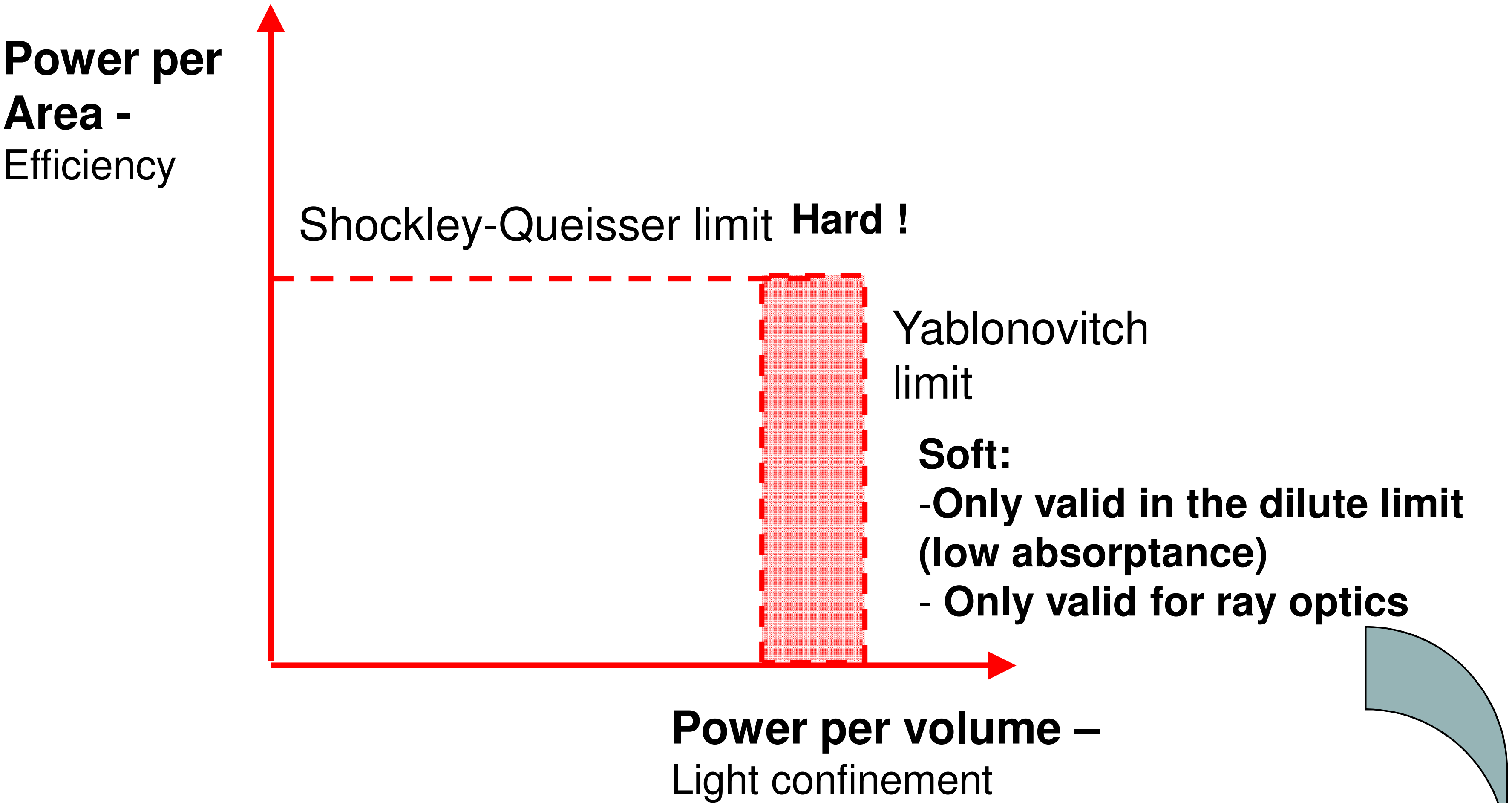
S. Pillai et al. JAP(2007)
K. Catchpole et al., JAP (2007);
Opt. Exp. (2008),…

U. Paetzold et al., APL (2014)
'Improvement of real device structure'

V. E. Ferry et al., Nano Lett. (2008);
….

J. Springer et al., SEMSC (2004)
'Absorption losses due to surface plasmons'

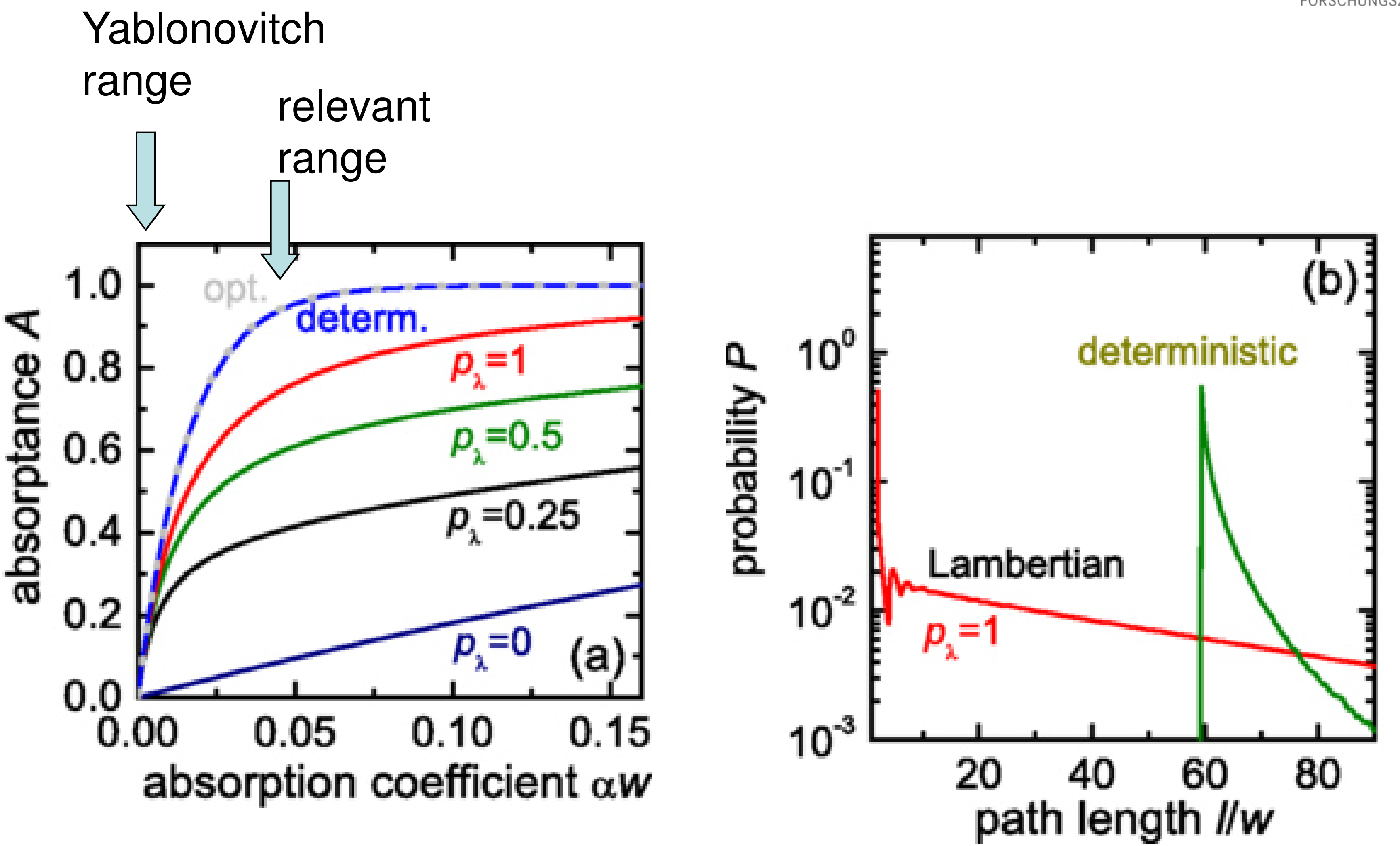
Ergodic limit for light trapping



Yu, Raman, Fan, Opt. Exp. (2010) **'2D Gratings beyond Yablonovitch !'**

Krostrup et al., Nat. Photon. (2013) **'Nanowires beyond SQ ?'**

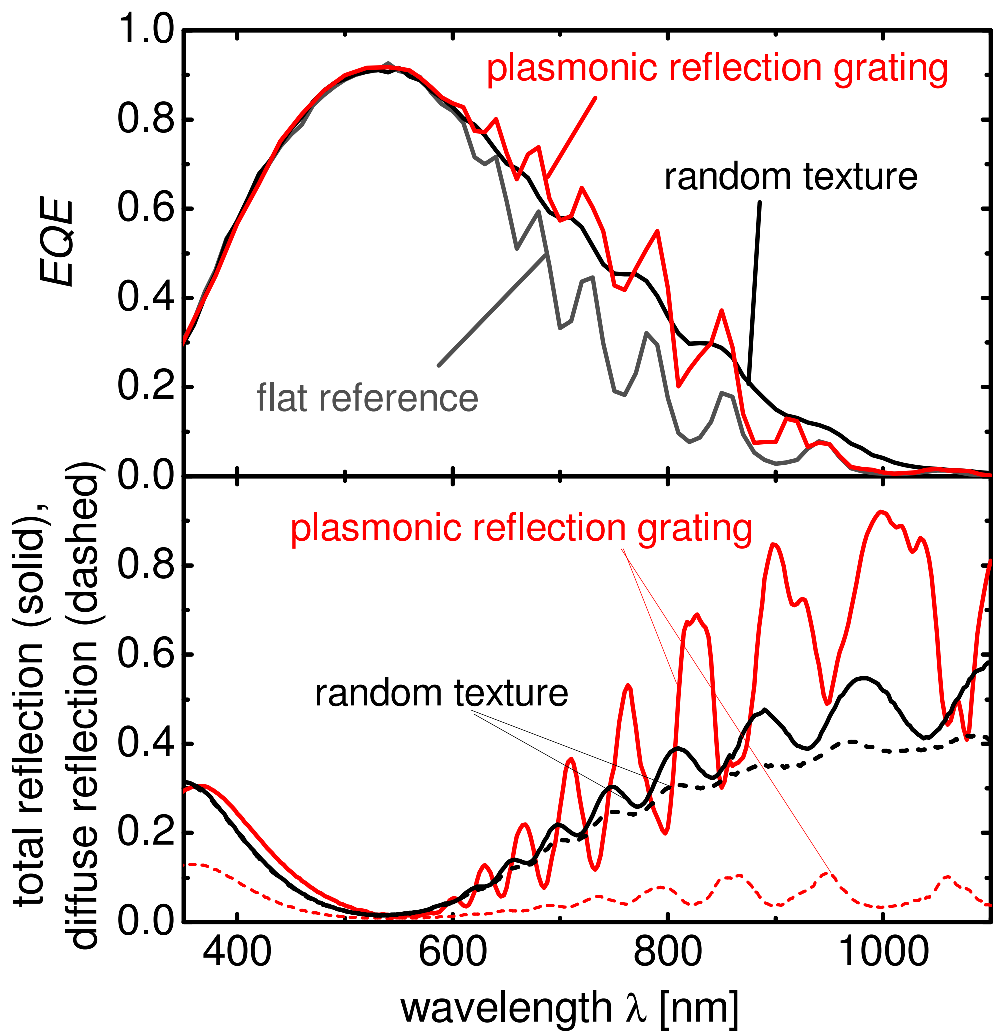
Periodic vs. Random light trapping (geometric)

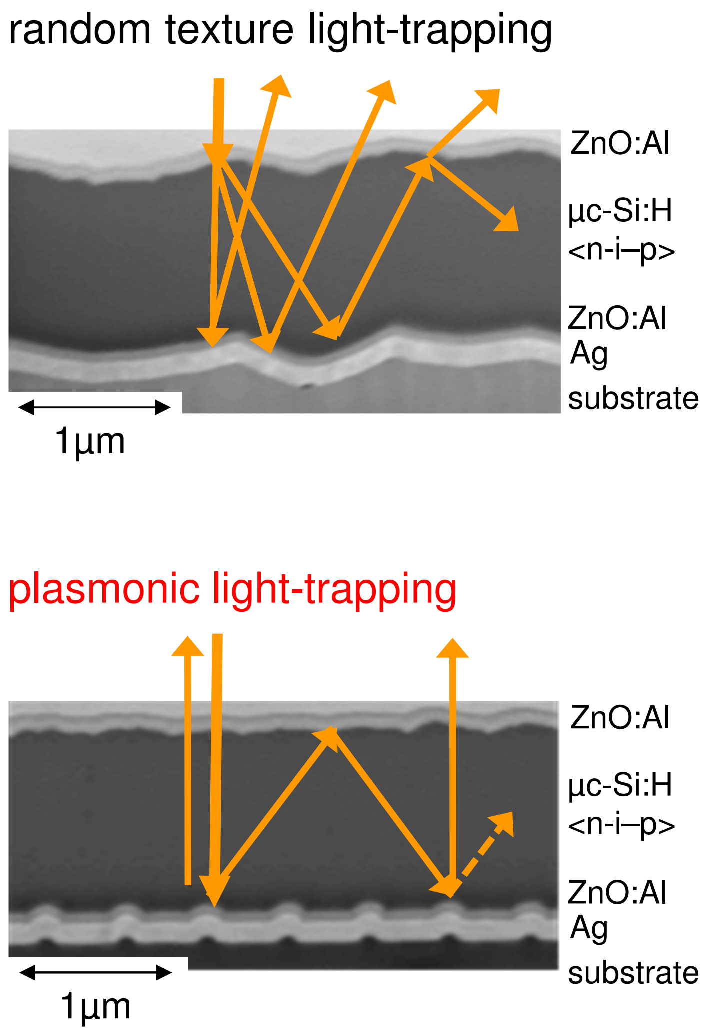


1) Relevant wavelength range is where absorptance is almost unity
2) Narrow path length distribution preferred over wide ones !
→ Deterministic beats random

UR, U. W. Paetzold, T. Kirchartz, Phys. Rev. B (2014)

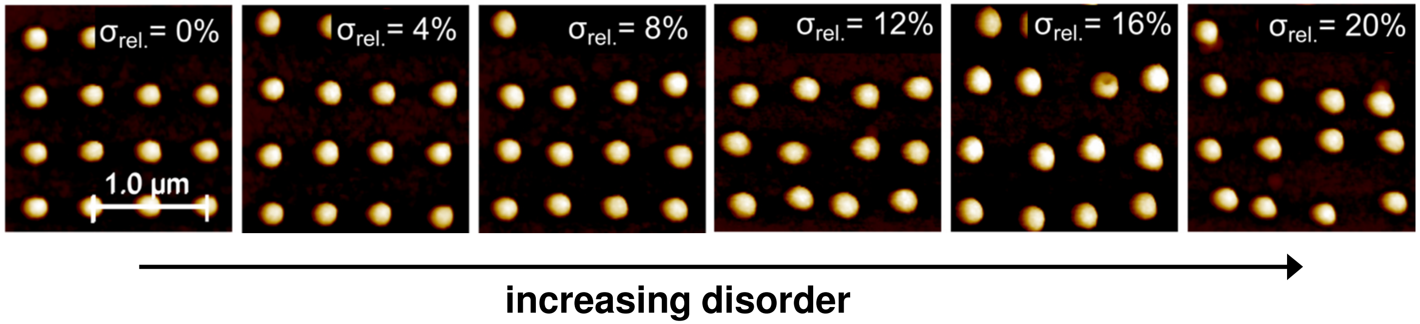
Periodic Plasmonic Light Trapping

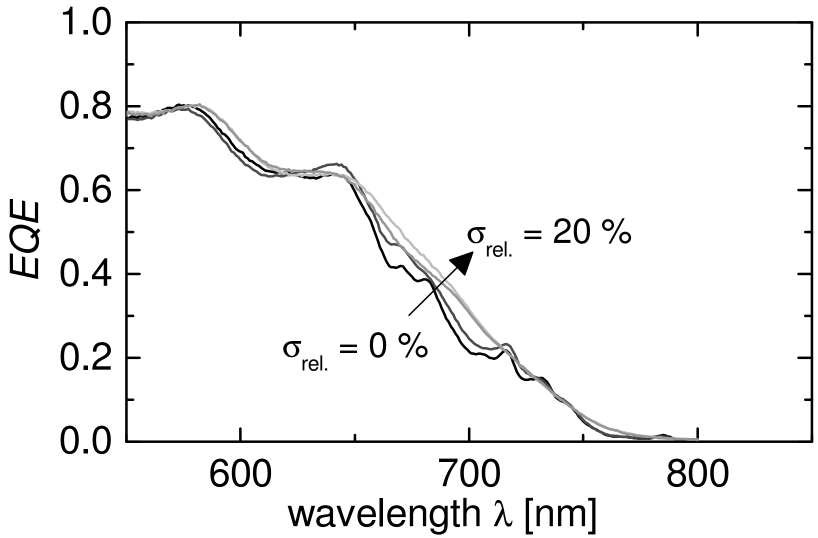


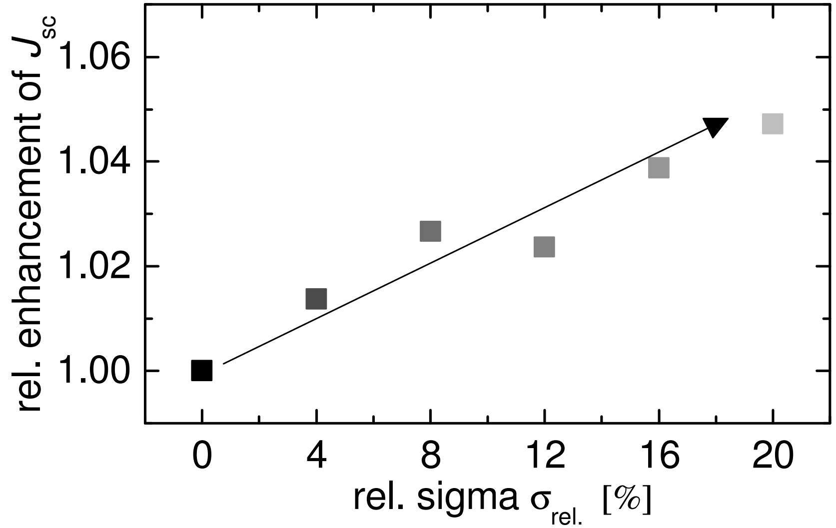


U. W. Paetzold et al. *APL* 99, 181105 (2011)

Controlled Disorder in Periodic Nanotextures







- ► **Resonant light-coupling to leaky waveguide modes disappears.**
- ► **Light trapping improves with increasing disorder.**

U. W. Paetzold et al. *APL* 104, 131102 (2014)
‚Disorder improves nanophotonic light trapping in thin-film solar cells'

Conclusions

1. Every solar cell technology needs light management (… sooner or later)
2. There is no deal with SQ (but possibly with Yablonovitch)
3. Despite of many claims, light trapping revolution has not yet materialized (…. but you never know)
4. Top-down approaches are important as proof of concepts and for the examination of the potential (optimistic picture)
5. Bottom-up approaches are important for steady, incremental improvements (realistic picture)
6. Critical analysis is required for the understanding of fundamental limits, loss/gain balance, economic feasibility