AMTECH GROUP

Solar | Semiconductor | LED

Doping options for high-efficiency c-Si solar cells

July 18, 2015

James Hwang

VP, Technology
Amtech Systems, Inc.

Contact email: jhwang@amtechsystems.com

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Amtech Group Overview

- Founded in 1981 by JS Whang
- Headquartered in Tempe, Arizona, USA
- Employees (world-wide): ~430
- Public since 1983 (NASDAQ: ASYS)

Tempe, Arizona, USA
Corporate office

Vaassen, Netherlands
Solar Diffusion/Anneal, PECVD, R&D

Clapiers, France
Solar & Semi Automation

Massachusetts, USA
Semi Diffusion

Carlise, Pennsylvania, USA
LED & Si Polishing

Shanghai, China
Ion Implant

<u>BTU</u> in Boston and **<u>SolayTec</u>** in Netherlands recently joined **Amtech Group:**

- **BTU –** inline furnaces (firing, diffusion..), reflow furnaces (PCB board, packaging..)
- **SolayTec –** Spatial ALD for Al_2O_3 passivation

Amtech Solar Product Coverage:

Mono Crystalline

Multi Crystalline

Tempress Diffusion
- POCl3
- BBr3
- Annealing
- Oxidation

Tempress PECVD
- SiN_x, SiO_x, SiON
- ARC and passivation

Kingstone IonSolar
- Phosphorus
- Boron

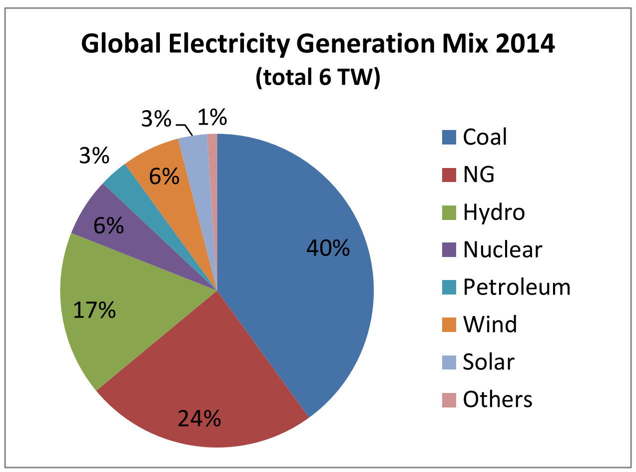
SolayTec ALD
- Spatial ALD - Al_2O_3

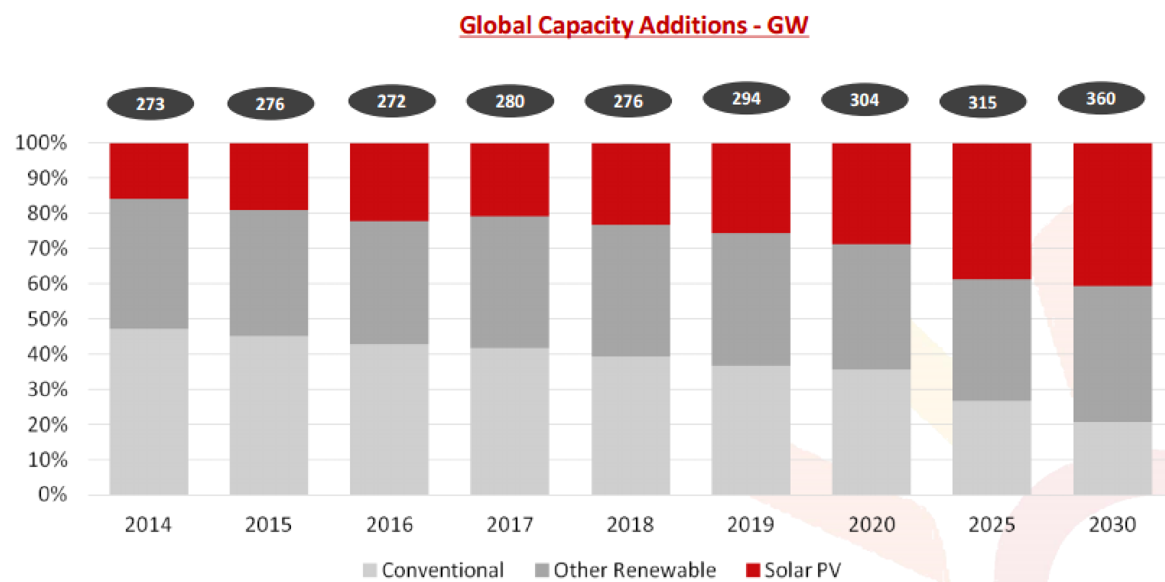
BTU firing furnace
- Fast firing
- Sintering

<u>**Can cover most of critical solar process steps: doping, passivation, firing**</u>

Global Electricity Generation Capacity

- **2014 total electricity capacity**: 6 TW
  (China 1.36 TW; EU 1.15 TW; USA 1.1 TW; India 0.31 TW; Japan 0.3 TW)
- **Annual PV capacity add** continues to increase from 20% in 2014 while other renewable add predicted relatively constant at about 30% (hydro 15%, wind 16%)



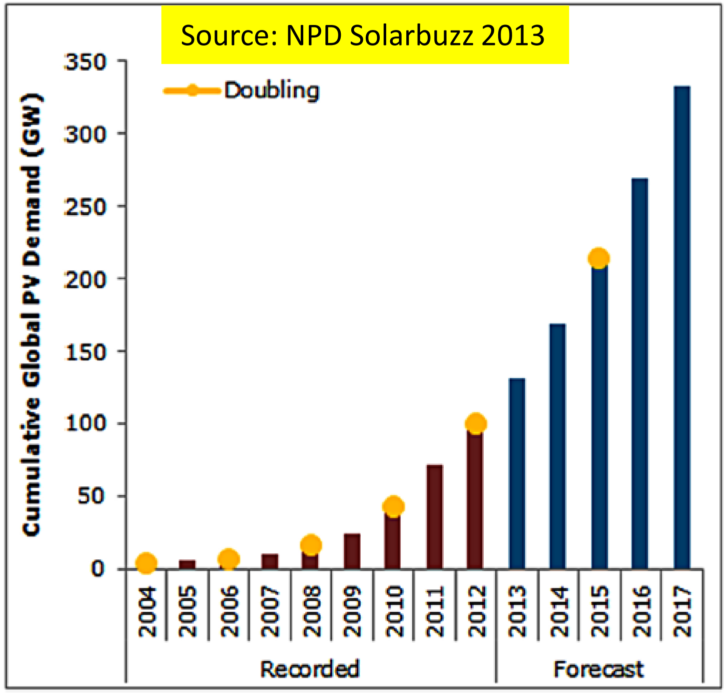


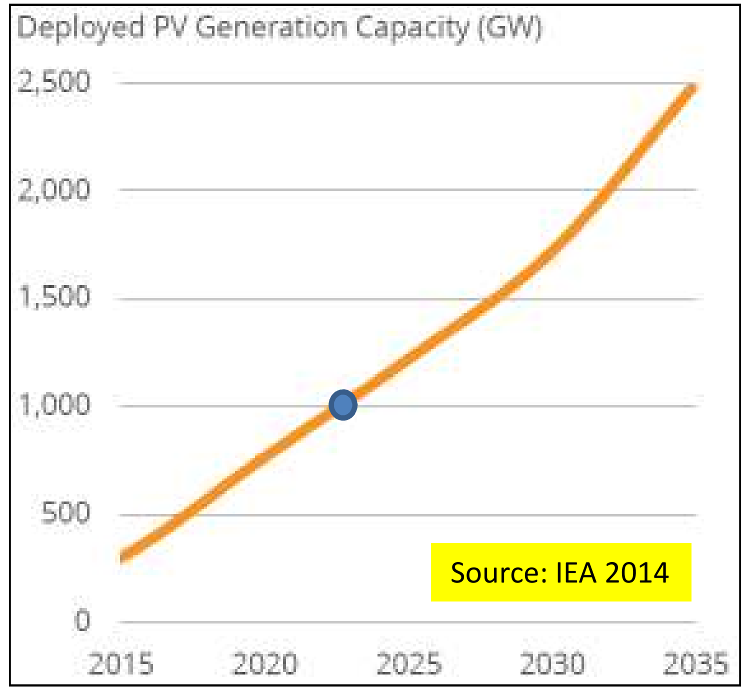
Source: Bloomberg New Energy Finance, Deutsche Bank

2014 Electricity Generation Mix for Key Countries

- **China:** Coal (70%) and Hydro (20%) *** annual capacity increase of 93GW (solar, wind, nuclear..)**
- **EU:** Coal (25%), NG (21%), Hydro (15%), Nuclear (11%), renewable (24%) ***~120 nuclear plants (mostly in France)**
- **USA:** Coal (39%), NG (27%), Hydro (6%), Nuclear (19%); 17 GW new add (36% from PV) ***~100 nuclear plants mostly in East Coast**
- **Japan:** Coal (36%), NG (28%), Nuclear (15%), Renewables (16%) *** ~50 nuclear plants**
- **India:** Coal (72%); aggressive annual growth (19.5GW), <u>surpassed Japan from 2014</u>

Global Cumulative Solar PV Installation





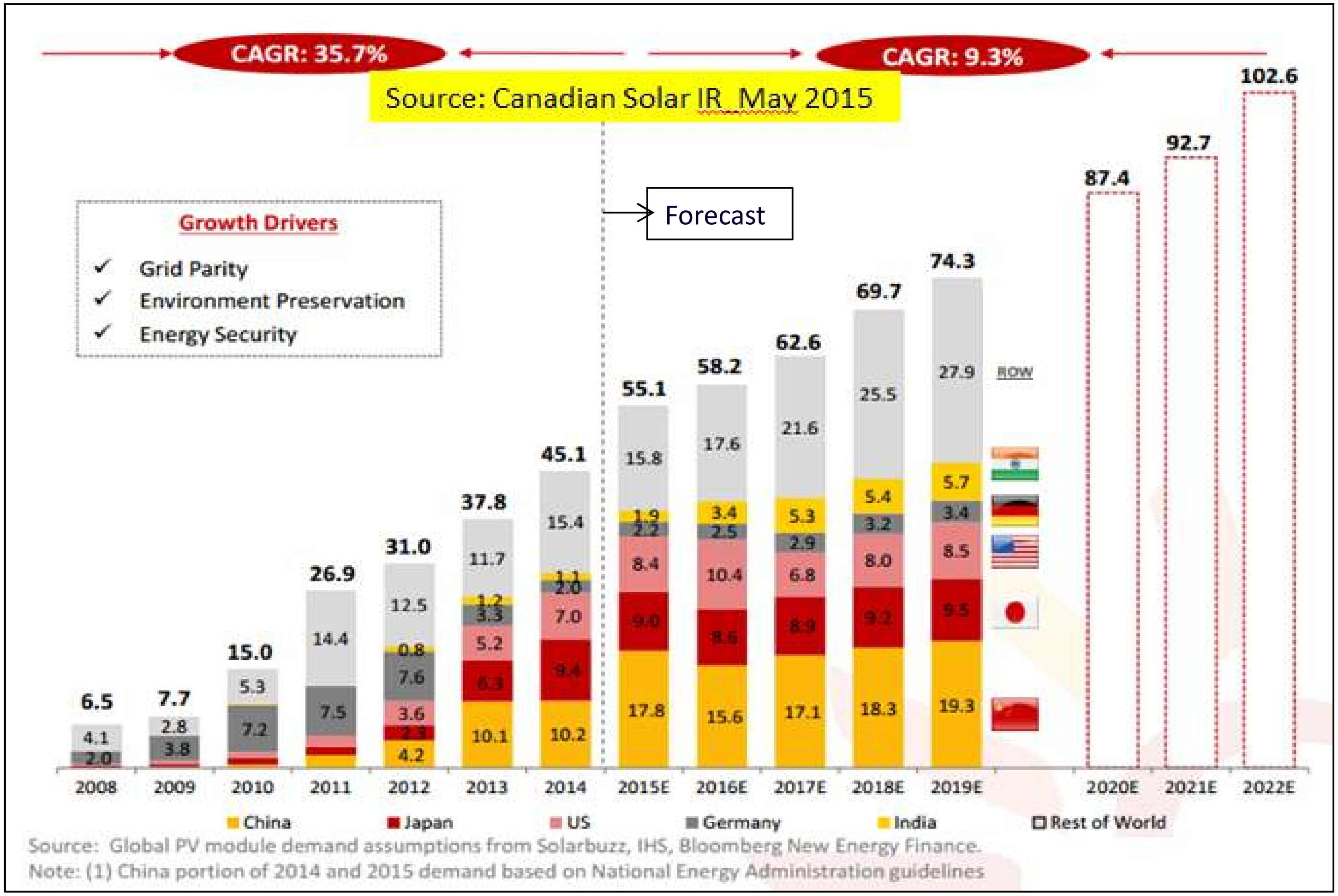
- 2014E : World 185GW (EU 89GW, Germany 35GW, China 27GW, Japan 23GW, USA 18GW,...),

  ~3% of total global electricity capacity (~6TW)

- Forecast 1 TW (1,000 GW) installation around 2023 – 13% by solar PV !

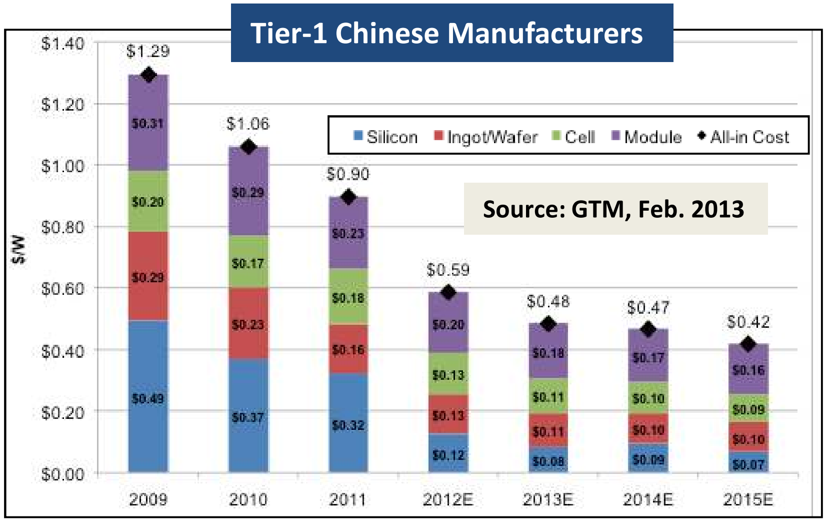
  Close to current total power generation capacity of USA

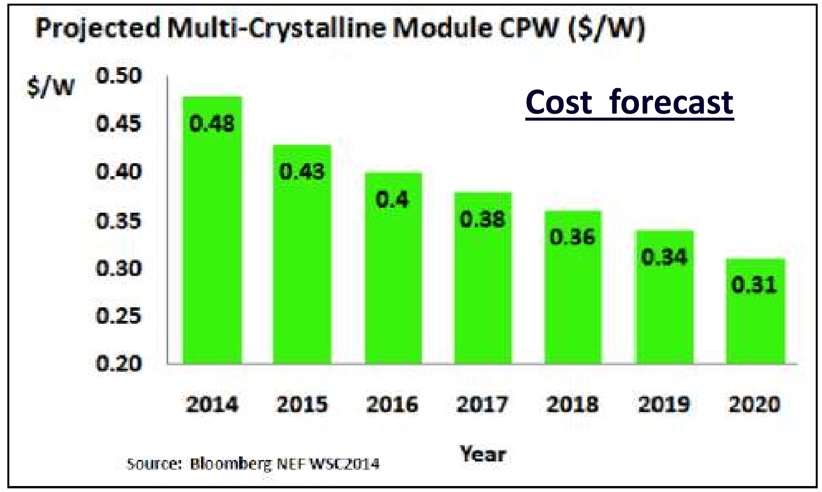
Global Annual PV Installation:



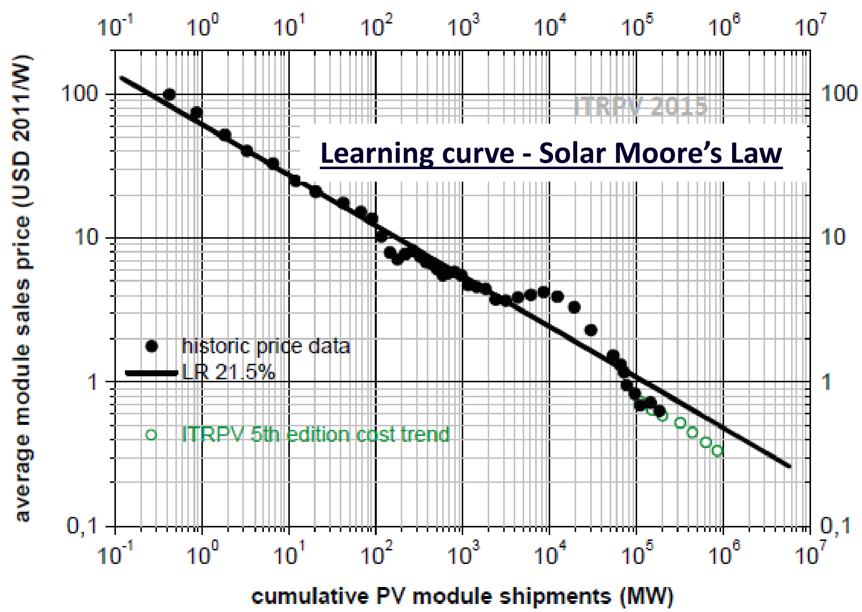
- Crystalline Silicon (c-Si) PV over 90% of annual total installation !
- Break 50GW installation in 2015

PV Module Cost & Price Trend

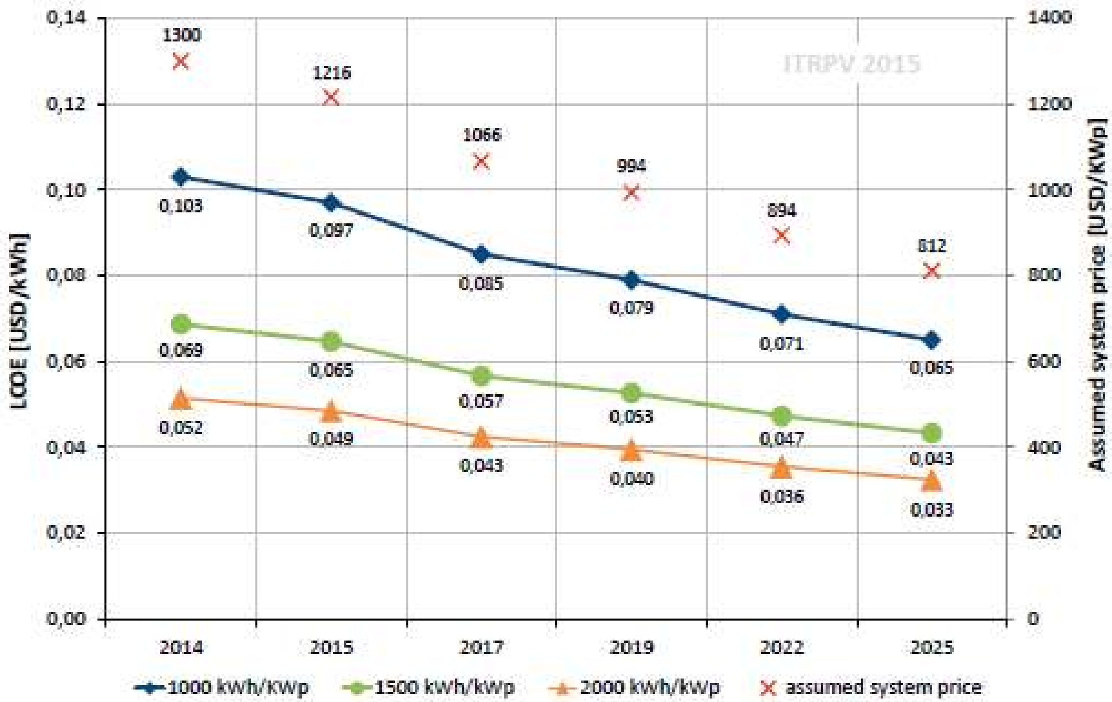




- Actual @ Q4'14: Jinko $0.45/W; CSI $0.49/W; Trina - $0.52/W (First Solar CdTe TF $0.56/W @ 2013E)
- Thin-film: no longer cost advantage!
- Learning curve: Average module price decreases at a learning rate (LR) for every doubling of cum. PV module shipments:
  - $0.42/Wp @500GW cum (2018)
  - $0.32/Wp @1TW cum (2023)



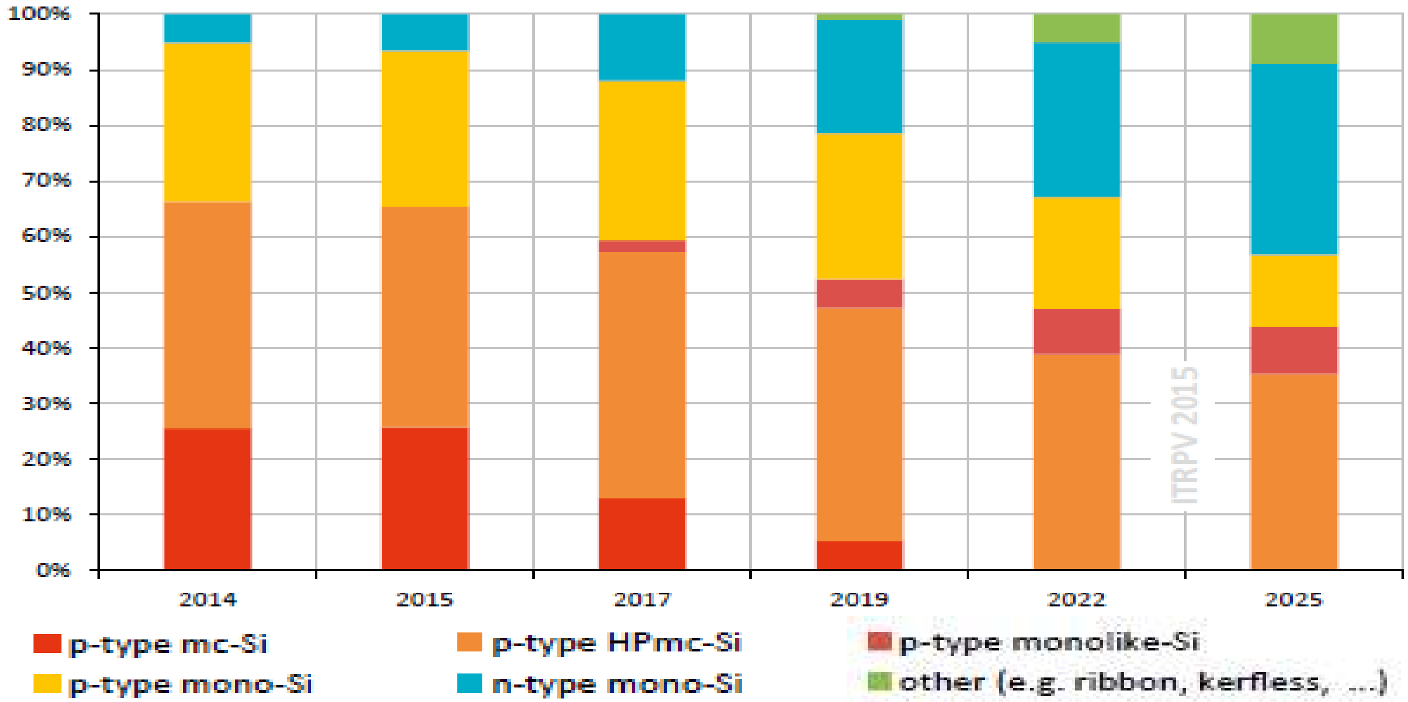
Levelized Cost of Energy (LCOE):



- LOCE = total cost /total energy generation (for lifetime)

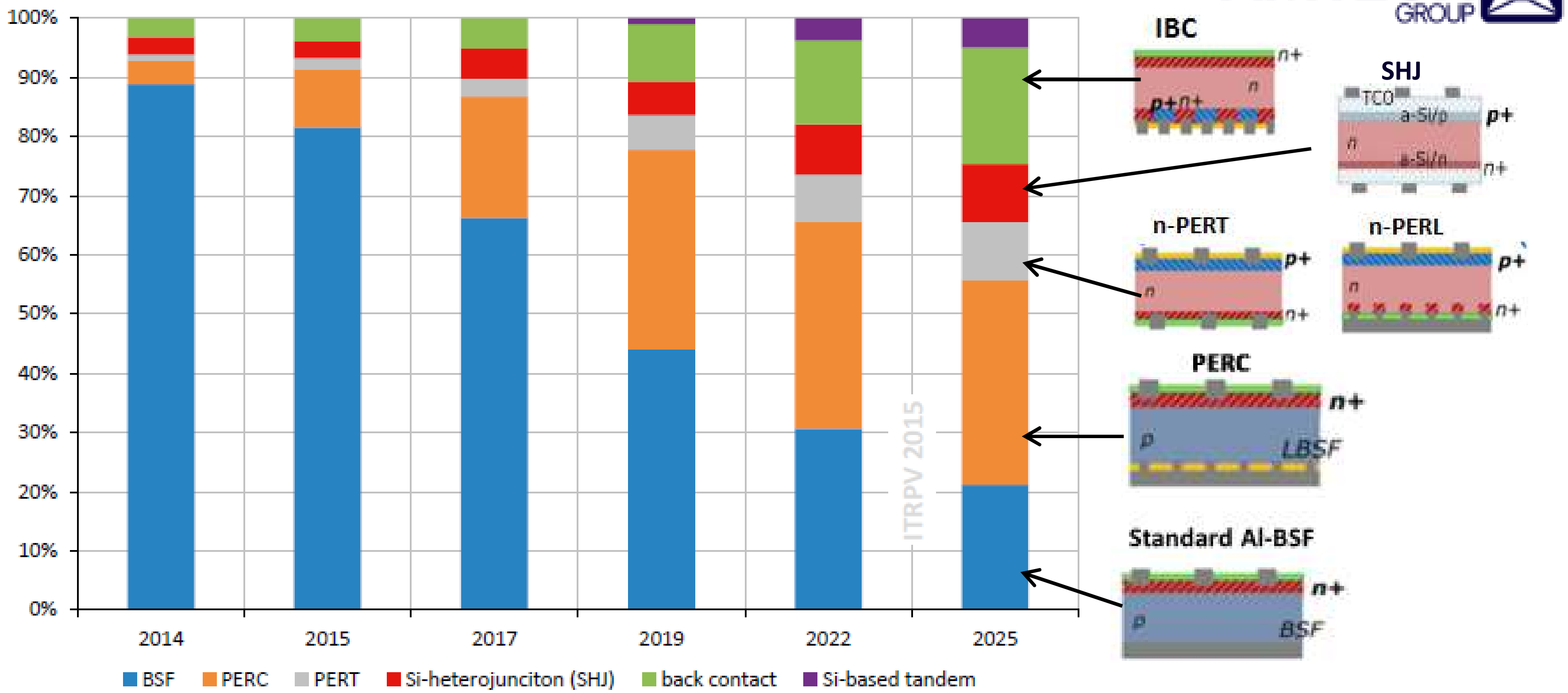
- Solar insolation or energy yield (kWh/kWp):
  - Arizona, California ~ 2000
  - Europe ~ 900
- Solar PV already surpassed **grid parity** in some US States of high electricity price such as California, New Jersey, New York, etc. and will in most of States in USA by 2017

Expected market share of c-Si wafer types



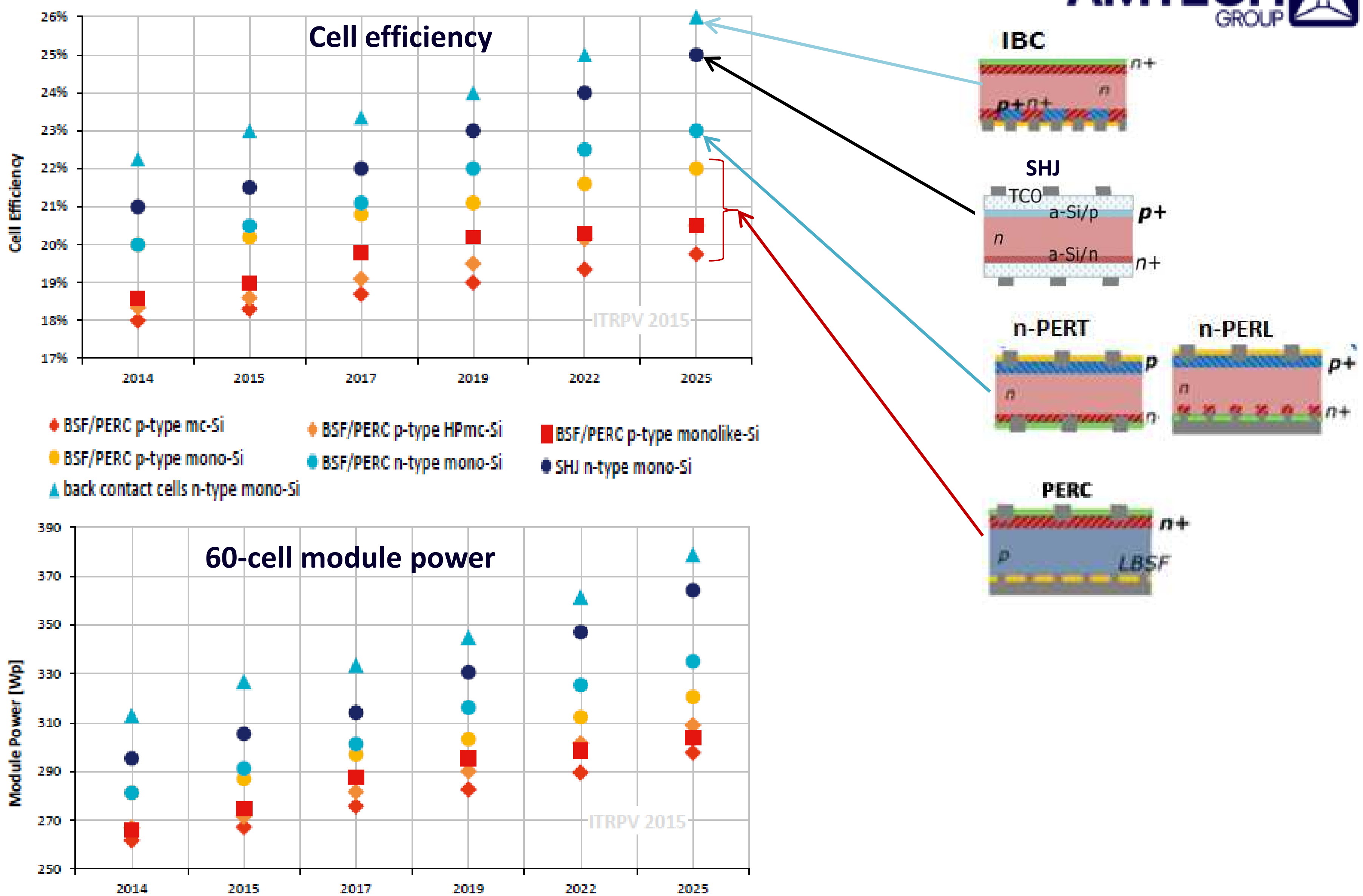
- Multi (std. multi & HP-multi):
  - Dominates today with >60%
  - HP-multi replaces std. multi
  - Share will reduce gradually
- Mono (p-mono & n-mono):
  - Mono market share is increasing as a result of rapid increase in n-mono
  - P-mono share decreases

Expected market share of c-Si cell technologies



- Double-side contact still dominating over single-side contact:
- PERC will gain significant market share over BSF
- All cells except for SHJ require doping for emitter or surface field:

Expected cell efficiency and module power trend



Doping Technologies in Production

- N+ emitter (phos) in p-type cells:
  - POCl3 diffusion: pre-dominant for standard multi, HP-multi and p-mono (over 70% market share of c-Si)
  - Phosphorus ion implant to take advantages associated with single-side doping : currently ~ 200MW for p-mono (Suniva and Shinsung)
- P+ emitter (boron) in n-type cells:
  - APCVD solid source & drive-in for IBC cells (SunPower >1GW),
  - BBr3 for bifacial n-PERT (Yingli, MSE ~ 400MW),
  - Ion implant & damage anneal for bifacial n-PERT (LG ~ 300MW)

POCl3 Diffusion

- AP(atmospheric pressure) HD (high-density) POCl3:
  - 5 stack tube furnace
  - 1000 wafers back-to-back loading per tube (2.38mm pitch)
  - Throughput: ~3200 wafers per hour
  - CoO: ~ 1.8 ct/wafer
  - Better control of surface doping density => better short-wavelength response
- LP (low-pressure) POCl3 :
  - 5 stack tube furnace
  - 1000 wafers back-to-back loading per tube (2.38mm pitch)
  - Throughput: ~3400 wafers per hour (shorter process time)
  - CoO: ~ 1.9 ct/wafer (due to higher Capex and Opex)
  - High surface doping density => degradation in short wavelength quantum efficiency

Boron Doping for P+ Emitter in N-type Cells

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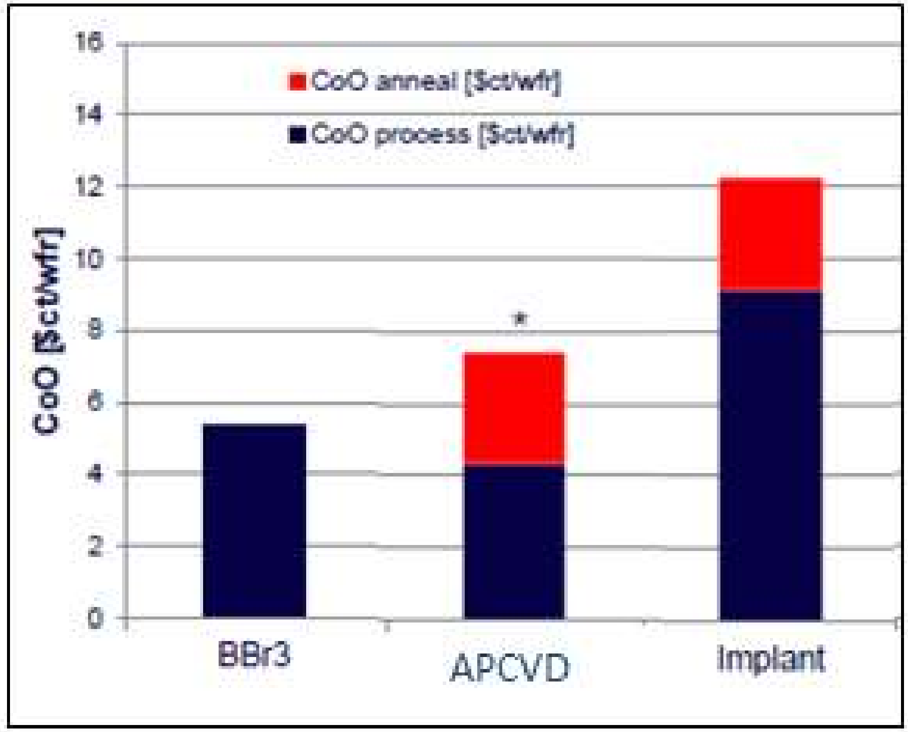
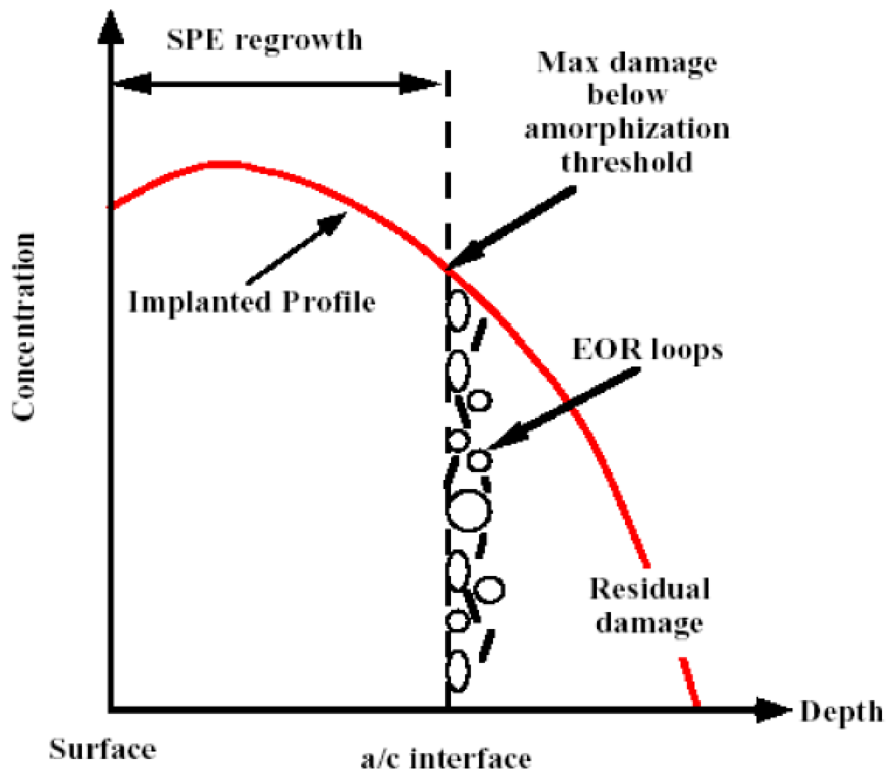
- Diffusion:
  - **AP-BBr_3 - in production**
  - **LP-BBr3 – not production-proven yet**
  - Lowest CoO due to simultaneous dopant deposition and diffusion
- Solid source deposition & drive-in :
  - APCVD solid source & drive-in – volume production for IBC cells by SunPower
- Ion implant & anneal:
  - **Pure boron implant** by beamline with mass analysis (MA) **& high-temperature (1050°C) long-time damage anneal** (highest CoO)



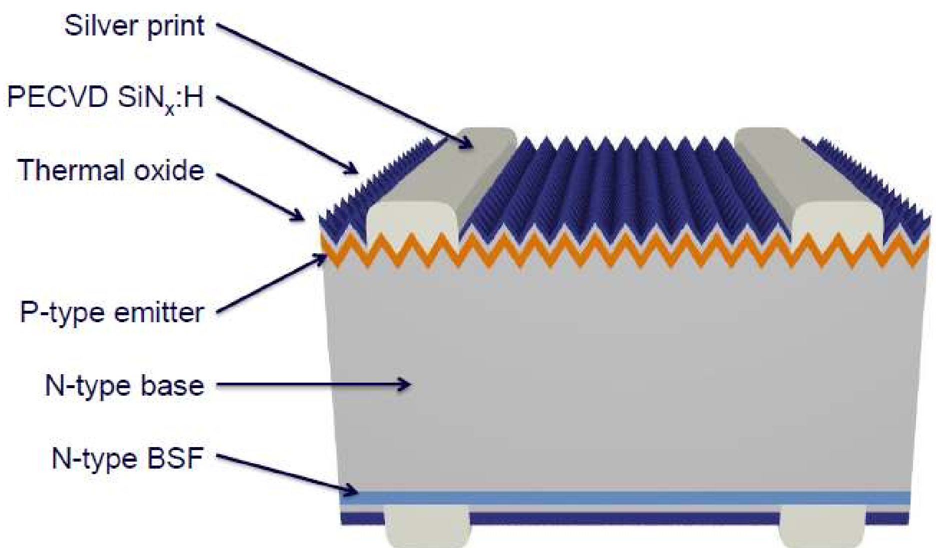
Technical challenges for boron implant

- **Ion-shower type boron molecular ion implant (BF3, B_2F4. B2H6, B10H14..) with no mass analysis** is a trend for a high throughput.
- Clean surface region by solid phase epitaxy (SPE) regrowth during post-implant anneal, but **defective end-of-range (EOR) region**.
- Challenging part - annealing of EOR extended defects which requires a novel anneal method of high-temperature but short time (within an hour) – fast heating and cooling



Full implant (B & P) option for n-type cell

- **<u>Full Implant (B & P)+ Single Anneal</u>** can be cost-competitive to **two diffusion steps (BBr3 + POCl3),** if the followings are met:
  - High-throughput boron and phosphorus implants (>3000 wafers per hour)
  - High-throughput boron implant anneal with fast heating and cooling capability (≥ 25°C/sec or 1,500°C/min) (1000 °C or higher but 1 hour or shorter)



- **<u>Status:</u>**
  - Ion-shower type of high-throughput **implanters <u>available</u>** (Applied, Kingstone, Intevac)
  - High-throughput, high-temperature, fast **anneal method <u>not available</u>,** yet – **novel advanced anneal concept required!**

Thank You for your attention!!