Black Swans Unmasked and Other Stories from my days in San Jose -

Further Thoughts on 2018 SPIE AL EUVL Conference

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Black Swans Unmasked

Stochastics effects, which are random and local variables, were in focus during the EUVL Conference this year. These effects have been around in manufacturing for a while, causing CD variation and line edge roughness (LER). They are now causing microbridging and broken lines as features are getting increasingly smaller at the 5 nm node, with fewer photons available per EUV dose compared to an equivalent dose of 193 nm photons. Last year, these random defects were called “black swans,” a name inspired by a book by Nassim Taleb (Random House, 2010). In his book, Nassim describes black swans as surprising or virtually unpredictable event that can have a massive impact. This year, several presentations quantified them as defects in the far tail of a Gaussian distribution, where the distribution is no longer Gaussian and we do not yet have a precise way of describing them. Although with very small probability at 7 sigma, they still add up due to billions of circuit elements that must be made perfectly in each chip, and in the end they can cause yield loss. At 7 sigma or beyond, I see them something like a seventh cousin of common white swans. We still do not know fully how to capture them, but they are not those formidable black swans either.

Other important thing we have now learned is that there is not only one type of black swan, but several kinds. They come not only from photon shot noise, as we believed earlier, but also from all steps in photoresist development, masks and optics. Because of stochastics we must do some things a bit differently, although we can still make circuits. As I mentioned earlier, we had been seeing stochastic effects previously in LER and CD variability. First, the fact that more than photon shot noise is in play here is evident in the long, asymptotic tail of the RLS triangle curve, where we notice that LER cannot be eliminated by merely increasing dose (i.e., number of photons). That gives the first hint of other factors. Hence, a claim by an esteemed lithographer during Q&A that the only way for us to address stochastics will be to get 1 kW sources, which isn’t going to happen (and hence neither will EUVL), is incorrect.

There were several papers in the Conference looking at various sources of stochastics – optics, mask, photoresist – with each effect adding its own contribution. Each may have several components, e.g., photoresist stochastics comes from not only from photon noise, but also from variation in the density of

absorbed photons, secondary electrons, photo-acid generators, quencher and local protection groups. One speaker pointed out that stochastics coming from materials are greater than those from photons. So the focus now shifts to heterogeneity in materials and processes. In the final circuits produced via EUVL, I suspect a couple of additional steps that will contribute to random effects, such as etch and metrology. The etching process is random and so is metrology, but in different ways than photoresist.

Silver Bullets for Stochastics

So how are we going to address stochastics? The good news is that people in the chip industry are very smart and I believe they are up to the challenge.

I see several ways to address stochastics. First is that if you cannot solve a problem you can reframe it, while keeping the goal in mind. As I pointed out last year, our fundamental problem is not the random noise in imaging, as that is just an intermediate step in making an electrical circuit in silicon, which is our final goal. Just to complete the argument, our ultimate goal is really not even electrical circuits, but improving information processing. So when we hit limits which we cannot overcome, we will go another route via new types of computers (for example, quantum computing is already happening). Going 3D has been another way for our industry to address the scaling challenge when 2D scaling gets too difficult. Another practical way to address stochastics will be post-processing and co-optimizing of processing steps. We have already gone way beyond Rayleigh resolution criterion, and we now just have a new limit from physics, so we must cleverly go around it.

So I see these ways to address stochastics:

•First, reframe the problem. An example of reframing for the photoresist development process is multi-trigger resist from new start-up Irresistible Materials. Previously, several related efforts were put in the category of “sensitizers,” with PSCAR being the most well-known, to go around the dose limitations. In short, we must design new types of photoresists or find a way to change some of the steps, and I see several possibilities of doing so. In terms of reframing the challenges of photon noise, there are at least a half-dozen ways to increase dose on wafer without increasing the input power to EUV sources.

•Second: control stochastics using its fundamental nature, which is randomness. For example, in space missions this is done by building redundancy – four computers instead of one. We also know up to a certain limit how to build this into circuits. So, one can take averages of several steps instead of depending on a single processing step. A good example of this is “vote taking lithography,” which not only eliminates most random mask defects but also decreases the non- uniformity of CDs. This concept of “averaging” can be extended to

other steps in a clever way. Thus, this concept of taking averages by breaking a single step into multiple steps can have implications in addressing the randomness of processing steps. I expect to see some creative ways this may be applied.

•Third: get back to basics. Remember that we may not be solving some these problems for the first time, and they may have been addressed before in different contexts. We need first to better understand the nature of each of these sources of stochastics. Distributions for each factor are different, and we need to find new knobs that we can turn. As we learned in the case of EUV sources, we could not increase conversion efficiency by merely using the design of experiments (DOE) concept, which allows us an optimum setting for known knobs. We had to create new knobs by looking very very carefully at every step,and changing the process to create controls where we had none before. From papers and discussions, it appears we have our work cut out for us, especially for photoresist.

Opinion vs Fact

At the start of the EUVL conference, the first plenary speaker, a retired lithographer, pointed to the presence of defectivity at the 5 nm node and extrapolated to conclude that “EUVL will not work in production in a meaningful way.” However, the speaker was wise enough not to tout another tried and rejected next generation lithography (NGL) options, but instead proposed abandoning current optical project lithography-based computer architecture all together. Quoting Daniel Patrick Moynihan, “You are entitled to your opinion. But you are not entitled to your own facts.” The presenter used data from several presentations to make that conclusion, while the authors of those presentations had different conclusions. However, the press was quick with headlines (“Random Errors Cloud Chip Roadmap”), and a few others followed with reports that a new showstopper for EUVL had been found. There were at least a dozen or more papers on analysis and solutions for stochastics, but they received no coverage in the media, as good news is no news many times.

Vimalkirti Sutra – Dharma of Scaling

Last fall, with my Zen teacher we studied a scripture called Vimalkirti Sutra. It is a dialogue with a unique Bodhisattva, who chose to remain in business and deal with worldly affairs. The original Sanskrit scripture is lost, and only a surviving Chinese version is widely studied. Therein was a powerful lesson on the intention of why we do what we do.

In this lesson, Buddha, together with hundreds of his followers, come to see Vimalkirti to discuss the WAY. Vimalkirti, who is in a small room, offers everyone a place to sit -something similar to scaling challenges we are seeing in Lithography. However, many loudly argue, how is there enough space to sit, even though it is being offered? So Vimalkirti famously replies, “Did you come here for the sake of Dharma, or are you just looking for a place to sit?” (The Vimalkirti Sutra, Burton Watson, pp. 75, Columbia University Press, 2010.) In the end, everyone is happily accommodated.

Most experts have their own agenda to back up their own opinions. Solutions are there, but we must abandon our conventional ways of thinking and reframe the problem differently. We need to find a way to address our true goal of scaling, and not get too attached to how it is done.

Moore’s Law as an Eternal Dharma? If you believe Dharma is broken - you do not understand it.

In the chip business, you are not famous until you have at least once in your career formally declared the death of Moore’s Law. Some have done it multiple times to claim the most fame. However, quoting Mark Twain, “The reports of my death have been greatly exaggerated.” The SPIE AL Conference is known for its famous declarations. At SPIE AL in 2014, there was a public declaration of the death of Moore’s Law, but Moore’s Law continues. One of the plenary speakers noted that senior experts close to retirement are getting low on new ideas, and it may be time to turn things over to a new generation with fresh ideas. I agree. Just as in the Judeo-Christian bible’s Book of Job, where the young newcomer Elihu offers an alternate explanation of the situation, new ideas may indeed be needed. For myself, I am among those outsiders who look at Moore’s Law as Dharma or the Eternal Way. If you think it is broken, that means you do not understand it. Moore’s Law refers only to hardware, while all information process technology depends also on software and interfaces. We humans try to process more and more information, until our Internet is mostly flooded by iPhone videos, movies and shows, and other trivial things. For those who are into philosophy, especially nuggets from the Upanishads, know that there is no end to the continued increase in information processing – until the end, when all that is knowable is simultaneously known. As you inch toward the ultimate, you do not increase your knowledge, but gain wisdom – sort of like getting a smarter hard drive, and not just a bigger one. AI and machine learning are small steps in that direction.

Bollywood Saves the Moore's Law

Yes, it is a true story although now a year or so old, but I wanted to give credit where it is due. It started when recently we realized that EUVL would have to go the way of multiple patterning very soon, unless the numerical aperture of scanner was increased. This brought forth very difficult choices in terms of mask, optics and throughput. The industry argued for many years on choices, and the final decision was to address the issue using anamorphic optics (squeeze the image 2x one way and 4x the other way), as has been done in cinema industry for a long time to address the scaling of a roll of film. So Moore's Law will be extended using high NA EUVL scanner, by borrowing the idea of optical scaling from Bollywood. (I choose to give credit to Bollywood and not Hollywood, as several industry leaders like the CEOs of Google and Microsoft grew up on Bollywood and not Hollywood.)

Making a buck or making a difference - thoughts on my days in San Jose

My visit to the Conference was shadowed by sadness over the death of a litho colleague in Austin earlier in the month, who passed away from an unknown cause. Many of my litho colleagues from SEMATECH's time met in Austin for a memorial service, and several of us from Austin, still in mourning, asked each other during SPIE if we knew what could have happened to Jeff. On my flight back to Austin, I got some closure on this as I was watching the movie "Bladerunner" when Graff says, "Sorry that she won't live, but then again, who does?" This pointed to the ethereal nature of life. Maybe we take things too seriously and do not realize our nothingness, as Roy Batty in the same movie says, "I've seen things you people wouldn't believe. Attack ships on fire off the shoulder of Orion. I watched C-beams glitter in the dark near the Tannhauser gate. All those moments will be lost in time, like tears in rain."

While in San Jose, I ate breakfast most days at Starbucks by the Fairmont. Since most of the tables there were occupied by homeless people, I had to ask them to make a place for me so I could sit down for a bite. By the time I was done with breakfast every day, I had to ask myself if I was just making a buck, or making a difference. What is the true impact of all this progress if we cannot even find a shelter for all? I find the situation best explained by a quote from Lao-Tzu:

Virtue Appears when Way (Tao) is lost
Kindness appears when virtue is lost
Justice appears when kindness is lost
Rituals appear when justice is lost
Rituals marks the waning of belief
and the onset of confusion.
(Lao-Tzu's Tao Ching, Translated by Red Pine, pp. 76 Copper Canyon Press, 2012)

What we do is just part of big web, and maybe inconsequential as Roy Batty says. We have a job to do and most of us do our very best work; many of us try to do it knowing we are still tied to its impact on the world. Maybe this advice from the Bhagavad Gita is worth pondering:

Karmanyevadhikaraste ma phaleshu kadachan
ma karmaphalahetur bhur ma te sango' stv akarmani.

Translation: "Your right is to action alone, never to its fruit at any time. Never should the fruits of action be your motive, never let there be attachment to inaction in you."(Bhagvad Gita, 2.47, Translated by Winthrop Sargeant, State University of New York Press, 2009)