Low cost, high efficiency solar cells: a review on their challenges and potentialities

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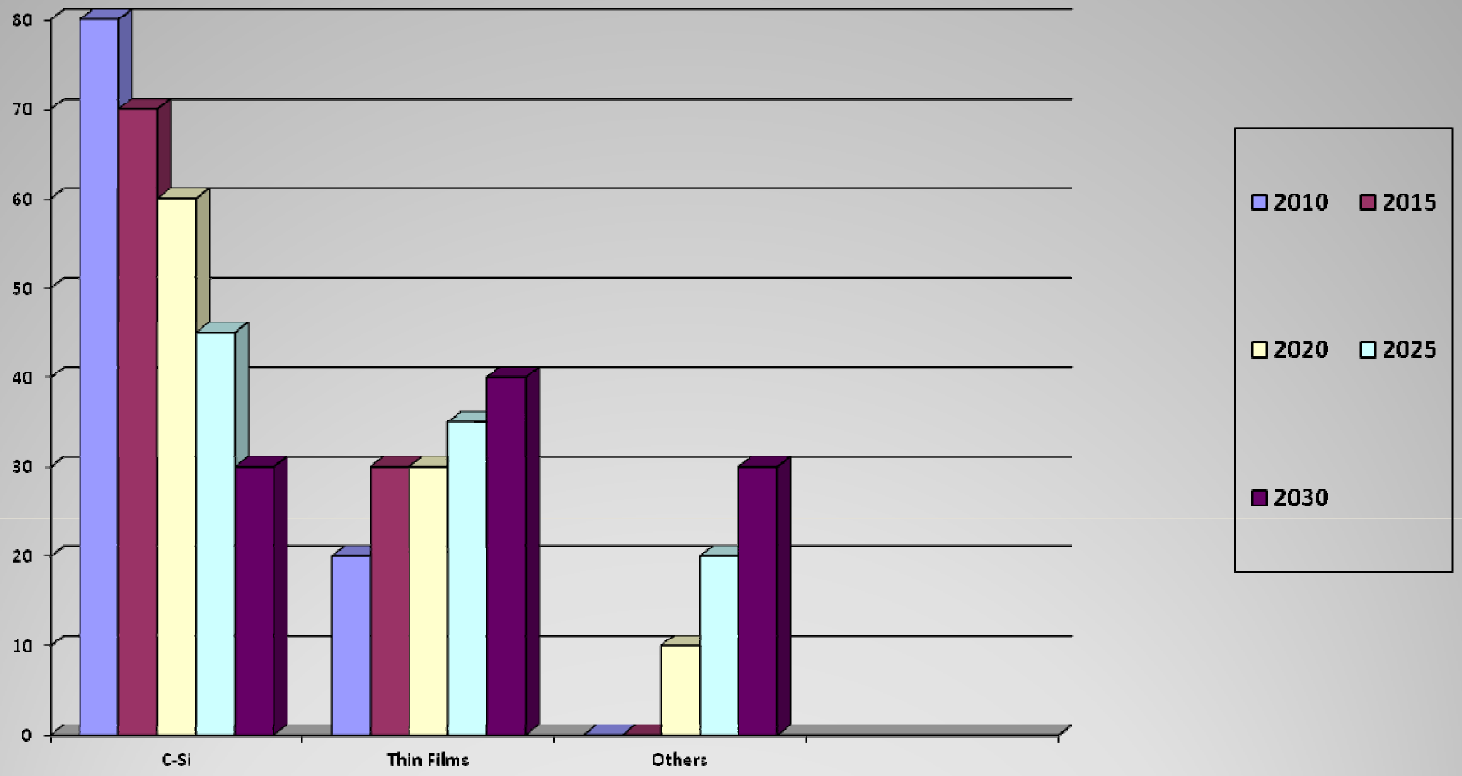
- Current trends in energy supply and use are economically, environmentally and socially unsustainable. Without decisive actions, energy-related emissions of CO_2 will more than double by 2050 and increased oil and gas demand will weaken the security of supplies and give rise to very dangerous local conflicts.

- Fukushima disaster demonstrated the need of better reactor management procedures, extreme security precautions and safer storage of radioactive subproducts and used fuel bars.

- Photovoltaics is a very safe source of energy, free of direct CO_2 emissions. In the last decade the annual growth rate of PV was ~ 40%, with a cumulative installed capacity of 23 GWp, in 2010 and more than 21 GW in the whole word in 2011.

  Its growth brought to a revolutionary transformation of the PV industry, in all its segments (material, cells, modules, systems)

Introduction



Crystalline silicon (c-Si) modules shared the 85% of the global annual market in 2010 with **module** efficiencies ranging from 12 to >19 %.

Solar cell market: materials

Manufacturer	Module efficiency (%)	Module type	Comments
Sunpower	19,6	E19/320	n-type, single crystal substrate
Auo solar	19,5	PM318B800	Single crystal substrate
Sanyo Electric	19,0	HIT-N240SE10	n-type, single crystal substrate
China Sunergy (CSUN)	19,0	Quasar 260	Single crystal substrate
Crown Ren. Energies	18,3	Summit 100LM	Single crystal substrate
JaSolar	16,84	JAM5(L) 72-215SI	Single crystal substrate
Trina Solar	16,4	TSM210DC80	Single crystal substrate
Jawei	16,3	JW-S135	Single crystal substrate
CNPV Solar	16,2	CNPV-135	Multicrystalline Si substrate
Yingly Solar	16,2	Panda265 Series	n-type, single crystal substrate

World's highest commercial modules efficiency

- Single junction commercial cells 17 ≤ η(%) ≤ 25 (Sunpower 24.2% n-type), Imec 23,4% FZ n-type) already close to the Shockley-Queisser limit (31%)
- *in comparison with*
- Compound semiconductor triple junction 40% (Sharp) *too expensive, only for concentration*
- Single junction compound semiconductor thin film cells (CdTe, CIGS) 8≤η ≤17,4 %(CIGS-Q-cell)
- Micromorph Si (a-Si , nc-Si) (Sharp 13%)
- Dye sensitized organic cells max 6%

Silicon solar cells vs others

BOS COST

BOS costs in 2010 was US$ 1.43 per watt, or 44.8% of a standard, utility-scale crystalline silicon (c-Si) solar plant. With the solar PV module prices continue to drop, in 2012 the BOS cost for a similar plant will increase up to 50.6% (*) or even more

CELL COST

The efficiency sensitivity for advanced silicon cells is more than ten times the feedstock cost sensitivity, the slicing pitch sensitivity is 3 times the feedstock cost sensitivity, and the ingot-growth fraction sensitivity is 1.5–2 times the feedstock cost sensitivity (**)

Therefore The conversion efficiency is the key factor which drives the economics of photovoltaics, and this depends mainly on the material nature and on the cell fabrication processes.

(*)M. Aboudi,, *Solar PV Balance of System (BOS): Technologies and Markets* PV tech 30 June 2011 (**) G. delCoso, C.del Canĩzo, W.C.Sinke *The impact of silicon feedstock on the PV module cost* Solar Energy Materials & Solar Cells **94** (2010) 345–349

Economics of a c-Si PV plant

Crystalline silicon

- Semiconductor silicon is the purest syntetic material today available. It is produced in more than 250.000 tons/year amount, with a cumulative annual production growth rate of 38% in a multibillion (projection for 2012, 253 Billion USS$) market

  Acceptors (B,Ga) concentration ≤1 ppba; Donors (P,As,Sb) ≤1 ppba; Carbon ≤0,3 (ppma);

  Total transition metal s≤10 (ppba): Total alkali and alkali earths metals ≤10 (ppba)

- Its key application is still microelectronics but the main stream today is for photovoltaics
- It is commercially available as polycrystalline silicon, single crystal ingots, single crystal wafers, multicrystalline ingots and wafers, (ribbon) and thin films

high purity→ highest PV efficiency
integrated process from MG-Si to Poli-Si

38% single stage yield with TCS→ recycling
high energy consumption(min 50KWh/Kg)
high cost of a poli-Si plant (2 Billion$/10Kton)
spills of TCS → environmental damage

Polycrystalline silicon from TCS as feedstock for PV applications: advantages and drawbacks

Poli-Si from monosilane

Lower process T (800°C vs 1050-1100°C)
~ single step, 100% yield → no recycling
forecast of a lower energy consumption

Solar grade silicon from UMG-Si (?)

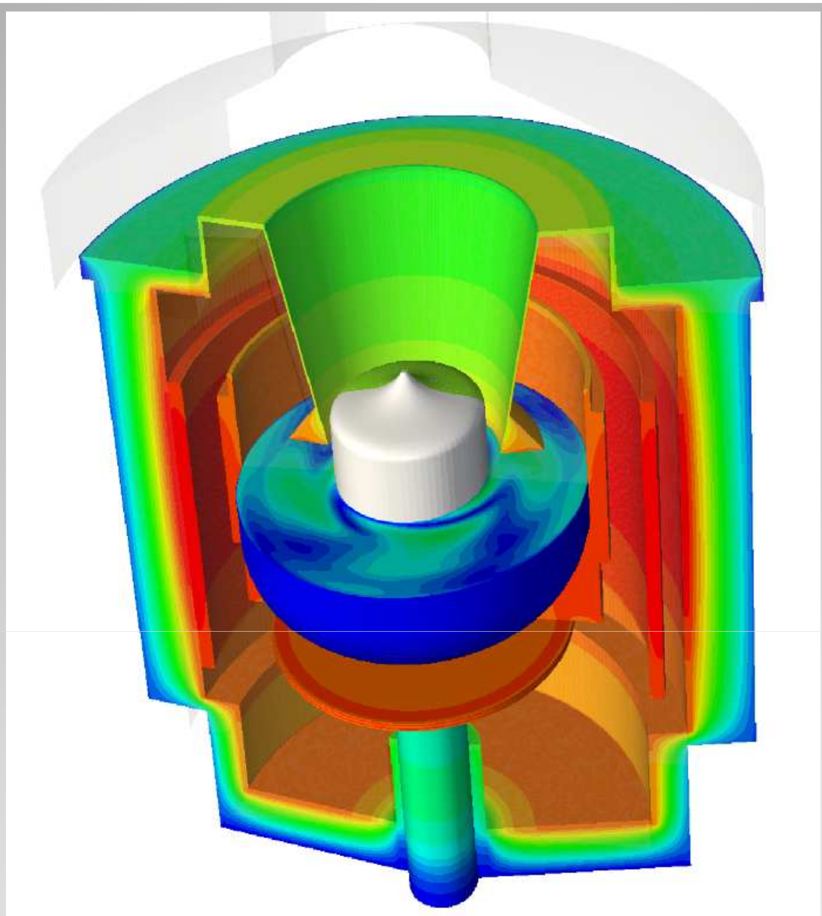
Alternatives?

⇧ Large ingots (up to 600 Kg, 400mmØ)
High purity, absence of crystal defects

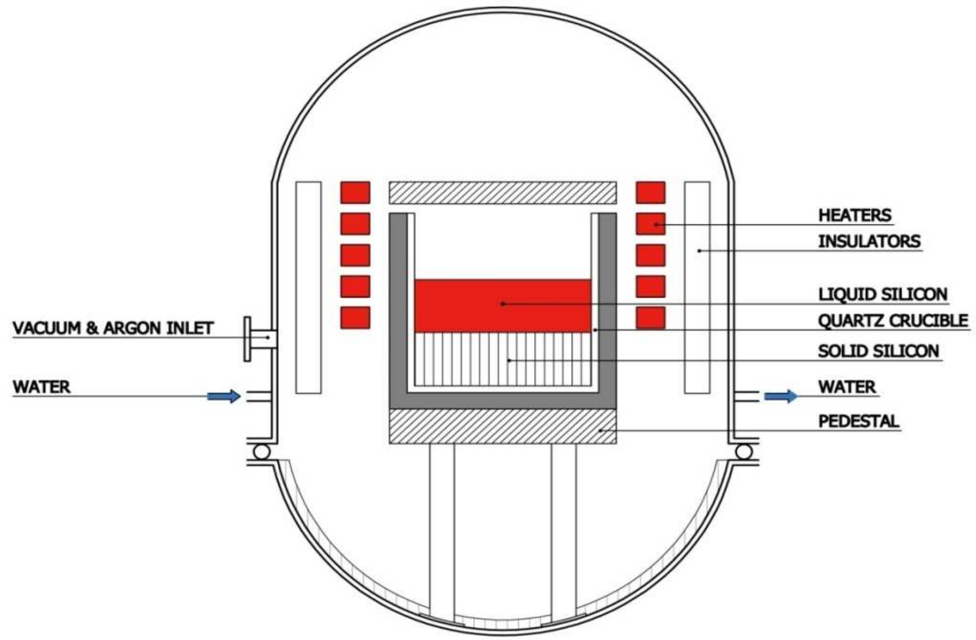
⇩ Low production rate (2Kg/h)
High energy imput (>30 KWh/Kg)
Carbon contamination

Also crystal growth processes deserve attention: CZ growth

Enlarge the diameter: larger & heavvier CZ ingots



Improve the energetics:manipulation of the hot zone

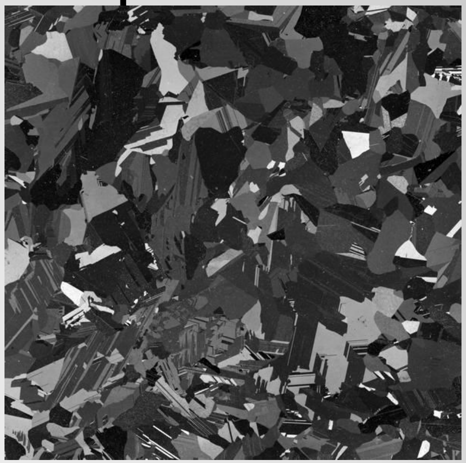


Multicrystalline silicon as the alternative

Advanced mc-Si DSSi furnace

Larger ingots (up to 800Kg)
Higher production rate (>15 Kg/h)
Lower energy input (~ 10 KWh/Kg)

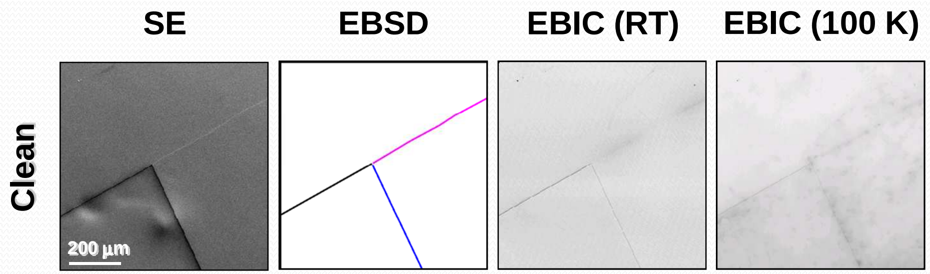
Impurity contamination (crucible & coating)
Presence of GB and dislocations→lower L_d
Lower values of K_{segr} →lower purification yield



mc-Si vs Cz-Si

Effect of GB in clean mc-Si

LA-GBs: Clean state



Fe conc. (cm^{-3})

~10^{12}

All LA-GBs have no EBIC contrast !

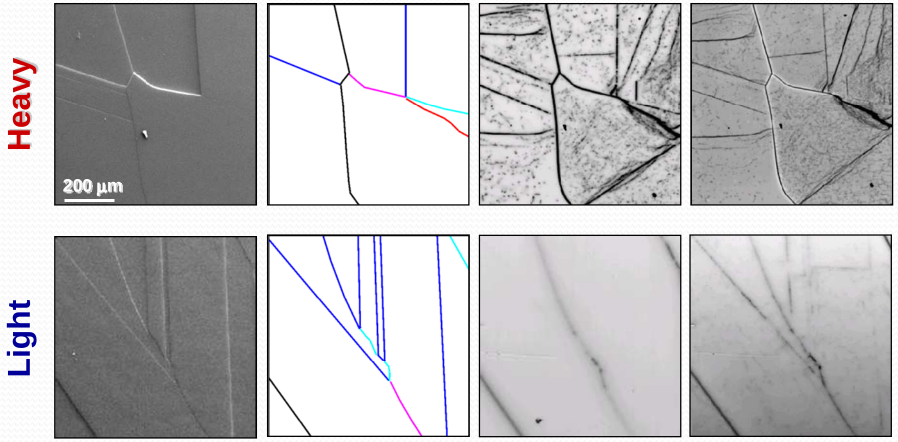
Not electrically active (in intrinsic)

Σ3
Σ9
Σ27
R

11

Effect of GBs in Fe-contaminated mc-silicon

LA-GBs: Fe contaminated



Contaminated with Fe,

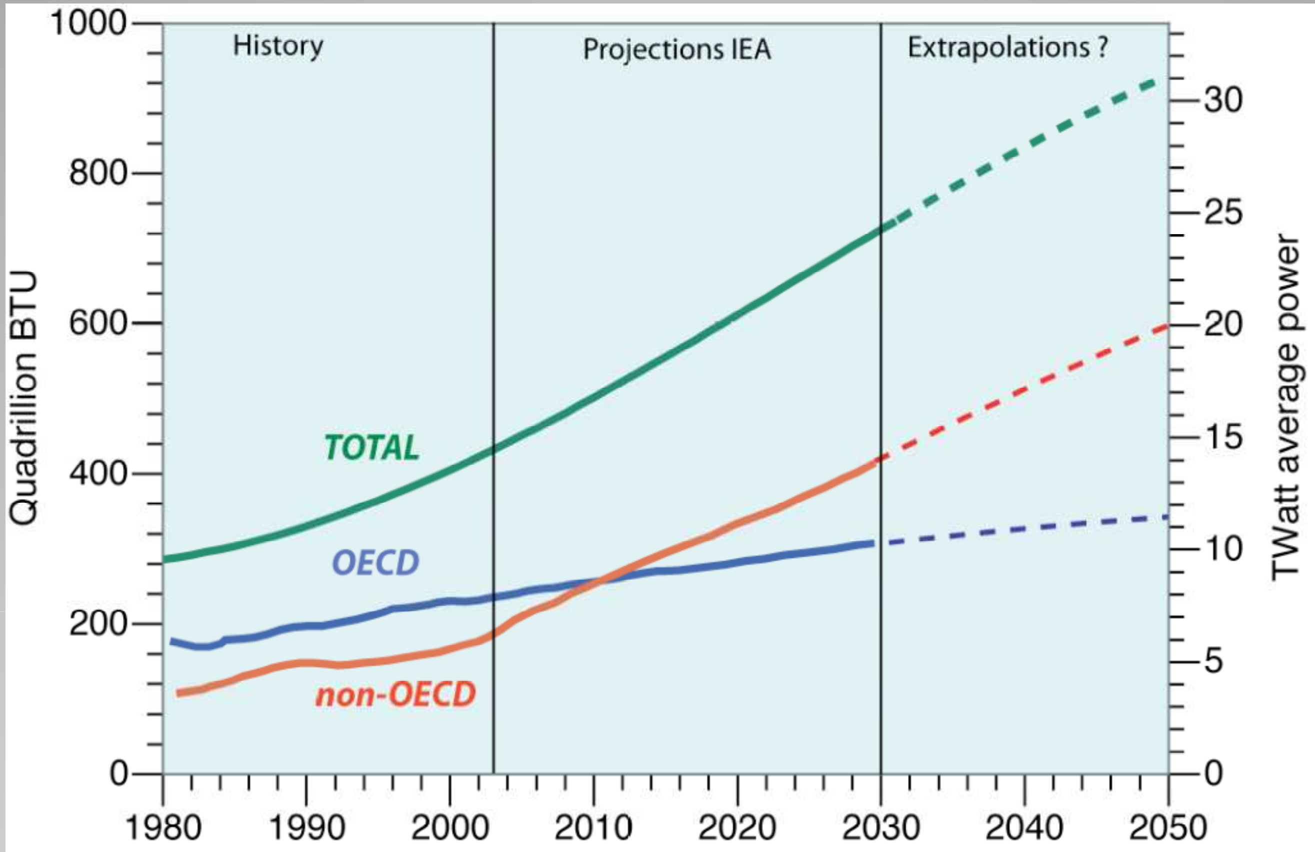
Became visible depending on GB character

12

- Lower efficiency of mc-Si due to recombination at GB and dislocations
- Lower purification efficiency of DSS process

- Defect engineering procedures
- Seeding the growth (monocast)
- Reduce the thickness of Cz Si wafers

Drawbacks of mc-Si and alternatives in view of use/achieve low cost Si wafers



BUT: could be poly-Si be the PV material for the next future?

Some figures

At $2g/W_p$ (full Si recycling, 100% crystal yield, module η=20%, wafer thickness 100μm)

the present poly plants supply is 233.000 tons/year. A cumulative production of 1 TWp (~0,2 TW_{eff}) will be achieved in 2020 (0,1% of total world's forcasted installed power in 2020) with 2 Million tons of crystalline Si.

NB:(Investment costs for a plant of 21.000tons/year ~4 Billion USS$ according Hemlock)

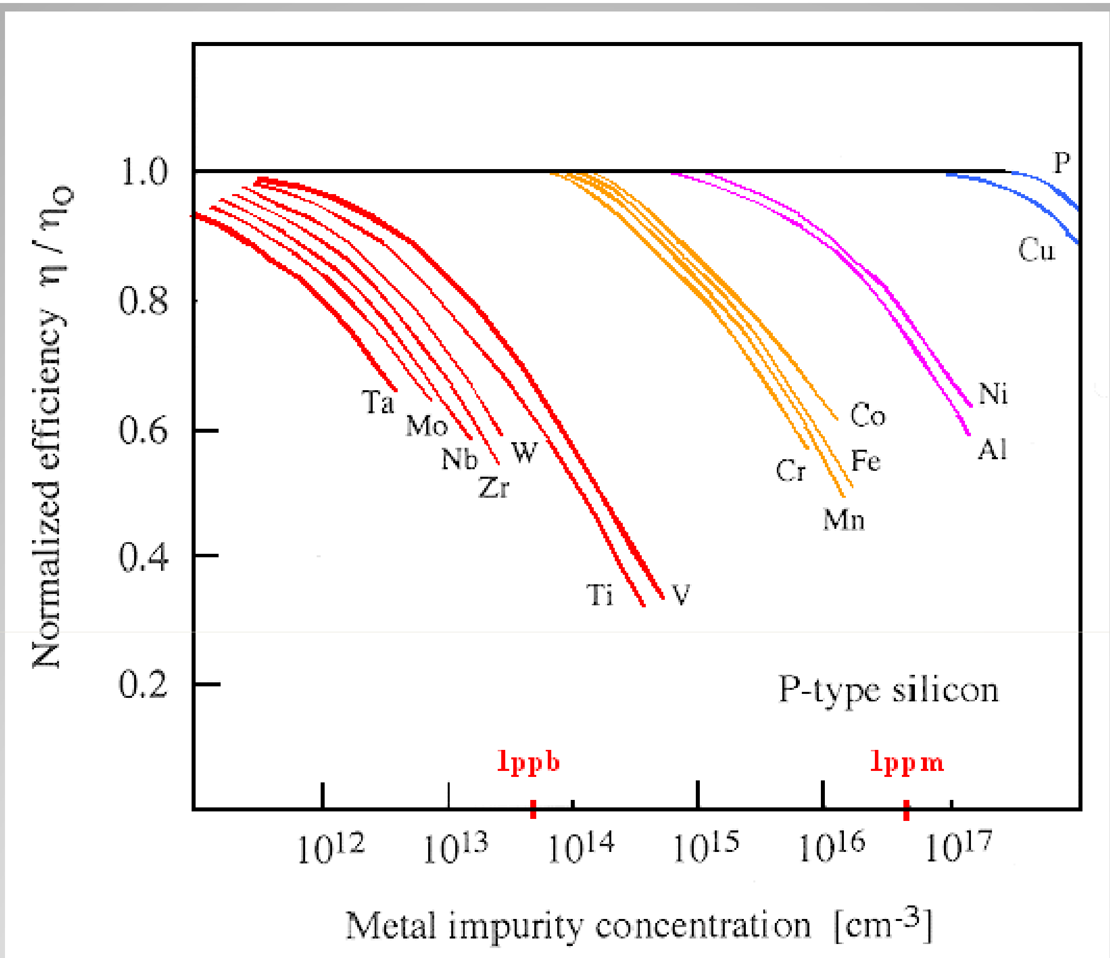
- To get the 10% of energy from PV plants, additional investment costs of 400 Billion USS$ *only for poly-Si* plants will be necessary

- With an increase of potential environmental damages from chlorinated vapours spills (the EG-Si chain is chlorine based)

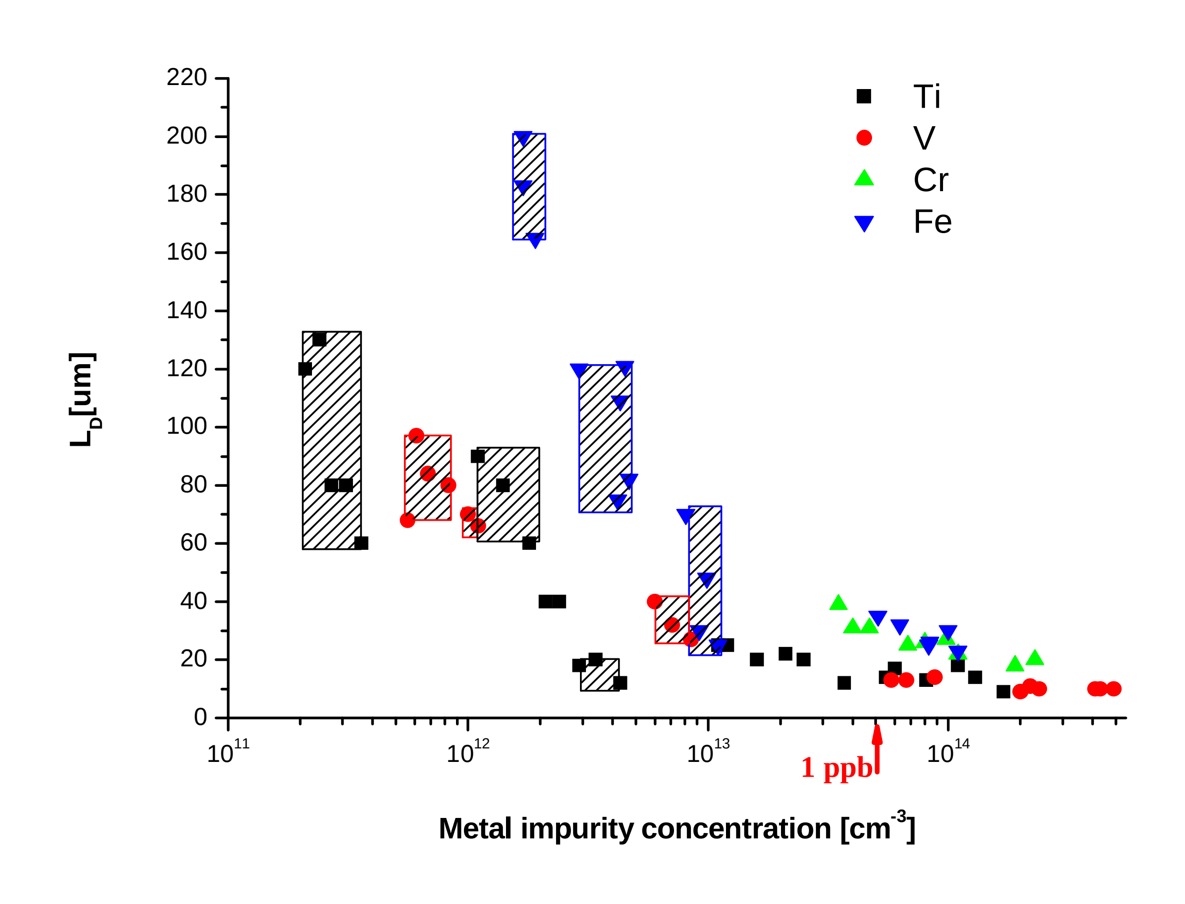
Some figures

- Recycling kerf losses (only partial solution)
- Solar silicon (impure,low cost silicon) vs EG silicon
- Thin film modules (less material,less cost)

Alternatives



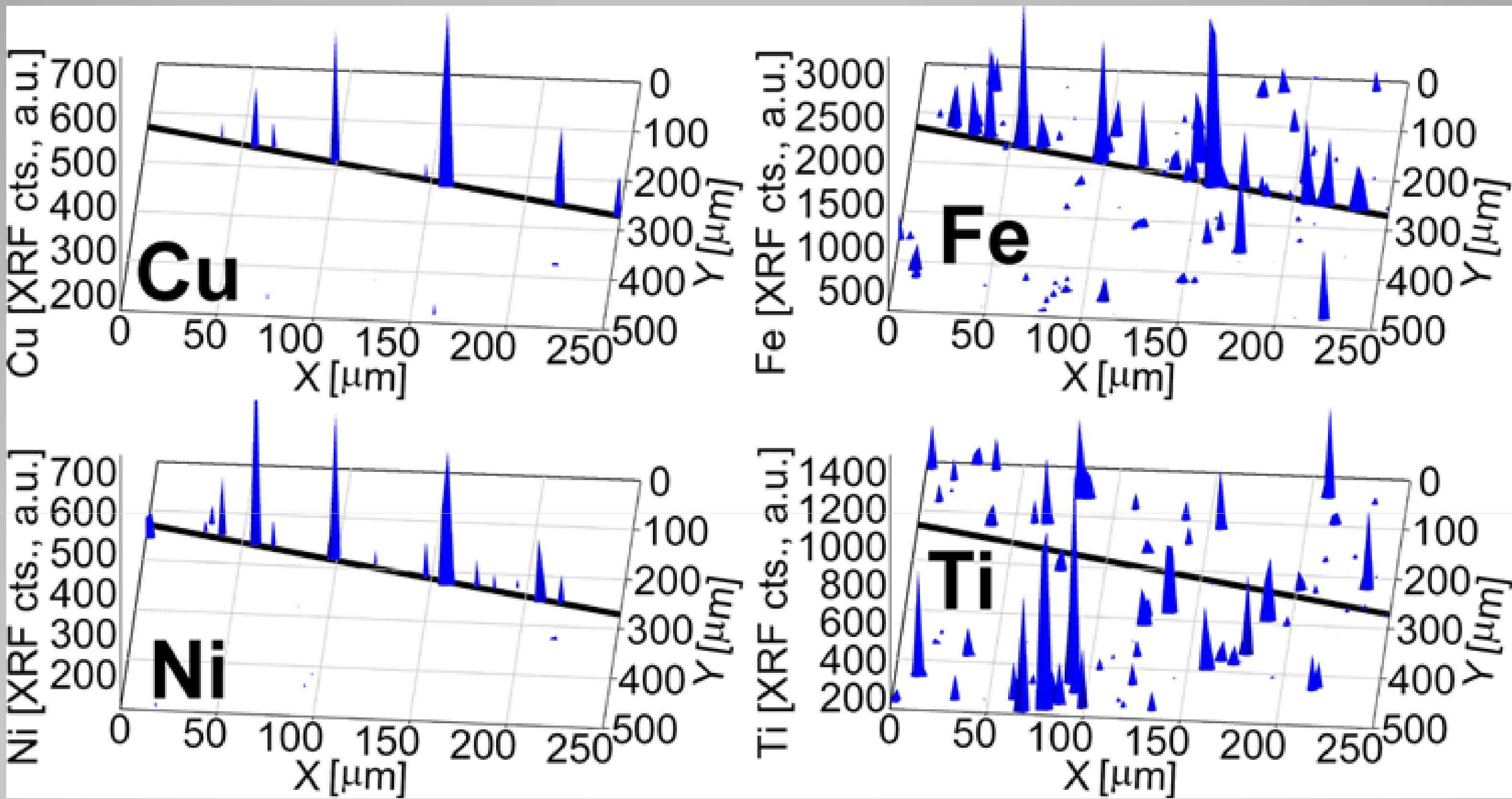
Solar silicon:effect of impurities in the cell



Solar silicon: Effect of impurities in the cell

Impurity	(Coletti) C_L ppma	Electrical activity α (%)	k_{eff}	(Riepe) $C_L$ppma
Cr	4,3	5,9	3.1 x 10^{-6}	1,2
Fe	5,5	0,11	1,5 10^{-5}	2,4
Ti	0,065	91	3,5 10^{-5}	
Ni	6,2			
Cu	3,5			1,8
Ge			0,32 (Riepe)	0,5 wt%

Limiting concentration of impurities in the feedstock



Distribution of impurities in mc-Si

- Pyro-and hydro-metallurgical processes (Elkem) → 100% UMG, mc-Si cells

  η =16%

  not sufficient for high efficiency, removal of dopants difficult
- Direct carboreduction from high grade silica and SiC(Solsilc)→ good for 50% UMG/EG silicon blend

Current results about UMG-Si

Area per kW ratio

$7m^2$ (mono c-Si, η 24,4%)

8,4 m^2 (mc-Si η 17,9%)

9,1m^2 (CIGS-Qcell 17,4%)

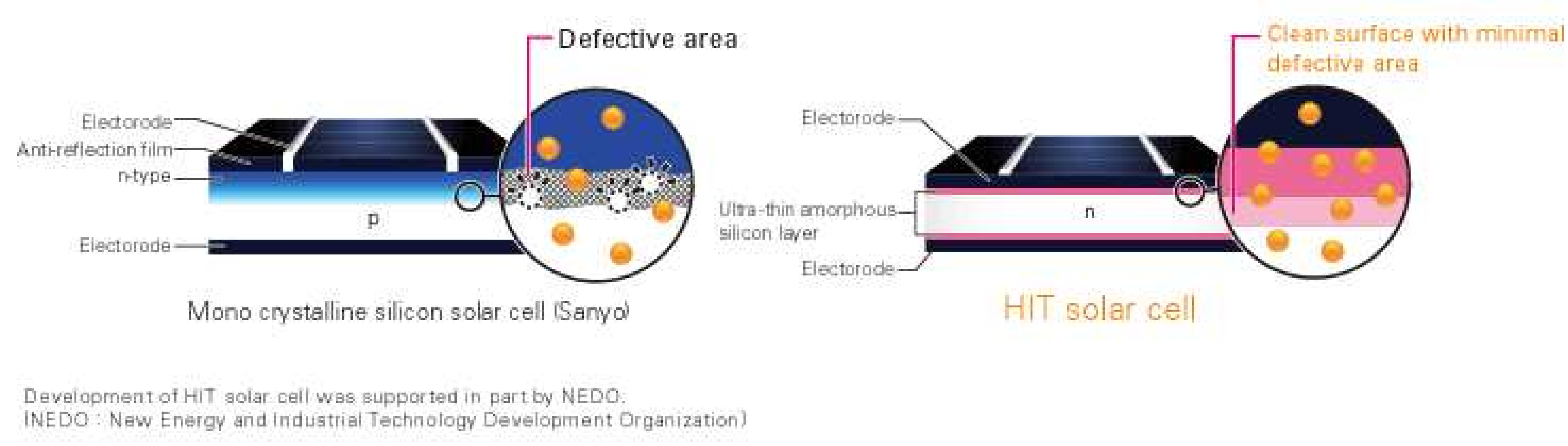
9,2 m^2 (CdTe 17,3%)

12m^2 (a-Si/nc-Si)

~15m^2 (a-Si)

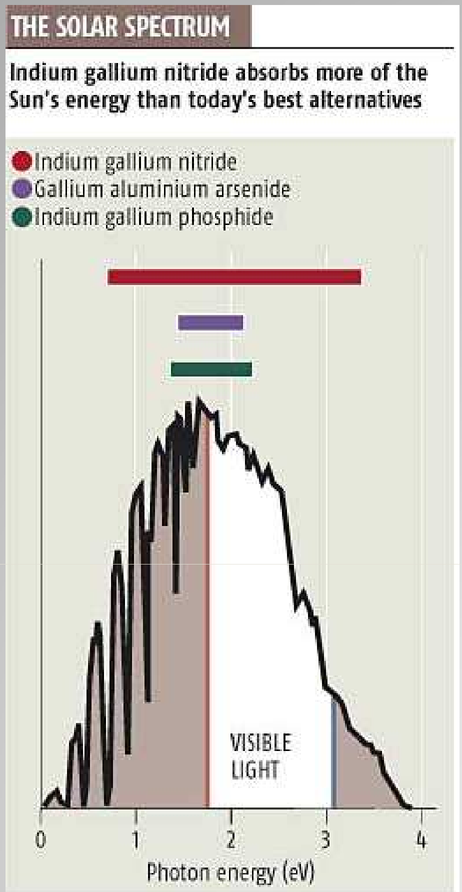
The BOS cost gives a huge advantage to c-Si

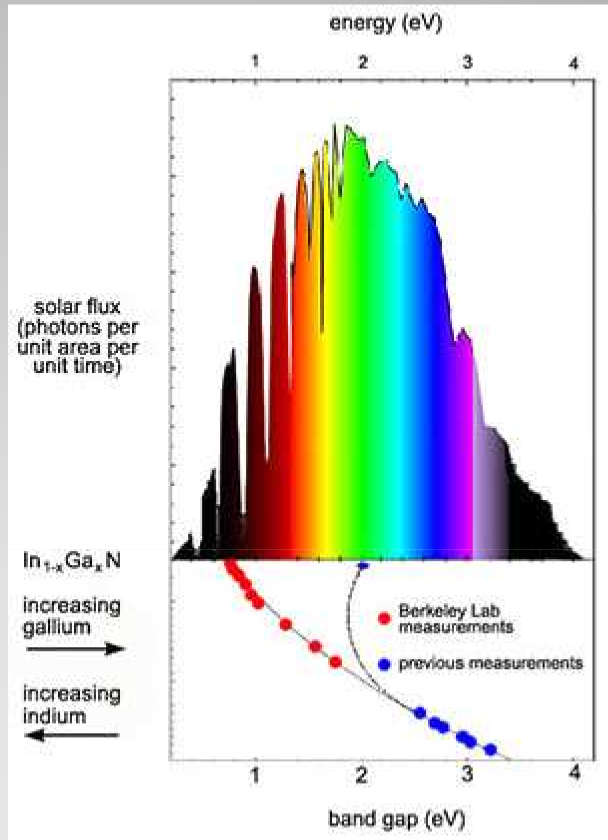
Thin film cells vs c-Si recent estimates (Nov 2011)



Typical configuration Me/ a-Si-H (p)/aSiH(i)/c-Si (n) / surface passivation: a-SiOx:H/BSF: μSi:H(n+)/Me
T CVD process 200°C $\eta > 24\%$

HIT cells:on the use of thin film CVD on c-Si substrates

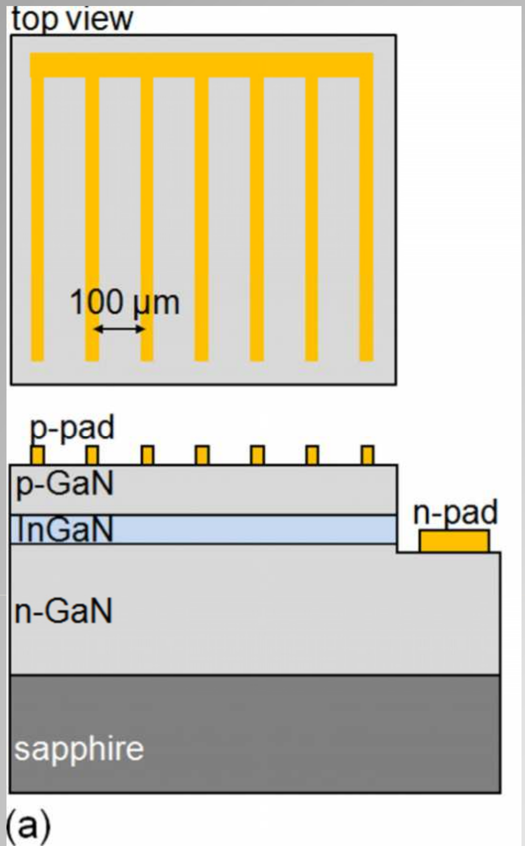


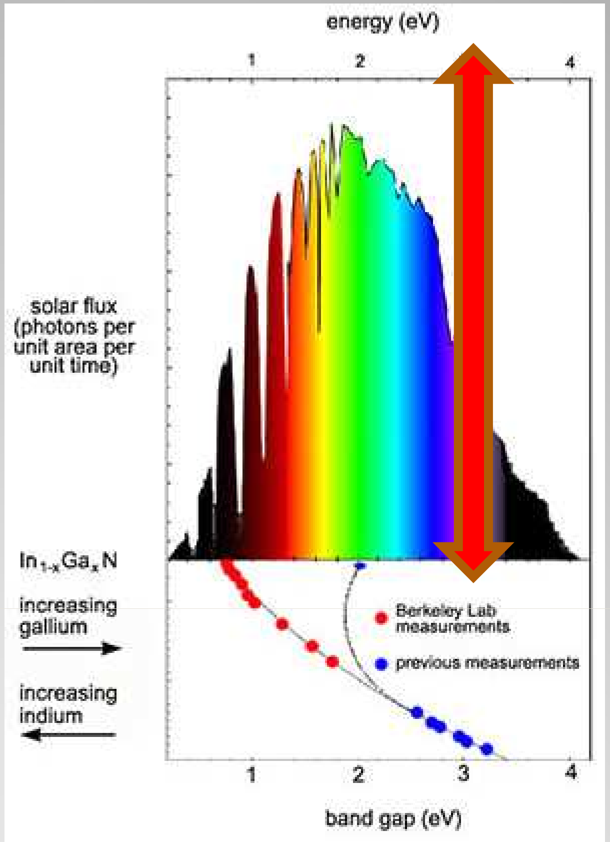


Thin film In-Ga nitrides as the solution?

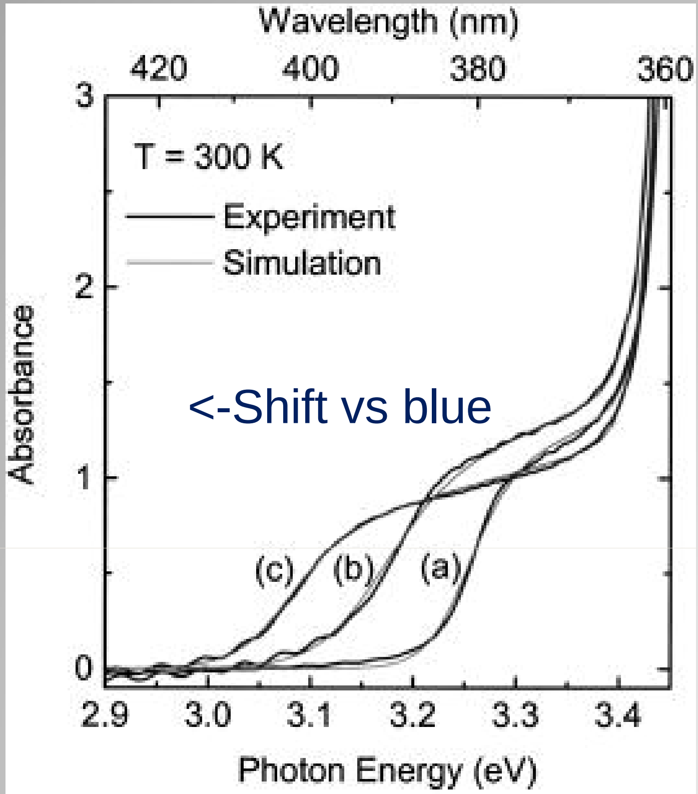
- Nitride LEDs are already in a full industrialization phase, after the Nakamura discovery at Nichia in 1993
- The solid state physics of nitrides are now well understood
- InGaN alloys cover almost the entire solar spectrum
- GaN might be grown on sapphire, (SiC, Si) but lattice mismatch generates high dislocation densities
- Carrier recombination at defects due to lattice mismatch and impurity incorporation, but nitrides tolerate larger dislocations densities than IIi-V compounds and Si
- Polarization related charges at the InGan/GaN interfaces generate a large electric field in the intrinsic layer, opposite in sense to the depletion field

Advantages and challenges of pin nitride cells



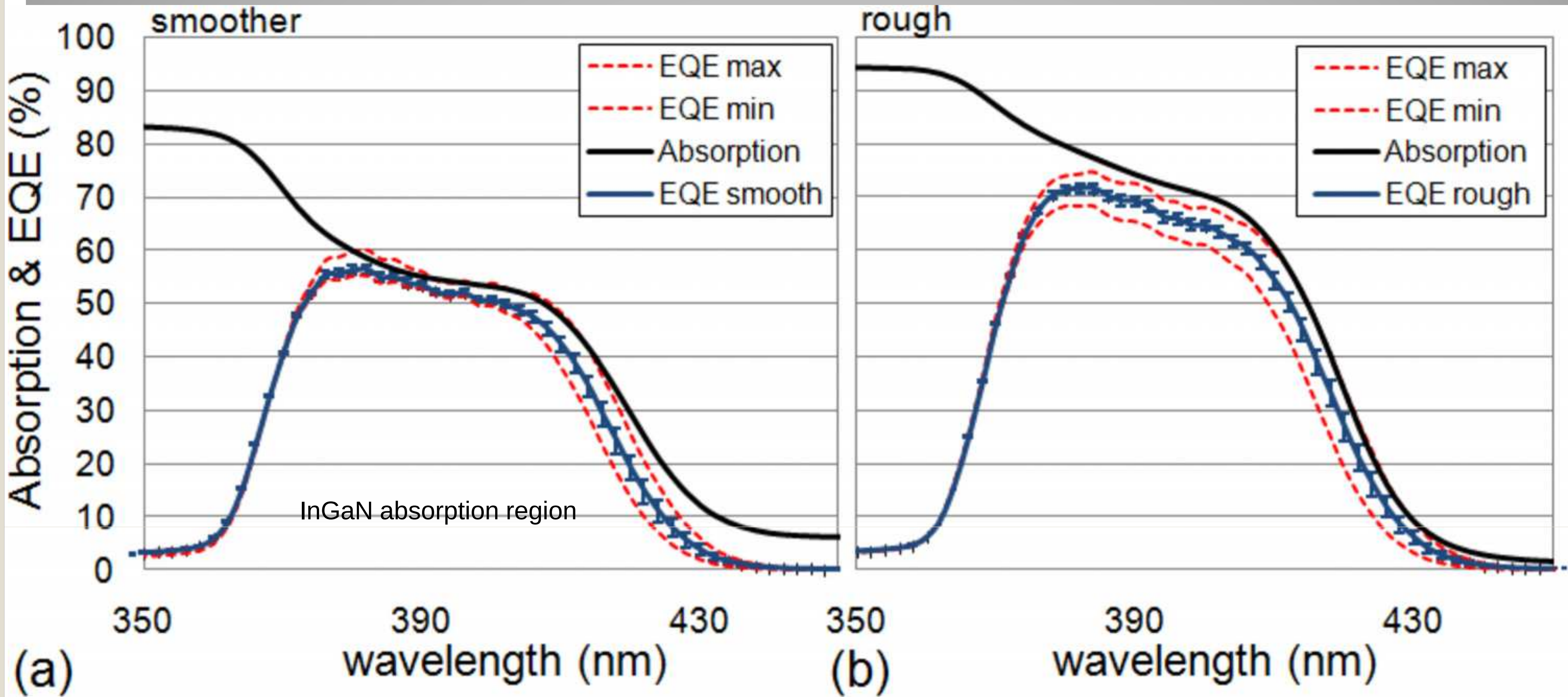


Schematics of a heterostructured cell with an $In_{0,12}Ga_{0,88}N$ layer (60nm thick)



(a) x = 0.054, (b) *x* = 0.072, (c) *x* = 0.100

Absorbance in $In_xGa_{1-x}N$



Carrier generation occurs within the InGaN layer with 100% efficiency. Light absorbed in the GaN absorption region (λ <365 nm) EQ=0 → 100% carrier recombination

Measured absorption and carrier generation (x=0,12)

device	Voc (V)	Jsc (mA/cm^2)	FF (%)	P_{max} (*)(mW/cm^2)	IQE= EQE/A
smooth	1,83	0,83	76,6	1,16	97
rough	1,96	1,06	78,6	1,57	93

Performance of a $In_{0,12}Ga_{0,88}N$ solar cell on a sapphire substrate ($1 mm^2$) 1 sun AM 1,5

- The band gap of the $In_{0,12}Ga_{0,88}N$ layer covers a small fraction of the blue range of the solar spectrum but IQE=100%
- Light coupling unsatisfactory (low EQE)
- Higher In compositions should result in extreme stresses
- Polarization induced charges at the InGaN/GaN interfaces may result in large electric fields inside the InGaN layer of opposite sign of the depletion field
- The sapphire substrate is expensive and in any case unsatisfactory for PV applications for its insulating properties

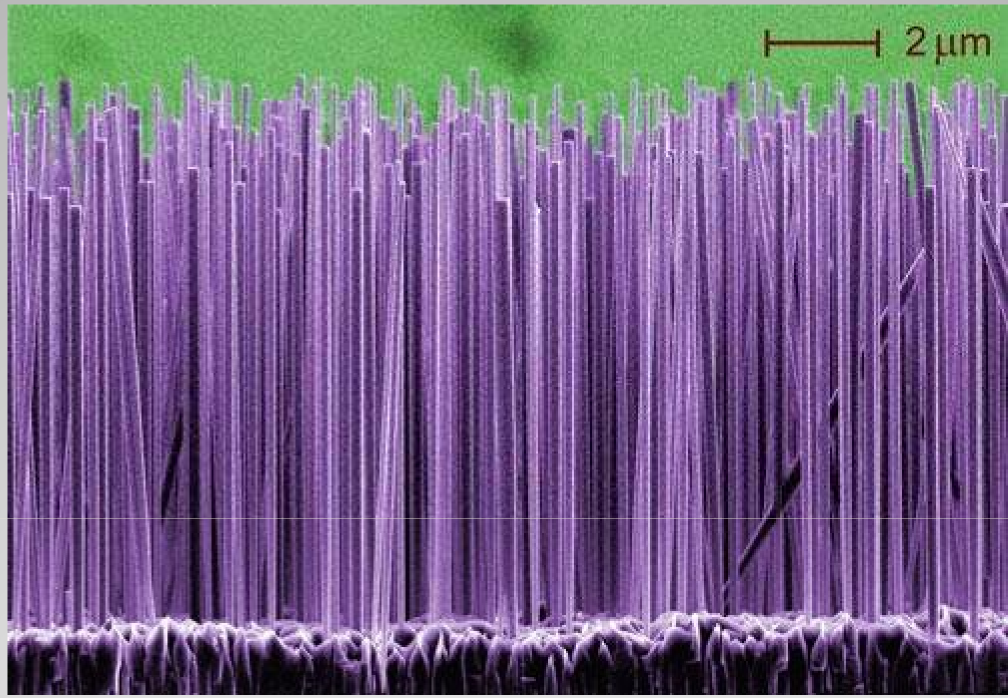
Challenges of a InGaN solar cell on sapphire substrates

- Imec succeded in the fabrication of 300 mm Ø epitaxial GaN substrates on single crystal Cz-Si
- A Me/GaN/InGaN/GaN/Si configuration might be adopted

but the quality of the nitride layers needs to be improved massively

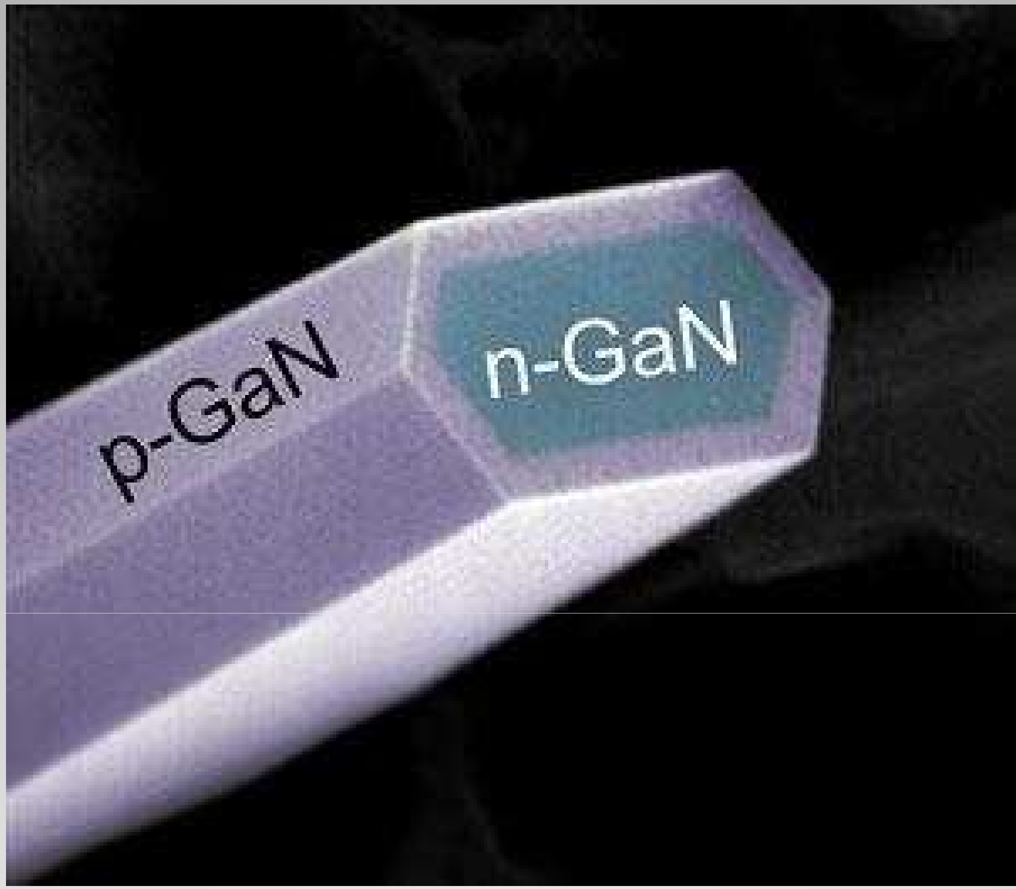
GaN nanowires might open new routes

Epitaxial GaN layers on Si



GaN nanowires have a bright future
CS Europe Nov 30, 2011

A wood of GaN nanowires



A p-n core shell diode by a GaN nanowire

- Silicon will remain the material of choice for many years, as active material or universal substrate for power generation applications where low cost and high efficiency is needed, but material science will provide significative advances especially in thin film materials and cell architecture for alternative applications(e.g.buildings)
- Organic cells will increase significantly their efficiency
- Graphene might be credited as substitute of Me interconnections in thin film cells with significant advantages
- InGaN, and Si and GaN nanowires may open new routes

Conclusions:the future of PV is still in our hands