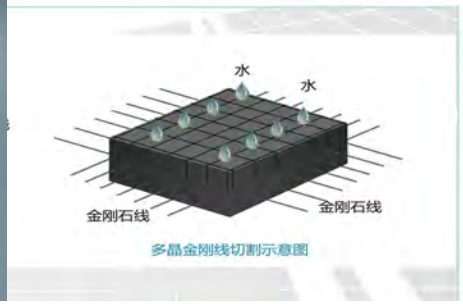
Trend of Crystal Growth Technology in Solar Industry

Dr. Zhixin Li
President & CTO, Linton Crystal Technologies
CEO, Linton Machine
IWCGT-7 Potsdam, July 5, 2017

A Brief Introduction to Our Company

- Linton Crystal Technologies (LCT) is located at Rochester, New York
- Linton Machine is located at Dalian, China
- LCT is a wholly owned subsidiary of Linton Machine (Previously Kayex)
- Linton Machine and its subsidiaries have ~600 employees in 5 facilities
- We are a world's leading capital equipment manufacturer for solar and semiconductor industries



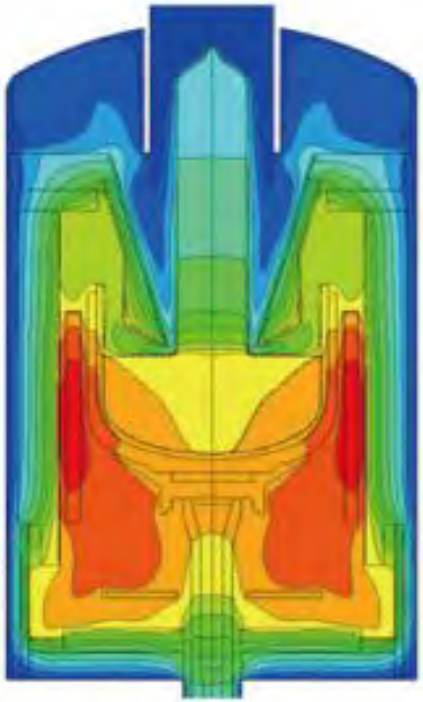
We make production equipment for solar and semiconductor industries:

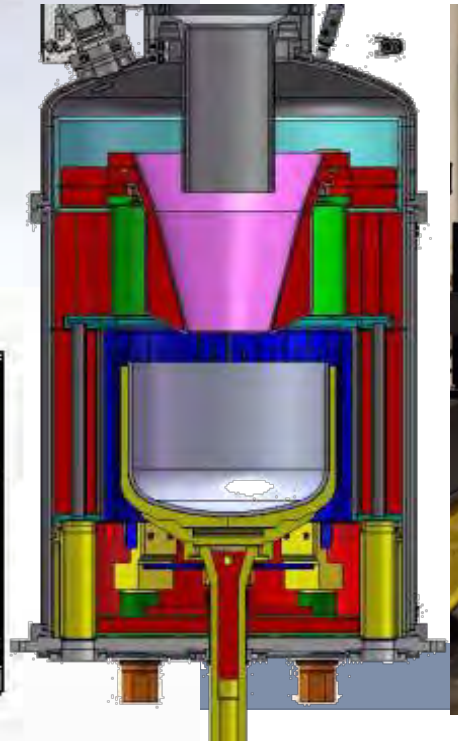
- Crystal Growers
- DW Wafer Slicing Machines
- Ingot Bricking Machines, G5-G8
- Grinders, Croppers
- Wafer Separators, Wafer Cleaners
- Automation Equipment
- Slurry Recovery Systems

Assembly Shop

KX170**Series** CZ Crystal Growers

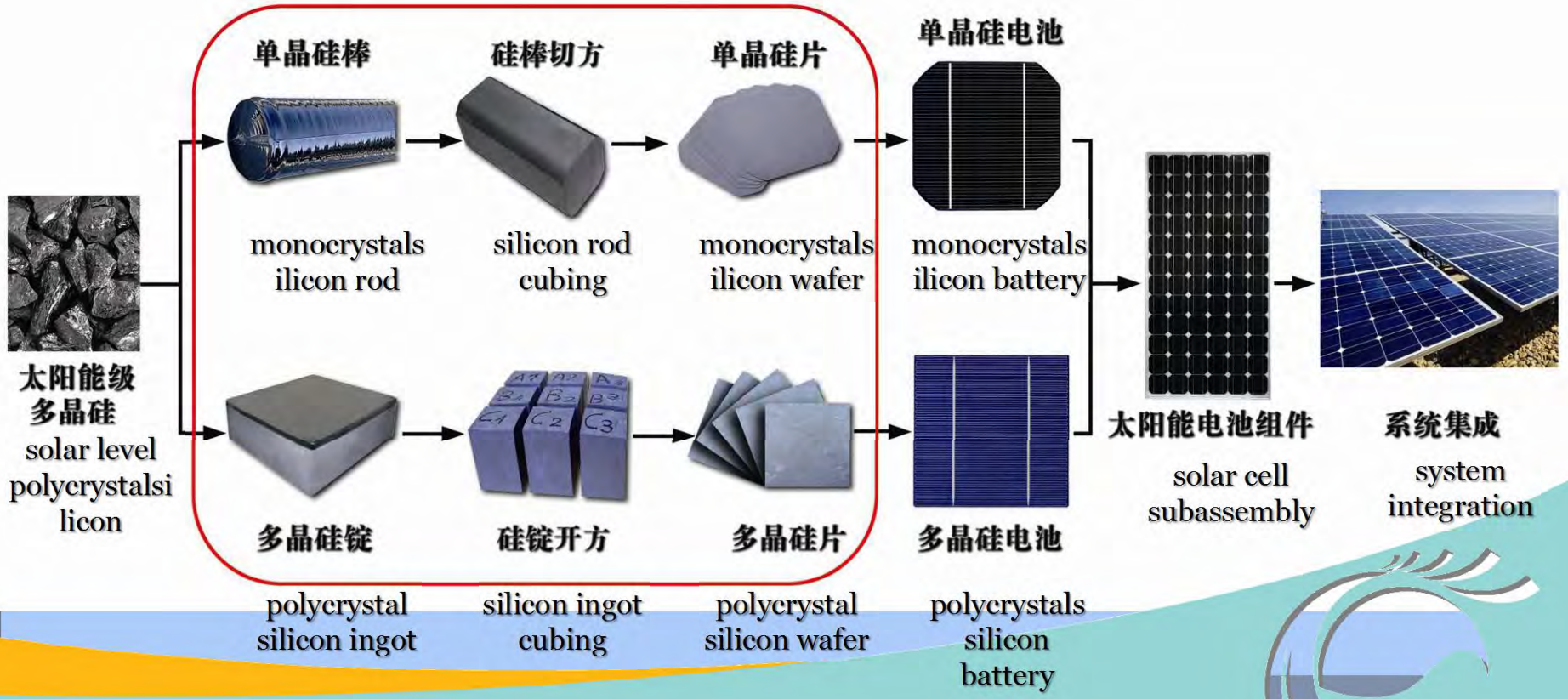
- 26”Hot Zone Standard
- Contains >300kg Silicon
- 8-9 inch Crystal
- >1.5mm/min Grow Speed
- >2.8 Ton/month output
- Complete Accesories

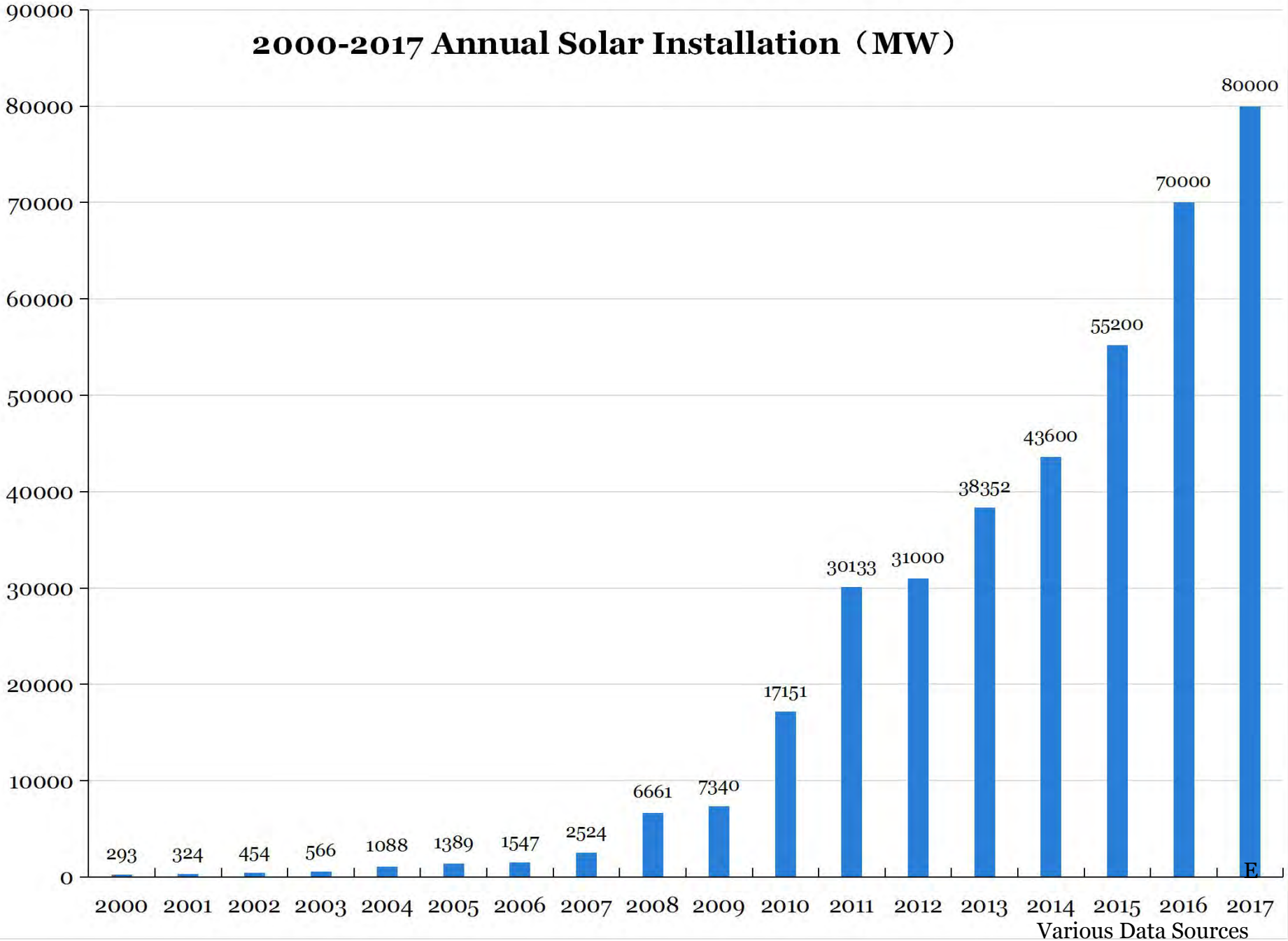




Trend of Crystal Growth Technology in Solar Industry

PV Industry Value Chain Schematic Diagram



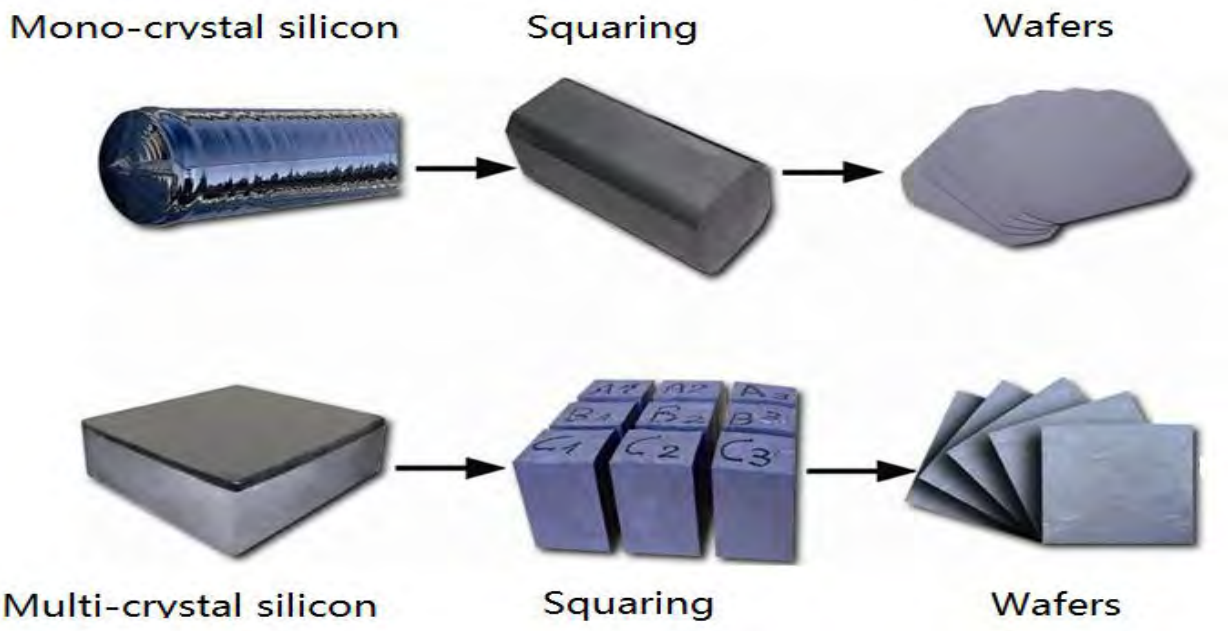

2000-2017 Annual Solar Installation（MW）
90000
80000
70000
60000
50000
40000
30000
20000
10000
0
293
324
454
566
1088
1389
1547
2524
6661
7340
17151
30133
31000
38352
43600
55200
70000
80000
E
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Various Data Sources

Silicon Crystals & Wafers for Solar

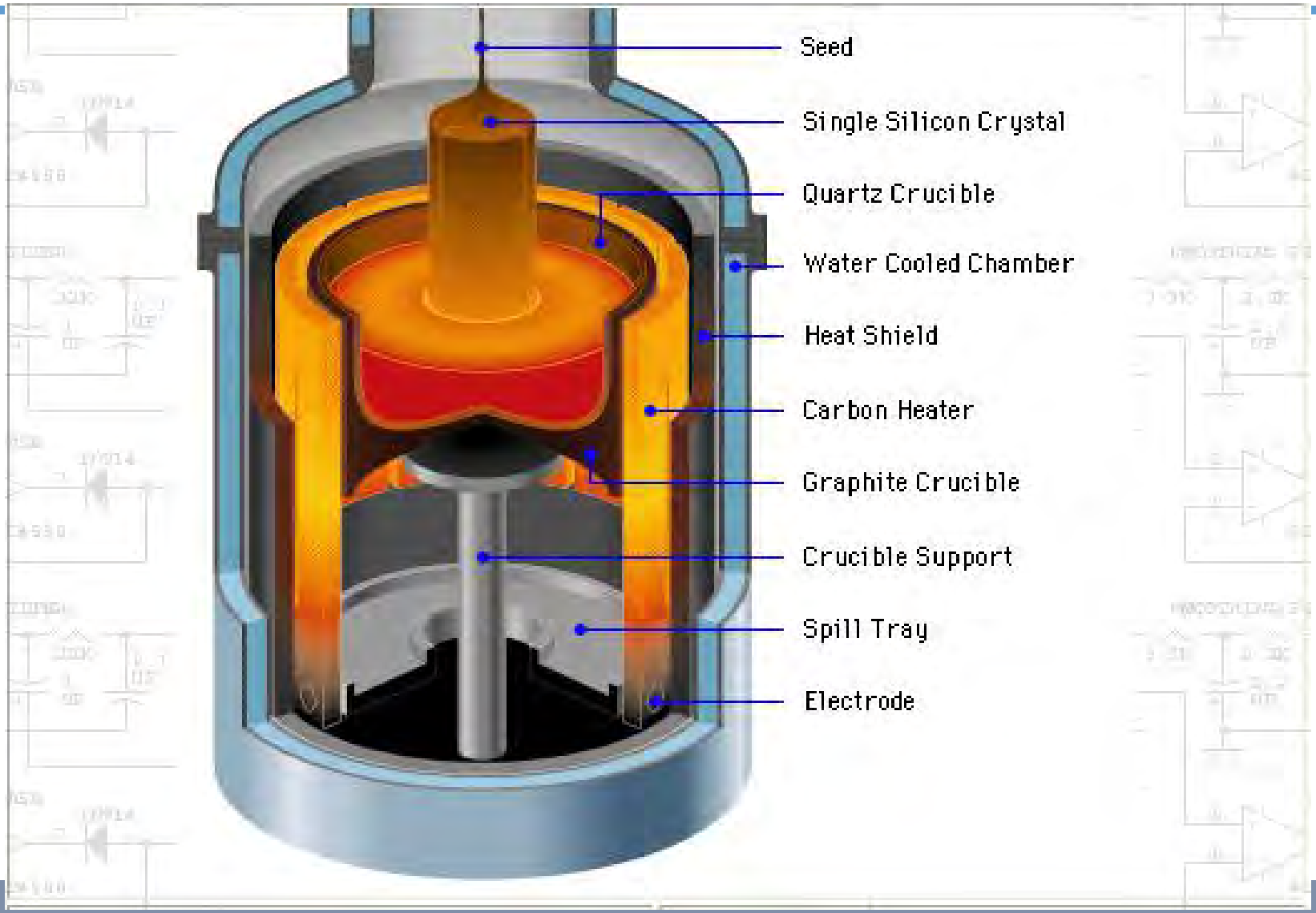
- **More than 500,000,000 kg crystals are produced each year**
- **More than 15,000,000,000 silicon wafers are made each year**

Typical wafer specs:

- Thickness: 0.190 mm
- Dimensions: 156 x 156 mm
- Chemical contents: 99.99999% silicon + dopants
- Each produces ~ 4 - 5 watts of power after circuits are printed
- Price is about US $0.60-0.70 each

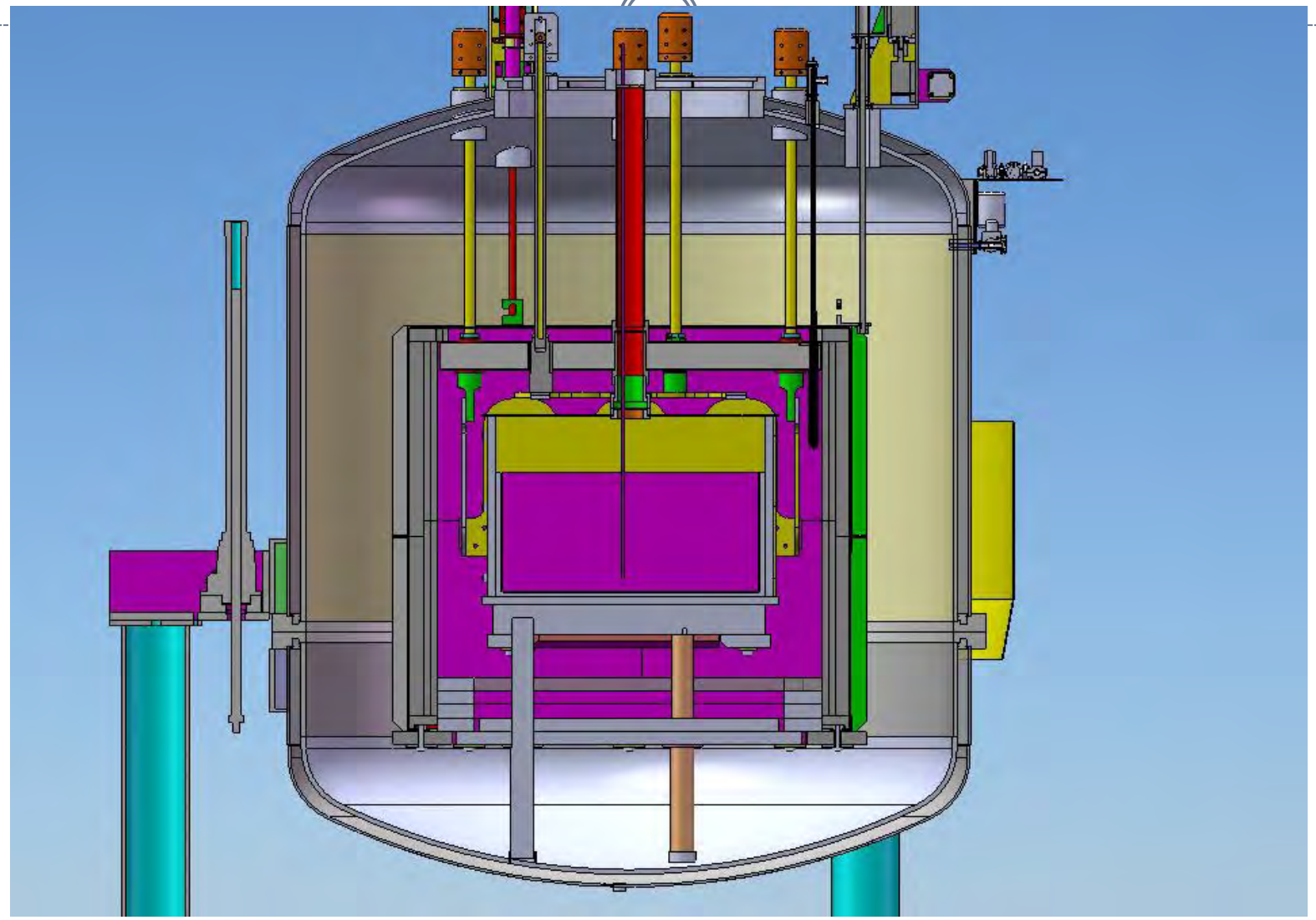


Schematic of CZ Mono-Crystal Growth

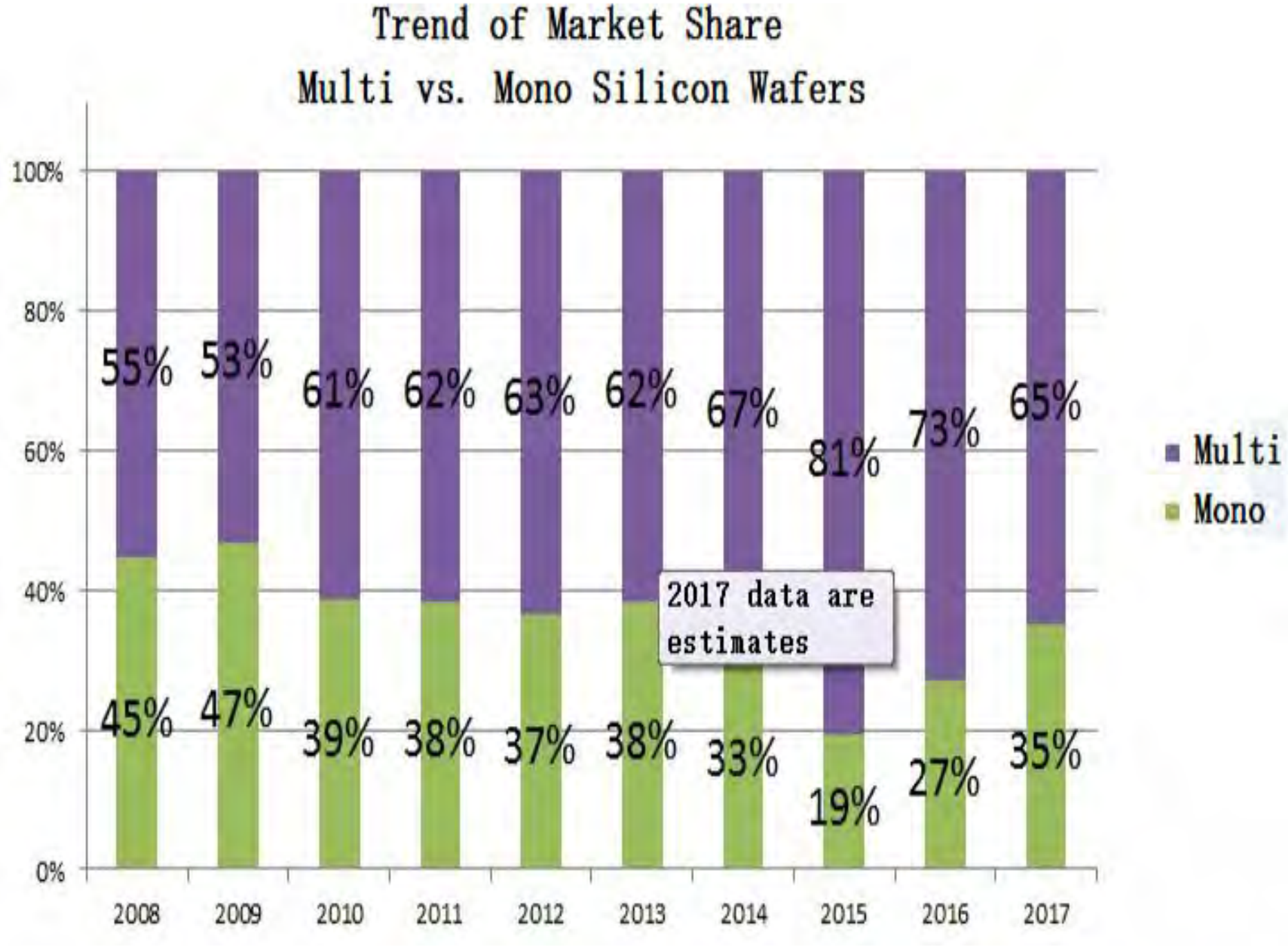


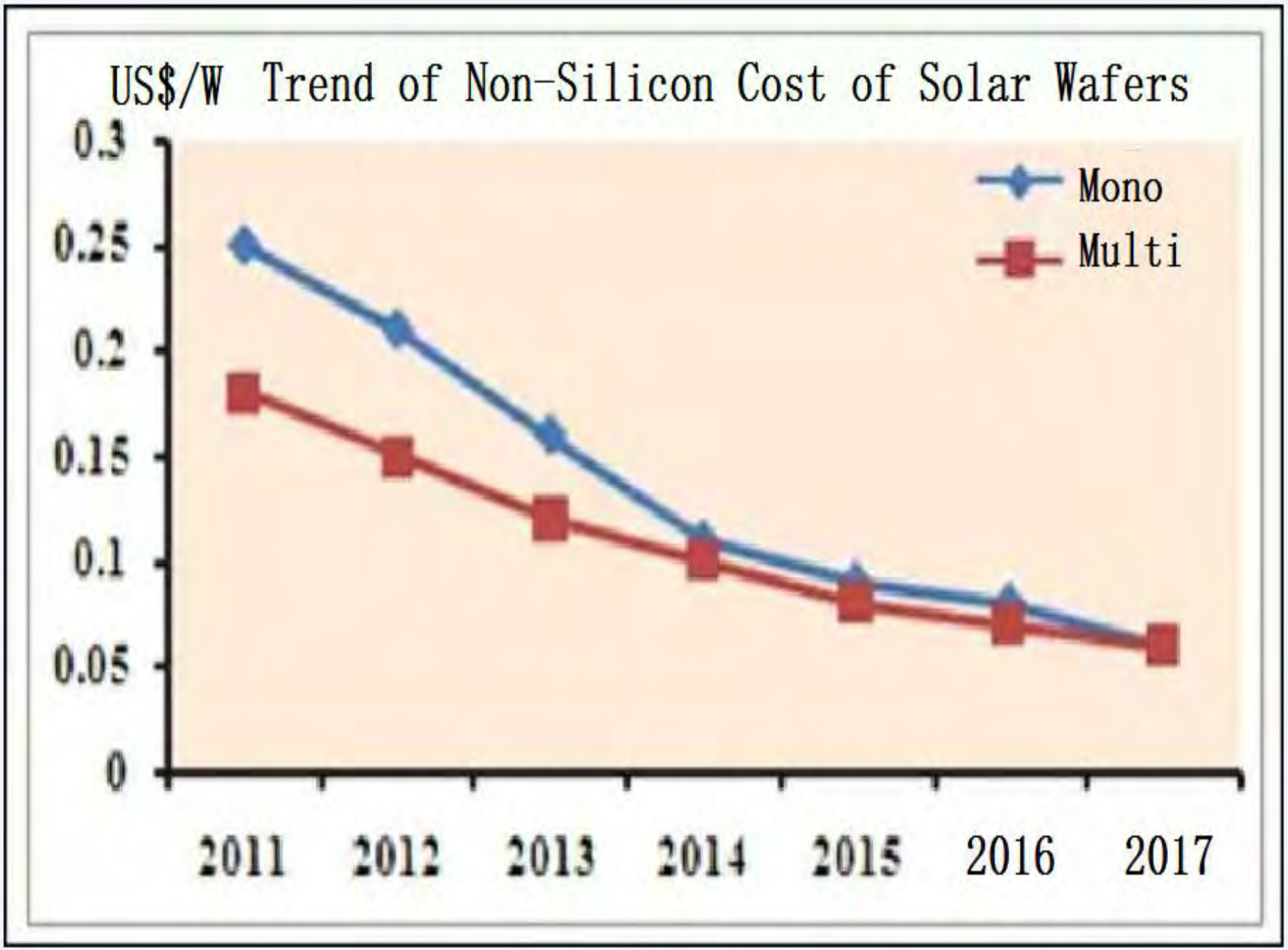
A crystal growth shop with CZ pullers

DSS Furnace Cross-Section



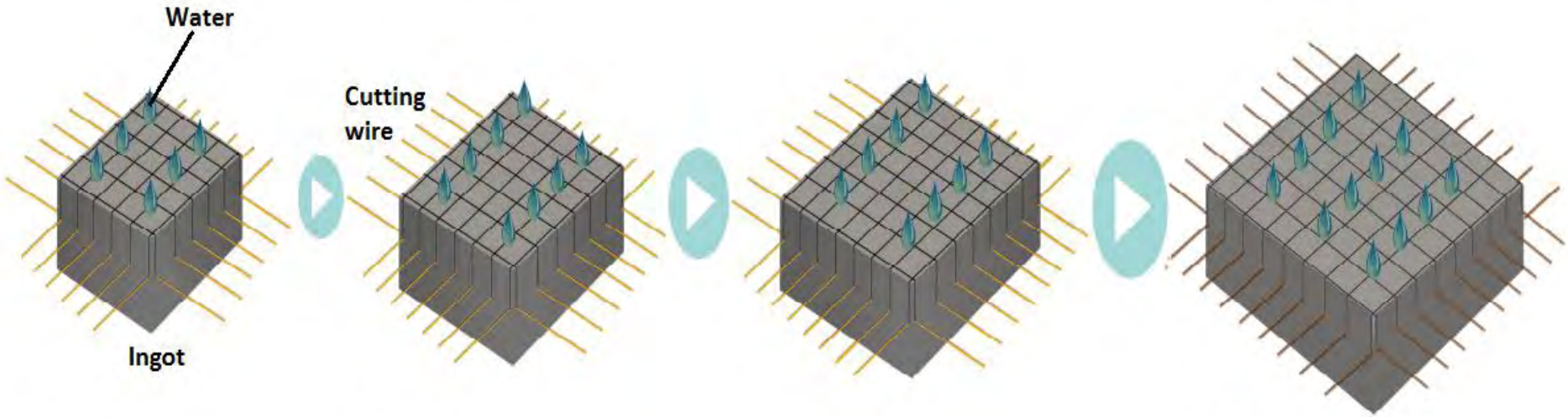
DSS Directional Crystal Growers in Production


Trend of Market Share
Multi vs. Mono Silicon Wafers
100%
80%
60%
40%
20%
0%
55%
53%
61%
62%
63%
62%
67%
81%
73%
65%
45%
47%
39%
38%
37%
38%
33%
19%
27%
35%
2017 data are estimates
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
Multi
Mono


US$/W Trend of Non-Silicon Cost of Solar Wafers
0.3
0.25
0.2
0.15
0.1
0.05
0
Mono
Multi
2011
2012
2013
2014
2015
2016
2017

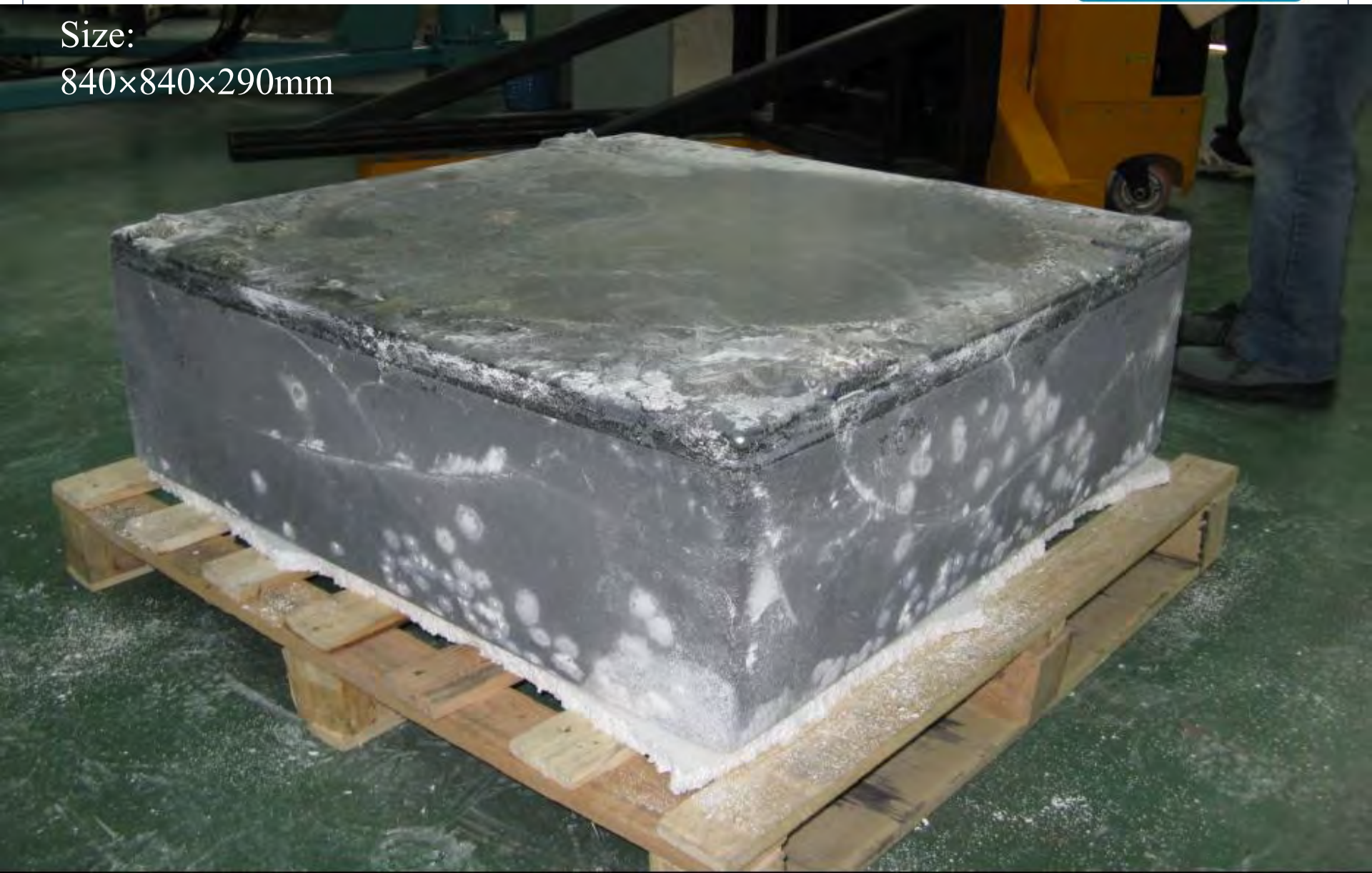
Cost Reduction Road Map: Multi- Wafers (1)

- **Larger: G4 , G5，G6，G7，G8 DSS Crystals**
  - G4: ~300 kg
  - G5: ~450 kg
  - G6: ~800 kg
  - G7: ~1200 kg
  - G8: ~1600 kg



470 kg G5 DSS Silicon Ingot, 2008

Linton Crystal Technologies



World's first G6 ingot
June 2009

Linton
Crystal Technologies

803 kg Ingot
990X990X340mm

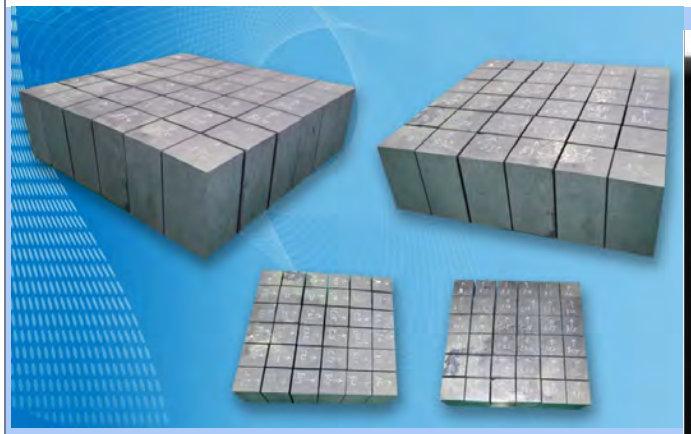
The world's 1st 1200kg G7 Ingot, 2013

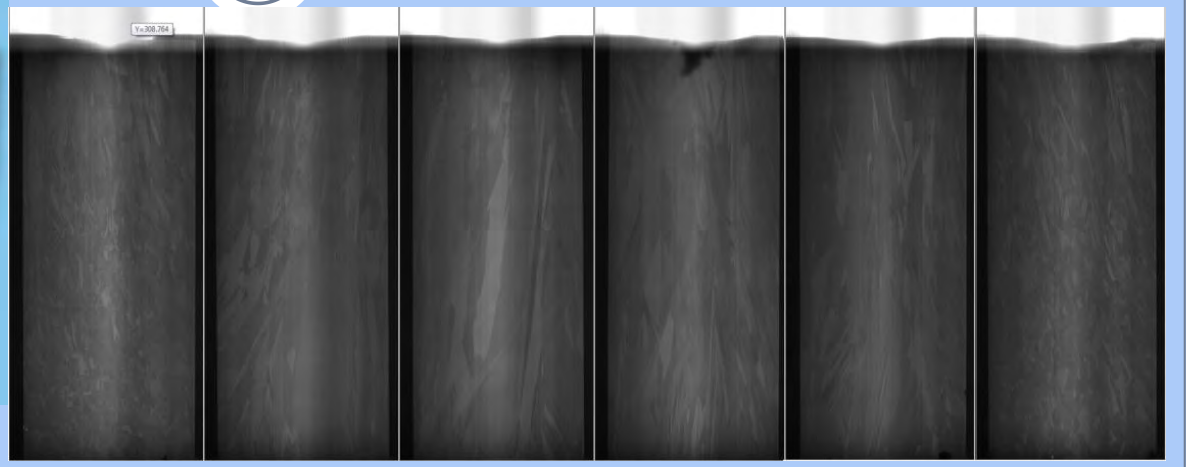
G8 DSS Ingot, 1750 kg

1340x1340x400 mm, March 2017

Linton Crystal Technologies

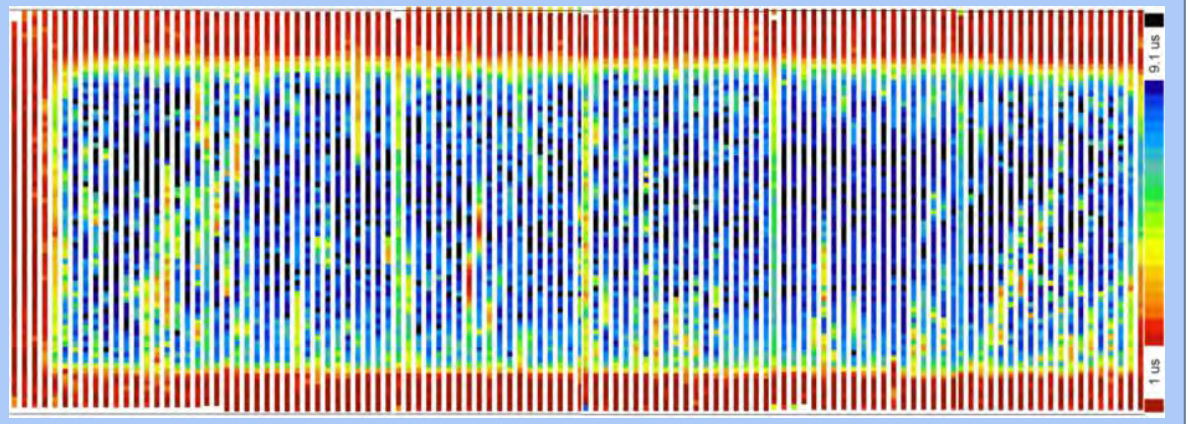
Carrier life time and IR image - Multi Crystal





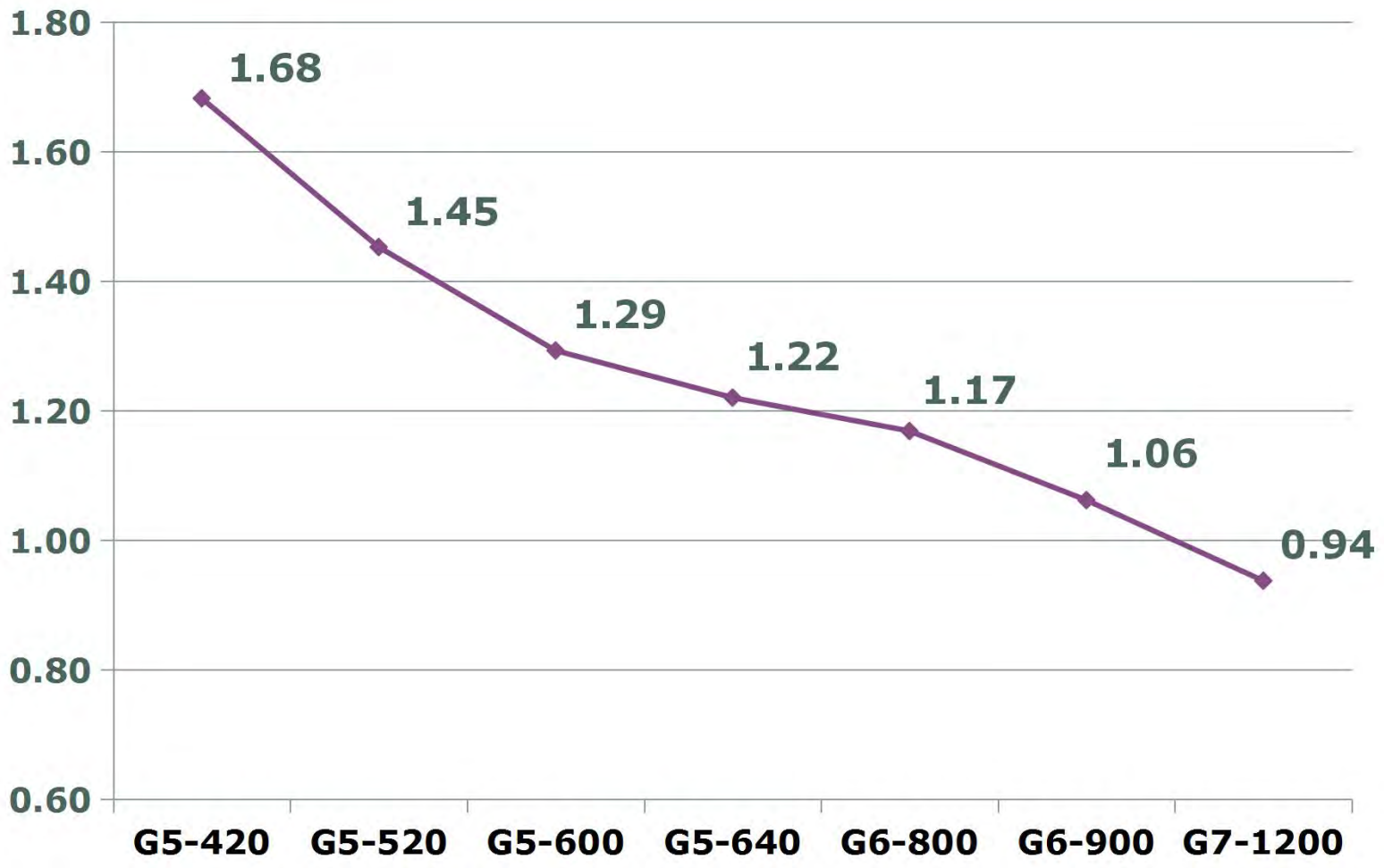
IR Image

G6 DSS Multi Crystal Cross Section IR and Life Time Images



Carrier Life Time

Crystallization cost (RMB/wafer) of different furnace types & ingot sizes–G7 offers lower cost than G5 & G6



Cost Reduction Road Map: Multi- Wafers(2)

- **Higher PV conversion efficiency**
  - Quasi- Mono wafers
  - High Efficiency Multi-wafers

  PV Conversion Efficiency increases from ~17% to >18%

  If one wafer offers more watts at fixed cost, then cost per watt is reduced

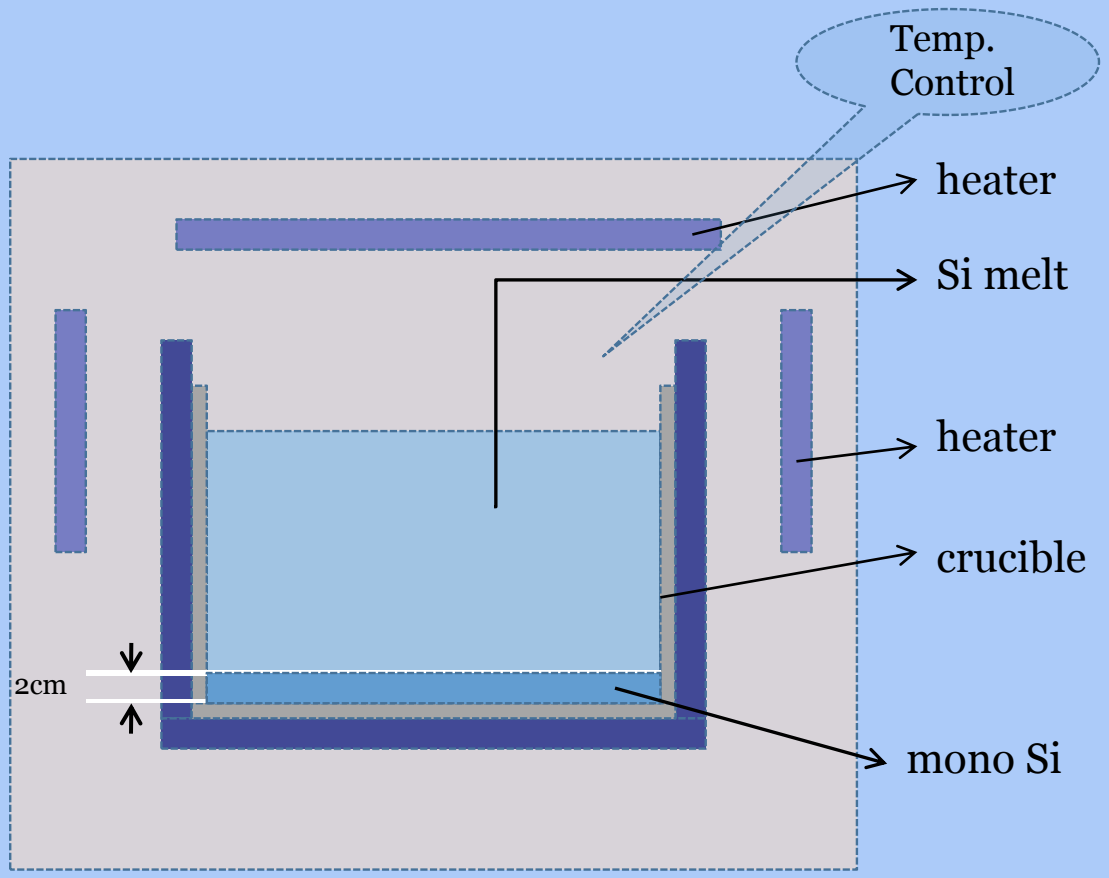
Mono

Multi

Quasi-Mono

High-Efficiency

Schematic of Quasi-Mono Crystalization



- Use existing DSS furnaces
- Modified hot zone
- Sead at crucible bottom
- Conversion efficiency higher than Multi but lower than mono
- Cost higher than Multi due to sead, lower yield
- Problem: dislocation?

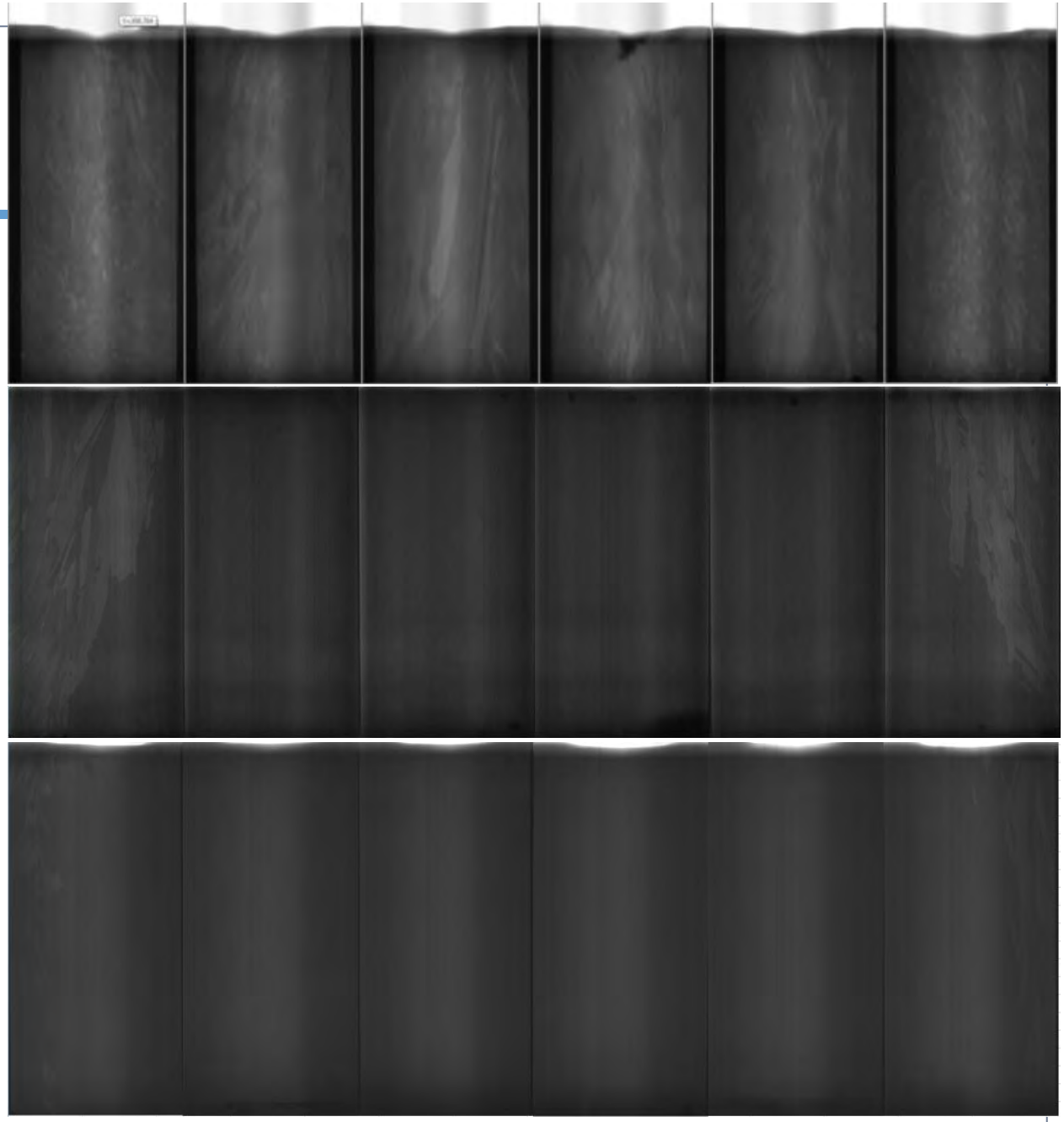
Mono seeds at bottom of quartz crucible for Quasi-Mono crystal production

Cross Section IR Images

Normal DSS Ingot

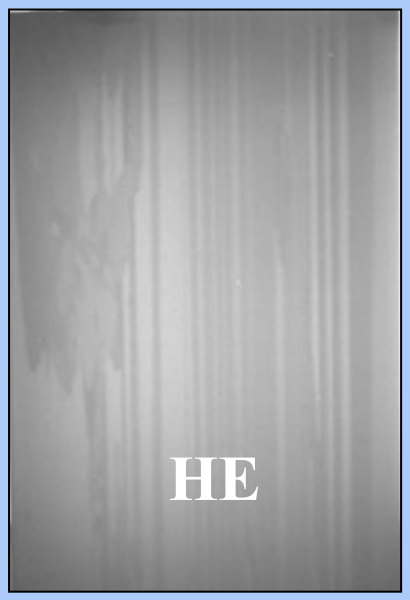
Quasi-Mono Ingot

Improved Quasi-Mono Ingot



Cross Section IR Images of Conventional and High Efficiency (HE) DSS ingots

Cross Section of Bricks



Mostly vertical growth of the crystalline grains for HE ingot

Mono-Crystal Wafers Achieved Even Bigger Cost Reduction Than Multi-Crystal Wafers

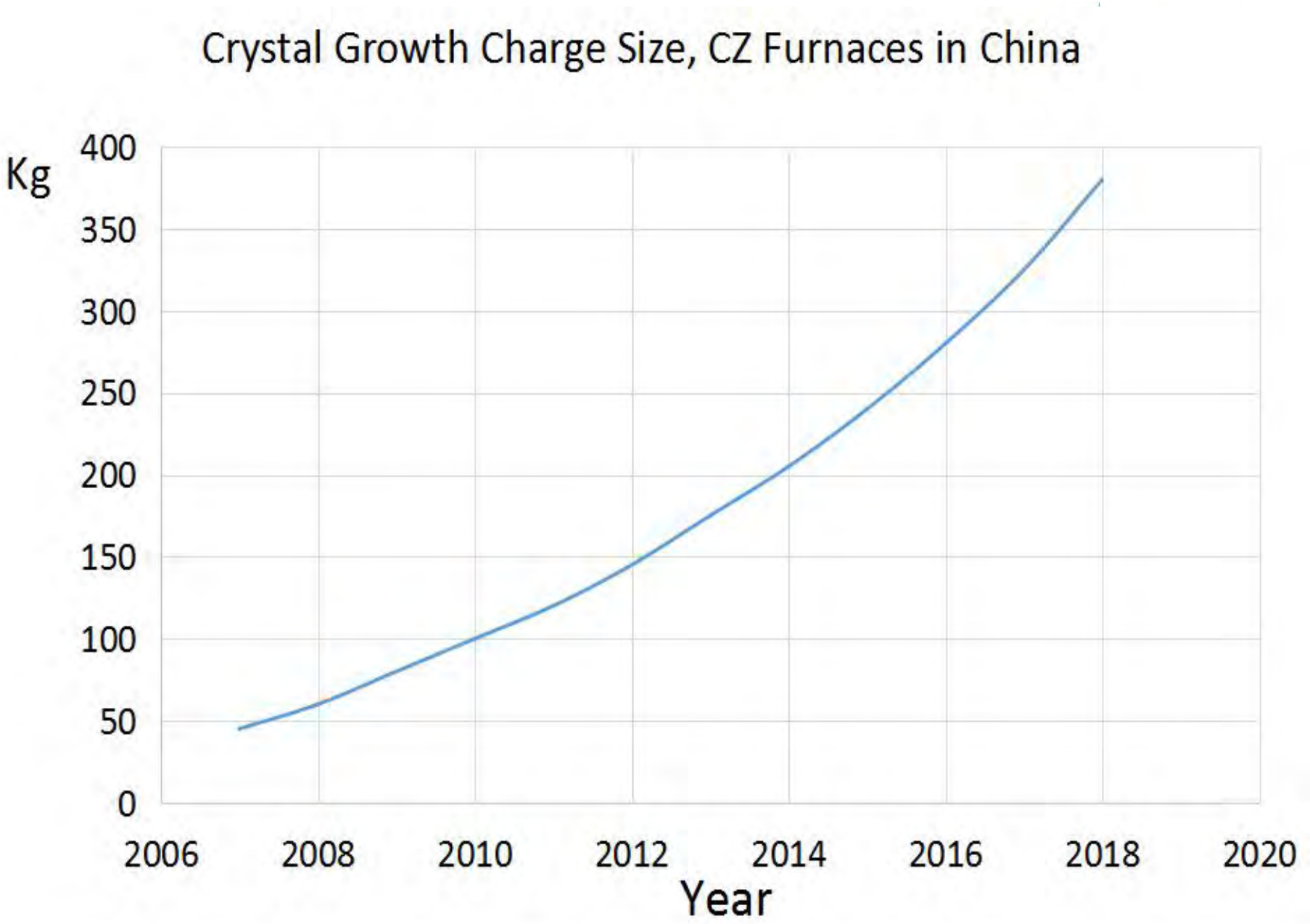
Very large scale production:
A crystal growth shop with 384 CZ pullers

More than 10 similar shops for this producer

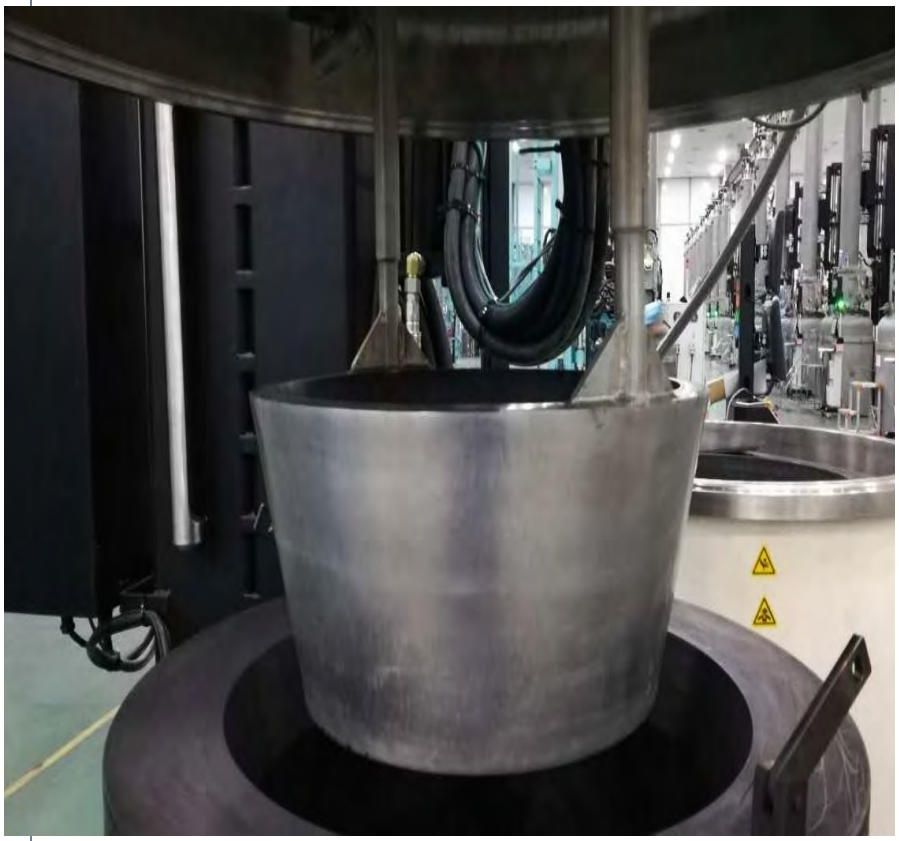
Newer & Larger Furnaces

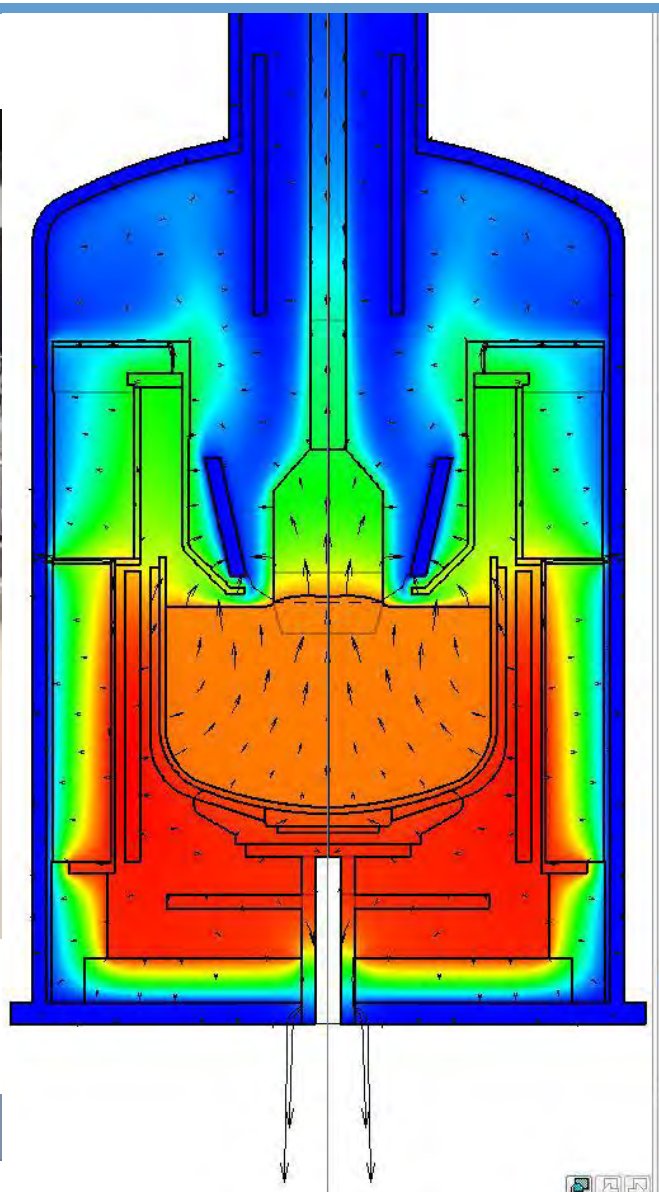
KX170**Series** CZ Crystal Growers
26”/28”/32” Hot Zones
Contains >300kg Silicon
Feeders: Internal & External
Long Receiving Chamber for
> 4 Meter Long Crystals

Longer Crystals due to Larger Charge Size


Crystal Growth Charge Size, CZ Furnaces in China
Kg
400
350
300
250
200
150
100
50
0
2006
2008
2010
2012
2014
2016
2018
2020
Year

Faster growth speed using water cooled heat shield 1.5-1.8 mm/min





Report

SUMMARY

-

Crystal rotation rate:
10 [rpm]

-

Crucible rotation rate:
-9 [rpm]

-

Current CP/CH:
299.993 / 287.475 [mm]

-

Average growth rate:
1.41258 [mm/min]

Average crystallization rate:
1.3677 [mm/min]

Growth rate at triple point:
1.4161 [mm/min]

Crystallization rate at triple point:
1.29261 [mm/min]

Growth rate at center:
1.40969 [mm/min]

Pulling rate:
1.4161 [mm/min]

-

Heater Power:
Control Group 1
Global: 62.4071 [kW]
Block 94: 62.4071 [kW]

-

Required pulling rate:
1.416 [1.40184;1.43016] [mm/min]

Calculated pulling rate:
1.4161 [mm/min]

-

-

Other Heaters Power:
Global: 0 [kW]

-

RF Global: 0 [kW]

-

Total Power:
62.4071 [kW]

-

Crystal mass:
20.5704 [kg]

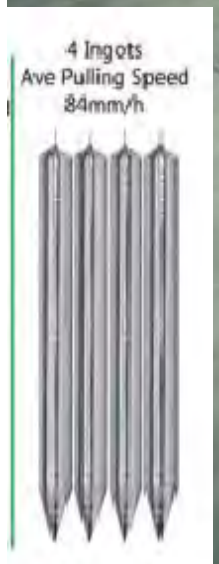
Volume of the bottom crystal part (b
-0.0003348 [m^3]

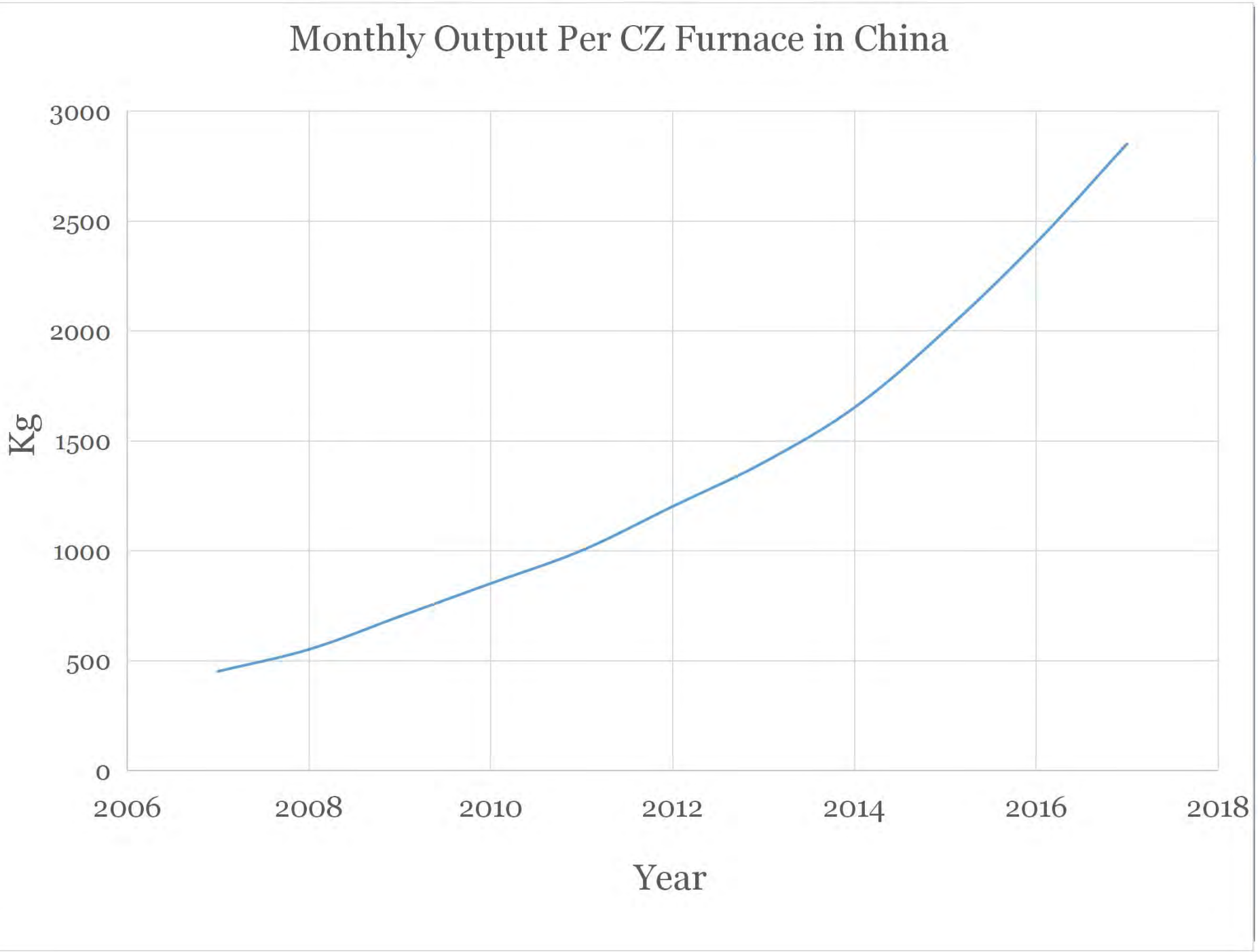
Meniscus height:
6.95203 [mm]

Meniscus weight:

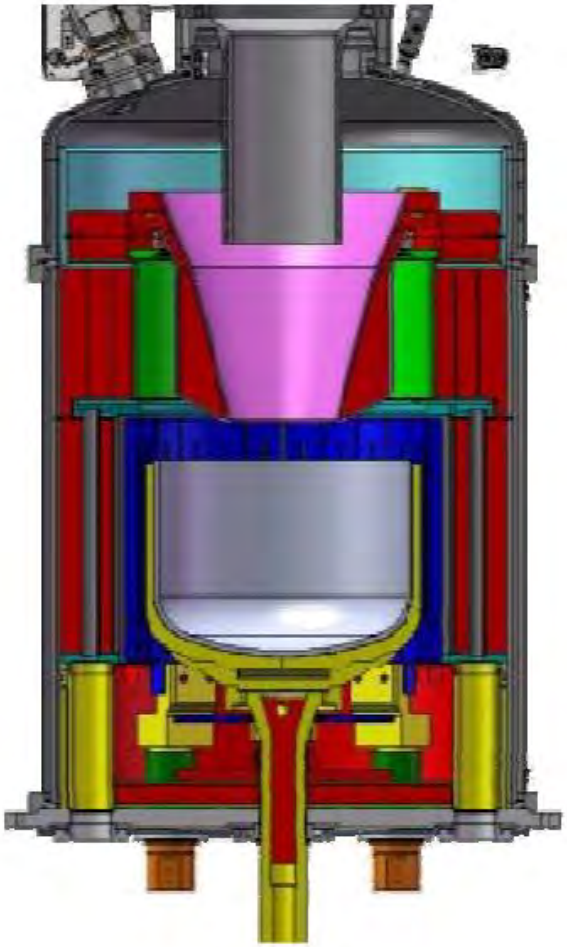
Report For...
Category
Frame

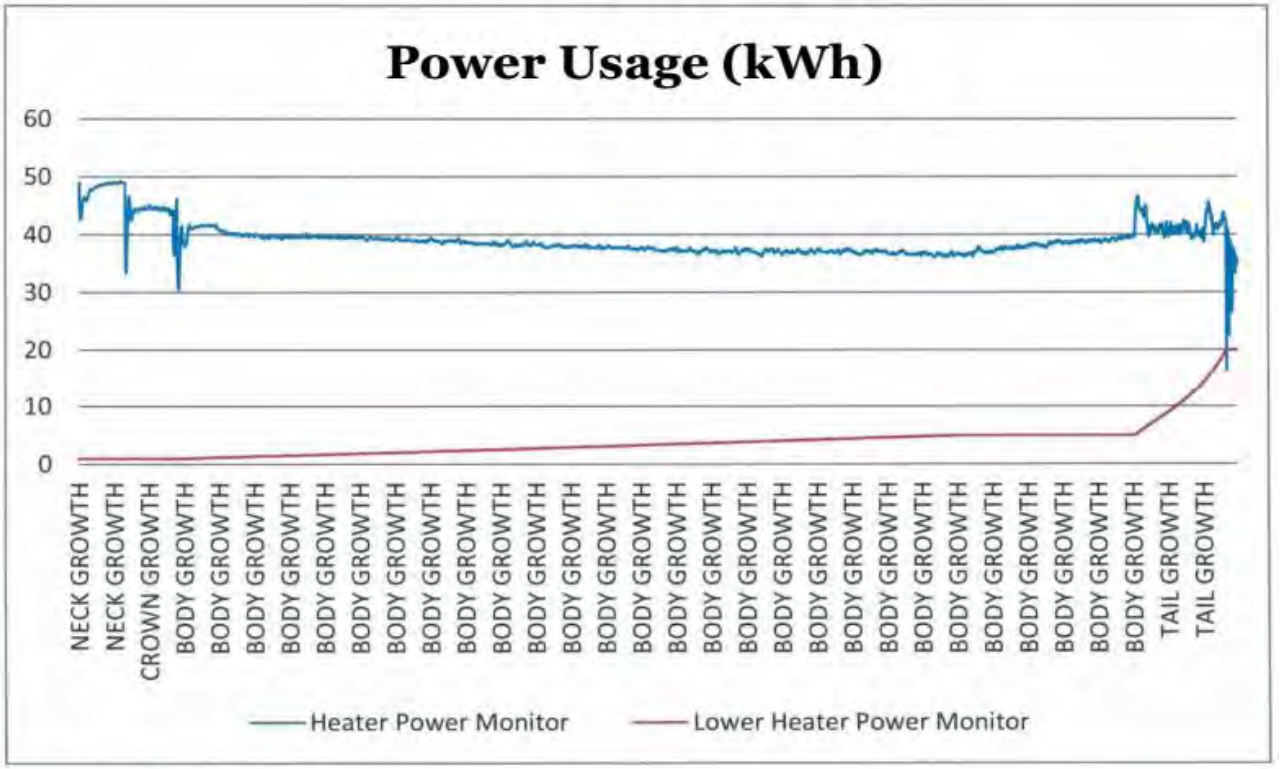
Long Life Crucibles Allows Multiple Pulls
Typically 3-4 Crystals Per Crucible
Over 1000 kg in Total

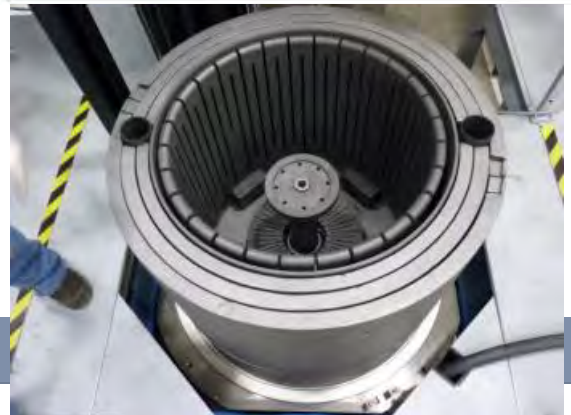



Monthly Output Per CZ Furnace in China
3000
2500
2000
1500
1000
500
0
Kg
2006
2008
2010
2012
2014
2016
2018
Year

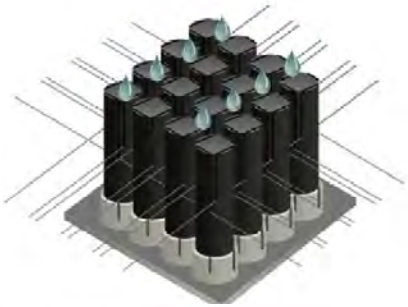
Low power Hot Zone resulting in energy savings

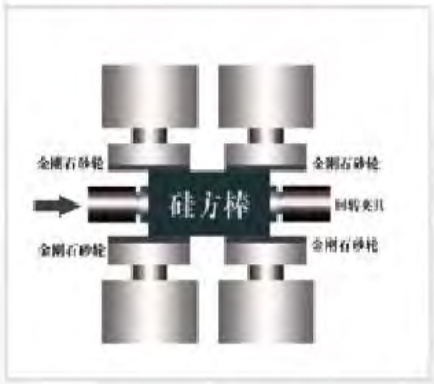


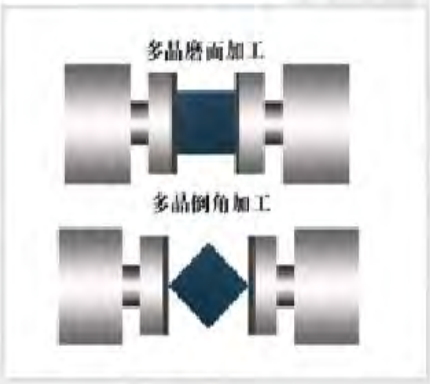


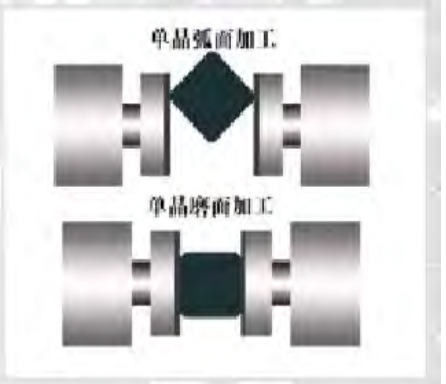


Central control and automation improve production efficiency & yield





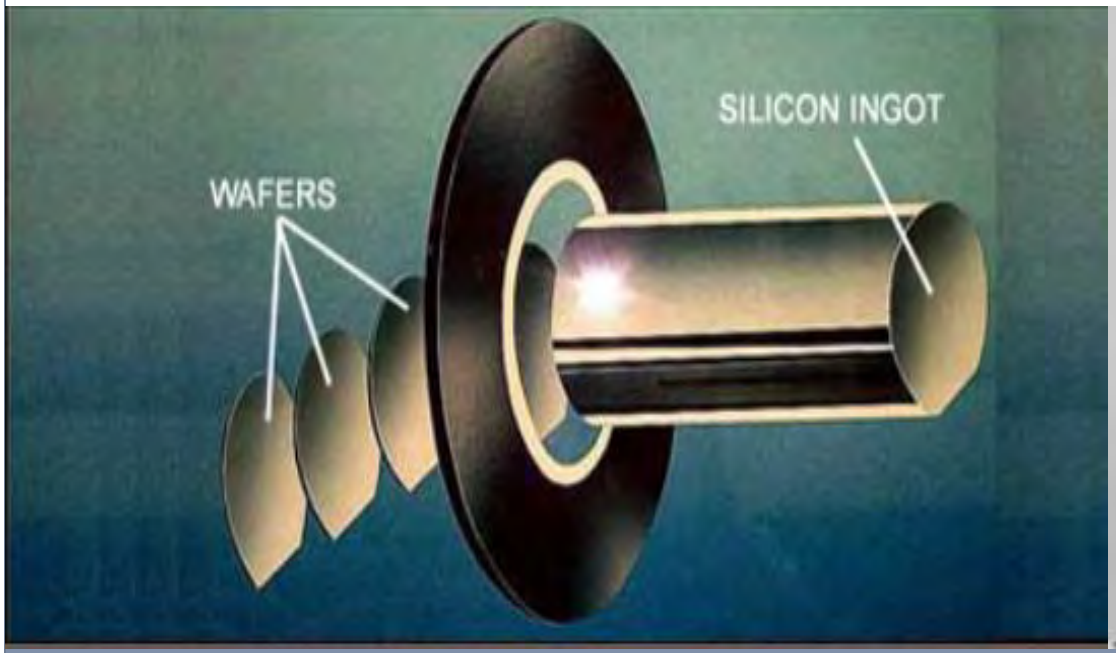


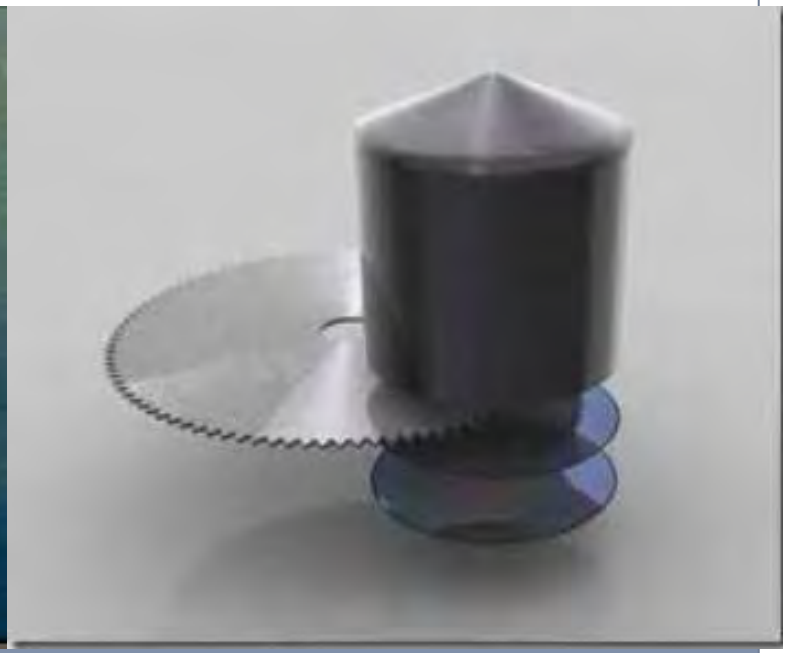


Wafer Cutting – Technology Leads to Revolutionary Cost Savings

Originally wafers are cut with saw blades

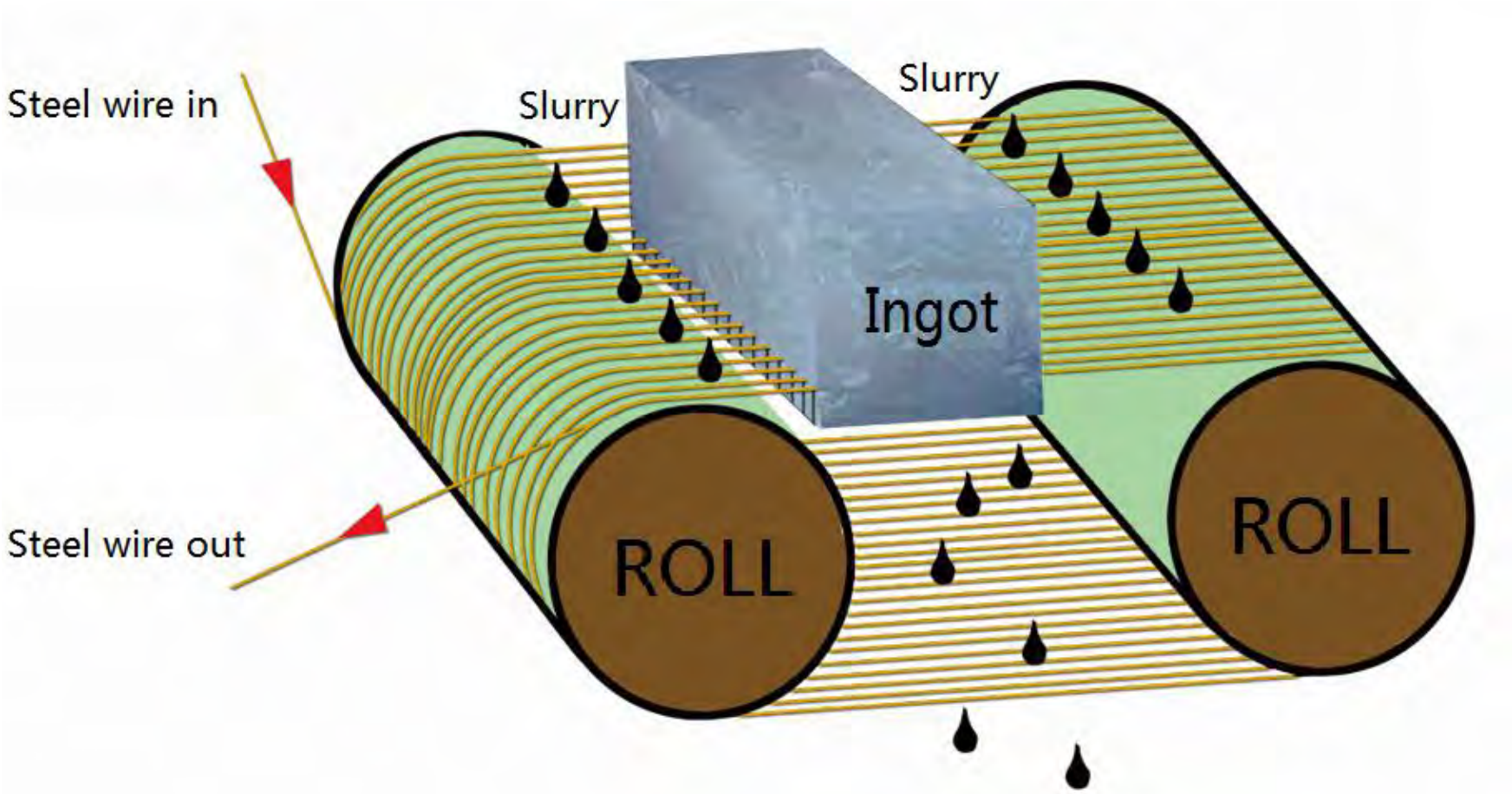
- One wafer for each cut – not efficient
- Too much kerf loss – more than 70% silicon lost in saw cuts
- Not suitable for thin wafers, which are needed in solar industry
- Too expensive, too slow, too wasteful
- Not suitable for solar wafer production, a new method must be found



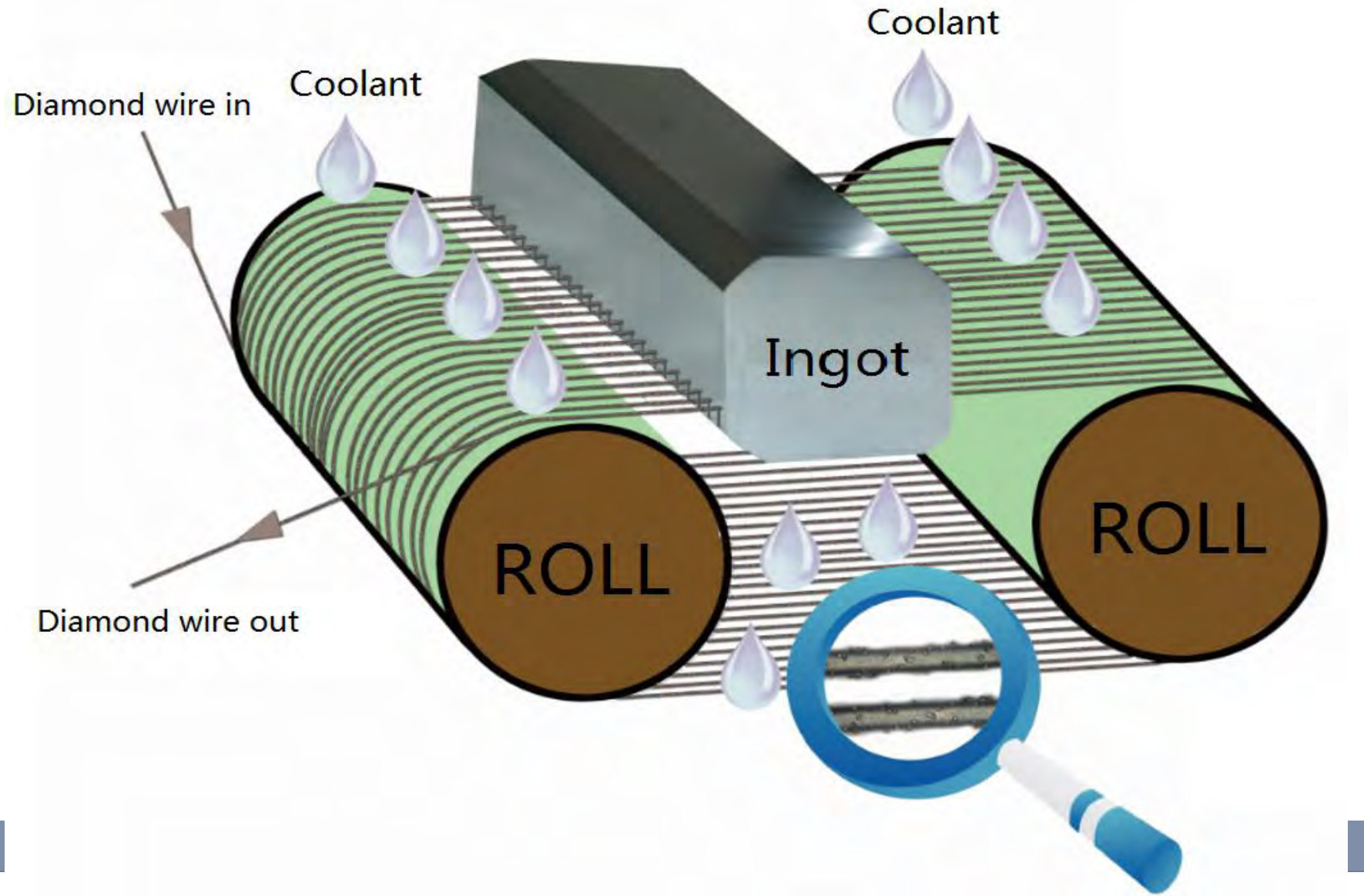


Wafer Cutting – Multi-Wire Saw Using Slurry

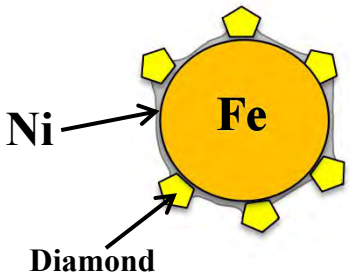
In the 1990's the slurry type multi-wire saws are gradually being used in wafer production

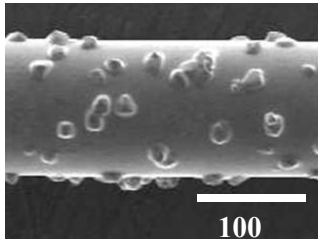


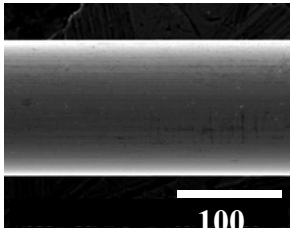
Diamond Wire Wafer Cutting – A New Technology

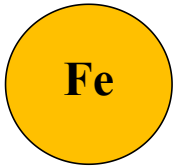


Comparison of Diamond Wire Cutting to Slurry Cutting

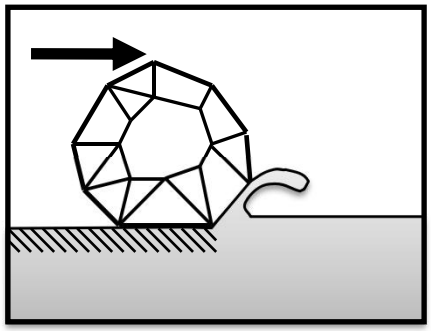






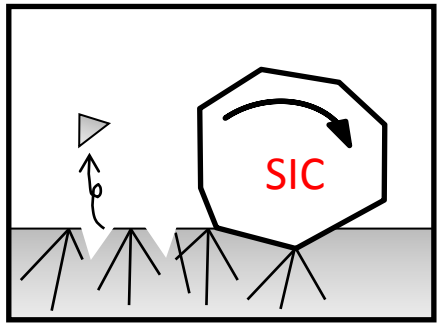


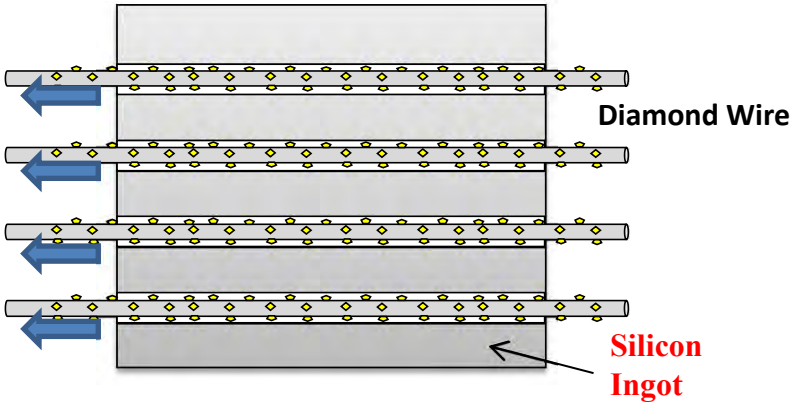
+ SiC Slurry

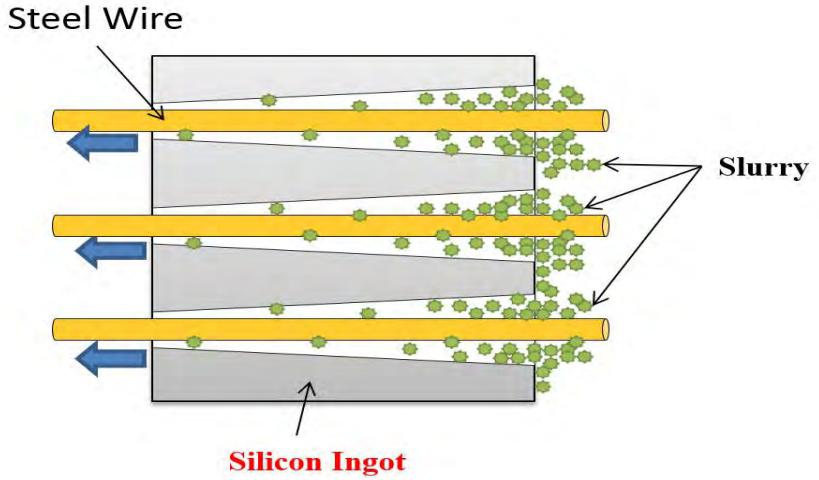


Diamond Wire Cutting

Slurry Cutting

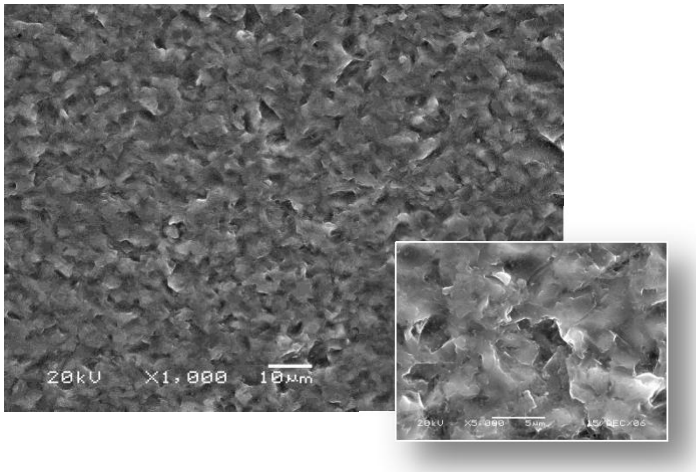




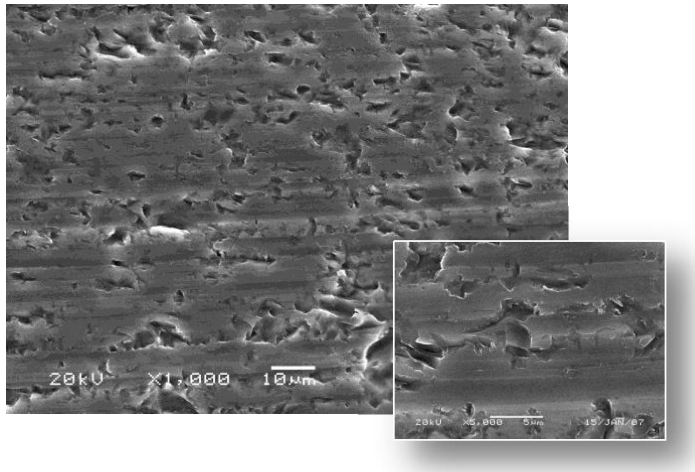


Comparison of Different Wafer Slicing Methods

- Less surface defects



Wafer by slurry



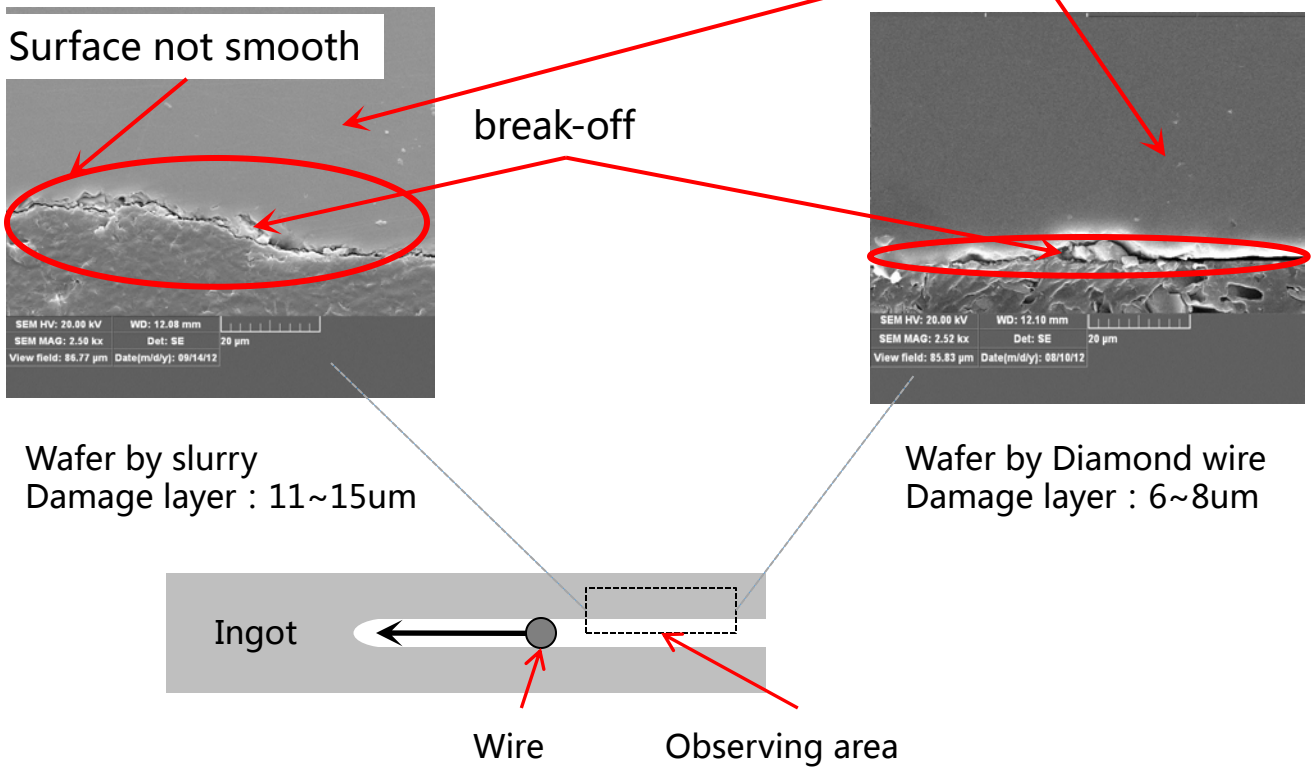
Wafer by Diamond wire

Comparison of Different Wafer Slicing Methods

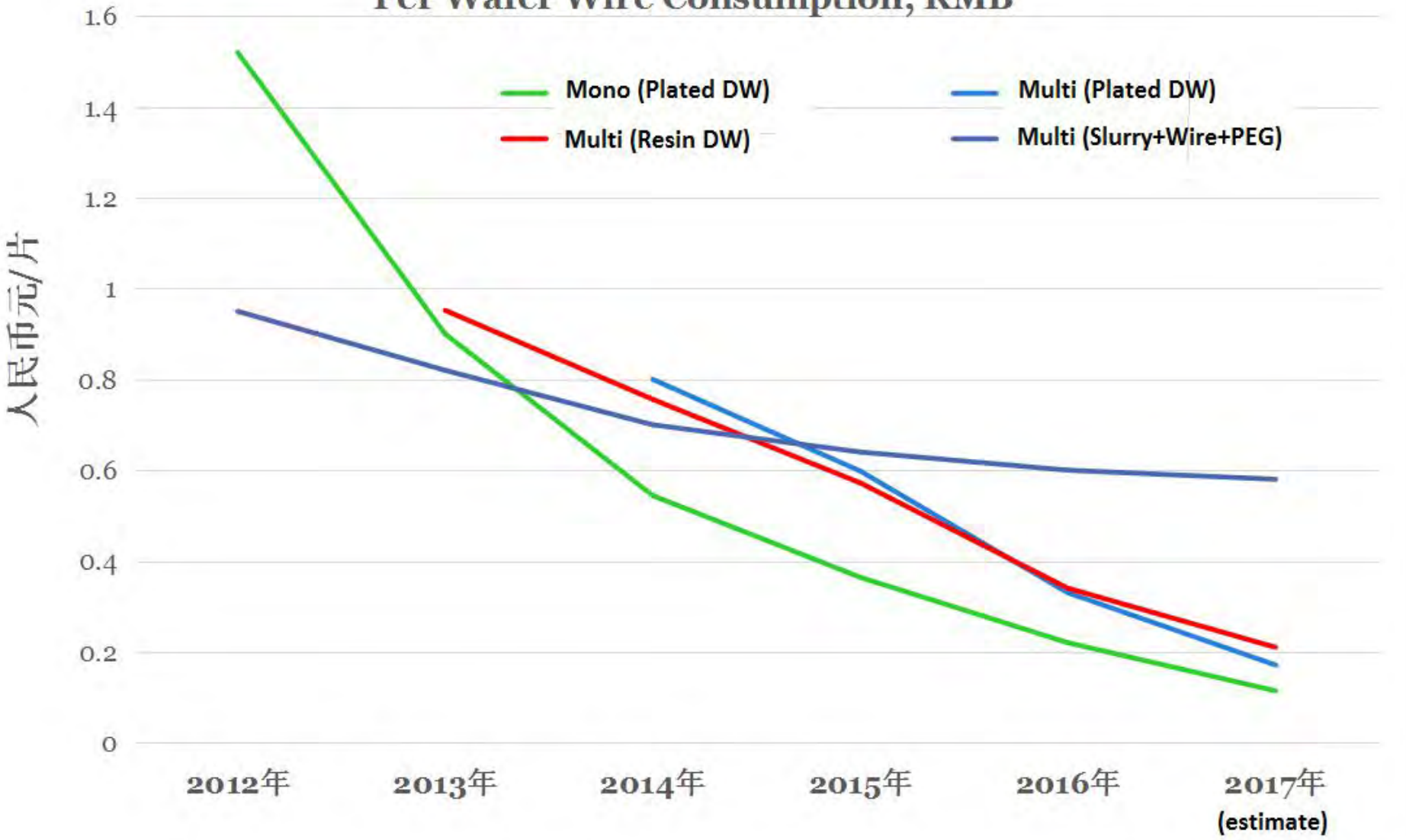
- Less surface damage

SEM photo of wafer cross section showing surface damage

Cross Section of Silicon Wafer



不同切片技术单片线耗成本趋势比较

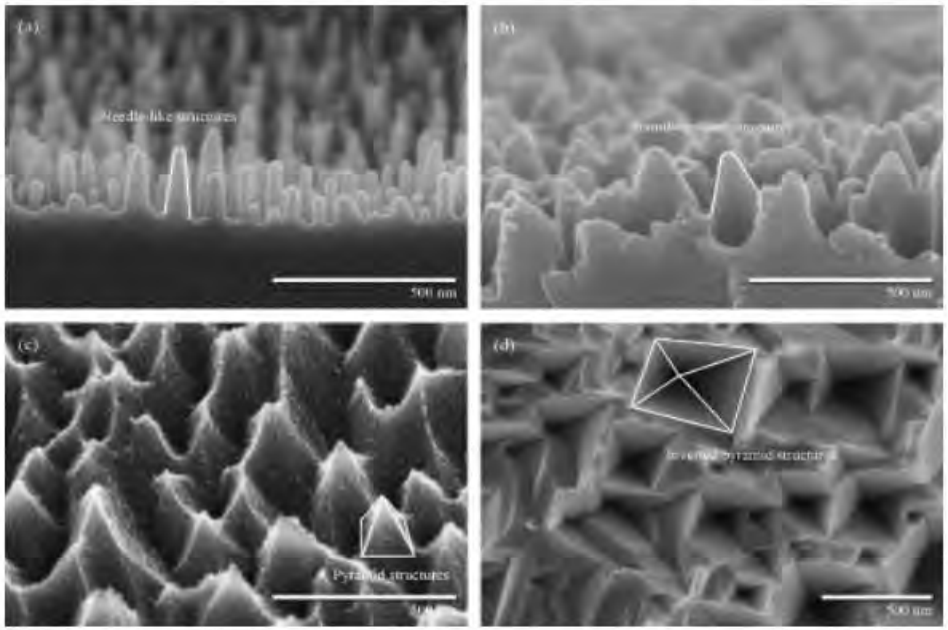


Comparison of Different Wafer Slicing Methods

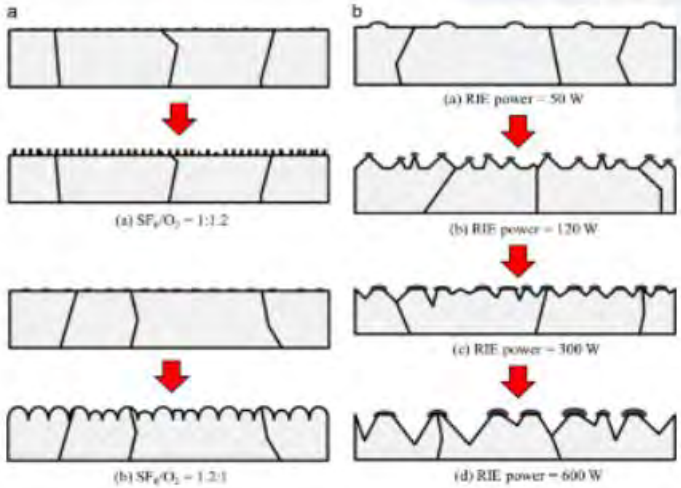
	Slurry	DW Multi-Crystal	DW Mono-Crystal
Wear Principle	3-Body	2-Body	2-Body
Wafers per machine per day	5000	14000	17500
Wire consumption (m/wafer)	120	4.5/1.5	1.1
Wire diameter (mm)	0.12	0.07-0.08	0.07
Kurf loss (%)	43%	31-33%	31%
Yield (wafer/kg of ingot)	48	58	60
Cutting fluid	PEG	Water	Water
Slicing cost (RMB/wafer)	1.40	0.85	0.70
Surface damage	High	High	Low
Metal Transfer	High	Low	Low
PV Conversion Efficiency	+0%	+0.2%	+0.2%

Combined cost savings of DW slicing is at least **1** RMB per wafer compared with slurry slicing

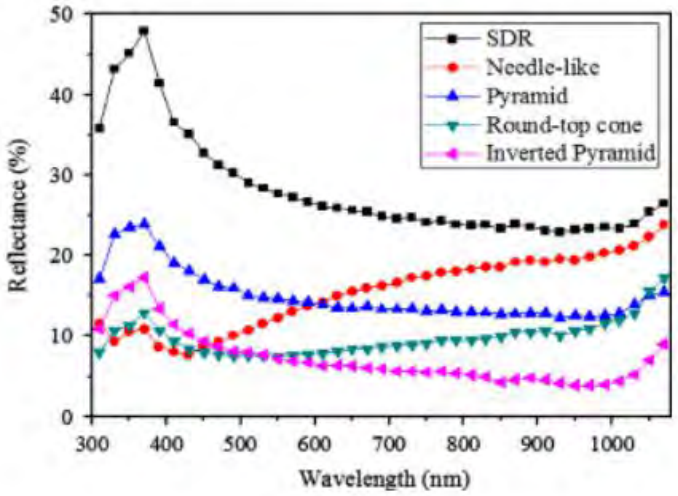
“Black Silicon” treatment is needed for diamond wire cut multi-crystalline wafers - a technical barrier

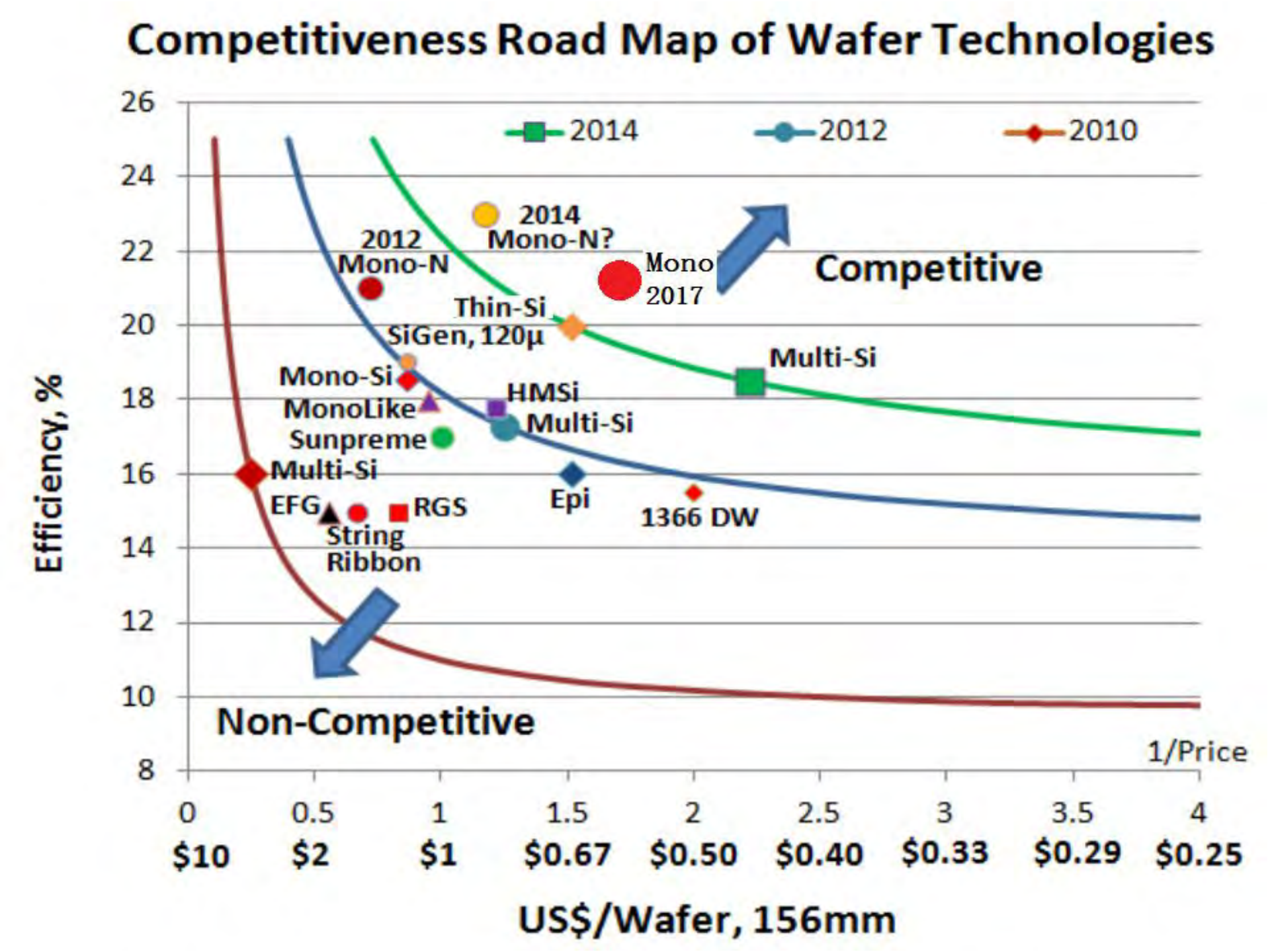


Surface features on an mc-Si wafer formed by RIE texturing: (a) needle, (b) RT cone, (c) pyramid, and (d) inverted pyramid structures



Explanation for formation of each surface feature




Competitiveness Road Map of Wafer Technologies
Efficiency, %
26
24
22
20
18
16
14
12
10
8
2014
2012
2010
2014
Mono-N?
2012
Mono-N
Mono
2017
Competitive
Thin-Si
SiGen, 120µ
Multi-Si
Mono-Si
HMSi
MonoLike
Multi-Si
Sunpreme
Multi-Si
EFG
RGS
String
Ribbon
Epi
1366 DW
Non-Competitive
1/Price
0
0.5
1
1.5
2
2.5
3
3.5
4
$10
$2
$1
$0.67
$0.50
$0.40
$0.33
$0.29
$0.25
US$/Wafer, 156mm

Summary

- Progress in crystal growth technology has been a powerful driving force behind the growth of solar PV industry.
- Multi-crystalline silicon wafers have so far maintained the leading position in solar market, benefited from generations of larger ingots, enhancement of PV conversion efficiency, and associated cost reduction per watt.
- Mono-crystalline wafers are gaining market share from multi-crystalline wafers, due to faster cost reduction resulted from technical advancements.
- Diamond wire wafer slicing technology greatly reduces production cost of crystalline silicon wafers, further strengthening their competitive advantage against other wafer technologies.

Thank you!

謝謝！

감사합니다!

ありがとうございました！

Merci!

Děkuji vám!

www.lintoncrystal.com

www.lintonmachine.com

lizx@lintonmachine.com