An Analysis of the Economics of Photomask Manufacturing Part – 1: The Economic Environment

Charles M. Weber – Portland State University
C. Neil Berglund – Portland State University
ISMT Mask Automation Workshop
February 9, 2005

Problem Statement

- The cost of producing photomasks
  - has increased by an order of magnitude over the last decade,
  - and is likely to continue to escalate for the 90-nm technology node and beyond.
  - Ultimately the cost of photomasks may rise to the point where it threatens the profit potential of most low volume designs.
- Suppliers of photomasks are thus looking for ways to reduce the cost of producing photomasks,
- and semiconductor manufacturers are looking for creative ways to amortize them.

ISMT Project LITG323
“Mask Industry Assessment”

- Conducted by
  - Portland State University’s (PSU)
  - Maseeh College of Engineering and Computer Science’s (MCECS)
  - Department of Engineering and Technology Management (ETM)
- Principal Investigators:
  - C. Neil Berglund – Portland State University
  - Charles M. Weber – Portland State University
- Purpose:
  - Investigate the economics of photomask manufacturing
  - Provide input into annual mask industry survey

Research Question

- What can a supplier of photomasks do to enhance the profitability of its customers, in addition to augmenting his/her own profitability?

Research Methods

- Interviews with two dozen experts
  - Photomasks and related disciplines
- Data have been transcribed, coded and analyzed.
- Numerical model of the semiconductor lifecycle
- Leads to stylized facts concerning
  - the economics of photomask fabrication,
  - and profitability in semiconductor manufacturing.
- Please see reference (Weber, 2003, Ch. 3) for details.

The Mask Shop's Perspective

- Finite demand.
  - Global market for photomasks <$3 billion (Kimmel, 2003@ BACUS)
  - Unit revenues for masks erode over time.
- Capital-intensive industry. Investment levels…..
  - ~$40M for 'conventional' (180-nm node or above)
  - >$100M for 'advanced' (130-nm node and beyond)
  - Photomask manufacturers fund making advanced masks from making conventional masks.
- Few players can afford to be in business.

State of Affairs

(Industry Survey by Kurt Kimmel @ BACUS, 2003)

- Mask business growth rate is 6.8%, as compared to 9% in semiconductors
- Currently <180-nm masks drive 37% of revenue (15% of mask shop volume).
- Small, but growing portion of masks require advanced resolution enhancement techniques.
- Hard defects are the primary yield problem!
- Severe data management issues
- 4 merchants control 65% of market
- Things will get worse as features shrink.

Expected Mask Costs

for Future Technology Nodes

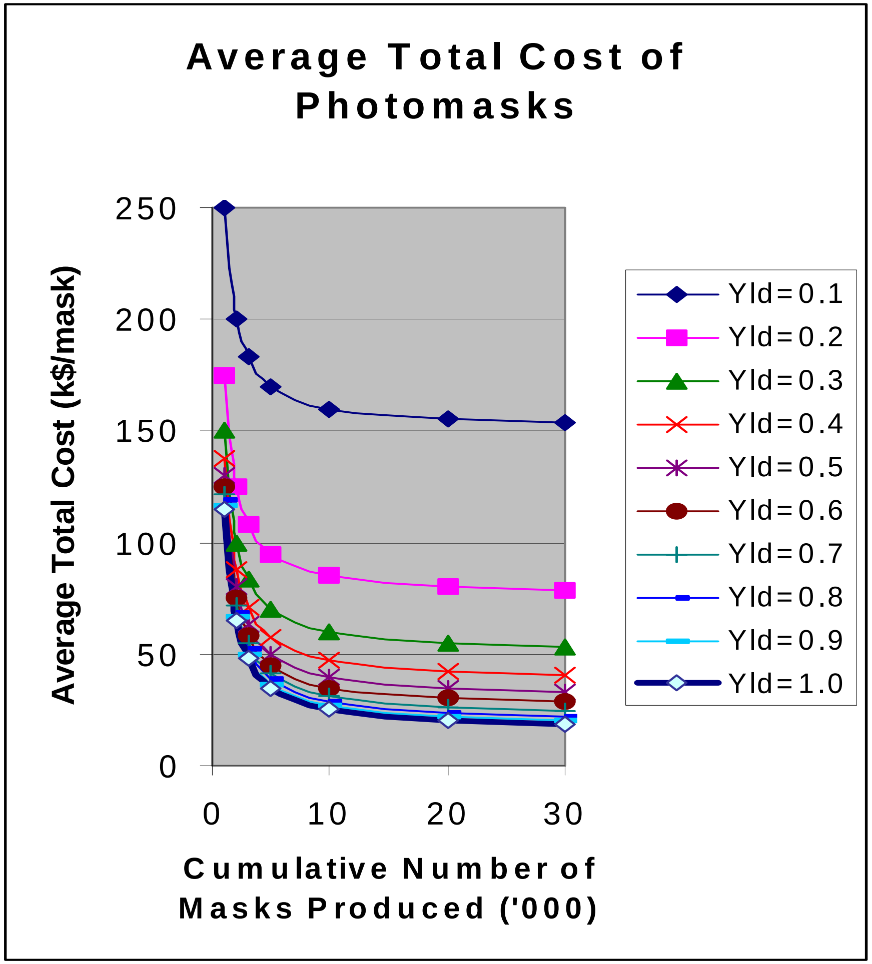
(Source: International Sematech)

- $0.5M per mask set for 130-nm node
- $1M per mask set for 90-nm node
- $2M per mask set for 65-nm node

Mask Shop Experience Curve: *Advanced Masks*

(Weber, Berglund, Gabella, 2004)

- >50% yield is critical for profitability.
- Amortization of fixed costs complete after 20,000 masks.
- Maximize equipment utilization.



Average Total Cost of Critical Layer Photomasks
Assumptions: variable costs equal $15k per mask; fixed costs of $100 million need to be amortized.

Initial Recommendations

- Improve yield rapidly.
  - Mask operations are similar to fab operations.
  - Transfer knowledge from customer.
  - However, yield knowledge is tacit (Polanyi, 1966).
  - Personnel transfer and extensive training is required.
  - How many yield engineers can a mask shop afford?
- Centralize mask making to enhance capital productivity.

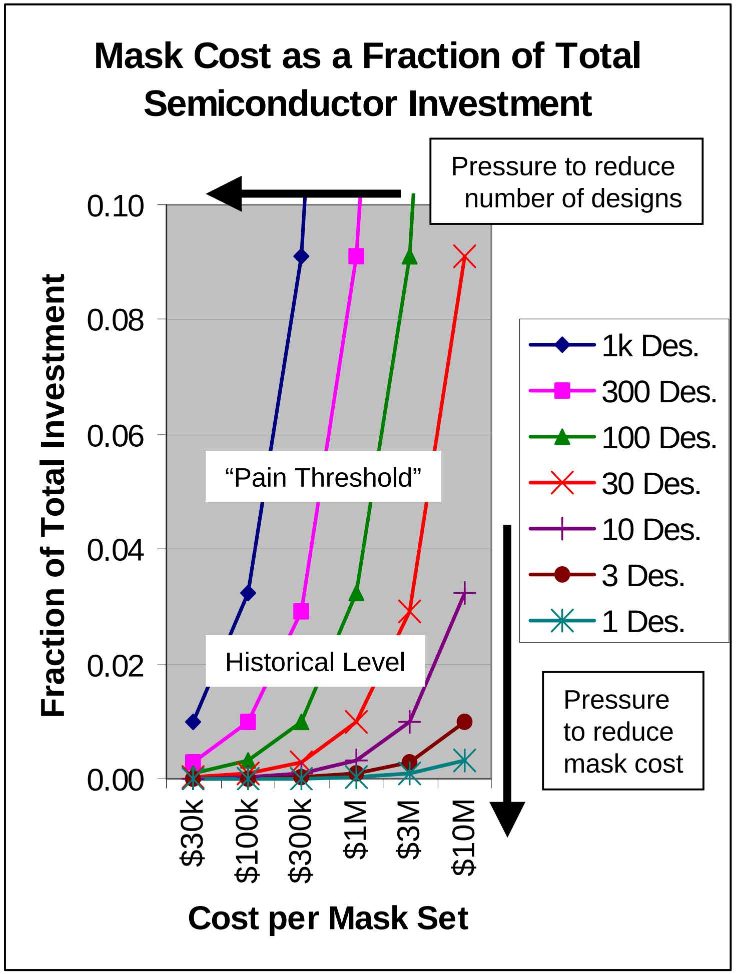
The Chipmakers' Perspective

- Amortization challenges
- Limited effects of yield learning for foundries and ASIC manufacturers
- The Designer's Learning Cycle
- Rapid turn-around time
- Shorter product lifetimes
- Early versus mature masks

Price Reduction or Market Shrinkage

(Weber, Berglund Gabella, 2004)

- If mask costs cannot be reduced,
- Then pressure to reduce the number of designs increases.
- Fewer designs means market shrinkage.
- Foundries and ASIC vendors are affected disproportionately. (Trybula, Intl. Sematech)

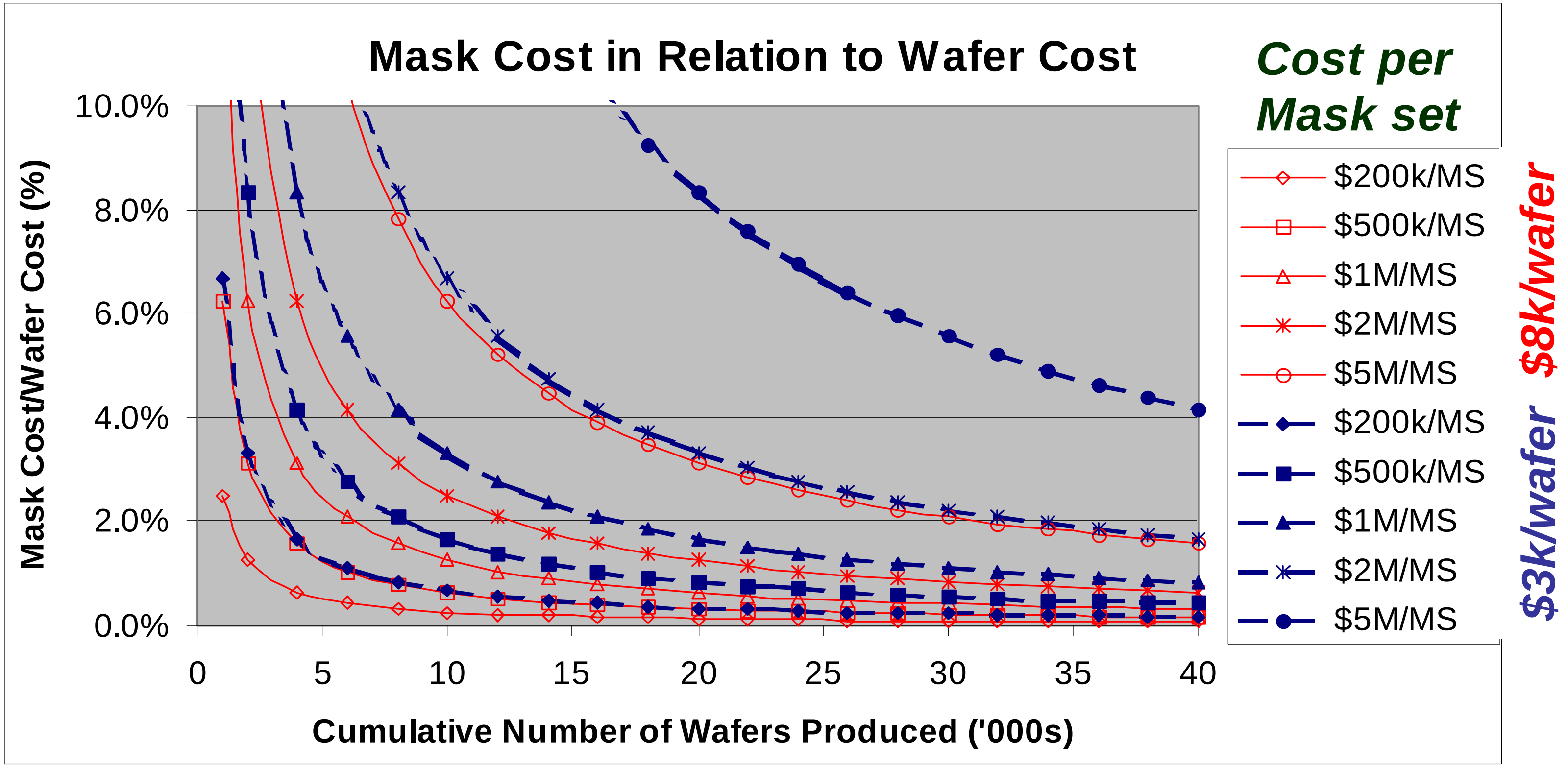


Model assumes a billion chips over the lifetime of a factory, a total investment of $3billion excluding photomasks.

Amortization Challenges for Foundries and ASIC Vendors

- Only best sellers can be printed.
- 10,000 new designs in 2000
- Only 3500 new designs in 2003
- Drop cannot be completely explained by the economic downturn.

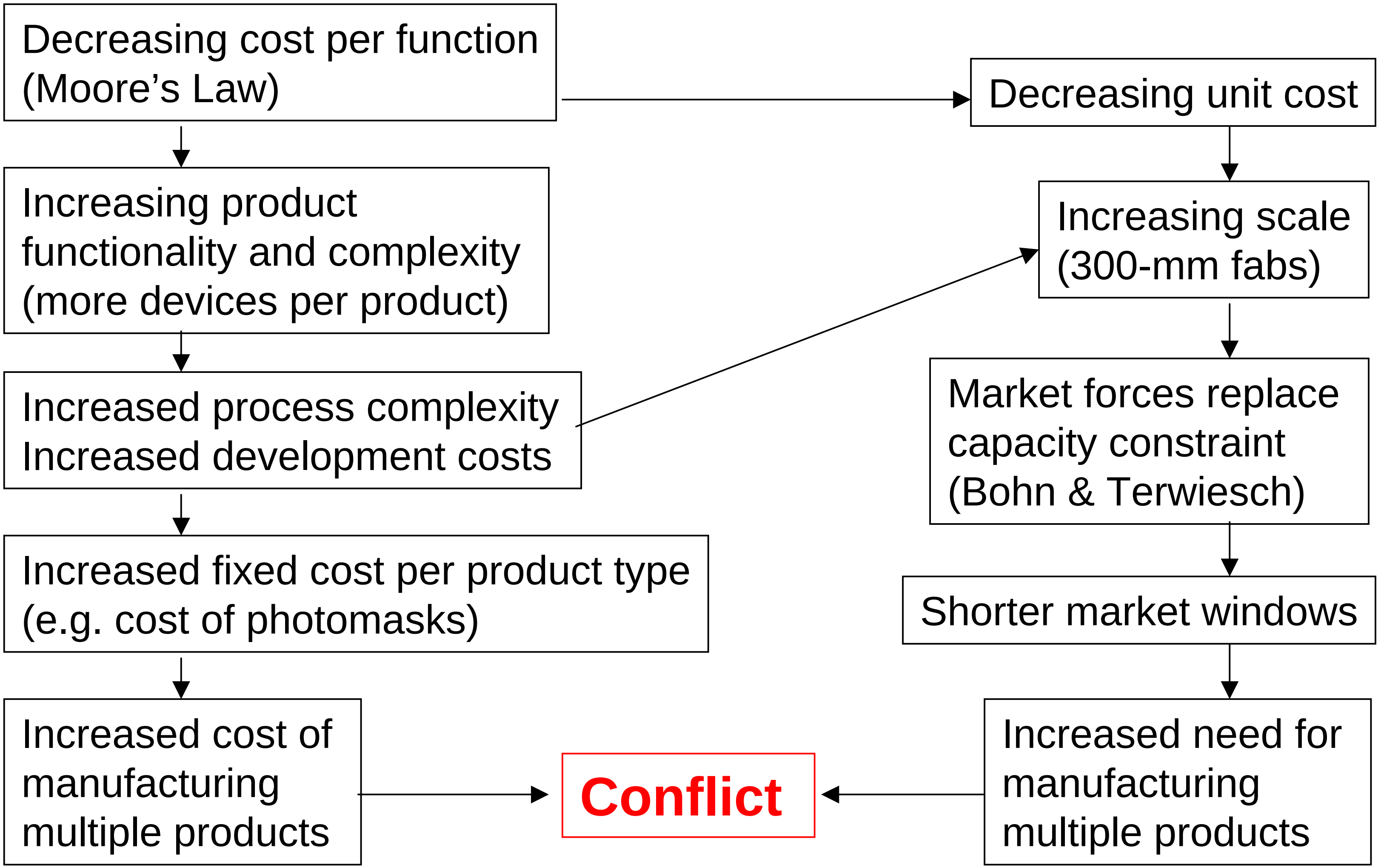
Mask Cost and Wafer Cost



Calculations assume 400 fully functional chips per wafer.

- **>20,000 300-mm wafers need to be produced for a 65-nm mask set to be amortized.**

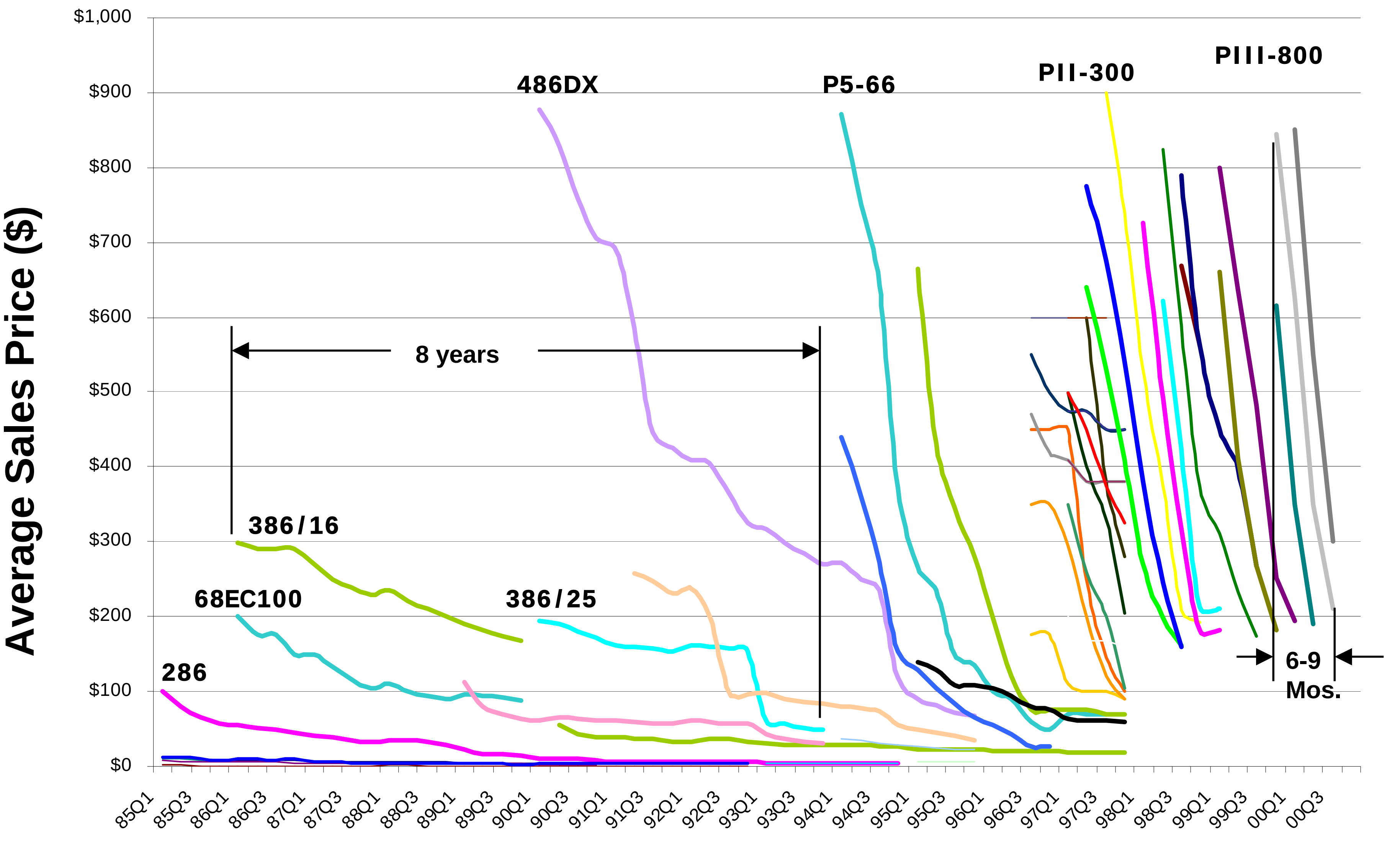
Scale versus Scope in Semiconductor Manufacturing



Scale versus Scope

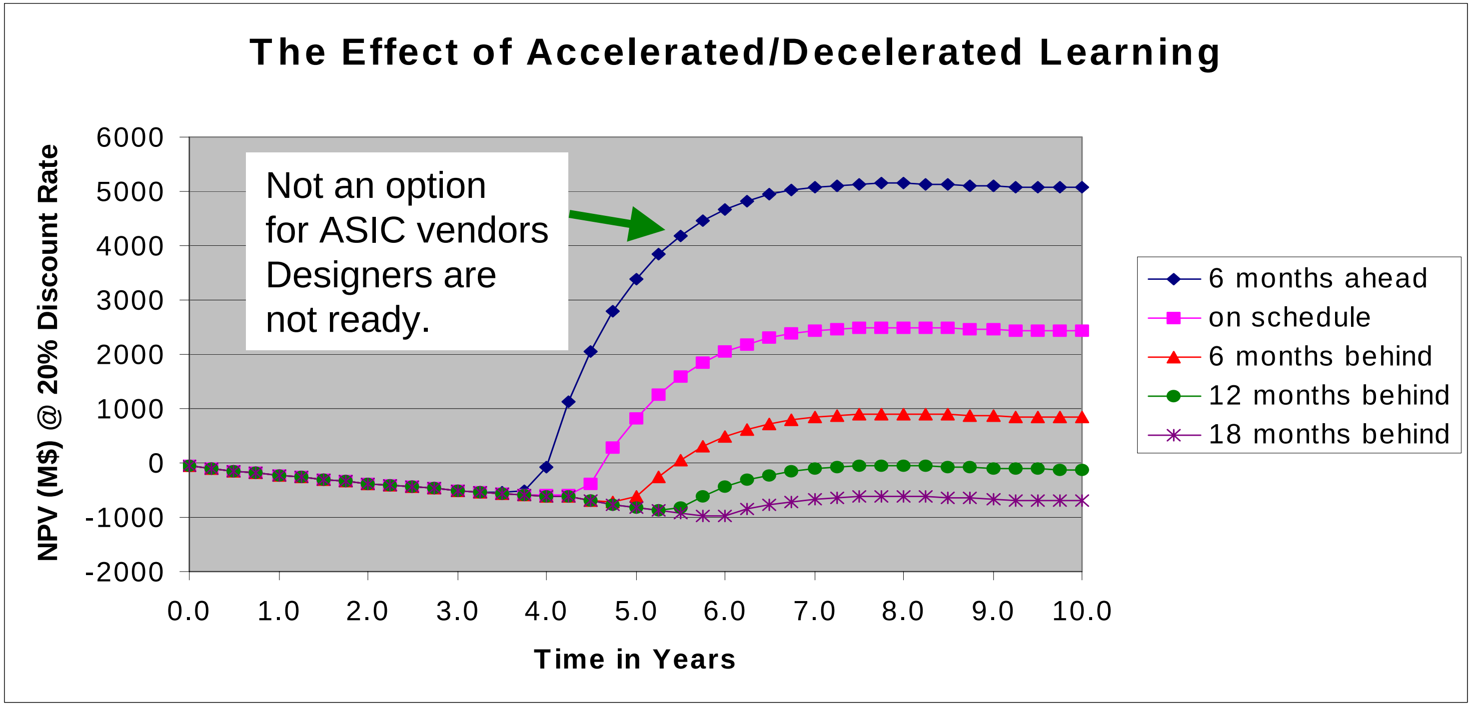
- A firm enjoys ***economies of scale*** when it can double its output at less than twice the cost. (Pindyck & Rubinfeld, p. 223)
- ***Economies of scope*** are present when the joint output of a single firm is greater than the output that could be achieved by two different firms each producing a single product (with equivalent production inputs allocated between the two firms). (Pindyck & Rubinfeld, p. 227)

Logic Life Cycle Drives the Industry



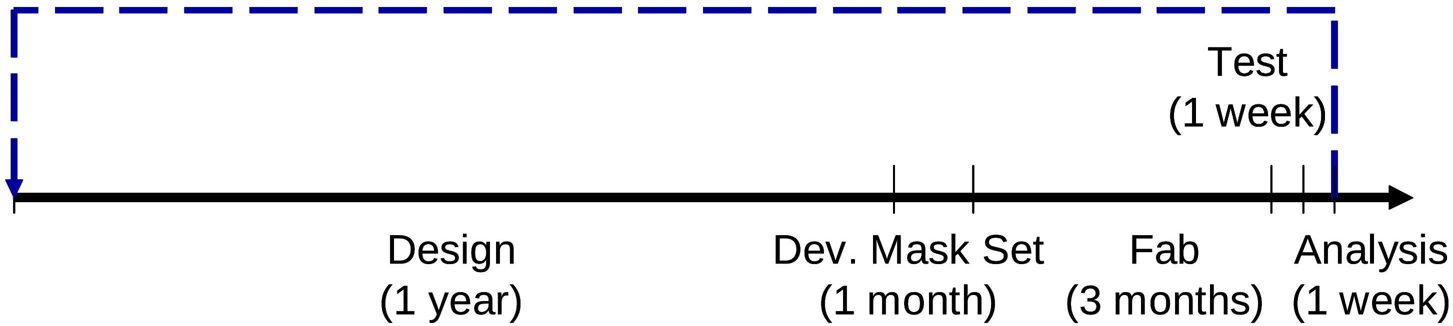
Life cycle is decreasing rapidly. (Source: Walt Trybula, Intl. Sematech)

Limits Effects of Yield Learning in ASIC Manufacturing (Weber, 2002)



- ASIC manufacturer profitability in a 200-mm wafer fab.
- When venture is on schedule, one minute on the critical path amounts to $2500.

The Designer’s Learning Cycle

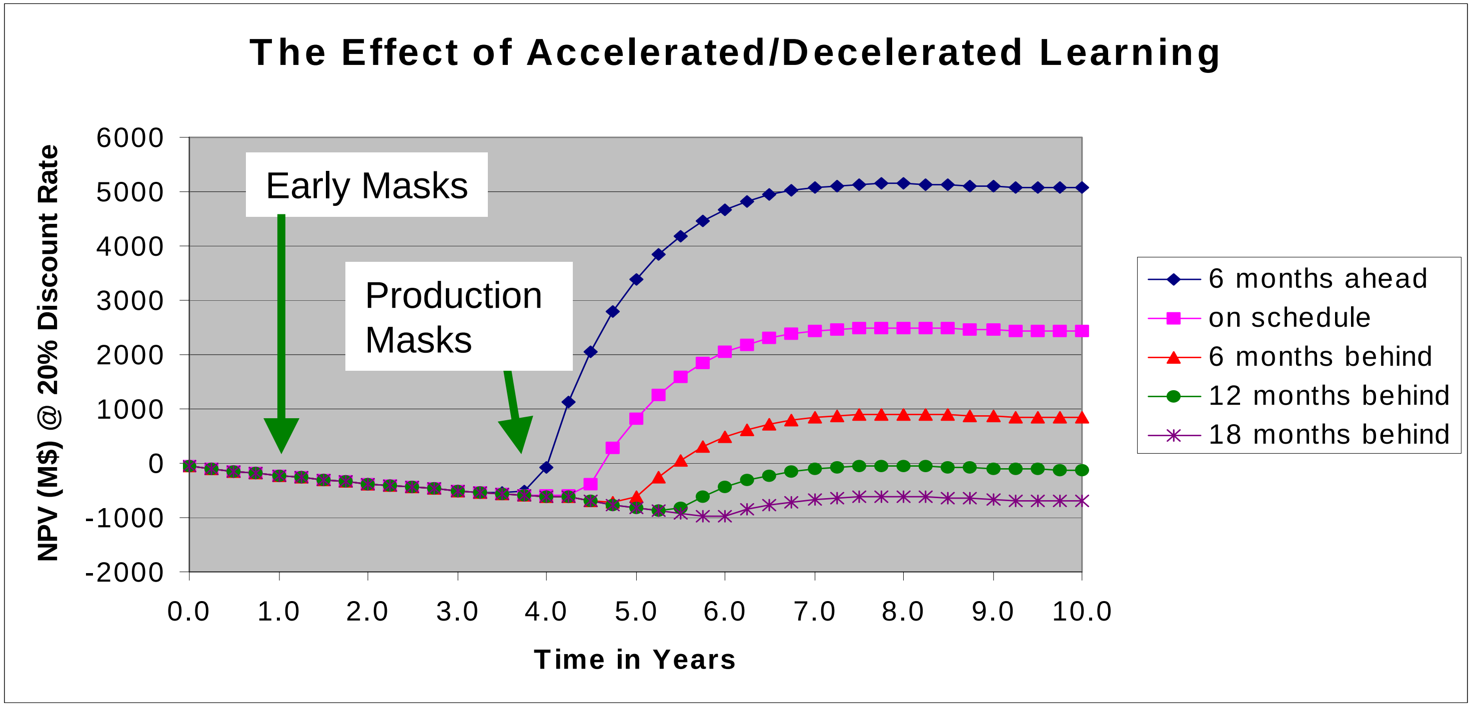


- Full learning cycle can take more than 15 months.
- Market fluctuates much faster. (Sematech GEM)
- Only end user firms with long planning horizon can afford to design chips.

Rapid Turn-Around

- Fab problems can cost $10,000 per minute. (Weber & von Hippel, 2000)
- Inter-continental delivery of masks is unacceptable to many fabs.
- Mask maker must build fabs close to customers. Centralization is very difficult.
- Capital productivity of mask shops drops.

Early Masks vs. Production Masks



- ***Early masks:*** low volume; low yield; long turnaround; very high cost; very high price.
- ***Production masks:*** moderate volume; higher yield; short turn around; relatively lower cost; much lower price.
- A mask shop that cannot make early masks won't get business downstream.

Summary

- For mask shops …..
  - Reducing defects is not enough.
  - Rapid yield improvement efforts may not be affordable.
  - Rapid turnaround prevents full utilization of equipment.
  - Cost reduction or market shrinkage
  - Enormous consolidation pressure
  - Market segmentation: advanced versus conventional.

Recommendations for Mask Shops

- ITRS: Move the mask problem onto the near-term problem list.
- Coordinated development:
  - Align mask development with leading customers (chipmakers) and complementors (e.g. stepper manufacturers, resist suppliers)
- Develop pricing strategies with customers.
- Joint ventures with customers.
- Merge!

Currently in Tech Transfer:

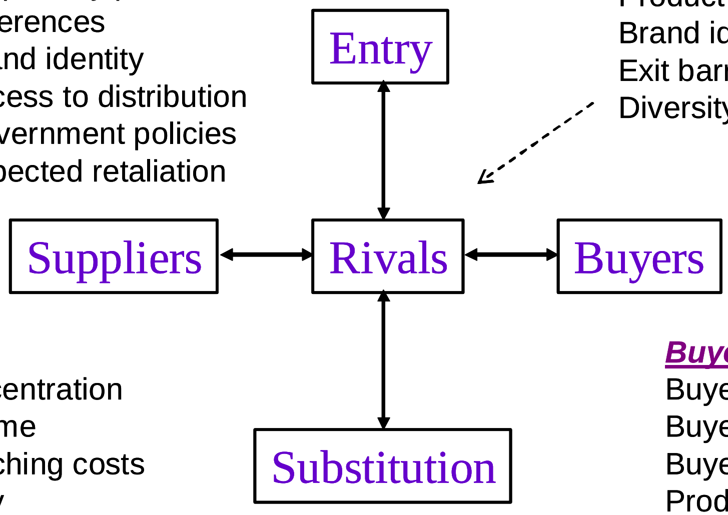
Strategic Threat Analysis for the Photomask Industry

Entry

Economies of scale
Proprietary product differences
Brand identity
Access to distribution
Government policies
Expected retaliation

Rivalry

Industry growth
Product differences
Brand identity
Exit barriers
Diversity of competitors



Suppliers

Supplier concentration
Supplier volume
Supplier switching costs
Brand identity
Impact on cost
Impact on differentiation
Supplier profile

Substitution

Substitute Products

Buyers

Buyer concentration
Buyer volume
Buyer switching costs
Product differences
Brand identity
Impact on quality
Impact on performance
Buyer profile

- Based on Porter Model

Currently under Investigation: **Best Practices for Mask Industry**

- A list of best practices suggested by analysis of economic environment is in tech transfer.
- Additional questions regarding best practices may be included in 2005 mask survey.

Currently under Investigation: **Scenarios for Evolution of the Semiconductor Industry**

1. Technical Substitutions for Photomasks
   - Maskless Lithography
2. Operational Solutions
   - Fewer critical masks per mask set
3. Vertical Integration of Advanced Mask Making
4. Bifurcation of Moore's Law
   - DRAM and Microprocessors on accelerated schedule
   - ASIC and perhaps foundries on slower schedule

Interim Conclusions

- A combination of scenarios 1-4 is likely to occur.
- Severe consolidation pressure for all four scenarios.
- The patterning problem may cause a restructuring of the semiconductor industry.
- Factory automation and operational efficiency are becoming critically important.

Factory Automation and Operational Efficiency in Fabs and Mask Shops

R.C. Leachman (UC Berkeley); C. Weber, C. N. Berglund (Portland State U.)

Problem Statement:

- Capital investments in the billions (100s millions) of dollars
- Profitability depends on operational efficiency.
- Processes, manufacturing environment and economic environment are highly complex.
- Highly dynamic manufacturing environment.
- Critical decisions must be made in real time.
- Real-time decisions may have to be based on simulations of fab and economic environment.

Limits of Many Approaches:

- Wrong evaluation metric → wrong answer!
  - ***Wafer cost or even die cost are insufficient!***
- Models that do not cover the complete investment horizon give the wrong answer!
- Models that do not assess risk are of little value!
- Insufficient number of managerial variables
  - Management responses tend to be multidimensional.
  - Need to make ***Apples-to-oranges comparisons!***
- Models do not run in real time.

The Value of Ownership Model

R.C. Leachman (UC Berkeley); C. Weber, C. N. Berglund (PSU)

Configurable, Real-time, dynamic factory simulation

- Predicts factory behavior
- Covers complete economic environment
- Spans required investment horizon
- Comprehends variability.
- ***Gets the right answer!***
- Drives decisions.

Project Implementation

- Collaborative development of e-manufacturing infrastructure
- Scalable models
- Three-year project horizon
- Intended start date: Fall 2005

Value of Ownership Approach

- Gives real-time assessment of impact on bottom line
- Latest data and latest expectations are entered into simulation.
- Simulation
  - **generates potential scenarios for action;**
  - **assigns $ value to each scenario;**
  - **assesses risk for each scenario.**
- Managers choose the best scenario.
- ***Ultimate MC Benefits:*** rapid, data-driven decision making capability based on $ value.