PHOTOMASK

BACUS—The international technical group of SPIE dedicated to the advancement of photomask technology.

BACUS NEWS

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The Semiconductor World of the 2020s According to Photomasks

How semiconductor growth depends upon solving photomask market challenges

Bud Caverly, Les Dahl, and Franklin Kalk, Toppan Photomasks, Inc., 131 E Old Settlers Blvd., Round Rock, TX USA 78664

ABSTRACT

The global photomask business faces both substantial opportunities and challenges in the coming decade. The semiconductor business is forecasted to grow at 9.9% CAGR from 2020 - 2030[1] which will drive growth in the photomask market. Coincident with this predicted growth, the photomask industry is facing significant equipment obsolescence issues that will require many of the legacy tools that support >=28nm technology to be renewed or retired and replaced in this timeframe. This presentation will review the challenges that these trends present to the photomask and semiconductor market. We will review the lithography system growth estimates from our previously published paper and extend that analysis to all photomask equipment. The business implications of this environment are critical to both the semiconductor and photomask supply chain.

1. Introduction

The predicted growth of the semiconductor market over the next decade will drive the need for significant investment in the photomask market. The investment for this level of market growth alone will challenge the

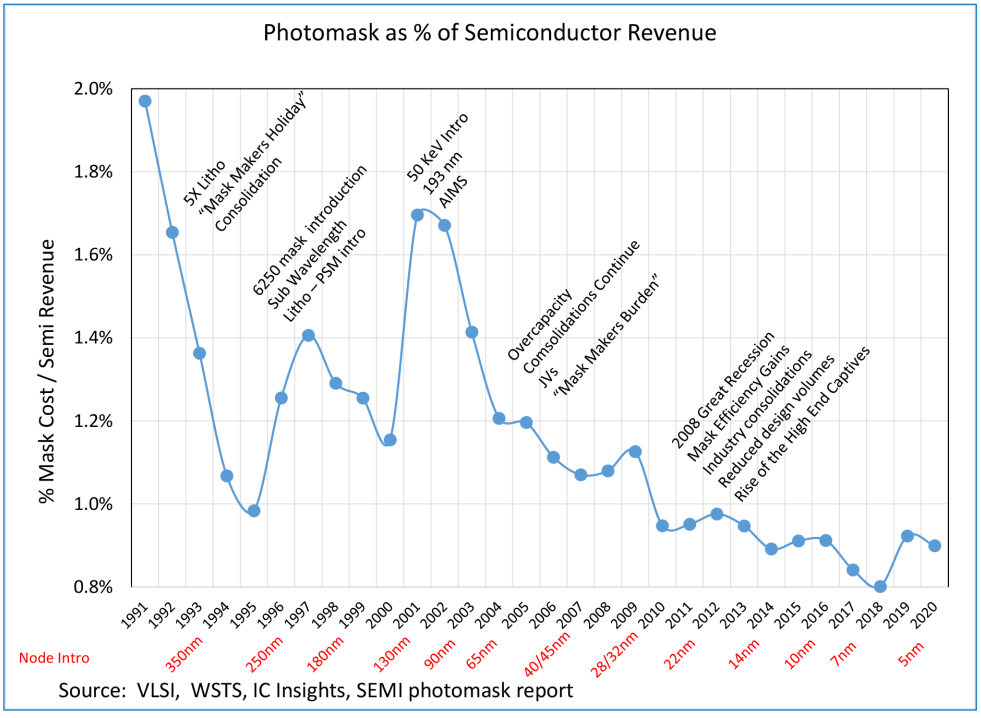

Figure 1. History of Photomask Market as % of Semiconductor Market[2].

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EDITORIAL

Change within the photomask community?

Emily Gallagher, imec

As a BACUS steering committee member, I have had the privilege of writing in this editorial space and have used it to write about global topics. My last two editorials dealt with the pandemic and climate change. In both cases, I narrowed the pervasive issue to its intersection with the photomask community. Today, I am again influenced by the news, but also by my role as BACUS president.

This November, an article caught my attention. Paul Krugman, an economist, intellectual and New York Times opinion columnist wrote about the "great resignation". Surveys indicate that workers are quitting even though wages are growing at rates consistent with an economic boom. Workers are confident, yet fewer are choosing to find jobs. There are only theories to explain this, and the one that resonates is that the pandemic shook everyone's foundation and knocked people out of their work ruts. Since nothing was normal, the status quo lost its hold. Change has been prevalent in many parts of life, including where and how we work.

Shifting to BACUS, I start with a reminder of who we are. The group started in 1980 as the "Bay Area Chrome Users Society" in California. It has expanded and is now an international group that works with SPIE to connect the wider photomask community (from design to wafer exposure). We are best known for organizing the largest annual photomask conference, usually held in September in Monterey, CA. This event recently joined the EUV community to create the SPIE Photomask Technology and EUV Lithography conference. How does the pandemic shake us, the photomask community, out of our status quo? Most conspicuously, the last two September conferences were held on-line. That was an operational change that could continue in some form. What other changes can be considered?

During her 2021 keynote, Christine Dunbar of GLOBALFOUNDRIES observed that the current semiconductor chip shortage has highlighted the importance of our industry to people at large[2]. This recognition coupled with a need for workers is an opportunity to attract students and non-traditional hires to our industry. Maybe the effort starts small – by influencing students in our sphere. Maybe we change our status quo within the BACUS organization to include more initiatives that are directed outwards. One example is the new student-industry mentorship program that was initiated at the 2021 conference. What else we can do to attract and grow the photomask work force? Be intentional and consider key questions like: Where is new talent needed? What skills are needed? How can we work differently and what should be retained? The pandemic gave us an unprecedented opportunity to rethink our lives. Let's take full advantage of it. What else can YOU do?

1. Krugman, P. (2021, Nov. 5) "Working Out: Is the Great Resignation a Great Rethink?", New York Times. https://www.epi.org/indicators/jolts/
2. Christine C. Dunbar, "Redefining innovation during The Renaissance of Computing" (spiedigitallibrary.org), **Proc. SPIE 11855**, Photomask Technology 2021, 1185510 (Presented at SPIE Photomask Technology + EUV Lithography: October 01, 2021; Published: 1 October 2021).

BACUS

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2021 BACUS scholarship winner

Maryam Baker, James C. Wyant College of Optical Sciences (United States), was awarded the BACUS Scholarship. This scholarship is awarded to a student in the field of microlithography with an emphasis on optical tooling and/or semiconductor manufacturing technologies. This scholarship is sponsored by BACUS, SPIE's Photomask International Technical Group.

The 2022 application for the $5,000 BACUS scholarship is due 15 February 2022.
Click here for information.

2021 BACUS Lifetime Achievement Award

Ken Rygler, Rygler and Associates, Inc.

On September 27th, the BACUS photomask society recognized Ken Rygler, of Rygler and Associates, with their 2021 Lifetime Achievement Award. This award is given to recognize an individual who has made distinct contributions of outstanding business or technical significance to the photomask industry.

Ken was recognized for influencing the entry of the E.I. Dupont Company into the merchant mask business in the 1980s. At that time, semiconductor chip manufacturers were divesting their photomask operations in order to focus on their core competencies. Ken recognized this as an opportunity to aggregate small mask operations into a global presence, maximizing the economy of scale of process and equipment. This ultimately led to the creation of DuPont Photomasks, and has eventually led to what is now one of the world's largest merchant mask manufacturers.

BACUS Best Paper Award 2021

First place

Paper: **Characterization of mask CD mean-to-target for hotspot patterns by using SEM image contours** [11855-33].

Winners: **Kan Zhou, Xin Guo, Yinsheng Yu, Hongwen Zhao, Wenzhan Zhou, Yu Zhang,** Shanghai Huali Integrated Circuit Corp., (China); **Ao Chen, Wenming Wu, Qijian Wan, Huaiyang Dou, Chunshan Du,** Siemens EDA, (China); **Liguo Zhang, Germain Fenger,** Siemens EDA, (United States)

Second place

Paper: **EUV attenuated phase shift mask: development and characterization of mask properties** [11855-50].

Winners: **Ikuya Fukasawa, Yohei Ikebe, Takeshi Aizawa, Tsutomu Shoki, Takahiro Onoue,** HOYA Corp., (Japan)

Third place

Paper: **Curvature based fragmentation for curvilinear mask process correction** [11855-28].

Winners: **Ingo Bork, Peter Buck,** Siemens Digital Industries Software, Inc. (United States); **Bhardwaj Durvasula, Nageswara Rao, Rachit Sharma,** Mentor Graphics (India) Pvt. Ltd. (India); **Vlad Liubich, Mary Zuo,** Siemens Digital Industries Software, Inc. (United States)

Zeiss Award for Talent in the Industry 2021

The Zeiss Award was established to support students working in the fields of EUV lithography and photomasks.

First place: $1,000

Paper: **Statistical analysis of the impact of 2D reticle variability on wafer variability in advanced EUV nodes using large-scale Monte Carlo simulations** [11855-2].

Winners: **Luke T. Long,** Univ. of California Berkeley (United States); **Adam Lyons,** ASML Silicon Valley (United States); **Tom Wallow,** ASML (United States)

Second place: $500

Paper: **iN5 EUV single expose patterning evaluation for via layers** [11854-23].

Winners: **Argho Das, Victor Blanco, Sayantan Das, Sandip Halder, Mircea Dusa,** imec (Belgium); **Nicola Kissoon,** ASML Technology Development Ctr. (Belgium)

Award sponsor:

ZEISS

Photronics Student Award 2021

Established to encourage students working in fields related to photomasks. Four finalists were selected from mask related student oral papers.

First place: $1,000

Paper: **Pathfinding the perfect EUV mask: understanding the EUV mask using the hybrid mask model [11854-41]**

Winners: **Hazem M. S. Mesilhy, Peter Evanschitzky, Andreas Erdmann,** Fraunhofer IISB (Germany); **Gerardo Bottiglieri, Eelco van Setten, Claire van Lare, Tim Brunner, Mark van de Kerkhof,** ASML Netherlands B.V. (Netherlands)

Second place $500

Paper: **EMA modelled alternative EUV absorber materials considering optical and stability behavior** [11855-7]

Winners: **Ravij N. Sejpal, Bruce W. Smith,** Rochester Institute of Technology (United States)

Award sponsor:

PHOTRONICS

2021 BACUS Prize

- **Masahiko Suguro,** Asahi Glass Co., Ltd. (Japan)
- **Onoue Takahiro,** HOYA Corp. (Japan)
- **Shoki Tsutomu,** HOYA Corp. (Japan)
- **Yoshiaki Ikuta,** Asahi Glass Co., Ltd. (Japan)

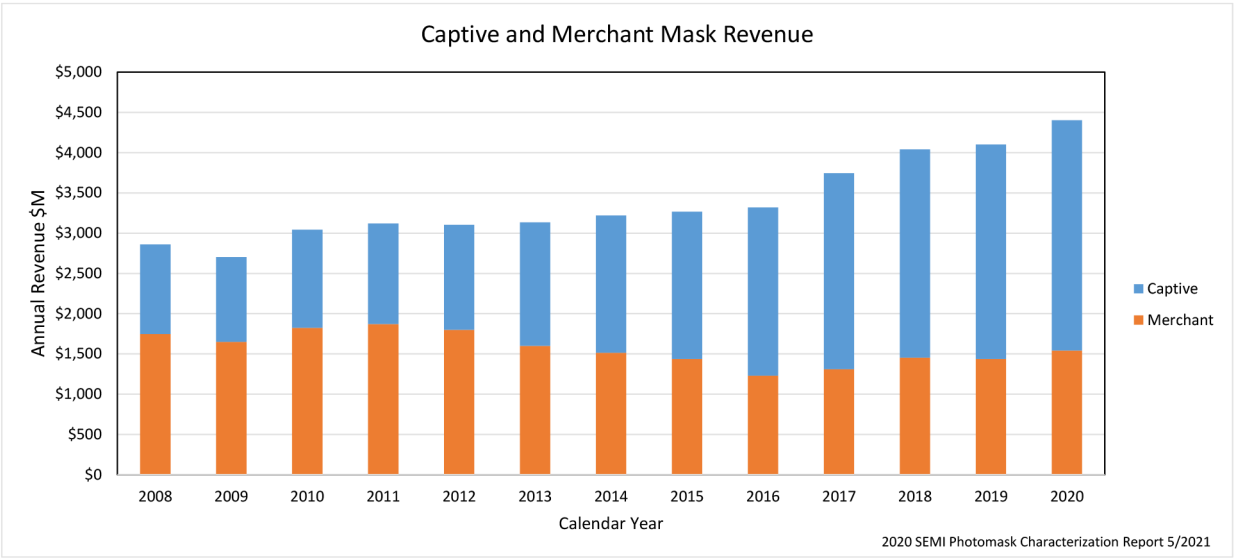

Figure 2. Captive & Merchant Mask Revenue 2008 - 2020[2].

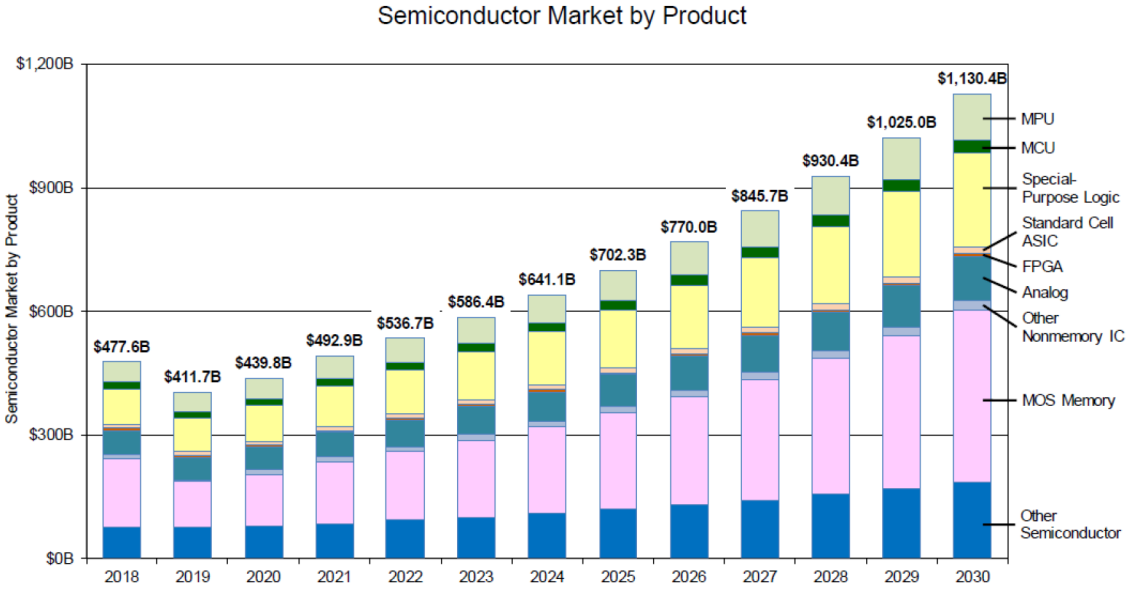

Figure 3. Semiconductor Market Growth[1].

photomask equipment market. In addition to this market growth there will be a substantial amount of photomask equipment requiring upgrade or replacement due to component obsolescence, further straining investment needs. Together, these two required investments often cannot be justified under current photomask market conditions. This presentation will review these business models vs. market growth expectations. We will further extend that analysis to all photomask equipment and estimate the total investment likely necessary to fulfill the obsolescence and growth requirements.

2. Photomask Market History

Within the semiconductor supply chain, the photomask market has had a challenging history over the past thirty years.

Short of a few upticks due to the introduction of new material (6" x 6" x 0.250") or new technology introduction (PSM and 50keV E-beams starting with the 130nm & 90nm nodes) the history of the photomask market as a percentage of the semiconductor market has been one of steady decline from approximately 2.0% in 1991 to 0.8% in 2018. As one industry author stated back in 2006, the Mask Maker's Holiday turned into the Mask Maker's Burden[3]. Note however the photomask market has seen an uptick to 0.9% in 2020 with the rise of multiple patterning usage and EUV mask introduction.

Overcapacity and low margins of the 1990s drove consolidations as well as absorption of several smaller captives into merchants. During that decade the merchant to captive mask operations ratio began to favor merchants. The investment required to stay current for Moore's Law in the 2000s drove heavy investment in new toolsets to support each new node. In many cases each new node required new equipment resulting in over capacity as previous generation toolsets did not achieve full utilization. This in turn drove further consolidation and joint ventures on the merchant side of the market while high end captives began to heavily invest in advanced technology mask operations to maintain their high margin leading edge semiconductor business. This led to the period where high end captives regained share dominance in the photomask market as see in Figure 2 below. From 2008 – 2020 the overall photomask market grew from $2.8B to $4.4B, but the growth was dominated by captives which went from 35% of the global photomask market share to 65%. The merchant mask revenue actually decreased in the 2008 – 2020 timeframe.

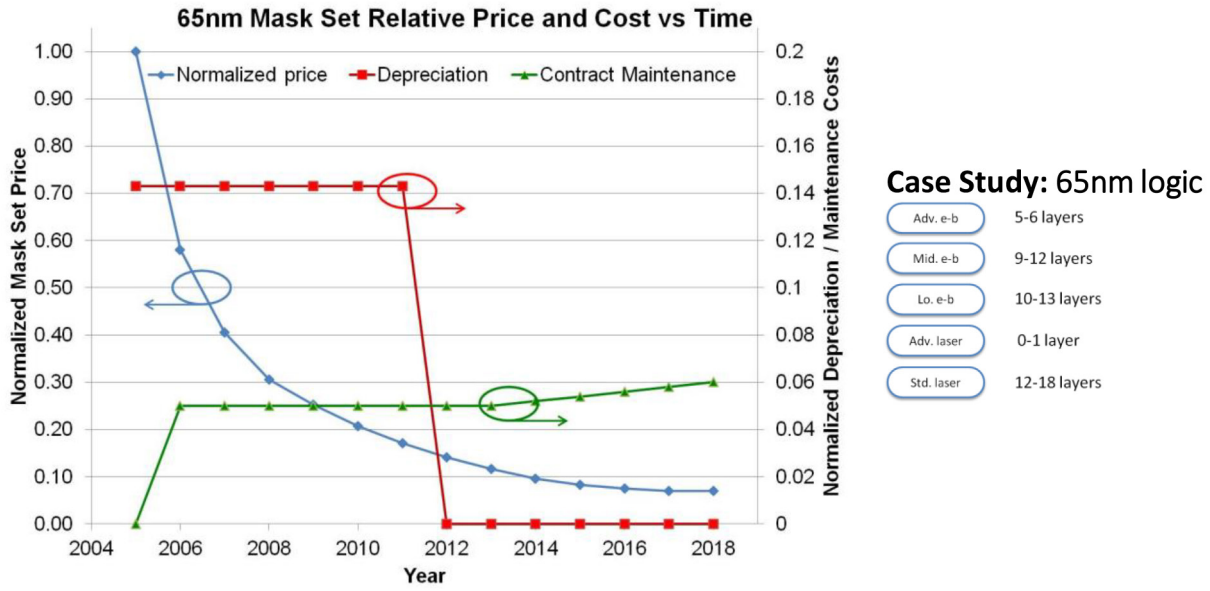

Figure 4. 65 nm Mask Set Costs vs. Normalized Price.

Investment $M	Comments
$ 17	Mid-Level E-beam & Suite
$ 5	i-line laser with 2nd level align
$ 3	Developer
$ 7	Dry Etch (Cr & MoSi)
$ 4	CD SEM
$ 5	Registration Tool
$ 16	Inspection
$ 5	Strip/Clean
$ 4	Facility/Other
$ 65	**TOTAL**

Figure 5. 65 nm New "Line" Cost.

In effect, captives became "dominant" in advanced mask technology while merchants followed the captives and addressed volume production technology 1-2 nodes below captives.

However, even with the rise of the captive business and increase in the overall global photomask business, it still left the industry with a decreased portion of the value chain. We believe the photomask market is entering a period where the mask portion of the Semiconductor value chain will increase due to two major market issues in both the semiconductor and photomask market.

3. Semiconductor Market Growth Challenge

The semiconductor business is forecasted to grow upwards of 9.9% CAGR from 2020 - 2030[1].)

This growth is being driven by a series of mutually reinforcing market mega-trends including telecom (5G/6G), IoT, Power management (Green power), automotive electrification & ADAS, Artificial Intelligence, Digital Twinning and Medical applications. Global/political challenges are also fueling investments as many regions have developed a renewed appreciation of the strategic nature of the semiconductor business. COVID-19 also accelerated many trends by several years due to significant work for home and teleconferencing needs. Note in Figure 3 that the Semiconductor Market growth is broad-based, not just 7nm and below. Indeed, it has been estimated that 70% of the chips sold are not "leading edge" technology[4] and this is not expected to change greatly in the next decade. Looking at Figure 3, clearly demand for high end processors and memory will drive a significant portion of growth. However, the 28nm and above technologies will likewise show tremendous growth. This is the exactly the market segment where merchant mask operations have high share and operational experience/efficiency.

Overlay that growth with the current semiconductor fab and photomask capacity situation. Both are reporting "sold out" or constrained capacity today across most technology nodes. To handle the increased semiconductor demand there will be new and expanded fabs which will lead to a higher number of new designs resulting in substantial growth in photomasks. Photomask market growth estimates range from 3.5% to 6% CAGR over the next several years but could possibly be higher. Therefore, any semiconductor growth will need to be supported by new photomask capacity, not just at the most advanced nodes but at 28nm and above nodes as well. But therein lies a conundrum.

As shown previously by F. Kalk[5], a 65nm logic set required approximately 24-31 E-beam layers and 12-19 laser lasers. From 2005 to 2018 you can see the normalized price of a 65nm set has dropped below 10% of the original price! This is normal in the semiconductor and photomask businesses in the past, as volumes increase and yields improve, but the node pricing has settled at values which are consistent with volume manufacturing, but not new investment a decade (or two) later.

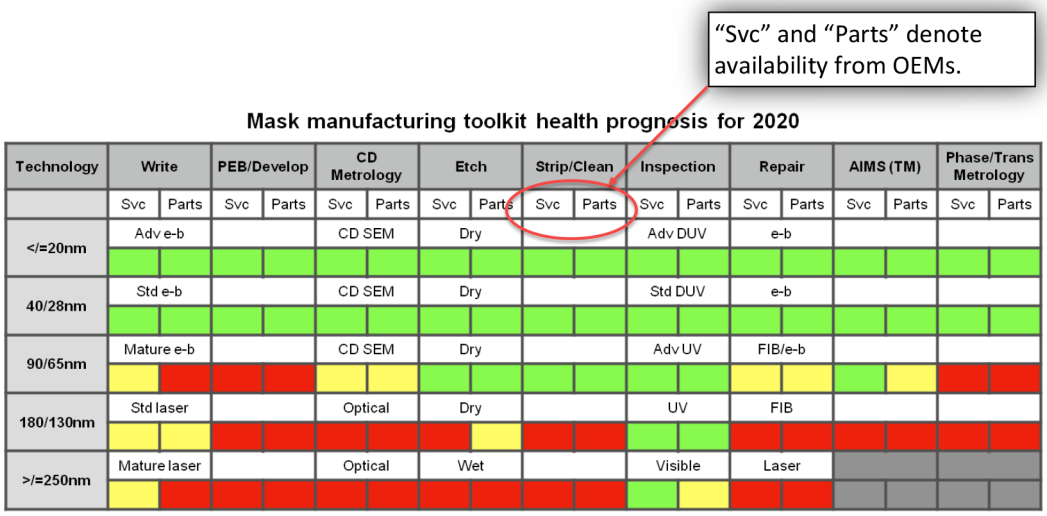

Figure 6. Supply Chain Obsolescence.

Module	Tools	# Tools "In Field"	Replace or Upgrade	Replace % "In Field"	Replace/Upg Est. Cost	Replace/Upg Efficiency	Total Cost
Write	CORE 2XXX	37	R	50%	$ 5	1.75	$ 49
	A3XXX	86	U	40%	$ 3	1	$ 96
	Omega	12	R	40%	$ 5	1.5	$ 16
	EBM3XXX	6	R	100%	$ 16	2	$ 48
	EBM4XXX	8	R	100%	$ 16	2	$ 64
	EBM5/6XXX	38	U	90%	$ 5	1	$ 154
	JBX7000	4	R	50%	$ 10	2	$ 10
	JBX9000	10	R	100%	$ 13	2	$ 63
	JBX3030	12	R	80%	$ 13	2	$ 60
	HL Hitachi	18	R	70%	$ 10	1.25	$ 101
	MEBES	4	R	100%	$ 5	2.5	$ 7
	TOTAL						**$ 667**

Figure 7. Global Litho Module Replacement/Upgrade Example.

But to handle the increased volume expected in the 40-65nm node, we would have to purchase a new "line". What does that look like? As shown above, to produce a full 65nm set requires a combination of E-beam and laser masks. The table in Figure 5 details those investment costs. These are conservative as we assume there is existing capacity on secondary tools used in manufacturing such as coaters, repair tools, AIMS tools and Phase/Transmission measurement tools. That of course may not always be true. Assuming the E-beam tool can produce ~ 6 masks per day and the laser tool ~ 7 masks per day plus adding ~ 6% of purchase price for service costs, the cost of depreciation and maintenance alone comes to approximately $3,500 per mask. Add material, labor, and other costs and that total rises to over $6,000 per mask. Put a semiconductor market normal Gross Margin % on that cost and that figure comes to a total far higher than the 65nm ASP of today. This is the challenge of new investments. No matter how efficient and effective new tools may be, Cost of Ownership (CoO) will ALWAYS be higher than fully depreciated tools.

4. Obsolescence Challenge

Coincident with the predicted Semiconductor Market growth, the photomask industry is facing significant equipment obsolescence issues that will require many of the legacy tools that support >=28nm technology to be renewed, retired and replaced in the next seven to ten years. This challenge was previously reported at SPIE Photomask Technology 2019[6]. See Figure 6 for obsolescence issues as of 2020. There have been further red and yellow areas added in 2021 and the list will grow as we move further into the decade.

Historically photomask equipment makers produced new tools for the "leading edge" and as these tools "aged", they became the production staple for "standard" technologies. However, the combination of obsolescence and broad-based growth in these standard technologies make this strategy no longer tenable. But given the parts obsolescence in Figure 6, photomask equipment manufacturers must now develop new tools and/or upgrades for the standard market. That is a real challenge for the manufacturers due to the small size of the photomask equipment market relative to the semiconductor equipment market. The small scale of the photomask equipment market challenges supply chains for existing tool upgrades and makes any new tool development more expensive as those development costs are amortized over a relatively small number of units. That has cost implications for 28nm and above technologies that may not be compatible with current photomask prices. There is a fine balancing act in Cost of Ownership that equipment manufacturers must master in this new situation.

Even with the above challenges, several photomask equipment manufacturers have understood this change and begun to develop and sell tools/upgrades to target this standard market. However, even though equipment makers have often improved throughput and efficiency of these replacement tools, the costs of these tools are not comparable with current photomask price conditions when compared to old tools that are fully depreciated.

The cost of upgrade or replacement of legacy photomask industry tools in the next decade is huge. As an example, see Figure 7. Here we look at one module of the mask making process and where we will need

to either Upgrade (U) or Replace (R) older tools. This table is based on our estimation of the number of tools still active in the field globally and what will be obsolete in the next decade (or already obsolete). The formula is # Tools "In Field" * Replace % "In Field" (% of tools that will be replaced/upgraded) * Replace/Upgrade Est. Cost * (Replace/Upgrade Efficiency (newer tools may be faster so it may not be a 1:1 replacement) = Total Cost. As you can see in Figure 7, globally for just the Litho module the cost would be over $660M. If we do the same rough analysis for Process, Etch, Metrology, Inspect, Repair, Clean/Strip, AIMS, Phase/Trans and Miscellaneous modules, we get a potential global total of $1B to $2B over the next decade! Needless to say, with the total global photomask market at $4.4B in 2020, that is a daunting investment figure.

This $1B - $2B investment is to keep producing the legacy basic volume of the existing work and it does not encompass the growth of the market. The mathematics of a "new line" will be similar here as Section 3 above. New tools will drive up mask costs even for standard IC technology. If not addressed, the obsolescence issue will show up in under supply and longer cycle times and delivery issues on these products. In the worst-case scenario, leading edge products can be held up for "standard technology" products. An example of this kind of economic issue is being seen today is a car that sells for $100,000 is being held up for chips that may be $5,000 in total.

5. Summary

We believe the photomask market is entering a period where the mask portion of the semiconductor value chain will begin to increase from historical lows due to:

1. mask capacity growth required for the 28nm and larger semiconductor explosion
2. legacy tool replacement and renewal needed for continued support of these standard nodes.

The business implications of this are critical to both the semiconductor and photomask supply chain. We suggest that alternative business models will be required to address the market financial challenges. It benefits all companies to cooperate in this endeavor or the predicted semiconductor growth has a high risk of being constrained by photomasks. Without this cooperation and understanding, the photomask market will likely constrain semiconductor growth.

References

[1] International Business Strategies, "Semiconductor Market Analysis", January 2021.

[2] SEMI, VLSI Research, WSTS and IC Insights various Photomask and Semiconductor Market Reports.

[3] LaPedus, Mark, "Photomask maker's joke no laughing matter", EE|Times 2 October 2006.

[4] Santo, B., "Global Foundries CEO Caulfield Stands Up for the 70%", EE Times 11 April 2021.

[5] Kalk, F. D., "Renew, Retire, Replace" eBeam Initiative, September 2018.

[6] Kalk, F. D., "Sustaining the mask manufacturing base" SPIE Photomask Technology 2019.

Industry Briefs

A Big Deal for the Future Miniaturization of Chips

Scott Foster, Asia Times

On September 17, Japan's JSR Corporation announced plans to make Inpria Corporation of the US a near wholly-owned subsidiary, a little-noticed deal that could have big implications for the global semiconductor industry. Tokyo-based JSR is the world's top maker of photoresists, light-sensitive materials used to form circuit patterns on silicon and other types of semiconductor wafers during the photo-lithographic process of chip production.

The company commands a photoresists market share of about 35%. JSR and other Japanese companies including Tokyo Ohka Kogyo (TOK), Fujifilm, Shin-Etsu Chemical and Sumitomo Chemical have close to 90% of the global market for semiconductor photoresists.

https://asiatimes.com/2021/09/a-big-deal-for-the-future-miniaturization-of-chips/

Berkeley Lab Honored with Three R&D 100 Awards

Media Relations

Improved cathode materials could help batteries operate reliably at high capacity and high voltage over repeated cycles without sacrificing performance, safety, or cost. Berkeley Lab scientists have developed a unique cathode material that uses a layered-rocksalt intergrown structure, combining the high capacity of lithium-rich metal oxides, fast kinetics of a cation-ordered layered structure, along with structural stability of a cation-disordered rocksalt structure. Such a material has been shown to offer high capacity, fast charging time and energy transfer, and superior cycling and thermal stability. In addition, the cost for raw materials to produce layered-rocksalt intergrown electrodes is estimated to be significantly less than that of lithium-rich layered oxides when expensive cobalt is completely replaced by cost-effective iron. This innovation exemplifies a new battery electrode design concept and opens up a new class of high-performance intergrown cathode materials.

https://newscenter.lbl.gov/2021/11/08/berkeley-lab-honored-with-three-rd-100-awards/

California-Based Technology Company Opens $200 Million Campus in Ann Arbor

Jordyn Pair, Mlive

KLA, which produces equipment that helps create electronic components, recently opened a $200 million research and development campus, featuring corporate functions and a "clean room."

The Ann Arbor headquarters — a six-story, 230,000-square foot building located on 18 acres in Ann Arbor Township — is focused on advancing semiconductor manufacturing through research of manufacturing tools and machine learning applications.

https://www.mlive.com/news/ann-arbor/2021/11/california-based-technology-company-opens-200-million-campus-in-ann-arbor.html

"Photomask is Nowhere to be Found"... Semiconductor Supply Shortage Worsening

Gun-il Yun, Korea IT News

There is concern that the shortage of photomasks will soon lead to delays in semiconductor shipments, fueling the semiconductor supply and demand shortage.

"As the photomask supply and demand situation worsens, orders are pouring in to major companies such as Toppan, DNP, and TMC, and prices are rising. 5-15% price increase is expected for high-end products and 15-25% for low-spec photomasks. It is very unusual for photomask prices to rise. It is known that not only are the random prices rising due to the rushing demand, but it is also difficult to find a photomask in time even if buyer pays more. The delivery time, which normally took 4-7 days, has recently increased by two or three times which is about 14 days. In some cases, the delivery date has been extended up to 7 times compared to the previous one."

https://english.etnews.com/20211026200001

Join the premier professional organization for mask makers and mask users!

About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

Individual Membership Benefits include:

- Subscription to BACUS News (monthly)
- Eligibility to hold office on BACUS Steering Committee

spie.org/bacushome

Corporate Membership Benefits include:

- 3-10 Voting Members in the SPIE General Membership, depending on tier level
- Subscription to BACUS News (monthly)
- One online SPIE Journal Subscription
- Listed as a Corporate Member in the BACUS Monthly Newsletter

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CALENDAR

2022

SPIE Advanced Lithography + Patterning
27 February - 3 March 2022
San Jose Convention Center
San Jose, California, USA
www.spie.org/al

Photomask Japan
26-28 April 2022
Digital Forum
www.photomask-japan.org

EMLC 2022
20-23 June
Leuven, Belgium
https://www.emlc-conference.com/

SPIE Photomask Technology + Extreme Ultraviolet Lithography
25-29 September 2022
Monterey, California, USA
www.spie.org/puv

SPIE is the international society for optics and photonics, an educational not-for-profit organization founded in 1955 to advance light-based science, engineering, and technology. The Society serves more than 255,000 constituents from 183 countries, offering conferences and their published proceedings, continuing education, books, journals, and the SPIE Digital Library. In 2020, SPIE provided over $5 million in community support including scholarships and awards, outreach and advocacy programs, travel grants, public policy, and educational resources. spie.org

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You are invited to submit events of interest for this calendar. Please send to lindad@spie.org.