Czochralski Growth of Silicon Wafers

Senior Design Project

Faculty Advisor: T.R. Sinno

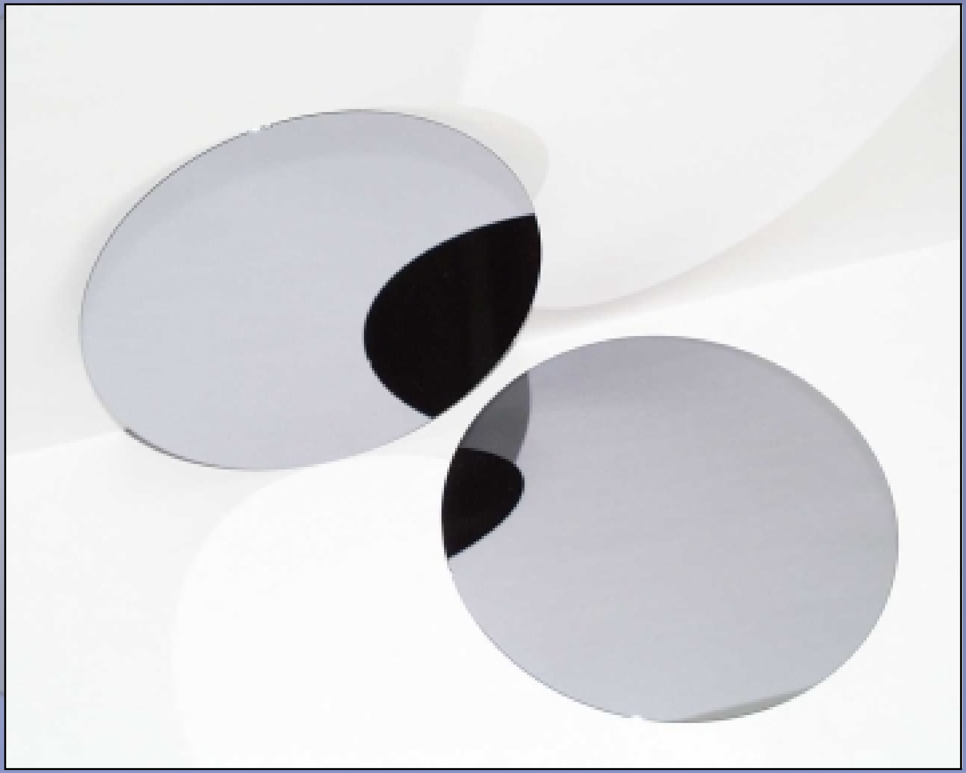
Sean Cusack
Eiji Takizawa
Joyce Tam

Project Outline

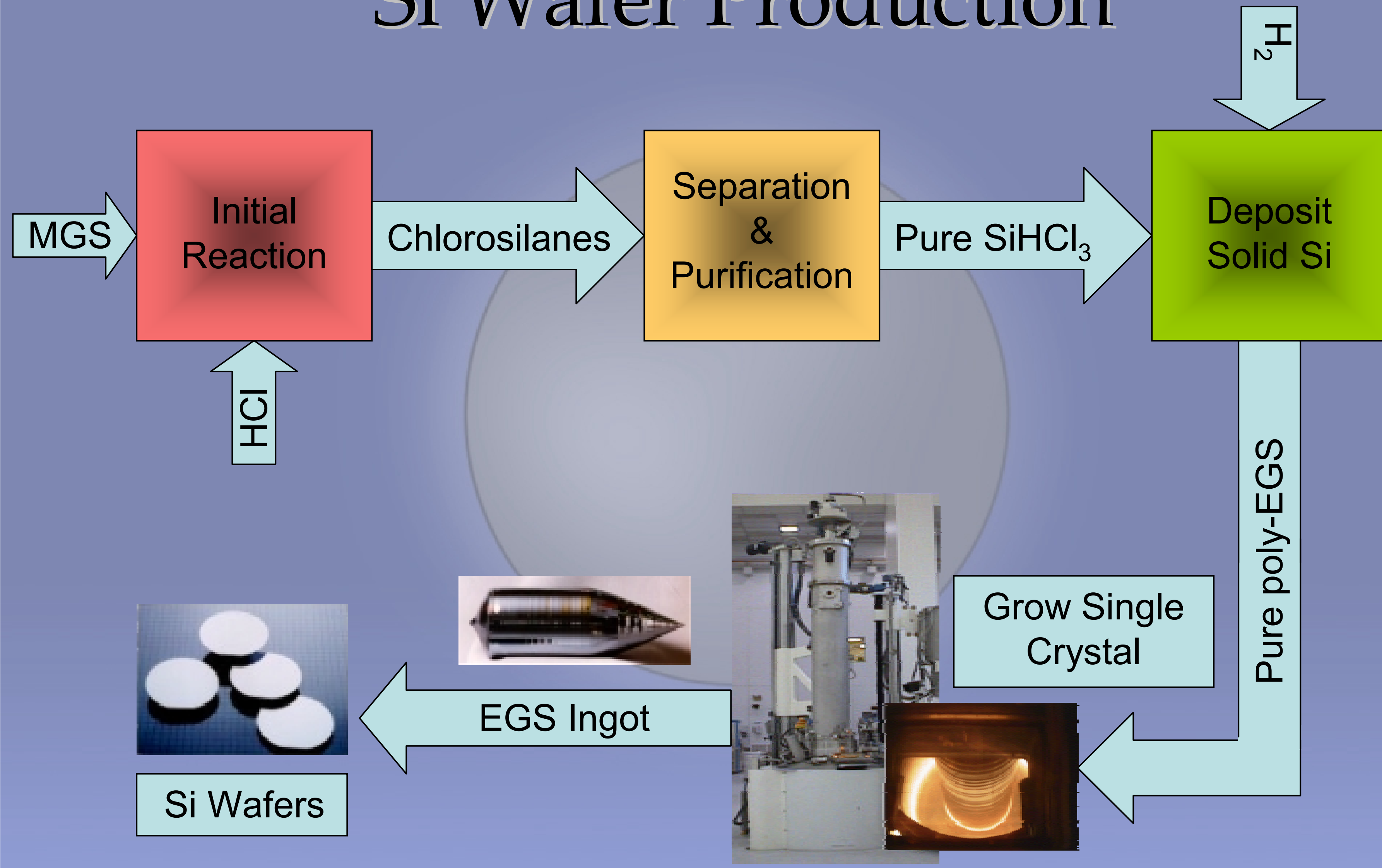
- Is it economically feasible to enter the silicon wafer market?
  - Describe a process to produce silicon wafers
  - Introduce a revolutionary method for reducing plant capital cost (batch recharge)
  - Evaluate economic feasibility of entering market using both traditional and batch recharge methods

Silicon Wafer Basics

- Wafer Diameters: 200mm or 300mm
- Wafer Thickness: ~650µm
- Wafer Purity: 150 parts/trillion impurities (99.99999999% Si)
- Single Crystal



Si Wafer Production



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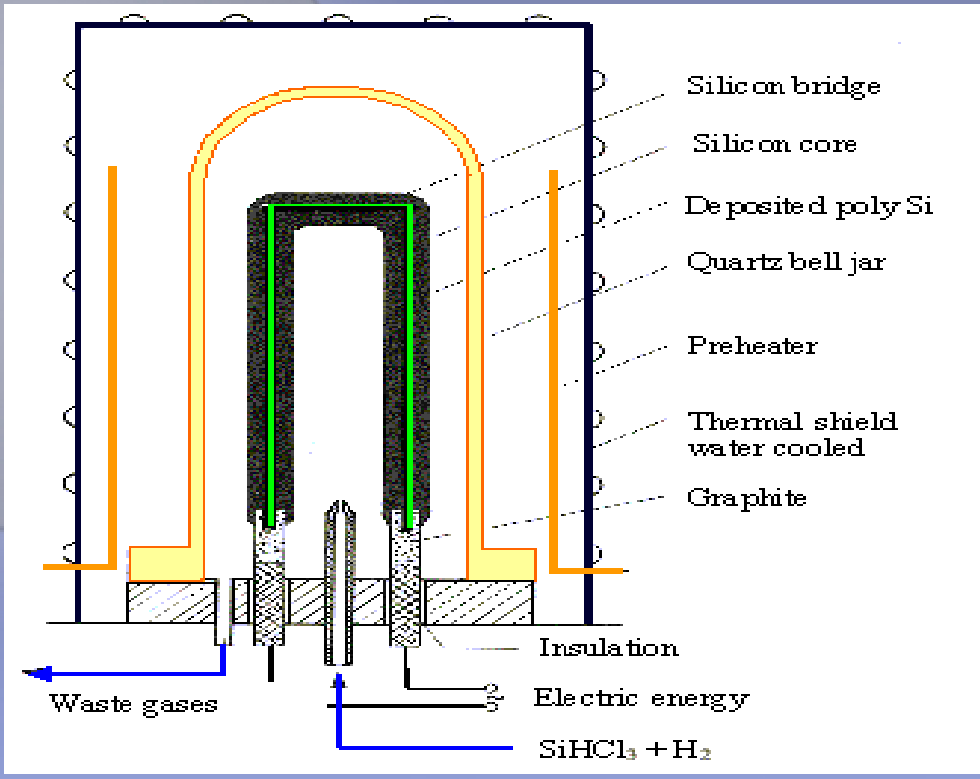
Deposit Solid Si: Siemens Reactor

- Pure $SiHCl_3$ in Gas Phase → Pure Si in Solid Phase
  - Chemical Vapor Deposition (CVD) process
  - Specific Reactor Type = Siemens Reactor

- Deposition process is slow
  - 10 days/ton

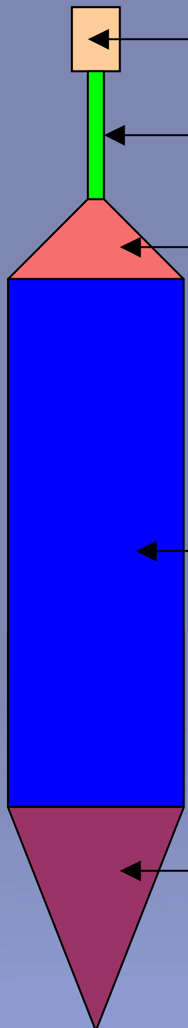
- How many Siemens reactors are required?
  - 12 Siemens reactors required



Czochralski Crystal Grower

- Poly-EGS is melted in a quartz crucible (SiO_2)
- Seed particle introduced to begin crystallization
- Seed pulled to generate desired wafer diameter
- Ingot is cooled
- Crucible is discarded (warping and cracking)

Finished Crystal Parts



Seed: Starts Crystal

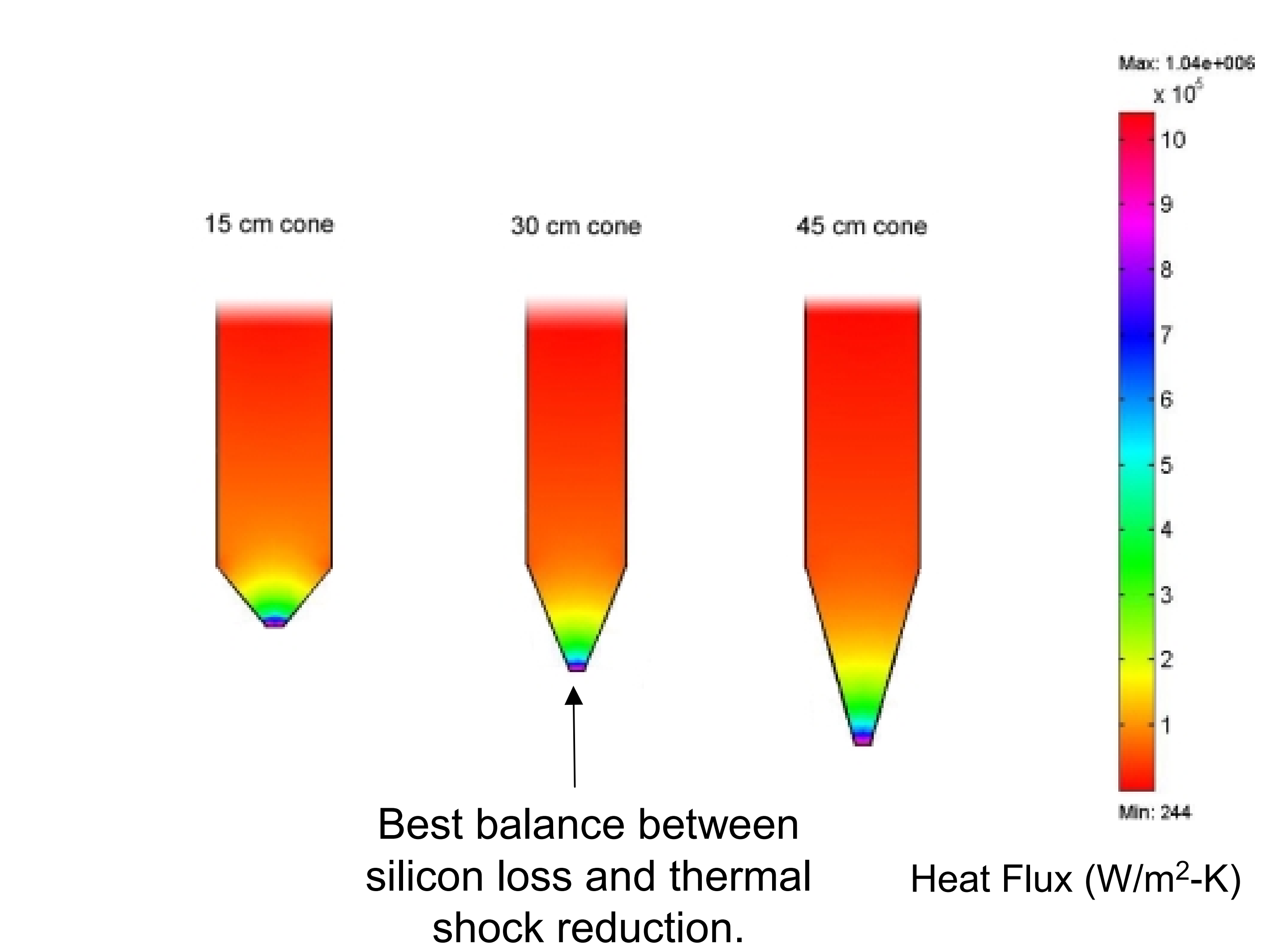
Neck: Prevents thermal shock

Shoulder: Transitions to body section

Body: Part of crystal sliced into wafers

End cone: Prevents thermal shock

End Cone Femlab results



Czochralski Results

- From presented data, we can calculate:
  - Throughput/Cz grower
    - Total number of Cz growers required

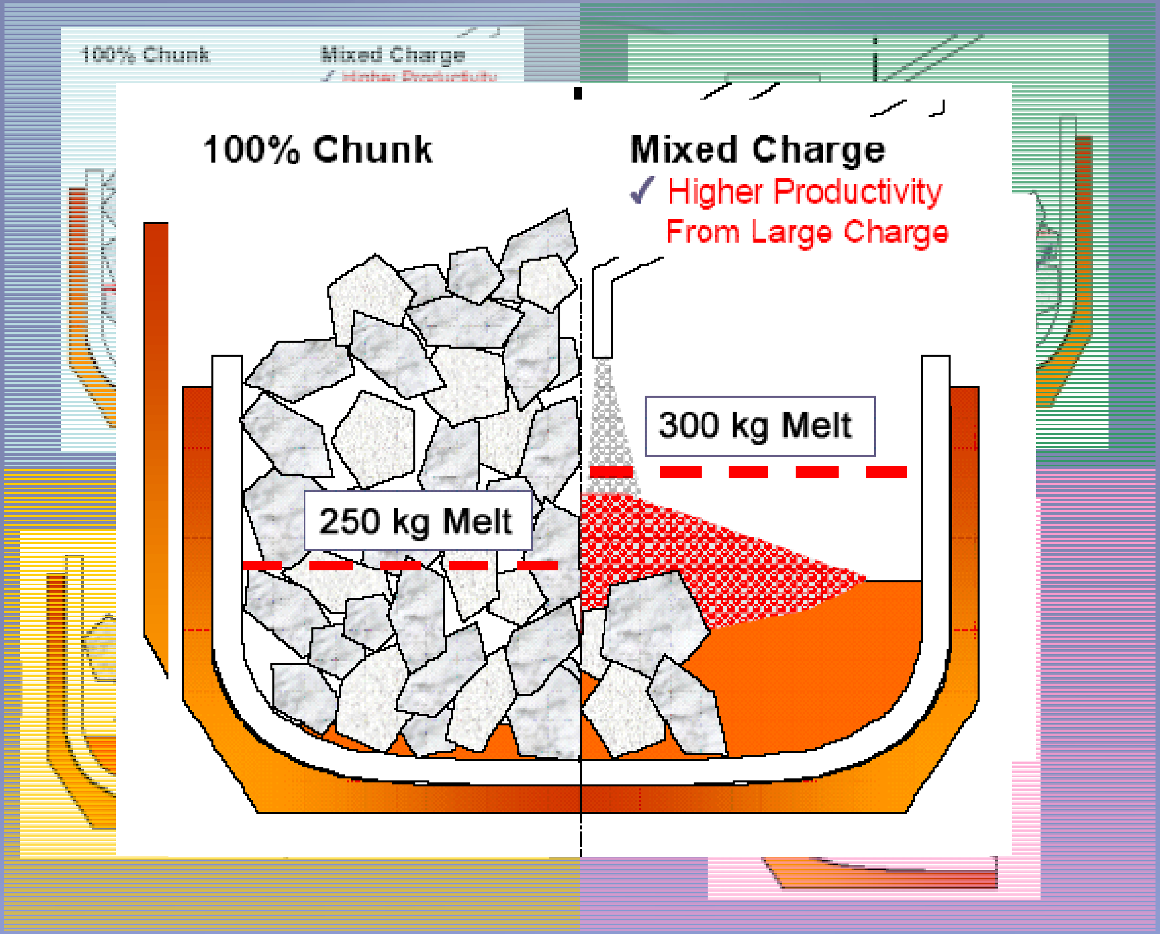
26 Cz Growers needed to produce

100,000 wafers/month

Batch Recharge Cz (BRCz) Method

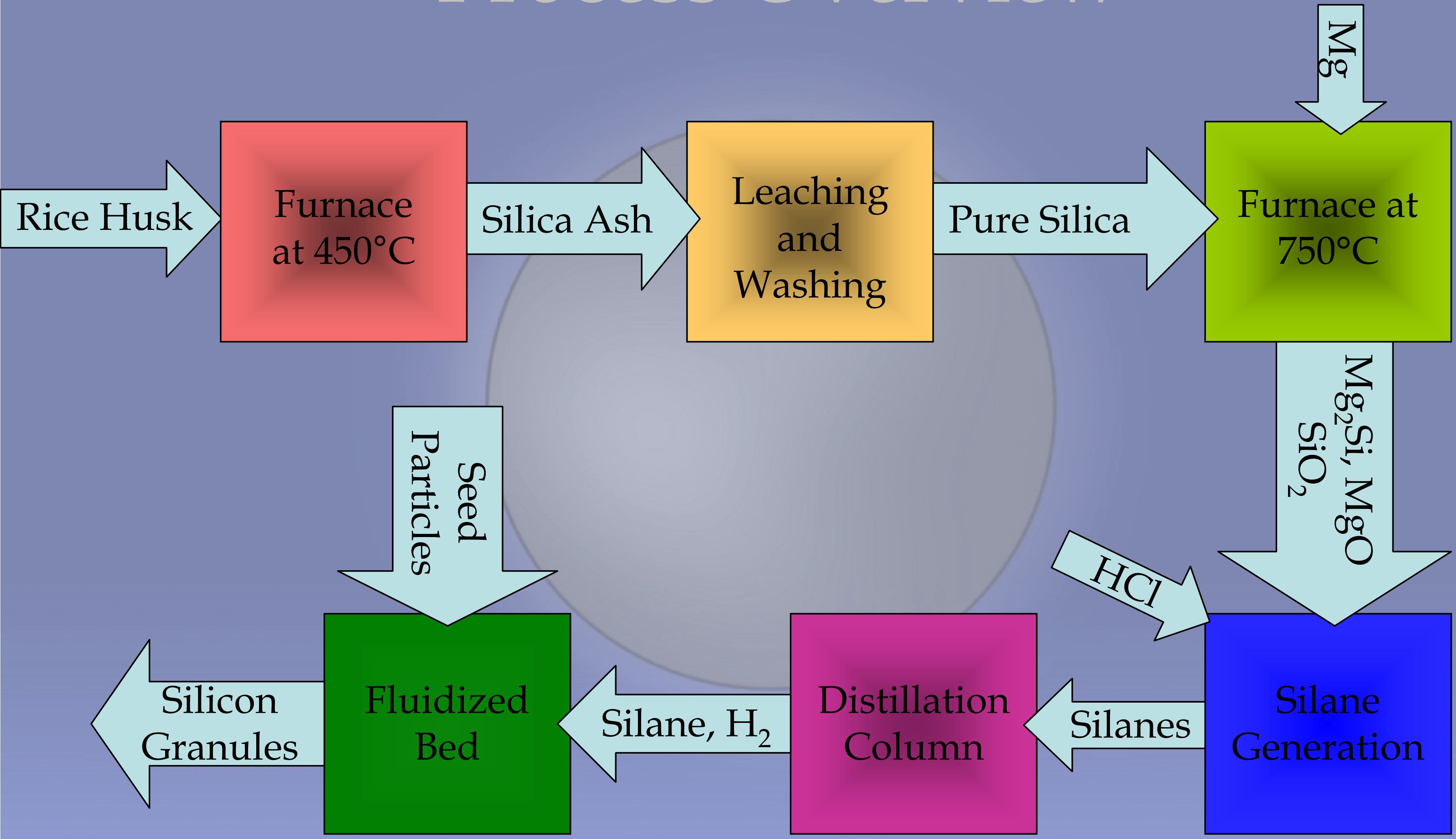
- Czochralski grower crucible can be recharged 7 times before it is discarded.
- Recharge is done using granular silicon.
- Initial charge of crucible is mixed.

Mixed Charge vs. Chunk Charge



Figures from MEMC

Process Overview



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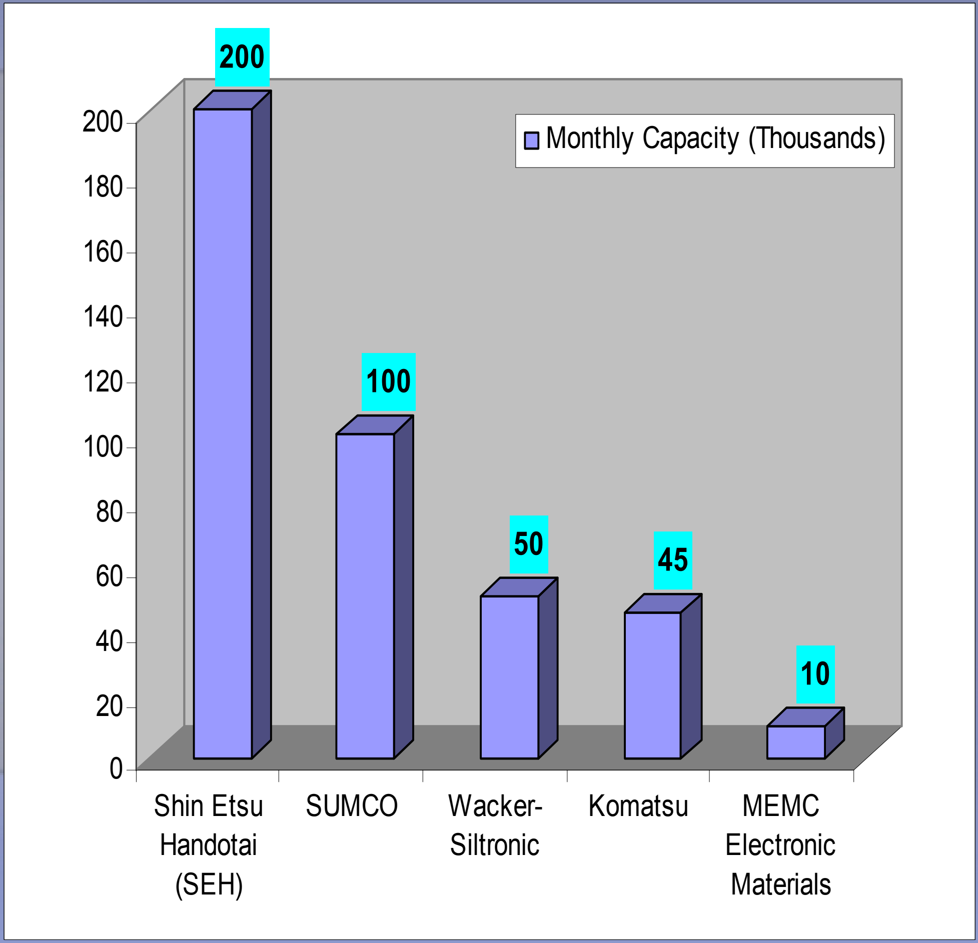
Summary of BRCz

- Benefits of Batch Recharge Cz:
  - Crucible life is extended
  - Throughput is increased (8 BRCz Growers = 9 Traditional Cz Growers)
  - Utilities are reduced
  - Larger charge size
  - Yield is improved
    - In traditional Cz, 7.5% (18.75 kg) of charge is lost as residual melt in the crucible (pot scrap).
    - $\frac{18.75}{(8)(300)} * 100 = 0.78\%$ of EGS is lost as pot scrap.
- Drawback of BRCz:
  - Need to build additional plant
    - But previous plant can be downsized

The Big Five

- The Big Five: SEH, SUMCO, Wacker-Siltronic, Komatsu, and MEMC
- 90% of world's Si wafer producers
- MEMC Expansion



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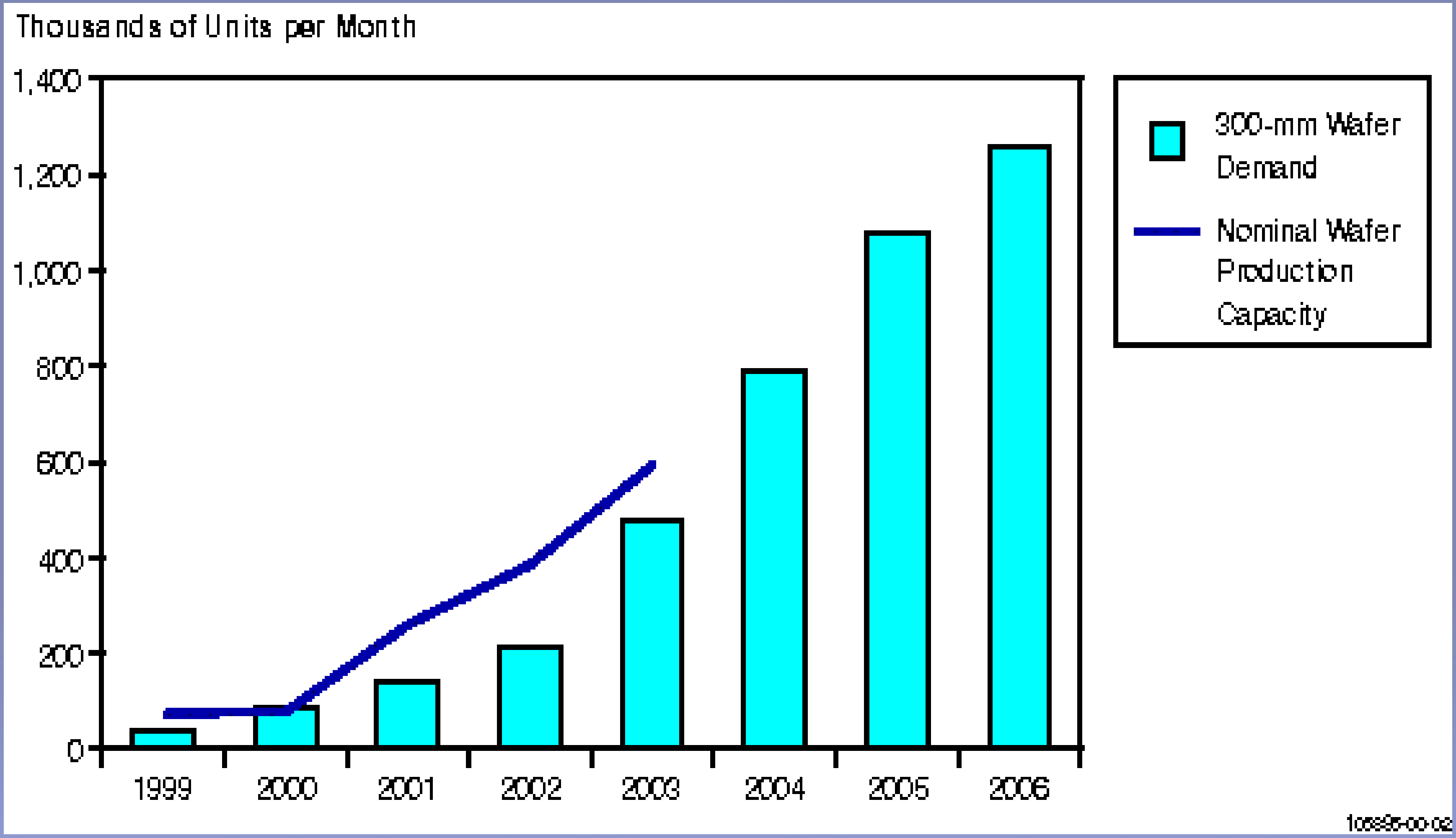
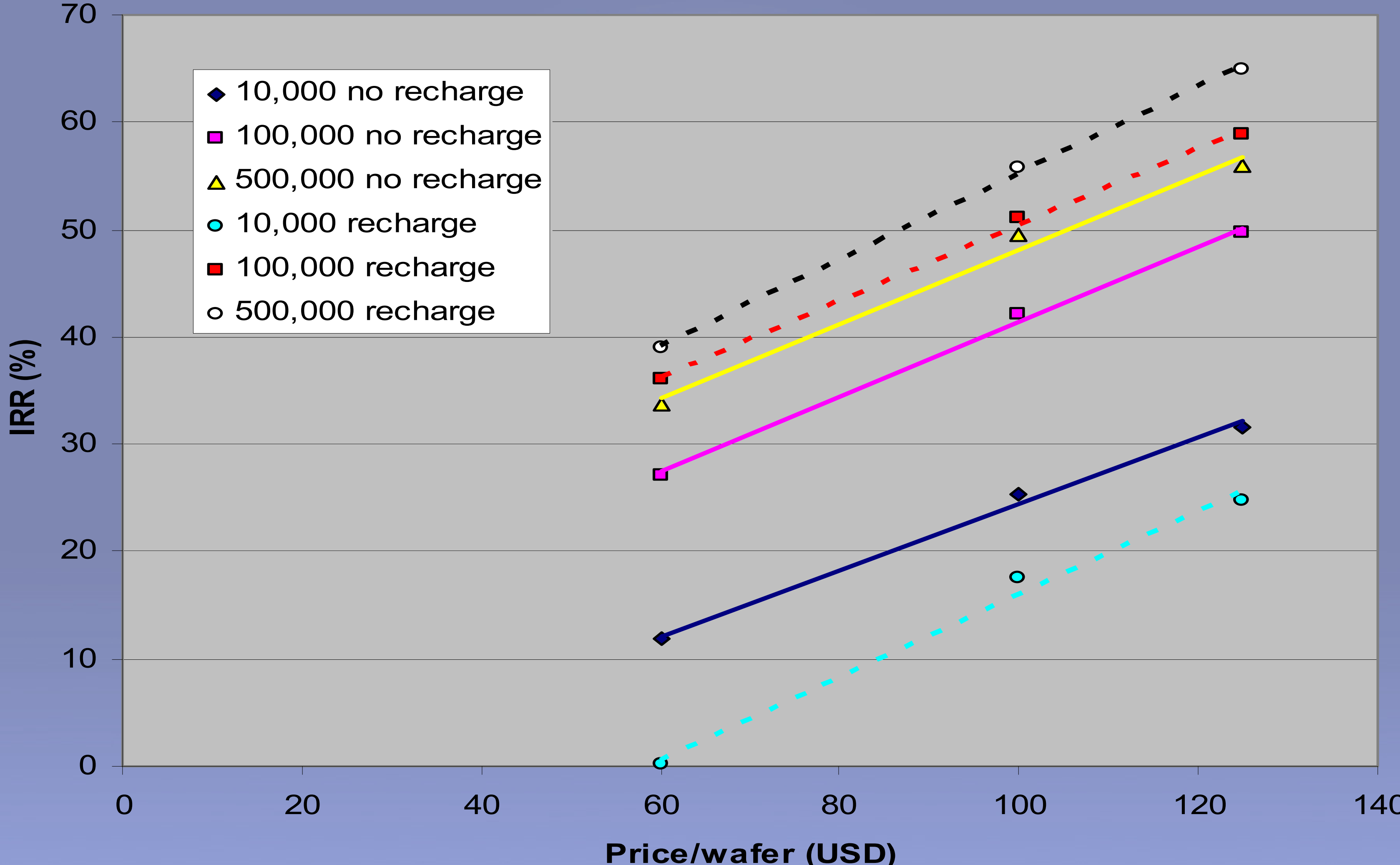
Market Wafer Demand Trend



Initial Considerations

- 300mm Wafer Market Price
  - $200/wafer
- 300mm Wafer Competitive Price
  - $125/wafer
- For each plant option there are three scenarios
  - 1. 10,000 wafers/month
  - 2. 100,000 wafers/month
    - Initial production plan
  - 3. 500,000 wafers/month
    - Counter wafer expansion expectations (MEMC)

IRR Trends



10,000 no recharge
100,000 no recharge
500,000 no recharge
10,000 recharge
100,000 recharge
500,000 recharge
IRR (%)
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
Price/wafer (USD)

Conclusions

- Main plant and alternate method economically feasible
- Batch Recharge is better option
- Primary Suggestion (500,000 wafer plant)
  - $60 per Wafer (39% IRR)
- Secondary Suggestion (500,000 wafer plant)
  - $100 per Wafer (55.8% IRR)

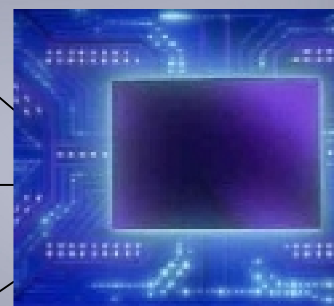
Acknowledgements

- Our Advisor – Dr. Talid Sinno
- CBE & MSE Departments
- Industrial Consultants
- The Aspen God: Professor Fabiano

Questions

Intro Supporting Slides

The Impact of Silicon Chips



1 billion PCs sold worldwide by July, 2002

2 billion projected for 2008 (BBC)

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What is a Silicon Wafer?

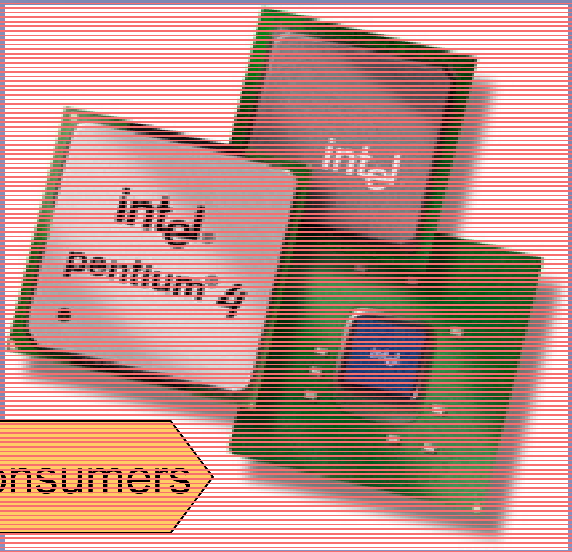
- Starting material for chip design

Plant End Processing

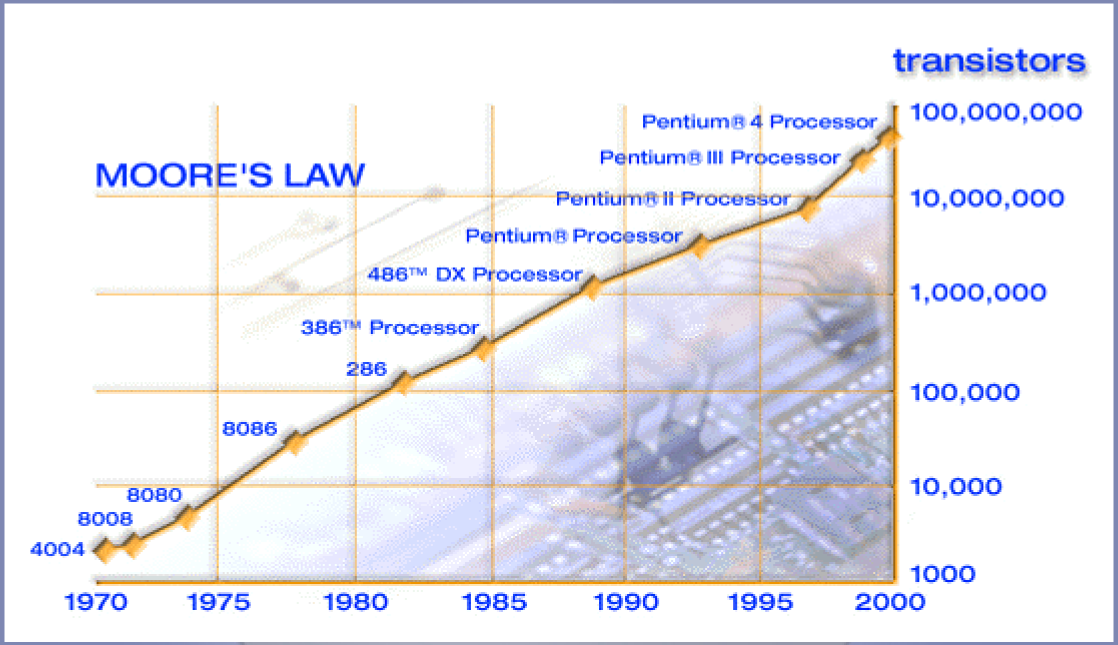
Customer End Processing

Sell to Manufacturers

Sell to Consumers



Silicon Purity: Moore's Law



- Number of transistors ~ processor speed
- Chip size is approximately constant
  - Transistor size must shrink
  - More control of material properties required = higher purity

The Si Wafer Market

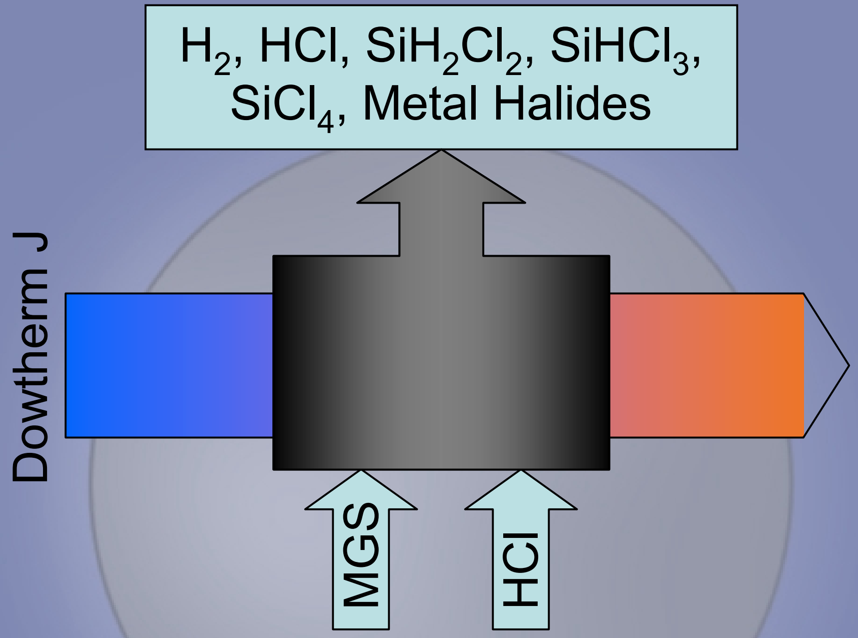
- Only 5 major Si Wafer manufacturers
- Possible market entry?

Cost Analysis Summary

	10,000 wafer plant			100,000 Wafer Plant			500,000 Wafer Plant		
Wafer Price ($)	**IRR**	**ROI**	**TCI**	**IRR**	**ROI**	**TCI**	**IRR**	**ROI**	**TCI**
60	11.80%	13.50%	$17.80	27.50%	37.10%	$91	33.80%	60%	$354.30
100	25.30%	30.50%	$17.80	42.20%	72.50%	$91	49.50%	93.60%	$354.30
125	31.50%	41.10%	$17.80	49.70%	93.20%	$91	56%	120.30%	$354.30
Recharge Method	**IRR**	**ROI**	**TCI**	**IRR**	**ROI**	**TCI**	**IRR**	**ROI**	**TCI**
60	0.10%	3.80%	$22.50	36.00%	57.60%	$71.80	39%	64.50%	$296.80
100	17.50%	17.30%	$22.50	51%	99.20%	$71.80	55.80%	115.50%	$296.80
125	24.70%	25.70%	$22.50	58.80%	125.60%	$71.80	65%	147%	$296.80

Process Supporting Slides

Initial Reaction: Fluidized Bed



- Fluidized Bed is used due to high ΔH_{rxn}=-58.6 kcal/mol $SiHCl_3$
- Cooling using a tube bundle inside of bed
  - Heat Transfer Fluid = Dowtherm J

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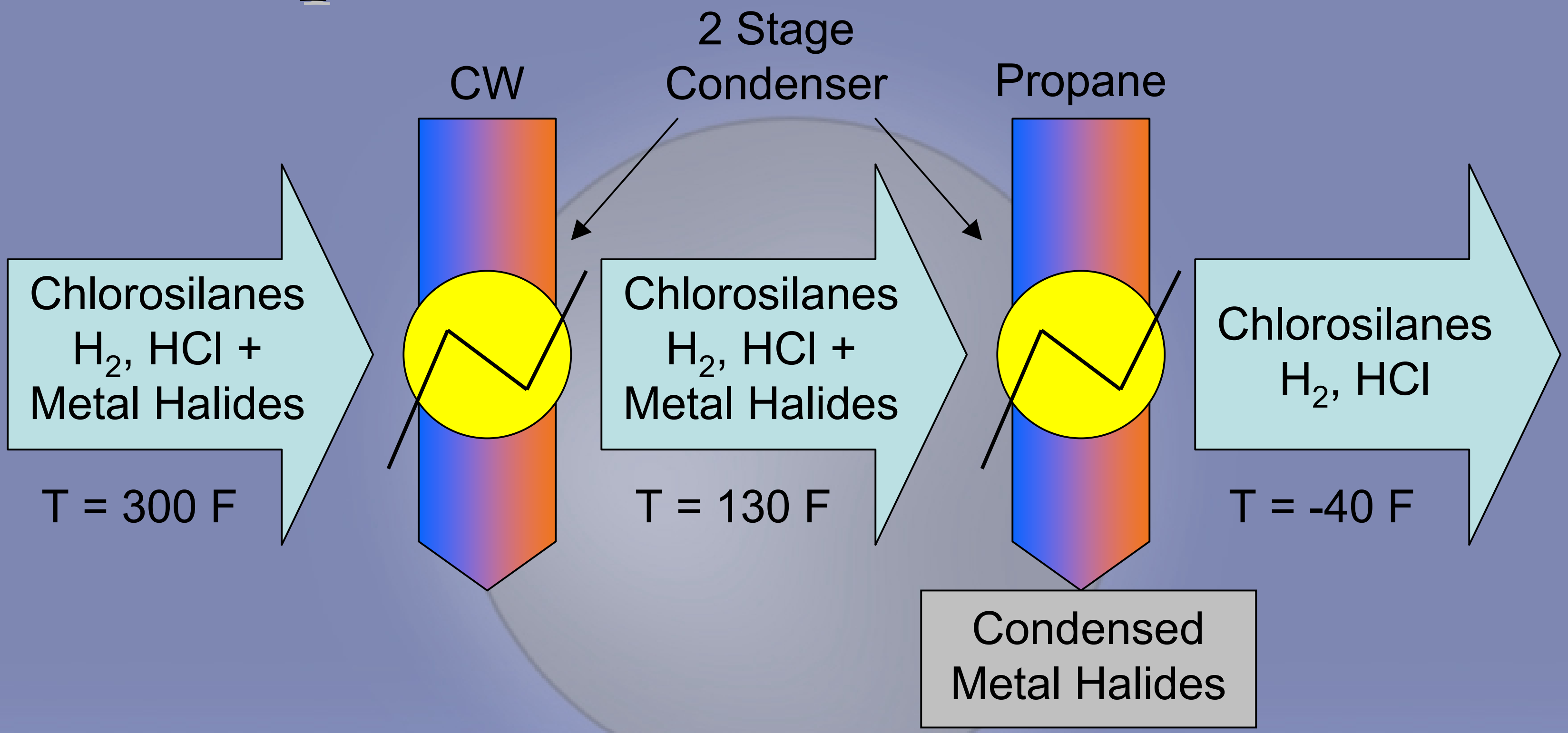
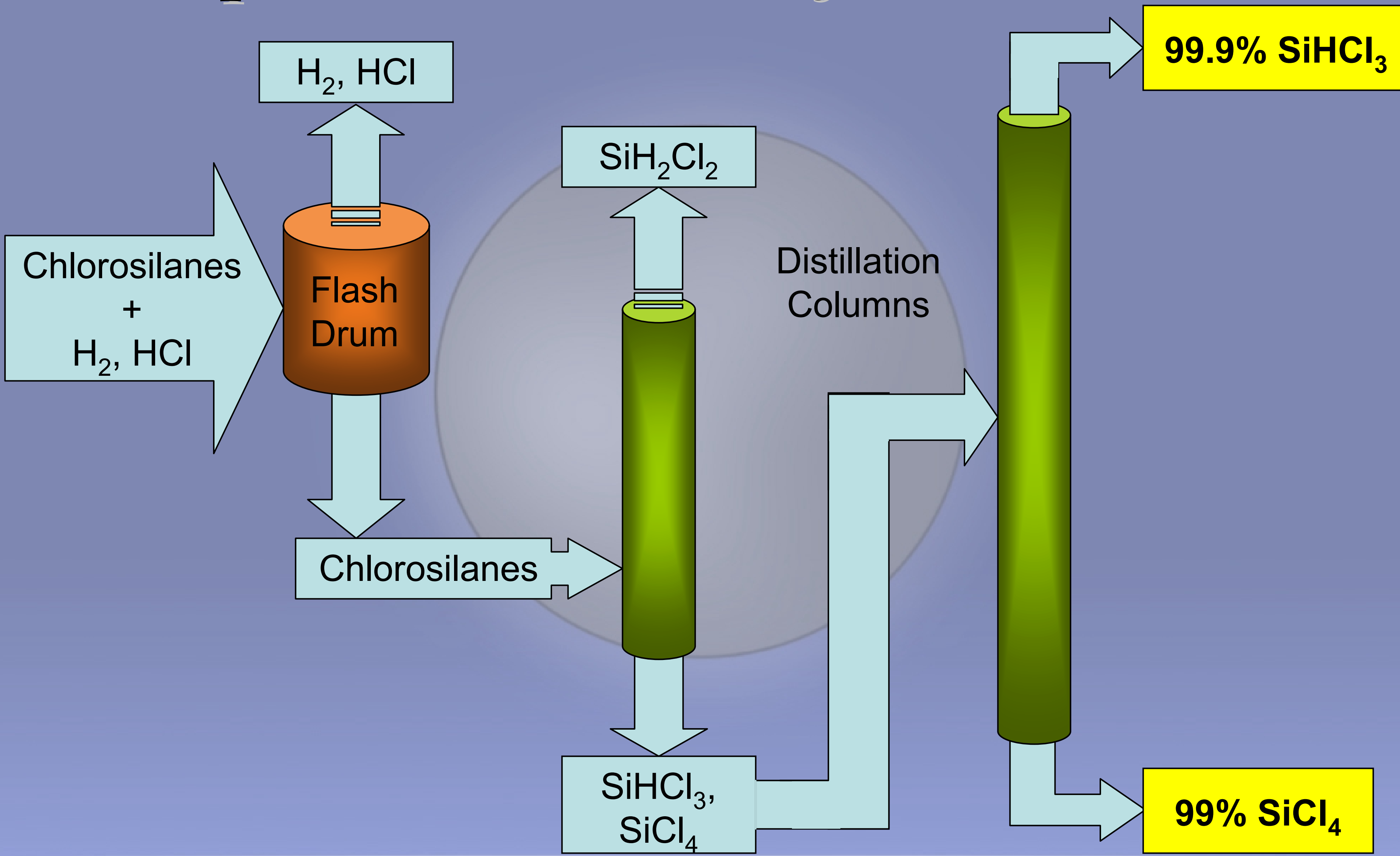
Separations: Metal Halides



- Cleaning required
  - Infrequently because of low flow rate

Separations: $SiHCl_3$ Purification



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Siemens Reactor Modeling

- Complex reaction:

$$SiHCl_3(g) + H_2(g) \rightarrow Si(s) + 3HCl(g)$$

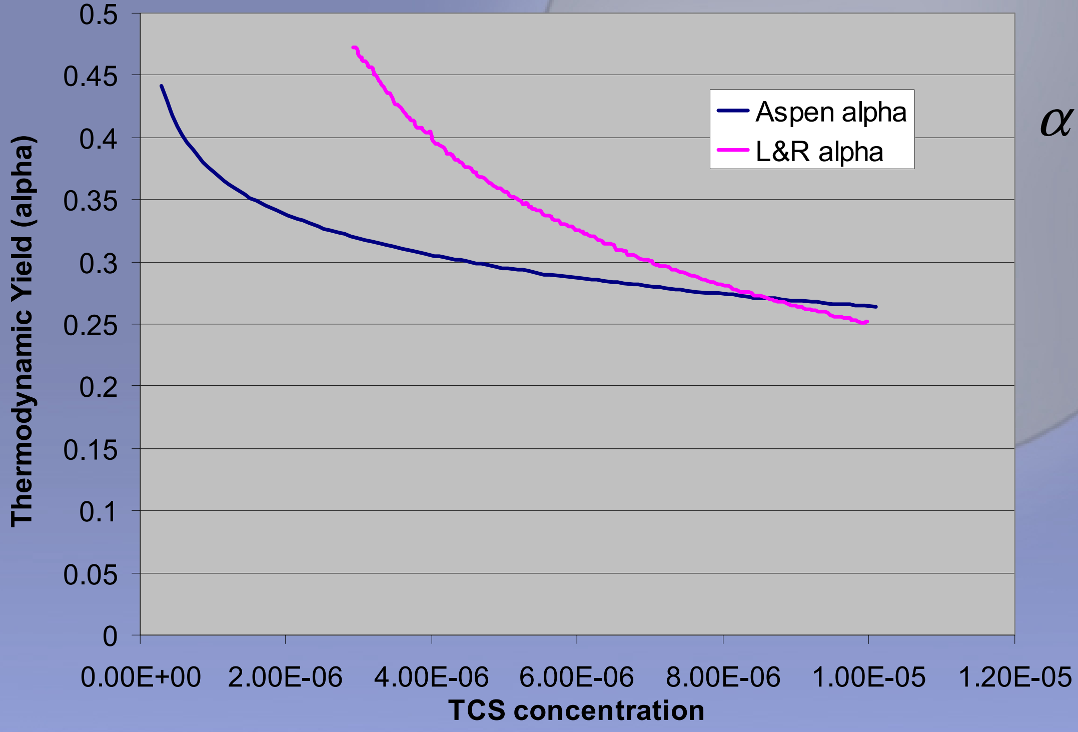
$$Si(s) + 2HCl(g) \rightarrow SiH_2Cl_2(g)$$

$$Si(s) + 4HCl(g) \rightarrow SiCl_4(g) + 2H_2(g)$$

  - Trichlorosilane only reacts on rod
  - Reaction rate constants not well known on rod

Thermodynamic Yield Study

- Laskafeld and Roznov prove that Siemens reactions go to equilibrium
  - Siemens reactor feed only contained $SiHCl_3$ and H_2



$$\alpha = \frac{(n_{Si}/n_{Cl})_{entering} - (n_{Si}/n_{Cl})_{equilibrium}}{(n_{Si}/n_{Cl})_{entering}}$$

12 Siemens Reactors Required

Grow Single Crystal

- Requirements for single crystal grower:
  - Cooling rate must be very slow
  - Must be able to define wafer diameter well
  - Must not introduce impurities into system
- Czochralski crystal grower

Determining Pull Rate

- MEMC uses 0.3 – 1.5 mm/min for 200mm wafers

$$R^{1/2} = \frac{C}{U}$$

- Our 300mm wafers will be pulled at 0.245 mm/min

Determining End Cone Length

Equation to be satisfied:

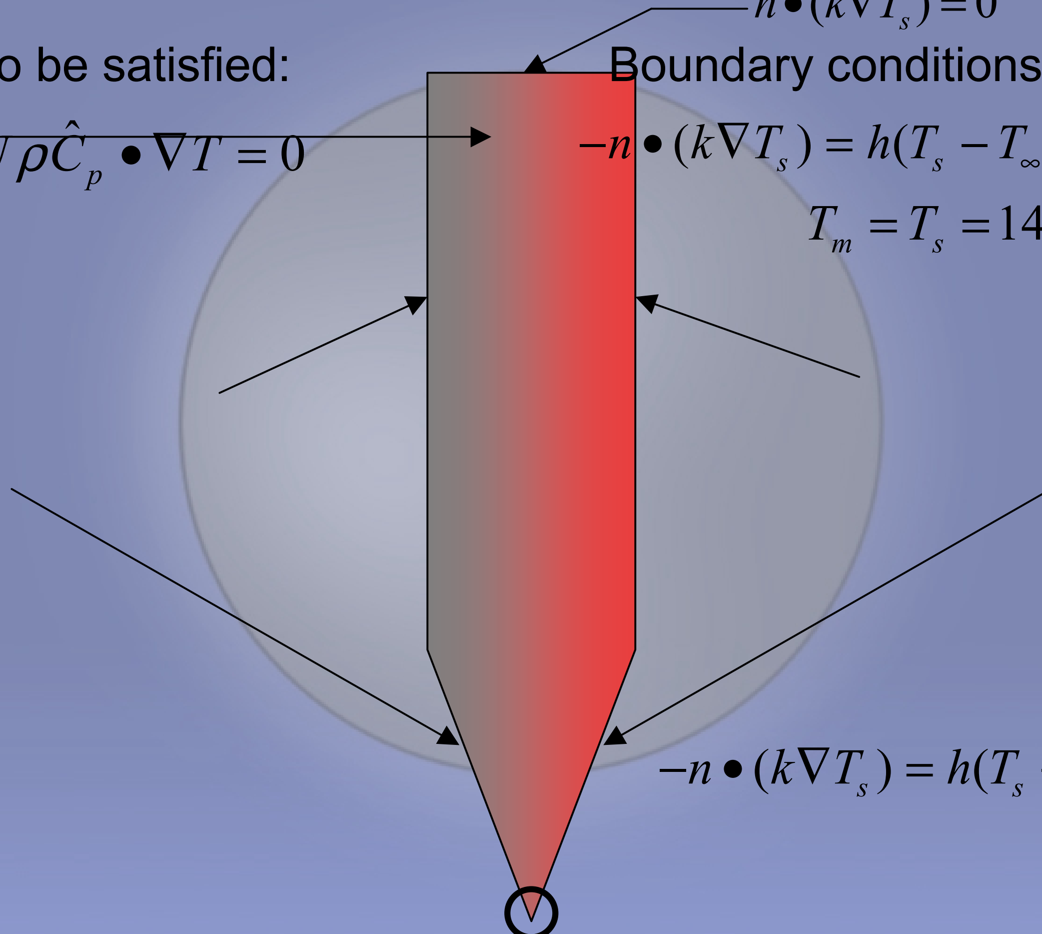
$$\nabla \bullet k \nabla T - U \rho \hat{C}_p \bullet \nabla T = 0$$

Boundary conditions to be satisfied:

$$n \bullet (k \nabla T_s) = 0$$

$$-n \bullet (k \nabla T_s) = h(T_s - T_\infty) + \sigma \varepsilon (T_s^4 - T_\infty^4)$$

$$T_m = T_s = 1420^o C$$

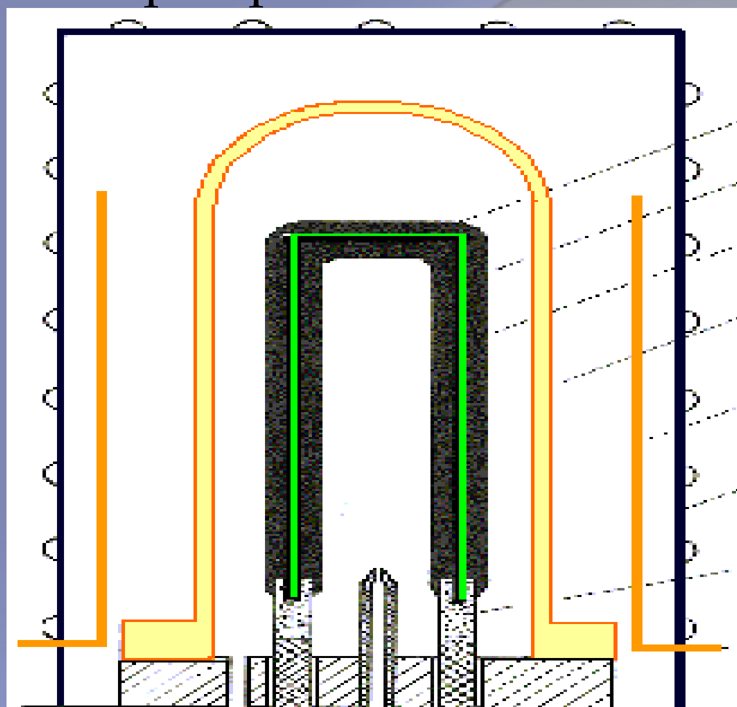


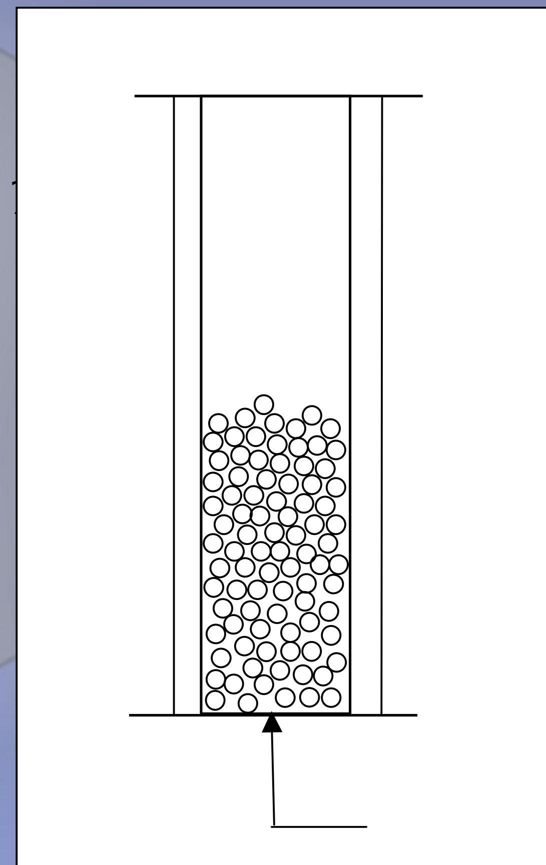
$$-n \bullet (k \nabla T_s) = h(T_s - T_\infty) + \sigma \varepsilon (T_s^4 - T_\infty^4)$$

BRCz Supporting Slides

Silane vs. Trichlorosilane

- Silane (SiH_4):
  - Cheap to produce
  -
  - C vs.
  -
  -





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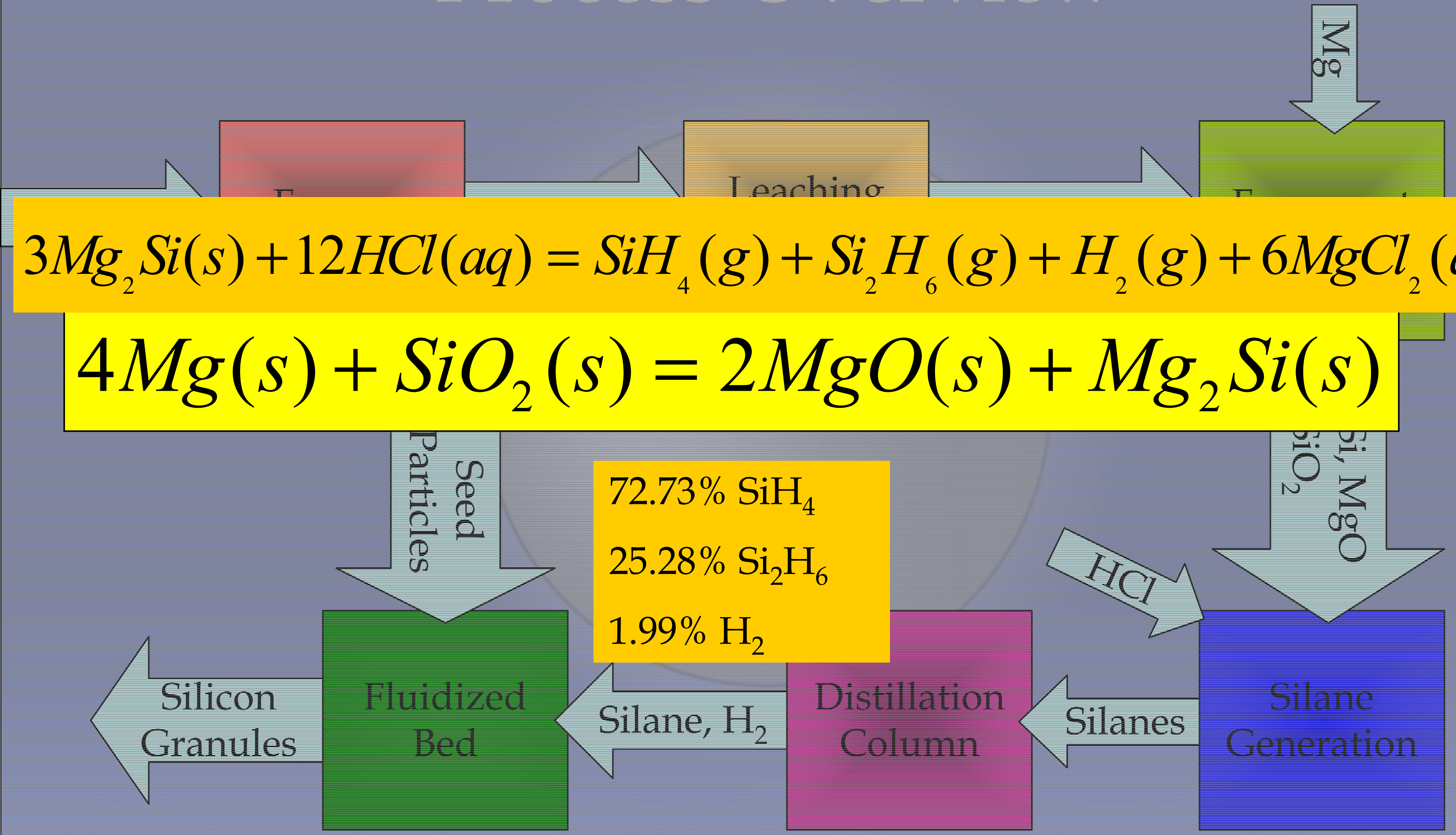
Batch Recharging

Process Overview



$$3Mg_2Si(s) + 12HCl(aq) = SiH_4(g) + Si_2H_6(g) + H_2(g) + 6MgCl_2(aq)$$

$$4Mg(s) + SiO_2(s) = 2MgO(s) + Mg_2Si(s)$$

72.73% SiH_4

25.28% Si_2H_6

1.99% H_2

Cost Analysis

- For a production rate of 100,000 wafers/month
  - Previous CTDC: $84.3 million
  - New CTDC: $72.6 million

  - Previous Operating Cost: $2.83 million/yr
  - New Operating Cost: $4.73 million/yr

  - Previous Utility Cost: $14.85 million/yr
  - New Utility Cost: $12.8 million/yr

Economic Analysis Supporting Slides

Economic Overview

- The Big Players
- Market Trends
- Viability of Si Wafer Market
- Cost Analysis
  - Main Plant (Primary Process)
  - Overall plant (Including Batch Recharging Method)
  - Conclusions/Recommendations

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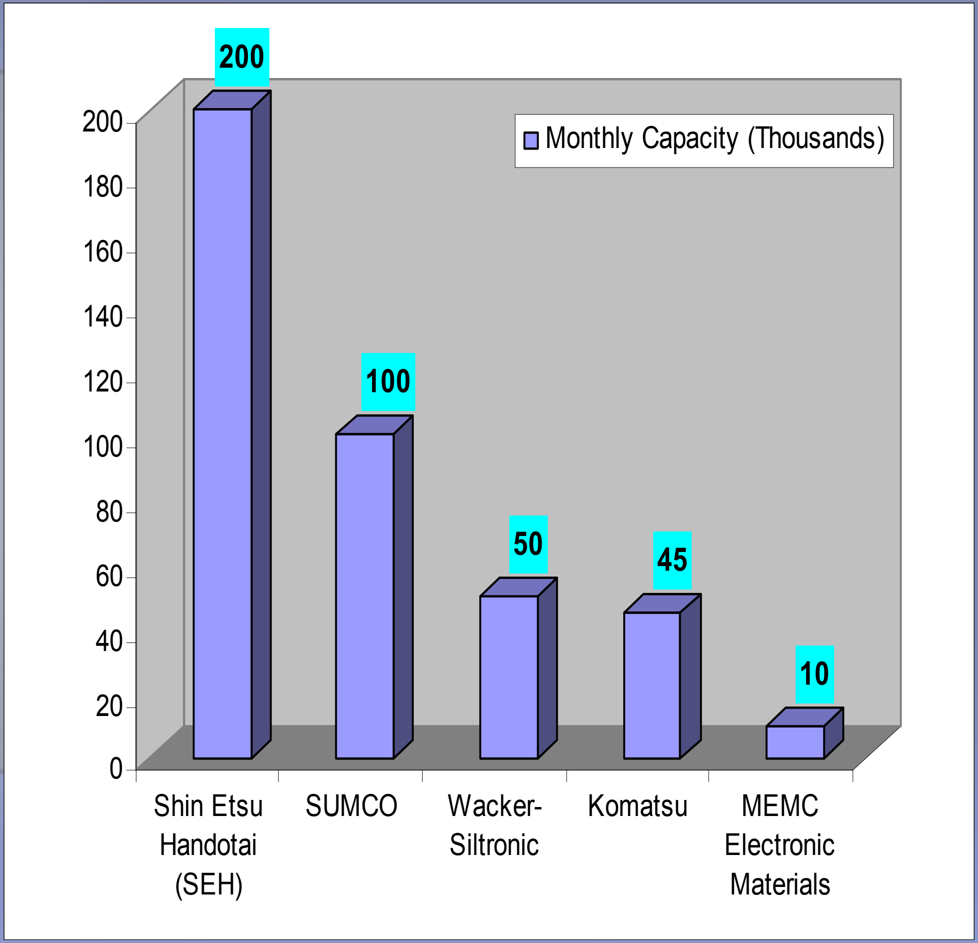
Wafer Diameter: 200mm vs. 300mm

- 200 mm
  - High Current Demand
  - Higher Throughput
  - Low Selling Price ($30/wafer)
- 300mm
  - Lower Current Demand
  - Lower Throughput
  - High Selling Price ($200/wafer)

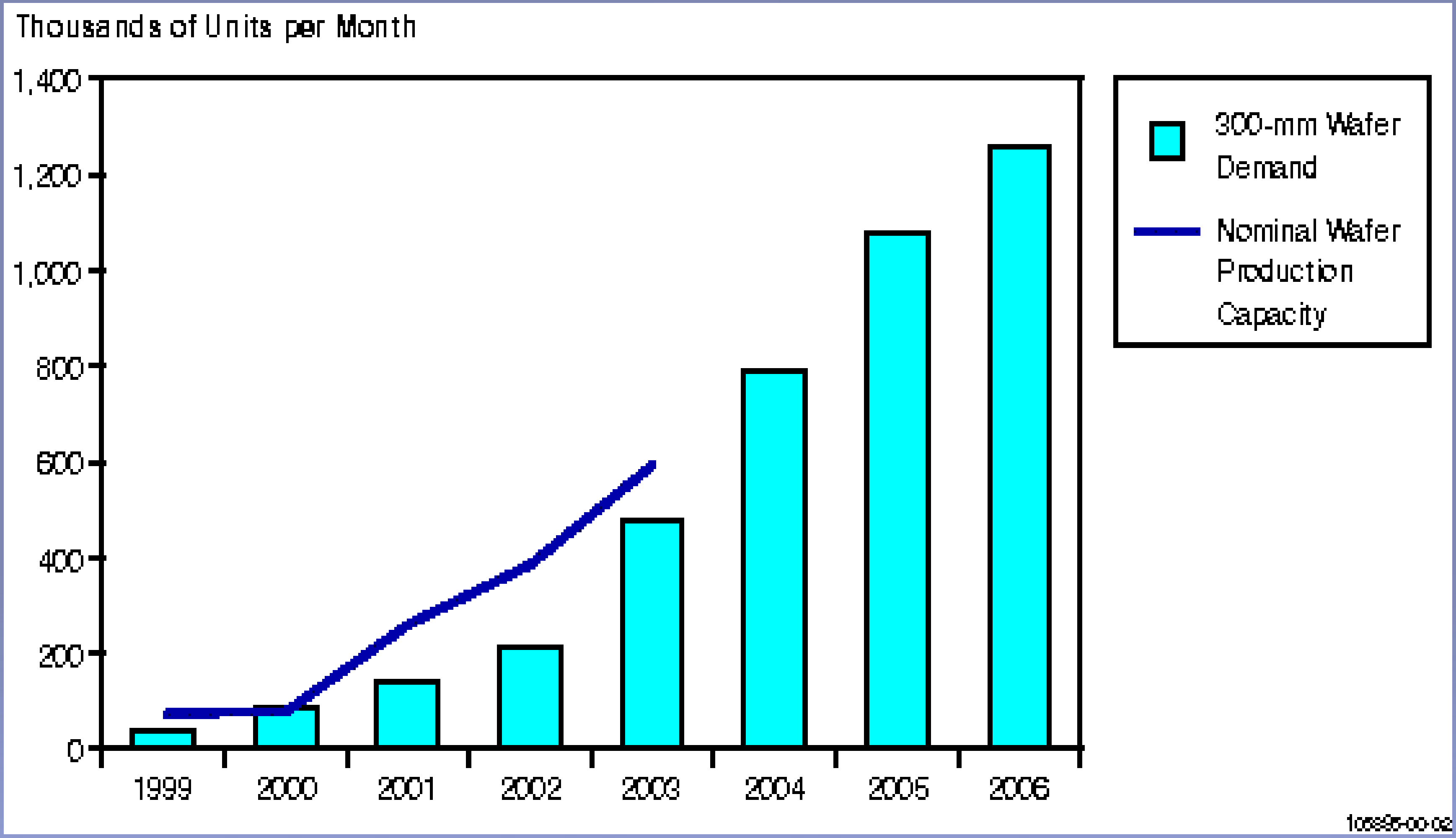
- Larger wafer = less manufacturing cost = **reduced cost for consumers**
  - Increasing Demand for 300mm wafers
  - Microprocessor companies currently transitioning between 200mm and 300mm technologies

The Big Five

- The Big Five: SEH, SUMCO, Wacker-Siltronic, Komatsu, and MEMC
- 90% of world's Si wafer producers
- Growing Competition => Merging Industries (SUMCO)



Market Wafer Demand Trend



Viability of Market

- Rising Global Chip sales
  - Global Chip Sales in August 2003: 13.4 billion$
    - World-wide sales increase
      - Asia Pacific: 6.4%
      - Europe: 3.8%
      - Americas: 2.5 %

- Reason to enter Si wafer market

1. Rising Sales → Higher Demand

Initial Considerations

- 300mm Wafer Market Price
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- 300mm Wafer Competitive Price
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  - 1. 10,000 wafers/month
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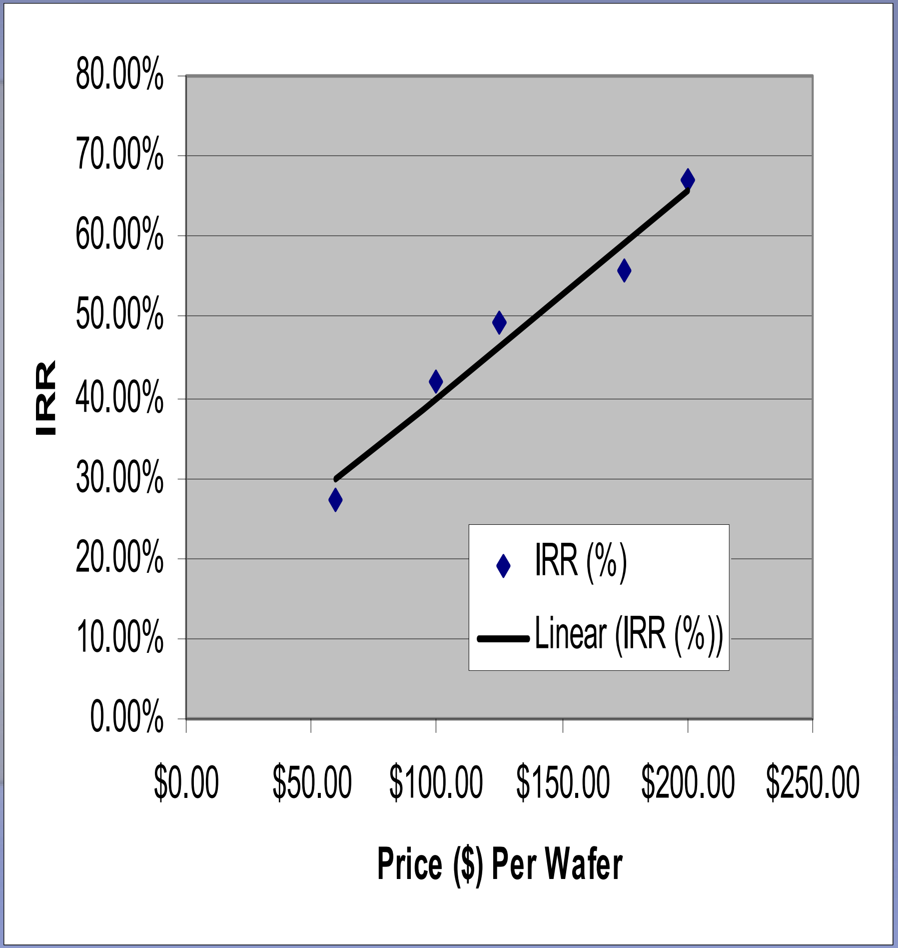
    - Initial production plan
  - 3. 500,000 wafers/month
    - Counter wafer expansion expectations (MEMC)

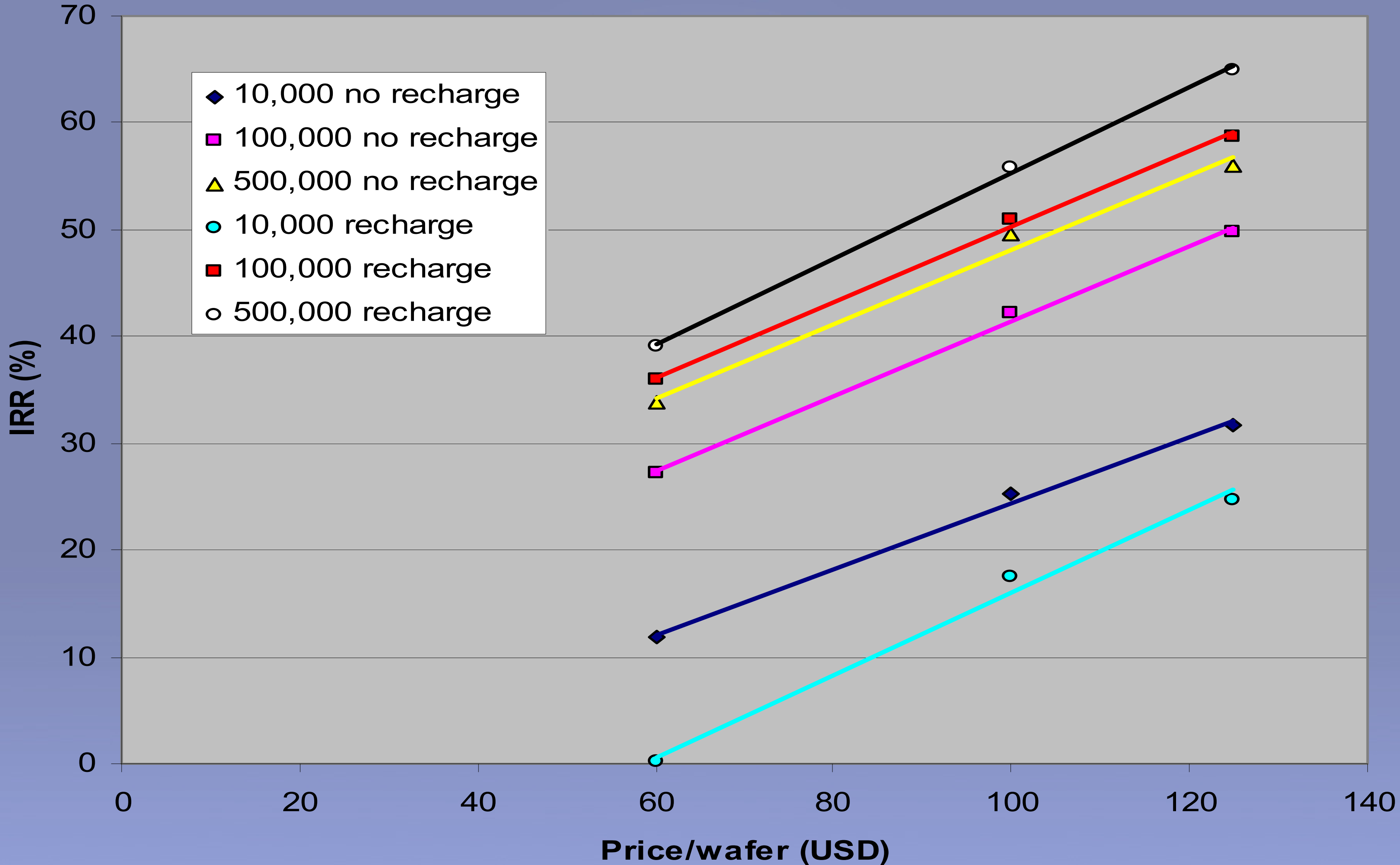
Main Plant (100,000 wafer/mo)

- At Competitive price of $125
  - IRR: 49.7%
  - ROI: 93.2%
  - Total Capital Investment: 91 million$

- At Price of $100
  - IRR: 42.2%
  - ROI: 72.5%
  - Total Capital Investment: 91 million$



IRR Trends



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A Further Explanation

- What you are thinking
  - Why the !@#$ are the IRR values so high?
- The numbers
  - For the 100,000 wafer/mo plant
    - 26 Cz growers required
    - 2.7 mil$ per grower → 70.2mil$
    - Number of wafers per ingot: 839
    - Number of ingots per month: 128
    - 107,000 wafers → 10.7 mil$/month (at 100$/wafer)

Conclusions

- Main plant and alternate method economically feasible
- Batch Recharge is better option
- Primary Suggestion (500,000 wafer plant)
  - $60 per Wafer
- Secondary Suggestion (500,000 wafer plant)
  - $100 per Wafer

Recommendations

- Highly Volatile Market
  - 200mm wafer surfaced in 1984
  - 300mm wafer surfaced in 1991
  - Changing technologies

- Recommendation
  - Profitability analysis on projected shorter life plants (5, 8, 10 years)
    - Provides better prognosis to changing market