K1 limits

**Figure 2.** DOF at 8% exposure latitude (nm), fitted using an ellipse in Klarity Prodata. The x axis has the different pitches, sigma settings, mask types, and illuminator. For every mask type and illumination setting, the densest pitch and the forbidden pitch were measured. Dots indicate the reported DOF is a lower limit.
Customer roadmaps – Logic, DRAM, NAND

*Note: Process development 1.5~2 years in advance

Figure 1: Minimum resolution versus time, for different types of ICs.
Polarization and Advanced Lithography notes
Steve Brainerd

NA, angles, dry, immersion, and resolution CONTROL

### Illumination: Coherent

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### Illumination: Partially Coherent

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Date: 10/20/2008
POLARIZATION CONTROL and EFFECTS

1. Polarization: Immersion lithography appears to be the best bet for extending the limits of the technology. Some form of polarization control is necessary at NA>1. The TM polarization is definitely "bad," but stopping it at the source does not provide the ultimate solution. Even purely TE source polarization gives rise to TM waves upon interaction with the mask. Linear polarization in a direction parallel to the critical features will require double exposure to accommodate both vertical and horizontal directions, unless all critical features are placed in one direction.

Timely introduction of immersion exposure tools will be very important for the continuation of Moore's law. OPC software that can deal with the peculiarities and extremes of immersion lithography will enable the optimal use of new tools. The important thing is to begin the implementation of immersion-aware OPC systems before anomalies appear on wafers printed using liquid immersion lithography.

References


Regardless of the path for getting there, a rising NA leads to increased unregulated and undesirable polarization effects throughout the optical path of an exposure system (Fig. 3). Already, toolmakers have found that they need to pay much more attention to light polarization effects than they used to, and have introduced polarization schemes into their latest tools to improve image contrast and resolution. Going forward, with the combination of hyper-NA exposure tools and the use of extreme off-axis illumination, the need will only grow to further understand the effects of polarization.

Although linear polarization, where the electric field oscillates in either the X or Y orientation, might offer the best contrast for a design with only parallel lines, they are not typically useful in a production environment. For TE (transverse electric field) polarization, also called s-polarization (e-ray (extraordinary ray): polarized perpendicular to plane of incidence. Also termed s-polarization.), the electric field oscillates azimuthally with respect to the optical axis; and TM (transverse magnetic field) or p-polarization (o-ray (ordinary ray): polarized parallel to plane of
incidence. Also termed \textit{p-polarization} is where the electric field oscillates radially with respect to the optical axis (Fig. 3).

Increased NA produces much more severe angles of light at the wafer, creating debilitating polarization effects. "What happens there is you get a phenomenal loss of contrast because of the angular effects and the interference that occurs there," said Shane Palmer, senior technologist at Sematech (Austin, Texas) and Texas Instruments assignee. "And so you like to have TE mode — the TE vector does not have that effect at the wafer, and it improves your contrast."

**Polarization by reflection:** Brewster angle (angle of incidence): Reflected light is linearly polarized when the angle of reflection $\pm$ angle of refraction = 90°.

The fraction of light reflected depends on whether the light has electric vector parallel (1,) or perpendicular (1,) to the plane of reflection. If $1_{\parallel}$ increases steadily from an angle of incidence of 0° to 90°, $1_{\parallel}$ goes to zero at an angle $\theta_0$, called the Brewster angle, which is simply related to the refractive index $n$:

\[ \tan \theta_0 = n \]

e.g. for $n = 1.5$, $\theta_0 = 56.3°$, as in the adjacent diagram.

You can deduce the formula for the Brewster angle if you know that the reflected and transmitted rays are at 90° to each other at the Brewster angle.
Brewster's angle

With simple trigonometry this condition can be expressed as:

\[ \theta_1 + \theta_2 = 90^\circ, \]

where \( \theta_1 \) is the angle of incidence and \( \theta_2 \) is the angle of refraction.

Using Snell's law,

\[ n_1 \sin (\theta_1) = n_2 \sin (\theta_2), \]

we can calculate the incident angle \( \theta_1=\theta_B \) at which no light is reflected:

\[ n_1 \sin (\theta_B) = n_2 \sin (90 - \theta_B) = n_2 \cos (\theta_B). \]

Rearranging, we get Brewster's angle

\[ \theta_B = \arctan \left( \frac{n_2}{n_1} \right). \]

**Birefringence measured as:**

\[ \Delta n = (n_e - n_o). \]

- \( n_e \) = index of refraction for the e-ray
- \( n_o \) = index of refraction for the o-ray
- if \( \Delta n \) is positive, crystal is positive uniaxial.
- if \( \Delta n \) is negative, crystal is negative uniaxial.

<table>
<thead>
<tr>
<th>Crystal</th>
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<th>( n_o )</th>
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</thead>
<tbody>
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<td>Quartz</td>
<td>1.5443</td>
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<tr>
<td>Ice</td>
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</tr>
<tr>
<td>Rutile (TiO2)</td>
<td>2.616</td>
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</tr>
</tbody>
</table>

Birefringence
Birefringence can also be measured as:

- \( L = \) phase shift difference between e-ray and o-ray.
- Shift measured as \( \text{nm/cm} \)

**Double refraction (Birefringence):** Snell's law deviates here as there are two refractive indices within the same material depending upon the plane of polarization.
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- Birefringence: 3 conditions:
  - 1. Rays propagating parallel to the crystal’s optic axis have a constant refractive index. Here the e-rays (TE) and o-rays (TM) have the same refractive index.
  - 2. Rays propagating perpendicular to the crystal’s optic: The e-ray will travel faster than the o-ray (TM) due to its lower refractive index in this direction. Both rays will travel in the same direction. This results in a phase shift between the two rays!
  - 3. Rays propagating 0 to 90° to the crystal’s optic: The o-ray will be refracted according to Snell’s Law. The e-ray (TE) will deviate from the o-ray (TM) due to the different refractive index in this direction. The e-ray will deviate away from the optic axis and out of the plane of incidence!

2. With the theoretical NA limit for immersion lithography with water somewhere just above 1.3, reaching higher NAs will require development of higher-index fluids, lens materials and resists. (Source: Sematech)

3. There are four potential influences in the optical path of a hyper-NA exposure tool (left), including in the illumination source (A), the mask (B), the projection lens (C), and the wafer (D). The illustration on the right details polarization types typically found in an exposure system for
Polarization and Advanced Lithography notes
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Polarized illumination is essential for improving contrast. Nikon's Polano polarization system, for example, enhances image contrast by ~20%. Speaking at SEMICON West last year, Gene Fuller, principal engineer at Nikon Precision Inc. (Belmont, Calif.), pointed out the improved line width roughness (LWR) with Nikon's polarization system — 4 nm vs. 6 nm LWR.

Polarization at the mask

One thing to keep in mind with immersion lithography is that, as the NA goes up on the wafer side of the lens, it also goes up on the mask side. In today's 4× exposure systems, the NA on the mask side is about one-fourth the NA on the wafer side, explained Franklin Kalk, CTO at Toppan Photomasks Inc. (Round Rock, Texas). The theoretical NA limit with water is ~1.35. "Well, on the mask side, then that's about a 0.34-0.35 NA, which is quite a bit higher than we're accustomed to," he said. "Right now, at 0.93, we're running only 0.22-0.23 NA. So the NA will go up — that increases the incidence angles at the mask, and brings in polarization effects and things like that."

The extension of optical lithography with immersion has three main impacts on maskmaking: increased angle of incidence at the mask, increased topography, and mask feature sizes on the order of the wavelength of light used for exposure.3

A challenge resulting from high-aspect-ratio topographies on the mask is three-dimensional effects, Kalk noted. "Historically, the mask features have been huge in lateral extent compared to the height of those features," he said. "But, in particular with altPSMs, strong shifters, the depth of the features now will be around the same as the width. So now you start to get topography effects, such as altPSM intensity imbalance." The mask absorber thickness has not scaled as quickly as the feature size, thereby increasing the mask 3-D effects.3
Polarization and Advanced Lithography notes

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"If you have bad effects going on at the mask, you can do several things, none of which really are very attractive," Palmer said. "One is to increase the magnification of the mask, so essentially your pitch becomes larger at the mask, so the polarization effects go away." Another possibility is to adjust the absorbing stack on the mask to reduce the effect of the polarization, he added. One way to adjust the absorber is just to make it thinner. Another way is to adjust the refractive index of the mask material, Palmer said.

"At 193, the mask can still get away with a fused silica substrate. But for half-tone phase-shifting materials, there's no doubt that the composition of the absorber on the mask is an effect," Kalk said. "I don't think we'll have to change it necessarily from what we're using. We may have to design a lot more carefully what the mask looks like, like taking into account what that material is."

"Probably the biggest physical change to the photomask is going to be that the quartz substrate will have to be a low-birefringence material," Kalk said. "Lenses are done in low-birefringence form because the exposure tools are very sensitive to birefringence because they're polarization-sensitive. Photomasks historically haven't been, so now we're going to become polarization-sensitive with immersion as the NA jacks up, and so we're going to have to have a low-birefringence substrate. That's going to be a pretty big change in our supply chain."

The magnification factor

Another way to alleviate polarization effects at the mask is to increase the magnification, thereby increasing feature sizes on the mask. This idea has been proposed several times in the past, but the industry has always balked at the idea. "We seem to visit it about every two years, and it's always thrown out," Kalk said. "The last time was just in the last few months, and I heard people saying, 'It's a good idea,' who in the past had said, 'No way.' So definitely the wind is blowing in that direction, but right now it's only a little bit."

"I think it's a very, very difficult thing to overcome, primarily because of the issues that run into it," Palmer said. "You're going to either have to now start stitching the pattern together by using multiple masks, which is not very attractive because of low throughput and it also adds a lot of error for overlay and what-not. In addition to that, going to larger mag, you have to increase the size of the lens. The lens people don't want that at all because that gets into a whole can of worms; you've got the weight of this thing and trying to compensate for all the forces that are interacting with the lens elements." All the retooling that would be necessary for such a shift is also not appealing, he added.

Double exposure

Still another way to get to 32 nm without EUV is the introduction of double exposures, which would also impose a considerable drain on throughput. "And that in itself sounds horrible," Palmer conceded, adding, however, "There are minuses to it, but there's also a hell of a lot of pluses to it. And one of them is that you can control the OPC a lot better. Let's say you split the two up into one exposure. You might try something like carrying
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almost all parallel lines, and then vertical lines on the other particular exposure. And now the end shortening effects become reduced. You can play games there because you have more room for correction.”

Although chipmakers do not relish the thought of the hit in throughput they’d take from such a scenario, they might be willing to tolerate that slower throughput if it means not having to go out and spend a lot of money on a next-generation tool, Palmer said.

"From the imaging perspective, there is a huge interest also emerging now into the double patterning scheme," Wagner said. "There's always an averseness to lowering throughput and I think the cost of ownership. But I think, on the other hand, the difficulties around it also increase. The cost of a mask set, for example, these days, if you look into the total cost, the mask is picking up a significant part of the total cost of ownership." Because the mask is so much easier to do in a double-patterning scheme, it could be that the cost of ownership is not actually higher, he added.

At 45 nm, most chipmakers will be reluctant to pursue double-exposure techniques, said John Sturtevant, RET technology support manager in Mentor Graphics' Design to Silicon Division (Wilsonville, Ore.). "But at 32, it may very well be that the requirement would be to break up the mask into two components — say one for X polarization and one for Y polarization, and then do a double exposure."

The polarization knob

At this point, and in the foreseeable future, most industry players do not seem to view polarization as an insurmountable problem. Polarization is a relatively new issue for lithographers, but the toolmakers and maskmakers are gaining experience with it, Wagner said. "For me, it's a little bit comparable to the introduction in the mid-90s of the off-axis illumination schemes — the annular light illumination and then the quasar illumination and these things," he said. "In the beginning, it was also very new, and the masks were reacting strange, and everything was a surprise. But after a few years, then you knew everything very well. You had a good understanding of the response of a pattern; you knew which patterns to choose. And then you introduced things like quasar and dipole illumination to even enhance the off-axis illumination schemes. And now they're basically a part of the standard OPC process when you're making your mask."

"Polarization, in a sense, it's a plus and a minus on many counts," Palmer said. "One, it can be used to enhance the contrast. So now you can use polarization as another knob to tweak, to increase your printability, which is very nice, where in the past they weren't really using much polarization. In fact, I believe the first polarization steppers or scanners coming out have only been released in the past year or so. It's an interesting effect that, when you play games with it and you adjust your mask, so now your OPC needs to include this as well. It can actually improve your resolution and improve your contrast."

Although polarization is a significant issue, "from an OPC simulation standpoint, it's a tractable problem that can be simulated properly," Sturtevant said.

Help from software
In fact, along with the tool and mask suppliers, OPC software vendors are answering the call for polarization control as well, with their models accounting for various polarization effects. Whether it's polarization at the source, at the mask plane, in the lens, or at the wafer itself, simulation engines should ultimately be able to handle it.

Palmer said that he expects the industry to rely very heavily on the software to optimize the lithography process. "It's like the old waveguide days — the guru sat there and had a little ball peen hammer and used to be able to tweak the wave and get rid of the extra modes by just tapping on the edge of the waveguide," he said, adding that those days are gone. "Now they're going to have simulators that essentially will optimize the illuminator, and will optimize the polarization for you, and do the OPC as well."

Late last year, Sematech began a joint program with Synopsys Inc. (Mountain View, Calif.) to develop advanced OPC models to enable the extension of immersion lithography. Preliminary modeling has shown promising results for immersion tools at the 45 nm half-pitch, with the ultimate goal being to extend immersion to the 32 nm half-pitch, extending models for exposure tools with $\text{NA} \geq 1.55$.

Still on Sematech's wish list is for the software to account for 3-D effects at the mask, Palmer said. "Most of the OPC vendors do not have full 3-D effects at the mask. It turns out it doesn't really become seriously important until you get down to below the wavelength that you're using on the mask." he said. "When you get down to 32 nm half-pitch, you're there. So that's where it's important. And there will be things that will need to be done at that point. You don't totally lose the image coming through the mask, but it will be polarized waves coming in, so you want that azimuthal polarization (using dipole or quadrupole illumination) to give you an increased contrast and improve the pattern fidelity."

The fact that polarization schemes of the equipment are still changing can be a challenge, noted Jim Shiely, R&D manager for mask synthesis at Synopsys. "The challenge is having the flexibility to handle all these varieties of source polarizations." Because it is a rapidly evolving area, Synopsys' approach has been to provide an extensible platform, noted Srini Raghvendra, senior director of business development and marketing, DFM. As customers find different polarization schemes or achieve higher NAs, for example, the software is able to adapt to those parameters and model effectively.

Mentor Graphics' Calibre suite of tools has, for a number of years, been able to handle an explicitly defined polarization in the illumination source, according to Sturtevant. Being released this year is software that will explicitly handle rigorous 3-D electromagnetic field calculations for the mask. "One of the concerns is that you can have a polarized source — even a perfectly, say, TE-polarized source — that you may use in the illuminator," he explained. "But as it hits the mask, you're going to be getting — just by virtue of the mask acting like a polarizing element itself when the chrome is so small relative to the wavelength of light — you're going to introduce other polarization."
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Steve Brainerd

Mentor's 3-D EMF tool will be able to handle and keep track of what polarization is induced by the mask itself.

However, as is often the case, the increased functionality will come with a run-time penalty, Sturtevant noted. "The world we live in, we're always trying to balance accuracy of our OPC model to simulate what happens on the wafer with run times, since we're doing this on a full chip," he said. "But we think that, at 45, folks will start getting more serious about needing that extra accuracy. And certainly at 32, that would likely be a requirement as part of the OPC treatment and simulation."

How far will immersion go?

It is widely expected that immersion lithography will be used in production at the 45 nm node, but how much further it will be used is still up for debate. "I would say the 45 nm node very clearly is immersion country," Wagner said, adding that a water-based system should even be able to support logic to the 32 nm node. DRAM and flash, however, will call for higher NAs to reach the 32 nm half-pitch, or they will have to switch to double patterning. "That's also where we expect this high-NA decision, to see our strongest market pull from the DRAM, flash — mainly from flash. It's such a huge growth market, this will be a huge market pull for us, for the very high-NA systems."

Ultimately, how far immersion is able to be carried comes down to an economic issue, Palmer said. "If I were a gambling man, I would say immersion's going to really have a tough time when you get down to about the 36-38 nm half-pitch, " Palmer said. "32 looks very difficult to do. 34 is a little easier. 36, I think, can be done pretty easily with 1.55 NA. You're really starting to cut a fine edge on all of this, which is very interesting."

Sturtevant sees a clearer picture ahead, however. "I would be very, very, very bullish on saying it absolutely will be extended beyond 45," he said. "If nothing else, history is our guide. I don't think we've ever seen anything that's been a one-generation technology, even though each generation has gotten harder and harder and harder to do. So I think at 45, we're going to see, certainly, pretty broad, widespread use of immersion. And it probably will even feature some deliberately polarized illumination sources, like what ASML and Canon and Nikon will have available. But I think that, at 45, it will be very straightforward, just generic TE polarization that's broadly applicable to all feature types. And then my guess is, at 32, people will start to get into layout-specific polarizations with double exposures and things like that. But I guess I'd say overall, I'd be very, very bullish on 32 being done with immersion."

References


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Hyper-NA Polarization Effects (from Nikon)

Lossless polarized illumination

Lossless polarized illumination optics has been developed, and will be applied for high NA exposure tools (dry and immersion).

Hyper-NA Polarization Effects (from Nikon)
2D L/S patterns (L/S of any direction)

6% attn-PSM

- **Blue line**: Annular + Azimuthal polarization
- **Red line**: Annular + Random polarization

**Hyper-NA Polarization Effects (from Nikon)**

- **NA=0.92 dry**
- **NA=1.00 imm.**
- **NA=1.20 imm.**

**ED-tree aerial image**
- % annular = 0.95
- Δ mask = ±2%
- Δ dose = ±3%
- Δ CD = ±10%

**Figure 4**: Sketch demonstrating the incident light of a scanner into the resist and the two states of polarisation (TE, TM).

**Notes**

- TE Transverse Electric field and TM Transverse Magnetic field. Desire TE only as TM does not interfere at high angles (sort of like scattered hv)

Date: 10/20/2008
Polarization Impact from paper: *First results for hyper NA scanner emulation from AIMS45-193i*

TE (transverse electric field) polarization, or s-polarization (e-ray (extraordinary ray): polarized perpendicular to plane of incidence. The electric field oscillates azimuthally with respect to the optical axis. DESIRED as it will interfere at high angles of incident resulting from high NA’s greater than 1.00 allowing an image to be constructed. It produces an image with high contrast.

TM (transverse magnetic field) or p-polarization (o-ray (ordinary ray): polarized parallel to plane of incidence. The field oscillates radially with respect to the optical axis. NOT DESIRED as it does not add to image formation as it does not interfere at high angles of incident resulting from high NA’s greater than 1.00. It reduces the image contrast.

This polarized light TE and TM effect is called the “vector effect”.