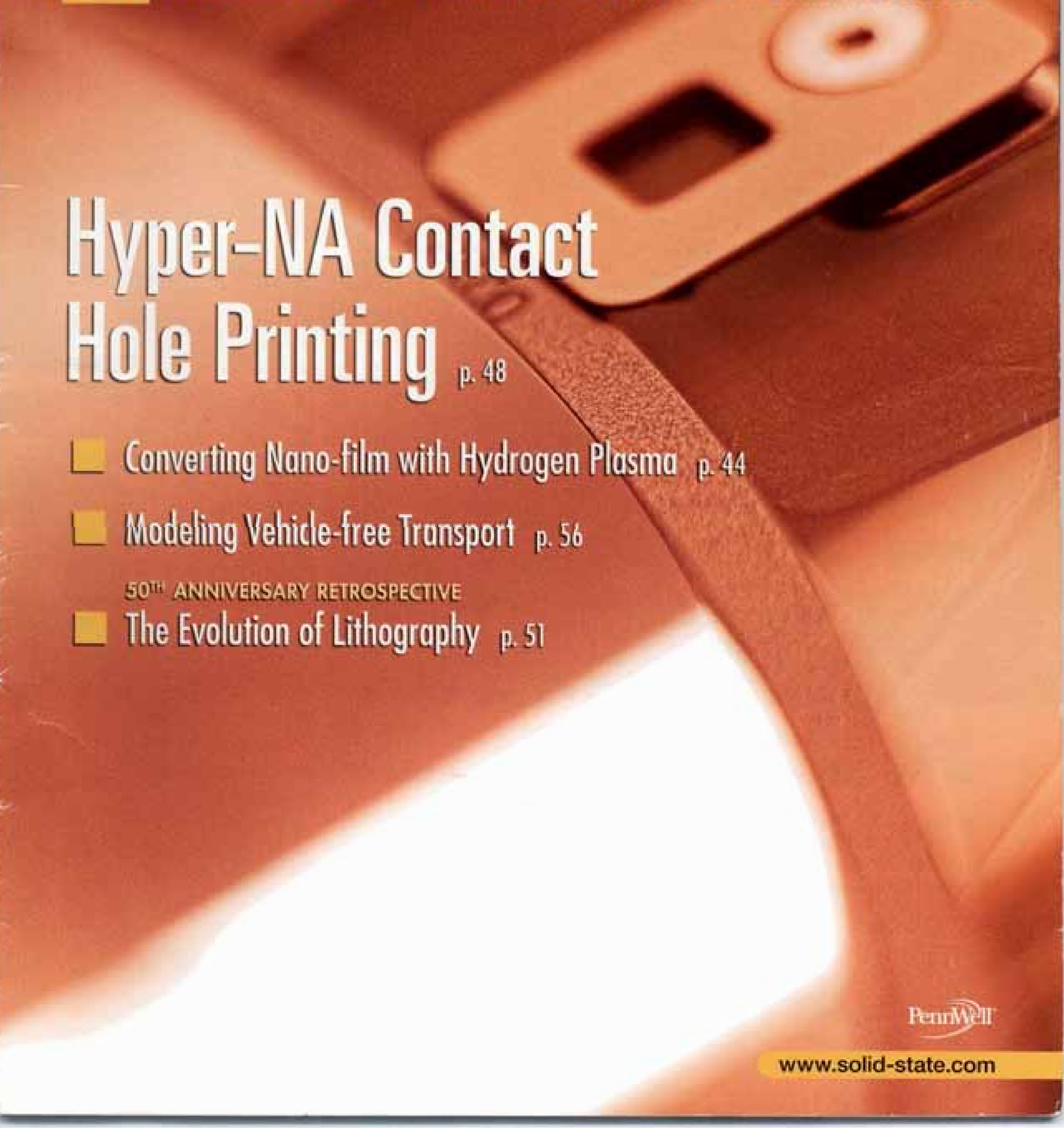
NOVEMBER 2007

Solid State TECHNOLOGY

Celebrating 50 Years of Excellence

THE INTERNATIONAL MAGAZINE FOR SEMICONDUCTOR MANUFACTURING



Hyper-NA Contact Hole Printing p. 48

PennWell

www.solid-state.com

Technology interdependence and the evolution of semiconductor lithography

EXECUTIVE OVERVIEW Advances in semiconductor lithography have driven the rapid growth of the semiconductor industry since its beginnings. From the contact printers of the 1960s to today's 193nm immersion scanners, this progress has been powered by the efforts of suppliers to push the technology envelope to improve tool resolution with better accuracy and higher throughput. In this article, we examine the evolution of semiconductor lithography using an "ecosystem lens"—expanding the focus to include not only the evolution of tool technologies, but also the co-evolution of the infrastructure of lens, energy source, mask, and resist technology to shed new light on the uneven progress of the past.

Since its emergence, semiconductor lithography has witnessed no fewer than 11 distinct attempts to introduce new tool technologies (see **table**). The introduction of these tools has enabled many advances in the semiconductor industry [1]. While the forward progress of the industry is beyond question, this progress has been punctuated by numerous false starts and cases of unrealized potential.

The lithography ecosystem

For the past three years, we have been researching ecosystem dynamics in the semiconductor lithography industry [2, 3]. Here, we re-examine the history of semiconductor lithography by focusing on the ecosystem of interdependent technologies that must co-evolve for progress to be realized. **Figure 1** offers a simple schema of the lithography technology ecosystem: the lens and energy source that are integrated into tools, the tools themselves, and the mask and resist that must be used with the tool for the lithography process to take place. Despite wave upon wave of technology transition in the industry, the basic structure of this ecosystem has not changed. Although the structure has been stable, the distribution and magnitude of challenges in the ecosystem has varied quite dramatically across the different technology generations.

Figure 2 presents a map of the location of ecosystem challenges. It shows the number of *Solid State Technology* articles published within the first five years of a technology's launch that discussed challenges and developments in the different ecosystems' technologies. (To the extent that industry attention tends to be focused on problem areas, this is a useful, objective proxy for challenges.) We describe these challenges below and consider their role in both enabling and hindering the emergence of new technology generations. These ecosystem challenges hold implications for the ways in which both semiconductor suppliers and manufacturers should approach coordination challenges, technology expectations, and investment timing.

Rahul Kapoor, Ron Adner, INSEAD, Fontainebleau, France

The 1960s

Contact. Contact printing was the earliest and the simplest of the lithography technologies to be commercialized by semiconductor equipment firms. Contact printers included a mercury lamp as a light source, a holder for placing the mask and the wafer, and an alignment unit that ensured that patterns from the mask were accurately transferred to the wafer. These printers did not use a lens, and the mercury lamp used as an energy source was an existing external component that was already being used in applications such as movie projectors. Similarly, the required resist was readily available in the market and was already being used in photography applications.

The main ecosystem challenge to contact printing's emergence stemmed from difficulties in making suitable masks. These challenges were rooted in the manual cutting process and in the emulsion plates used to create masks, which resulted in high defect rates. These limitations, which resulted in mask errors and poorer resolution, held back the progress of contact printing.

To address the challenges presented by the growing complexity of

Semiconductor lithography technology transitions*

Technology generation	First industry sale	Initial resolution (μm)	Market dominance
Contact	1962	7.00	N/A
Proximity	1972	3.00	1973
Projection	1973	2.00	1977
E-beam	1976	0.5	Never
X-ray	1978	0.3	Never
G-line	1978	1.25	1982
I-line	1985	0.80	1991
DUV 248nm	1986	0.45	1998
DUV 193nm	1996	0.15	2006
DUV 157nm	1998	0.10	Never
DUV 193nm immersion	2005	0.04	Early Days

* Source: VLSI Research and other industry sources.

circuits and the increasing size of wafers, the maskmaking industry introduced two innovations during the late 1960s. First, the computerization and automation of maskmaking using high-speed step-and-repeat cameras allowed for reduced geometries and greater accuracy. Second, the substitution of emulsion plates by chrome patterns on soda lime blanks for master masks that could be cleaned and reused several times enhanced the productivity of the maskmaking process.

The 1970s

Proximity. A primary disadvantage of contact printing was low process yield. This was due to the damage inflicted on the mask and the wafers as they were repeatedly brought in and out of physical contact with each other during the lithography process. With proximity printing, the mask and the wafer were separated by a tiny gap in order to reduce the defects that had been caused by their direct contact. This reconfiguration allowed for significant process improvement. The transition to proximity printing required adjustments on the part of toolmakers. It did not, however, present major innovation challenges to the lithography ecosystem. Proximity printing captured dominant industry market share (in dollar terms) one year after its launch.

Projection. Projection scanners introduced the use of lenses as a component in lithography tools. They incorporated a series of reflective mirrors to transfer the image of the mask onto the wafer. The ecosystem challenges during the development and emergence of this generation were in the lens system itself and in the 1× masks, which needed to be etched with correspondingly smaller geometries and greater accuracy. To meet the mask manufacturing challenge, maskmakers needed to significantly refine their production processes to deliver "perfect" masks. A part of this adjustment was the switch from using step-and-repeat cameras to using electron beam systems in the production process. Projection scanning achieved dominant market share four years after its market launch.

Although optical lithography has been the mainstay of semiconductor manufacturing, there have been several attempts to introduce non-optical technologies that would offer smaller geometries by using the much shorter energy wavelengths that lie outside of the visible spectrum. Among these, the two that attracted the most interest,

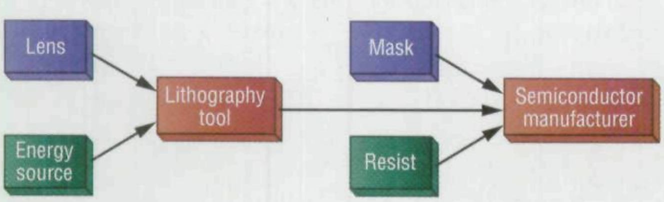


Figure 1. A schema of the semiconductor lithography ecosystem.

resources, and market share were X-ray and electron-beam (E-beam) lithography. Approaches using ion-beam lithography and e-beam projection lithography have also been pursued, but neither has ever been commercialized.

X-ray. The use of X-rays for lithography was proposed due to their very short wavelength. The short wavelength, however, created substantial ecosystem challenges due to required changes to the source and the mask. The industry expended enormous effort in developing

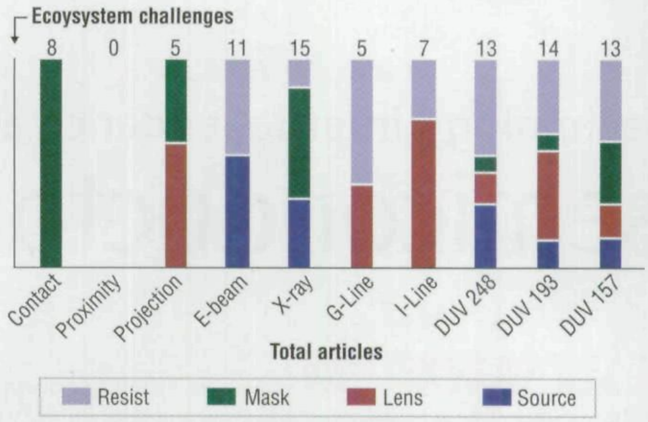


Figure 2. Number of *SST* articles published within the first five years of each technology's introduction that discussed challenges and developments in the different ecosystems' technologies.

synchrotrons as X-ray sources. An even greater obstacle than the source was the challenge of creating the required 1× masks. These needed to have dramatically reduced feature sizes and, because of the X-ray's short wavelength, excluded the quartz and soda lime glass materials that were already in use because of problems with energy transmission and overheating. Developed to overcome this shortcoming, the mask materials, such as combinations of silicon carbide and tantalum, created manufacturing problems for the IC manufacturers due to their lack of mechanical rigidity. Many observers in the industry agree that masks are the "limiting piece" of the X-ray puzzle [3]. Although it was first introduced in 1978 with great fanfare, X-ray printing has never entered the mainstream; as of the time of this writing, its infrastructure challenges have yet to be overcome at a competitive, commercial scale.

E-beam. Electron-beam (E-beam) technology involves patterning the resist on the semiconductor wafer directly using electron beams that follow a pre-programmed pattern, thereby eliminating the need for a mask. The major ecosystem challenges posed by E-beam technology were the development of a suitable electron source and new resist chemistries that work with the emitted electrons. The key concern with this technology, however, has been its low throughput, which has relegated E-beam writers to high-end, low-volume niches and precluded their adoption in mainstream semiconductor applications.

G-line. The challenges in making 1× masks pushed the industry to develop step-and-repeat (stepper) technology. The G-line stepper, which used the 436nm wavelength, embodied two key modifications to previous optical technologies. First, light was projected using a refractive lens system. Second, the light was projected on only a part of the wafer at any one time such that multiple exposures of the circuit design were made in order to complete a wafer. These two developments significantly eased the maskmaking challenge because the circuit patterns on the mask could now be 5× or 10× the dimensions that needed to be printed onto the wafer.

Beyond challenges in the design of the tool, the transition to G-line steppers imposed significant challenges on the ecosystem. It required the development of a refractive lens composed of several precise glass elements that would minimize distortion and transmit light accurately onto the wafer. The transition also required the development of a resist formulation that would allow for sufficiently small geometries, that is, a resist in which exposure to light energy would trigger a chemical reaction only in the molecules that were directly exposed to the light, without setting off a reaction in adjacent molecules. The resist challenge was resolved through the development of new novolac-based materials, which replaced the negative resists that had been used to this point. G-line steppers achieved market dominance four years after their launch.

The 1980s

I-line. I-line steppers used light with a shorter wavelength (365nm) to improve the resolution achievable with the G-line generation. The main infrastructure challenge was to develop a lens that would transmit light at this lower wavelength. This required the development of a new glass material and corresponding changes to the lens production process, as well as some modification to the resist formulation. The remaining elements required only incremental changes for the transition from the G-line generation. I-line steppers achieved market dominance six years after their launch.

DUV 248nm. The next technology transition occurred with the shift to using the deep ultraviolet (DUV) 248nm wavelength. The reduction in wavelength required fundamental changes in the energy source, the lens, the mask, and the resist. Mercury lamps, which had been the mainstay of all previous optical generations, were not able to provide sufficient energy at a wavelength of 248nm to cause adequate chemical reactions in the resist. This challenge was overcome by the development of excimer lasers using krypton fluoride (KrF) gas.

The materials that had previously been used to make lenses faced absorption problems with 248nm wavelength. The solution on which the industry ultimately converged, fused silica, required major changes to the lens manufacturing process. Maskmakers, too, needed a new material that would provide improved transmission of the 248nm wavelength, which, in turn, required changes to the mask manufacturing process. Perhaps the biggest challenge was the existing novolac resists, which could not absorb enough energy from the new wavelength to cause an adequate chemical reaction. To solve this challenge, a new chemically amplified resist had to be developed for semiconductor manufacturers to create fine circuits using the new lithography technology. The DUV 248nm technology achieved market dominance 12 years after its launch.

The 1990s

DUV 193nm. The drive towards finer resolutions continued with the introduction of tools using the DUV 193nm wavelength. As was the case for the DUV 248nm technology, the very low light wavelength created new challenges throughout the ecosystem. Since KrF lasers could not produce light with wavelength of 193nm, a new excimer laser that used argon fluoride (ArF) gas was developed. New challenges were also posed by light absorption problems with the existing lens materials. These challenges were overcome with the development of a new lens material, calcium fluoride (CaF_2). The resist and the mask also had to undergo major developments so that this new generation could create value for users.

With the change to the 193nm wavelength, the existing resists, which were engineered to react to the 248nm wavelength, were no longer adequate to the task, so a new generation of chemically amplified resist needed to be developed. DUV 193nm (dry) scanners are on the verge of achieving market dominance 11 years after their launch.

DUV 157nm. The next step in the industry was to exploit the 157nm wavelength to achieve still smaller feature sizes. This required the development of a new excimer laser that used fluorine (F_2). The reduction in wavelength created transmittance problems with the existing lenses. To overcome this problem, lenses required much higher concentrations of CaF_2 than ever before, which created enormous challenges in the lens manufacturing process. Resist has been a challenge as well.

Perhaps the biggest challenge in the DUV 157nm ecosystem resided in maskmaking. Both the mask substrate and the pellicle materials had to be changed to effectively transmit the low energy wavelength. The mask challenges have yet to be resolved on a commercial scale. With the emergence of DUV 193nm immersion technology that has extended the life of the 193nm wavelength, further development of 157nm generation seems to have been put on hold.

Lessons learned

The progress of semiconductor lithography, enabled by the technology transitions reviewed above, has been the key engine of progress for the semiconductor manufacturing industry as a whole. In our research, we have identified a clear pattern of ever-greater ecosystem challenges corresponding to increasingly longer lags in market penetration. The DUV 248nm case is a telling example of how ecosystem challenges, in this case chemically amplified resist, impact the growth of a new technology. **Figure 3** plots annual sales of DUV 248nm tools and the number of articles appearing in *SPIE Proceedings* that discuss resist development for the 248nm wavelength. What is striking is the correspondence between the decline in article count, which signals the resolution of major resist-related challenges, and the takeoff of the DUV 248nm technology.

Conclusion

Understanding the evolution of lithography technology requires that we understand the evolution of the entire lithography ecosystem. The

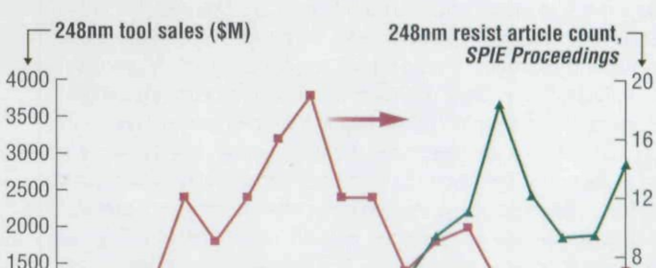


Figure 3. Plots of annual sales of DUV 248nm tools and the number of articles on 248nm resist development appearing in *SPIE Proceedings*. Sources: VLSI Research and *SPIE Proceedings*: "Advances in Resist Technology and Processing, 1986–2004."

current DUV 193nm immersion technology as well as next-generation candidates such as extreme ultraviolet (EUV) will be subject to these same ecosystem dynamics. In setting industry expectations for the path of their emergence, it will be important to consider not only the pace of advance in tools and components, but also the extent to which this pace will be matched by progress in mask and resist technologies.

The key message is that although the different elements of the ecosystem are developed and refined according to their own trajectories, the pace of progress of the ecosystem as a whole is regulated by the progress of the weakest link. Meaningful commercial progress for the different industry participants is therefore determined not only by their own rate of advance but, critically, by the rate of advance of their ecosystem partners. ■

Acknowledgments

We thank Risto Puhakka and Bob Mariner of VLSI Research, Giang Dao of SEMATECH, and M. David Levenson of *Microlithography World* for their generous support of our research, as well as the many industry professionals who have generously shared their experiences with us.

References

1. G.E. Moore, "Lithography and the Future of Moore's Law," *Proc. of the International Society for Optical Engineering*, Vol. 2438, pp. 2–17, 1995.
2. R. Adner, "Match Your Innovation Strategy to Your Innovation Ecosystem," *Harvard Business Review*, Vol. 84, No. 4, pp. 98–107, 2006.
3. R. Adner, R. Kapoor, "Innovation Ecosystems and Innovator Outcomes: Evidence from the Semiconductor Lithography Equipment Industry: 1962–2004." INSEAD Working Paper, 2006.
4. K. Derbyshire, "Issues in Advanced Lithography," *Solid State Technology*, Vol. 40, No. 5, p. 16, 1997.

Rahul Kapoor is a PhD candidate in strategy at INSEAD, Boulevard de Constance, Fontainebleau, France; e-mail him at rk@rahulkapoor.com.

Ron Adner is Akzo-Nobel Fellow of Strategic Management and associate professor at INSEAD; e-mail him at ron.adner@insead.edu.

50th Anniversary Perspectives: The Future of Lithography

Photomasks

Is nucleoepitaxy in the future?

Franklin Kalk, CTO, Toppan Photomasks Inc.

The semiconductor industry's growth over the past 50 years has been fueled in part by a host of lithography innovations. The key innovations related directly to the photomask include the reduction stepper, the pellicle, the electron beam mask writer, mask inspection and repair, and resolution enhancement techniques (RETs). Each of these addressed a technical challenge and ultimately lowered manufacturing cost.

Reduction stepper. With 1× lithography, the photomask was an exact replica of the entire wafer-level die array to be imaged. Photomasks were produced by a tedious process in which a photorepeater imaged the die array onto the mask from a master image on a reticle (a mask containing an image of a single die). The GCA DSW4800 reduction stepper moved the photorepeating process to the wafer and eliminated the slow and costly reticle-to-mask process step.

Pellicle. The reduction stepper introduced a defect challenge. Because the stepper prints the image that has been etched on the photomask multiple times onto the wafer, mask defects are replicated multiple times. The photomask must be produced with zero printable defects and must be maintained defect-free to prevent wafer defects. Before the pellicle was invented in 1978, masks had to be cleaned frequently, an expensive process. The pellicle captures particles on a film several millimeters above the mask's image surface, ensuring the particles are out of focus and do not affect image intensity. The pellicle prevents defects and reduces mask-cleaning frequency, thereby increasing productivity and reducing manufacturing cost.

Electron beam mask writer. As feature densities grew in the 1970s, existing mechanical optical pattern generators were unable to provide the desired combination of resolution and throughput. The EBES electron beam mask writer (developed at AT&T Bell Laboratories in the mid-1970s) and its successors enabled precision photomask manufacturing for 25 years. That technology has continued to evolve in the early 21st century with the introduction of variable-shape electron beam systems. Today's tools write OPC-laden 65nm masks on 1nm address grids with sub-10nm placement accuracy in ~10hrs.

Mask inspection and repair. Mask defects can be a function of time. A photoresist layer may reside on a mask blank for days or weeks (including 10 hours in the mask writer), vs. minutes on a wafer. Keeping a mask perfectly clean for such a long time is challenging. Automated inspection and repair allow the mask manufacturer to verify the pattern integrity and find and repair defects, reducing scrap costs.

RETs (OAI, OPC, and PSMs). RETs represent complexity to the mask manufacturer and the wafer lithographer, but they provide savings in the overall semiconductor manufacturing process because they allow low k_1 and, when combined with high numerical aperture (NA), the printing of deep-subwavelength features.

Over the next 10 years, lithography and photomasks will change rapidly, in the following order:

193nm immersion lithography (193i). Water-immersion ArF scanners with NA ≅ 1.35 will enter production, enabling 45nm half-pitch printing. New mask absorber stacks are being developed to suit the high NAs that immersion lithography offers.

Double patterning technology (DPT). To meet the needs of 32nm half-pitch (and potentially 22nm), double patterning will enter production to augment 193i, most likely for flash memory manufacturing first. Pattern splitting and mask manufacturing toolkit accuracy (especially for overlay) are active development areas.

EUV. EUV is expected to be ready for production for 22nm half-pitch technology. DRAM manufacturers may struggle to make DPT work adequately until EUV is production-ready. Critical EUV challenges are source power and the mask manufacturing infrastructure. It is likely that EUV will require RETs when it enters mass manufacturing, which will add another layer of complexity to full