The Future of Semiconductor Lithography:
After Optical, What Next?

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Online version of paper: http://www.future-fab.com/documents.asp?d_ID=4397#
(7/9/2007) Future Fab Intl. Volume 23

Abstract

The leading contenders for next generation lithography (NGL) are reviewed: extreme UV, electron-beam, and nanoimprint lithography. It is possible that none of them will win out over 193 nm lithography with double patterning and high index materials.

Since the manufacture of the first integrated circuits with contact printing in the early 1960s, optical lithography has remained the only manufacturing approach used for high-volume IC production. As Moore's law pushed dimensions ever smaller, it has always seemed that the resolution capabilities of mainstream optics would eventually run out, requiring the 'next generation' of lithography to come to the forefront. By 1980, many people thought that electron beam lithography was the chosen successor, ready to take over at the 1 μm 'barrier' that optical could never overcome [1]. By the mid-1980s, X-ray lithography was heir-apparent, since it was common knowledge that optical was dead below 0.5 μm [2]. In fact, the death of optical lithography has been predicted so often that it has become a running joke among lithographers. Sturtevant's law seems as relevant today as when John Sturtevant first expressed it in 1997: the end of optical lithography is always 7 years away.

But the resolution limits of optical lithography are very real. The smallest pitch that can be imaged by a conventional optical imaging tool is $0.5\lambda/NA$, even with all of the 'optical tricks' at work. The optical wavelength is stuck at 193 nm for a variety of very practical reasons (mostly related to the costs and time required to develop 157 nm lens materials). And while the numerical aperture has risen to about 1.35 recently using water immersion, it is not clear whether high-index materials (especially lens materials) will be available in time to allow NAs to keep climbing. It may prove extremely difficult to push optical lithography to pitches below 80 nm. Is it possible, then, that even though Sturtevant's law has remained intact for nearly as long as Moore's law, 2007 may be the year that it is finally violated (meaning the end of optical lithography is 2013). Will a 'next generation lithography' (NGL) finally be ready to succeed its aging predecessor? If so, what NGL will rise to the top of the heap, and how far will it take us?

While many challengers to mainstream optical lithography have come and gone, today there are really only three serious contenders: extreme ultraviolet lithography (EUVL), some form of multibeam direct write electron beam lithography, and nanoimprint lithography. Let's quickly look at their prospects.

EUVL. The big money is on extreme ultraviolet lithography (EUVL), quite literally. Spearheaded and largely funded by Intel, a large group of government and industry players are backing EUVL with hundreds of millions of dollars in investment. With the hope of putting EUVL into manufacturing by around 2013, ASML and Nikon have both promised beta tools for evaluation within the next few years. But the remaining challenges are huge, and many (this author included) are skeptical.

According to the 5th International EUV Symposium held in 2006, the top critical issues facing EUV are:

1. Reliable high power source and collector module
2. Resist resolution, sensitivity, and LER met simultaneously
3. Availability of defect free masks
4. Reticle protection during storage, handling and use
5. Projection and illuminator optics quality and lifetime

Each of these issues requires one to several orders of magnitude improvement before EUV could be considered production worthy, and missing a target spec by as little as 30% could mean the failure of EUV as a viable production lithography technology.

The hope for EUVL is that it can prove to be a multinode technology, entering into production service at 32 nm half-pitch and lasting for three to four technology cycles, with some claiming that 11 nm half-pitch will be possible [3]. However, 11 nm is sub-wavelength for EUV, requiring numerical apertures that are almost unthinkable (greater than 0.5), or strong RET such as phase-shifting masks with Angstrom-level control over mask topography. The 16 nm half-pitch node is a more likely limit for EUVL in even the most optimistic of scenarios. And if EUVL is not introduced at the 32 nm half-pitch node, which seems increasingly likely, that would make EUVL at best a two-node technology.

E-beam Lithography. Resolution has never been a problem for electron-beam lithography. Researchers regularly printed 20 nm features 30 years ago. The problem has always been throughput (and by extension, cost). Direct write e-beam tools measure their throughput in hours per wafer, not wafers per hour. Attempts to project electron images (SCALPEL, PREVAIL) fell victim to mask difficulties and space-charge effects that created unacceptable trade-offs between resolution and throughput. Today, some still hold out hope that massively parallel beams of electrons can be harnessed for high throughput and high resolution, while eliminating masks [4]. The expectation is that this technology could reduce costs for low-volume foundry parts, where mask sets represent the lion's share of both manufacturing cost and turn-around time. While there are some development efforts underway (in particular Mapper, a company in the Netherlands [5]), the level of development seems grossly insufficient to produce production-worthy tools in the next five years, even if the technical hurdles can be overcome.

Some sort of maskless lithography, either with electrons or optics, could still prove valuable to the foundry business. But it is unlikely that such technology would be useful at the leading edge of semiconductor manufacturing anytime soon.

Nanoimprint Lithography. Embossing, pressing a relief pattern from a hard master into a softer substrate material, is certainly a well known and long-used printing technique. And since this method is used for making DVDs and music CDs, it is known for both its high resolution and low cost. Could it be applied to semiconductor manufacturing? Nanoimprint lithography (NIL), in both its hot embossing and UV cured forms, has become quite popular in the world of nanotechnology research, where tools costing much less than $1M can achieve 20 nm resolution at reasonable throughputs. But using nanoimprint for semiconductor manufacturing will require a significant effort to solve a few very difficult problems.

To begin with, NIL is a 1X technology, requiring a master template (mask) with the same dimensions as the circuit pattern. However, optical 4X masks with OPC and high Mask Error Factors are nearly as challenging to make, and may in fact cost more than 1X NIL templates. Mask inspection and repair, however, are not available for NIL templates with sufficiently small defect sensitivity. Overlay control is also challenging, since small distortions of the wafer must be compensated for by precisely squeezing the template before printing. Throughput for commercial NIL tools is too low, but the barriers to adequate throughput are more practical than fundamental.

Undoubtedly the biggest challenge for nanoimprint is wafer defects. Those in our industry with long memories are frightened by any technology even remotely resembling contact printing. But it is not inevitable that NIL defect levels will always remain too high. With a fraction of the resources devoted to EUV lithography, nanoimprint has demonstrated wafer defects at a level (and dropping at a rate) comparable to those of EUV mask blanks [6]. It is a mystery to this author why NIL continues to receive so little attention from the semiconductor industry.

The prospects for the three most promising NGL technologies for 32 nm half-pitch look bleak. But what if 193 nm lithography did not need to be replaced after all?

DPL. Recently, industry momentum has moved behind double-patterning lithography (DPL), a technique where two separate wafer patterning steps intersperse features to cut the pitch resolution in half (Figure 1). If such a technology could be made to work, 32 nm half-pitch patterns can be double-patterned using 1.35 NA scanners with a k_1 for each exposure of 0.45. There are two major downsides to DPL. The first is, quite obviously, the cost. Given the extra processing and the need for two critical patterning steps to create one final pattern, we can expect the lithography cost for the critical levels to about double. Since the critical levels represent about 1/4 - 1/3 of all the lithography steps and lithography represents about 1/3 of chip manufacturing costs, a very rough estimate gives an overall 10% increase in the cost of manufacturing – an unpleasant thought for our cost-conscious industry. If, however, existing 1.35 NA steppers (which will be needed at the 45 nm half-pitch node) can be used instead of purchasing a new generation of scanners (or worse, a new set of EUV tools), the overall costs could in fact be much lower using double patterning than any other technology.

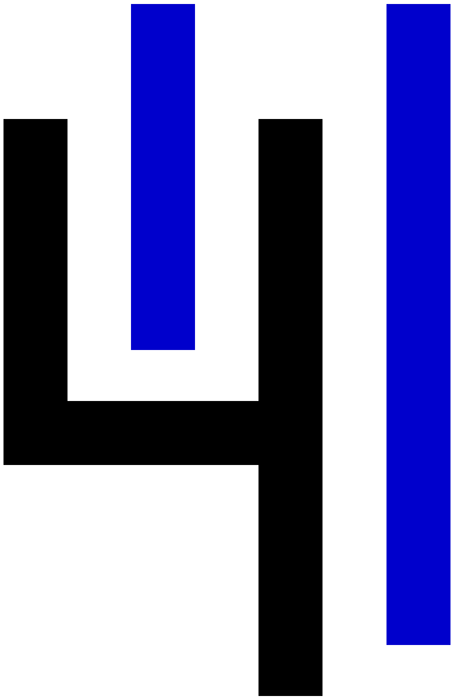

Figure 1. Interspersing two patterns can cut the final wafer pitch in half, potentially improving the pitch resolution by a factor of two.

The next serious difficulty is the coupling of overlay errors into CD errors for most double patterning schemes (or the coupling of CD errors into overlay errors for sidewall-spacer DPL schemes). The resulting overlay requirements will be in the range of 3 nm. Surprisingly, scanner makers are reporting that this level of performance may be achievable in the very near term. Nonetheless, the challenges, and the risks, are high. And some flash manufacturers have reportedly already begun using DPL in manufacturing.

High Index Materials. Finally, the continued rise in numerical aperture that has sustained 193 nm lithography for far longer than most of us imagined possible may not be over. The combination of a high-index fluid (target refractive index of 1.65) and a high-index lens material for the last element (needing an index greater than 1.7) could allow numerical apertures to rise to 1.55 or possibly 1.6. This would enable double patterning to meet the 22 nm half-pitch requirements while keeping each exposure at $k_1 > 0.35$ (the limit for using quadrupole illumination). The difficulty of achieving this goal should not be underestimated – material development projects almost always take much longer than anticipated. Still, early progress on the development of lutetium aluminum garnet (LuAg) as a lens material has been faster than anticipated [7], leaving some hope for success on this front.

So it is a horse race, no doubt, as to which lithography technology will win out. The big money may be on EUV, but the smart money is on 193 nm lithography with double patterning for 32 nm half-pitch. And 22 nm half-pitch is possible with high-index immersion (though it is still very uncertain). Nanoimprint is the dark horse candidate – it must demonstrate capability at 32 nm in order to win the race at 22 nm. Finally, I shouldn't rule out one very distinct possibility: no one finishes the race. Ultimately, the limits of lithography are economic, and it may turn out that no *economically* viable technology emerges at the 22 nm half-pitch node. If that's the case, smart companies will not manufacture at that feature size, though it may be impossible to resist the temptation to try. After all, Moore's law can't continue forever.

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