# PHOTOMASK

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# Minimizing "Tone Reversal" during 19x nm Mask Inspection

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## ABSTRACT

19x nm defect inspection is the strongest candidate for initial EUV production until high-throughput E-Beam or Actinic inspection is ready. However, EUV mask inspection on an optical, 19x nm wavelength tool has some difficulties compared to optical masks. The issue of varying base pattern contrast is an example of one such difficulty. This paper explores the defect sensitivity differences among the base pattern sizes, as well as the relationship between base pattern contrast and defect sensitivity. Focus offset and polarization adjustments on programmed defect test masks are used to create new inspection recipes.

## 1. Introduction

EUV (Extreme Ultraviolet) lithography is one of the most promising techniques for imaging 5 nm node, and smaller, wafer features. Mask defects that matter are the ones that print during exposure at 13.5nm. To support EUV development and production schedules, mask defectivity must be reduced to be at or near optical mask defect levels. This task is complicated by the fact that actinic EUV mask inspectors are not readily available. In the absence of the tool, all available methods of detecting and characterizing these defects must be deployed[1-3]. E-Beam and DUV pattern mask inspection tools are the candidates currently available for initial production. It is known that E-Beam

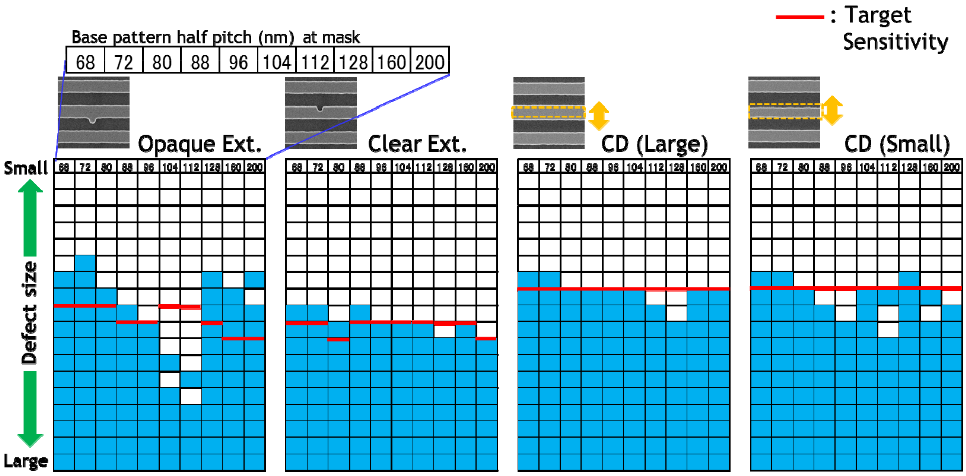

*Figure 1. Sensitivity analysis @19x nm wavelength tool.*

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# EDITORIAL

## Off all Conferences, BACUS is the Most Fun!

### **Tony Vacca,** Automated Visual Inspection

Bold statement, I know. However, if you have been a regular attendee of BACUS (SPIE Photomask Technology Conference) over the decades, you are probably already nodding your head “yes”. If not, a little historical background is required in order for me to make my argument that BACUS is the most fun of all. I will first define my version of “fun” at a technical symposium. When you are in a beautiful part of the world surrounded by the brightest minds in your industry and they are approachable, sometimes even humble, and most of all witty; that is fun!

Some may assume that the long-standing BACUS Entertainment is what makes BACUS fun, however I submit that the original founders of BACUS created the environment from which the entertainment grew. Without a few laughs, even the most insightful conference can leave one feeling like it was just another day at work. I believe that the original BACUS committee members had something different in mind. Maybe along the lines of, “Let’s create a cutting-edge technology conference and have fun while we do it!” After all, they were all drinking wine at the Bacchus Inn restaurant in Santa Clara in 1980 when they chose the Greek god BACCHUS “the god of wine and intoxication” as a potential conference name (just needed to find some words that will complete the acronym). Oh, I know, burp, how about BACUS (Bay Area Chrome Users Society). I guess they ran out of wine before a better idea arrived.

The first BACUS entertainer (or Baccanalian) Jim Reynolds, felt that it would not be appropriate to end the conference without a few laughs. He wrote and performed two songs poking fun at the photomask industry and some of his friends at Micromask. Little did he know that he had started a tradition that would carry on for decades!

Under the direction of Stewart Lyle, the BACUS entertainment show grew to a cast of over 10 people plus a hired live band and numerous lighting/sound and stage personnel. A number of these productions were epic performances at places like the Fox Theater in Redwood City, but then, another downturn occurred… The show had grown too expensive and too controversial, so a few years went by with hired entertainment for the banquet. I attended these conferences and always thought that BACUS was not the same without some form of home-made entertainment.

I offered to resurrect the entertainment show in 2012 with the same budget that Jim Reynolds had for the first show, nothing. After that very short show, a number of people approached me interested in performing in next year’s show. In the past six years, the entertainment is now once again performed (all by volunteers) in a beautiful theater thanks to our entertainment sponsors!

This is far from a complete list but, I would like to thank a few of the originators of the BACUS conference and entertainment including: Jim Reynolds, Jim Wiley, Steve Dunbrack, Ron Johnstone, Paul Johnson, Robert Murphy, Scott Ashkenez, and Gregg Hearn. Thanks to their vision, this conference is still going strong 38 years later!

At the end of the day, we all are forced to attend some pretty boring although sometimes beneficial conferences. If you have to pick one, I suggest attending the one that is the most fun, BACUS! I doubt that jokes about yield loss are told at any cardiologist’s conferences. I am just saying, BACUS is a little special and a lot of fun!

By the way, if you find yourself at the butt of a joke during the BACUS Entertainment, please consider it an honor. We don’t make fun of people unless we like them…

One Baccanalian,
Tony Vacca

BACUS
N • E • W • S

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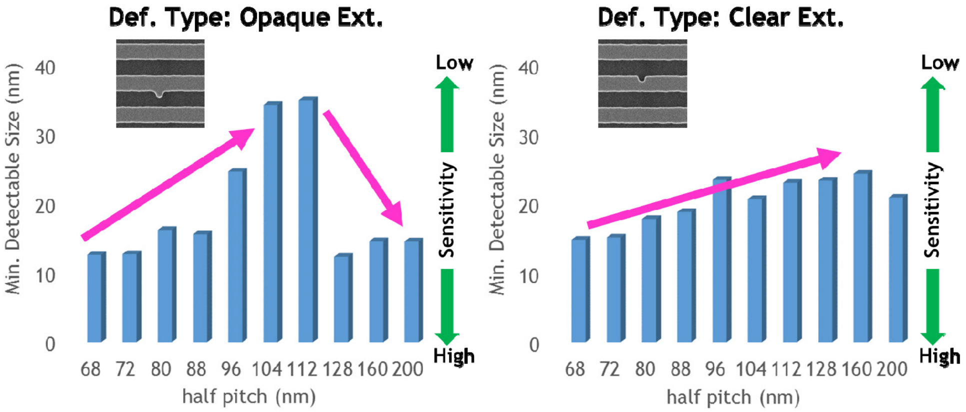

*Figure 2. Minimum detectable defect size.*

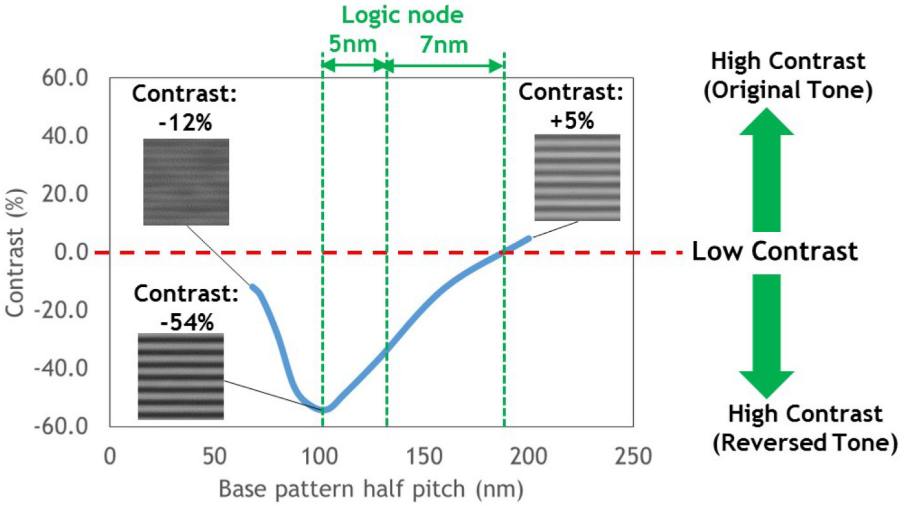

*Figure 3. Base pattern contrast evaluation.*

inspection tools show higher defect sensitivity than DUV inspection tools due to the small beam size. However, the throughput is much slower than that of DUV inspection tools. DUV inspection at 19x nm wavelength is widely used for optical mask inspection[4-7]. The optics and algorithms on these DUV inspection tools have been optimized for EUV masks, and rigorous analysis executed[8-10].

EUV mask inspection requires more advanced approaches than currently employed on optical masks. Where both transmitted and reflected light are used for optical mask inspection, only reflected light is available for EUV because the masks are reflective and the backside opaque layer prevents transmission through the substrate. EUV blanks consist of many layers: LTEM (Low Thermal Expansion Material) substrate, backside conductive layer, front side reflective stack of 40 pairs of Mo/Si bilayers, a Ru protective cap, and the Ta-based absorber material. Mask inspection must detect not only film surface defects but also bilayer and backside defects. At the same time, the minimum defect size continues to shrink; according to the ITRS-2 road map, the defect criteria will be 10.1 nm in 2017 and 6.7 nm in 2019. Another challenge of DUV inspection is "Tone Reversal." Base pattern contrast varies among the pattern or pitch size, and the base pattern contrast flips at a specific feature size. These issues make mask inspection difficult, especially for die to database inspection[11]. It would be expected that defect sensitivity may vary as the base pattern contrast varies because the visual representation of the base pattern size changes significantly through pitch. However, this may not always be the case, and it becomes a goal to determine just how much base pattern size and contrast may affect defect sensitivity.

This paper explores defect inspection sensitivity with various base patterns and contrasts and strives to develop optimization methods to minimize the sensitivity gaps.

## 2. Analysis of Present State

We begin this study by evaluating defect sensitivity using Line and Space (L/S) types of programmed defects on a 19x nm wavelength mask inspection tool. Figure 1 shows the evaluation results. There are four types of programmed defects: Opaque Extension, Clear Extension, Critical Dimension (CD) Large, and CD Small. Each programmed defect was printed on multiple L/S patterns at the following half-pitches: 68, 82, 80, 88, 96, 104, 112, 128, 160 and

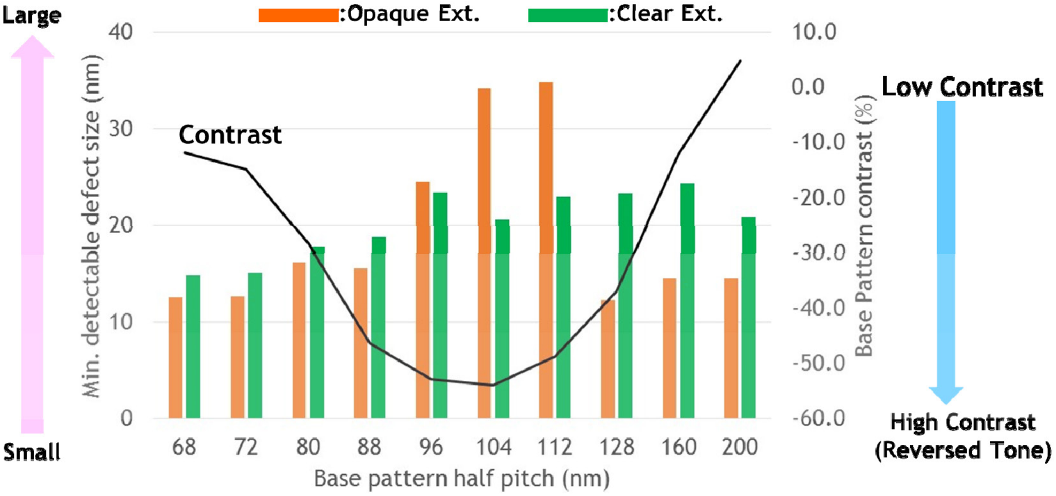

*Figure 4. Base pattern contrast vs. sensitivity.*

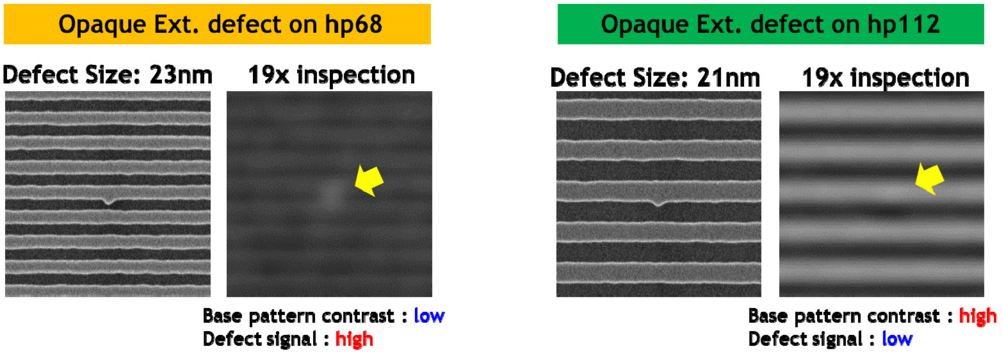

*Figure 5. Comparison of same size defect on different pitches.*

200 nm. The defect sizes get smaller from bottom to top. The red line in the figure represents our target line. These programmed defects were inspected with standard settings. The defect sensitivity trend looks very different among the defect types. In the case of Opaque Extensions, defects on the half pitches 104 and 112 nm show extremely lower sensitivity than other half pitches and they do not meet our target. The other base patterns show good sensitivity and meet the target. In the case of Clear Extensions, defects on most of base pattern pitches meet the target with the exception of the 128 nm pitch. In the case of CD Large, defects on 112 and 128 nm pitches do not meet the target and finally, in the case of CD Small defect type on the 88, 96, 112, 160 and 200 nm pitches, they also do not meet the target line. This data confirms that current inspection settings meet some of the targets, but not on all pitches.

Figure 2 shows the comparison of detectable defect size on various base pattern sizes. The left and right figures show opaque extension and clear extension defect respectively. In the case of opaque extension defects, detectable defect size is around 10 nm for 68 to 88 nm and 128 to 200 nm, but the defect on half pitch 104 and 112 nm shows lower sensitivity with a minimum detectable size around 30 nm. For the clear extension defects, the detectable defect size is increasing through the base pattern pitches.

Figure 3 shows the base pattern contrast evaluation results. The contrasts are analyzed using the formula shown below.

Contrast: (Rc - Ro) / (Rc + Ro) *100
Rc: Reflectivity on clear (Multilayer)
Ro: Reflectivity on opaque (Absorber)

The point at which contrast crosses the zero line, is where "Tone Reversal" occurs. In this example, the base pattern contrast reaches zero at an approximate 180 nm pattern size. Contrast continues in a negative direction as the pitch goes from 180 nm to 100 nm then reverses direction again toward zero. The base pattern varies from -54 % to +5 % among the base pattern pitches.

Figure 4 shows the relationship between base pattern contrast and defect sensitivity. The orange and green bars show the minimum detectable defect size of Opaque and Clear extensions respectively. Overall, higher base pattern contrast conditions show lower defect sensitivity, and lower base pattern contrast conditions show higher defect sensitivity.

Figure 5 shows a comparison of the same size defect across different pitches. The pictures show SEM and 19x nm defect inspection images of Opaque Extension defects. The left picture

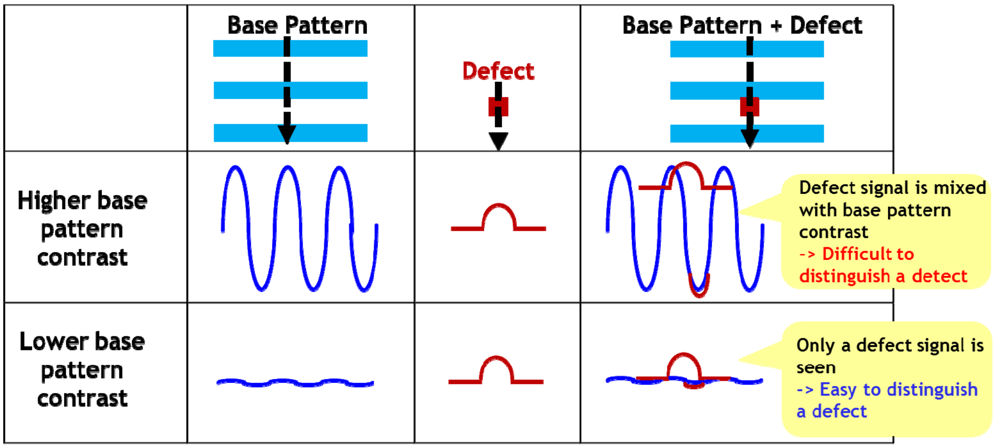

*Figure 6. Hypothesis formulation.*

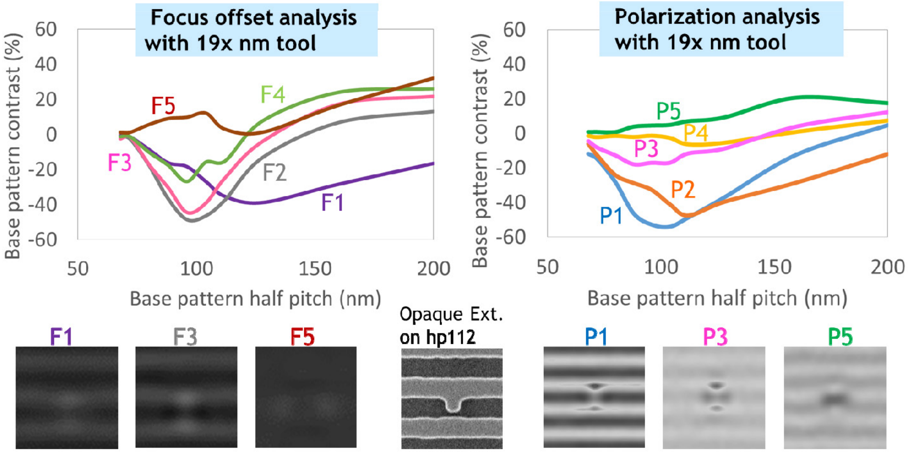

*Figure 7. Base pattern contrast manipulation.*

shows a 23 nm defect on half pitch 68 nm and the right side picture shows a 21 nm defect on half pitch 112 nm respectively. Even though these two defects are very close in size, the defect signal looks very different. The defect on half pitch 68 nm appears bright and isolated, while the defect signal on half pitch 112 nm is lower and hard to distinguish within the 19x nm wavelength image.

## 3. Experiment and Optimization

To understand the defect sensitivity difference between the base pattern pitches, a hypothesis formulation was made and is demonstrated in Figure 6. That formulation assumes that if the base pattern contrast is too high, the defect signal becomes mixed with the base pattern peak, making it very difficult to distinguish the defect from the pattern on the 19x nm inspection tool. On the contrary, if a base pattern contrast is too low, only the defect signal is seen, making it easy to detect on the 19x nm inspection tool.

The question that needs to be answered is, if base pattern contrast is lowered, will the sensitivity of the 19x nm inspection tool be improved. To answer the question, base pattern contrast analysis was done. Figure 7 shows the results of that analysis. The assumption is that focus offset or polarization setting changes would have an effect on base pattern contrast. The left figure shows the focus offset analysis. Base pattern contrast was evaluated with five different focus settings (F1 to F5). The right figure shows the polarization analysis. The pictures show the defect images at 19x nm inspection wavelength. Opaque extension defects on half pitch 112 nm are compared with different focus or polarization settings. Those defects look very different among the five focus offset and polarization conditions. The resulting conclusion is that base pattern contrast is adjustable.

The next step, was to determine if manipulation of base pattern contrast by varying focus offset would improve defect sensitivity. The result are shown on Figure 8. Both opaque extension and bridge defects were used for this analysis. The defect signals were checked with many contrast conditions. It was expected that the lower base pattern condition would show higher defect sensitivity, but the result did not meet our expectations. Surprisingly, the standard setting showed the highest defect signal, and the defect signal decreased as contrast decreased. This result suggests that both base pattern contrast and defect signal both decrease due to defocus. We conclude through this analysis that reducing base pattern contrast is not the right solution toward the goal of maximizing defect signal.

Again, the most important thing is to maximize defect signal.

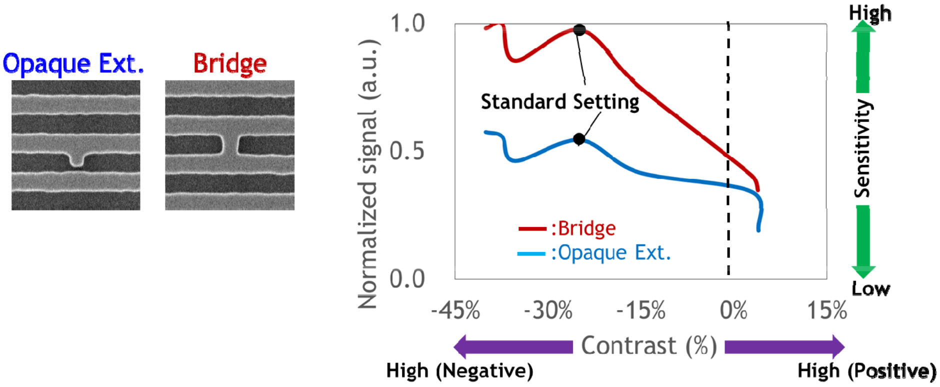

Figure 8. Base pattern contrast vs. defect signal.

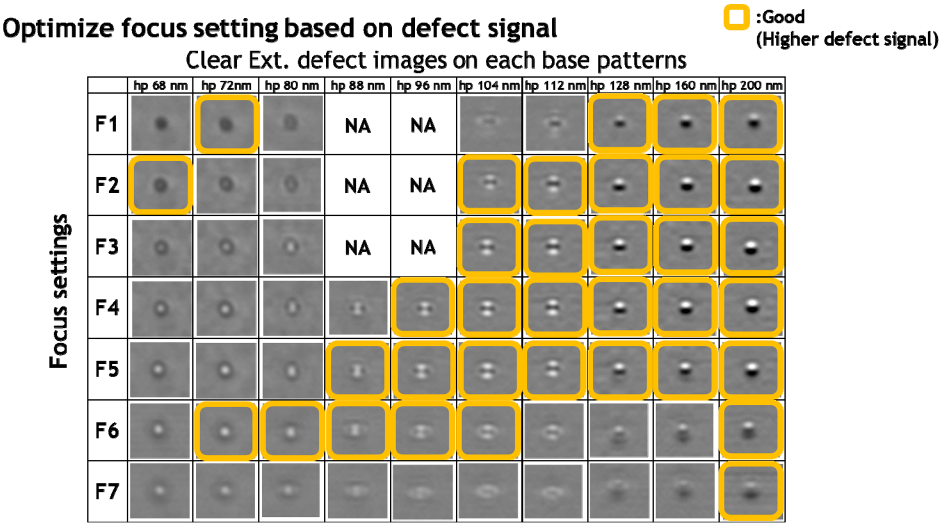

Figure 9. Focus optimization based on defect signal.

Figure 9 shows a snapshot of the focus optimization results. Defect images were captured with seven different focus offsets (F1 to F7). The orange color shows the condition with a defect signal high enough to detect the defect. The results confirm that no single focus setting is able to detect all of the defects, but that a combination of focus settings can. For example, the F2 plus F6 settings can detect all of the defects.

Figure 10 shows the polarization optimization results. Optimal polarization condition is evaluated with five different polarization settings (P1 to P5). The orange color shows the condition with a defect signal high enough to detect the defect. Each defect looks very different among the polarization conditions. As with the focus setting work, these results confirm that no single polarization setting is able to detect all of the defects, but that a combination of polarization settings can. As seen in Figure 10, a combination of P1 and P4 or P5 can detect all of the defects.

Finally, defect sensitivity was analyzed again with optimized settings. Figure 11 shows the programmed defect evaluation results. The blue and orange color shows the original and optimized settings respectively. The original inspection had sensitivity gaps, but optimized settings can improve those gaps. This data confirms that the optimized settings can detect all of the target defects.

## 4. Summary

19x nm defect inspection is the strongest candidate for initial EUV production until high-throughput E-Beam or Actinic inspection is ready. In the meantime, the defect sensitivity of 19x nm tool can be optimized. It is confirmed that the defect sensitivity varies based on pattern sizes and defect types and therefore, a wide range of pattern sizes and defect types need to be used to optimize inspection sensitivity. Focus offset and polarization settings can be optimized to successfully develop new inspection recipes that could meet a target defect criteria with multi-pass inspection and is adaptable to EUV production designs.

## 5. Acknowledgments

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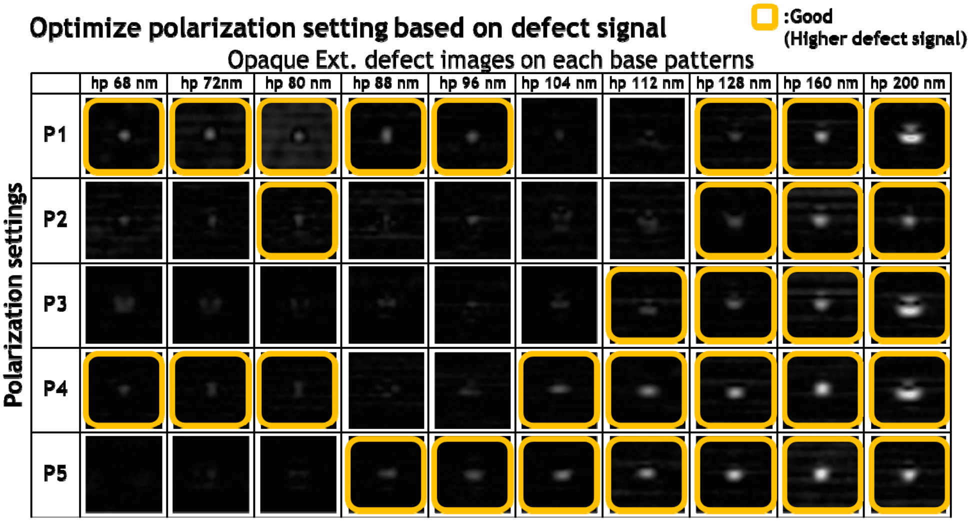

Figure 10. Polarization condition optimization based on defect signal.

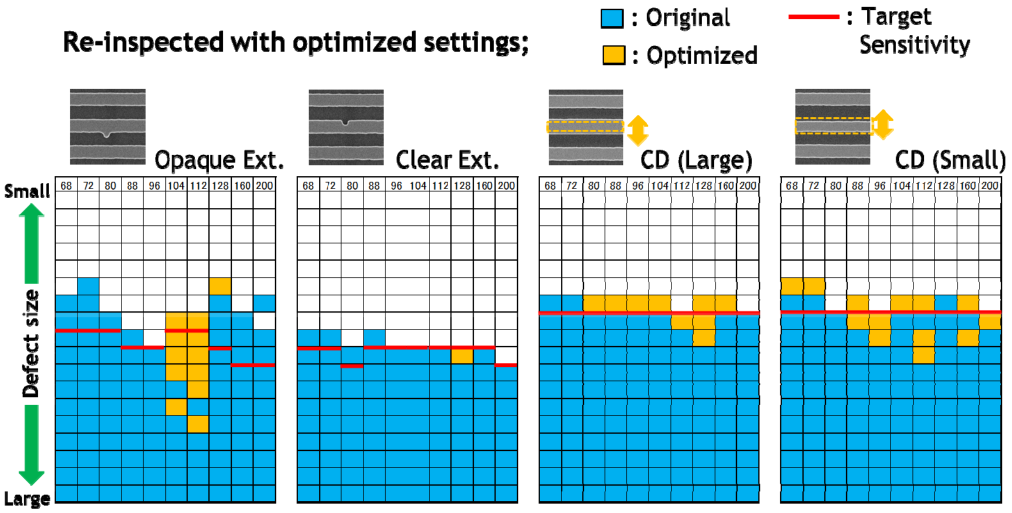

Figure 11. Sensitivity analysis with optimized inspection settings.

would like to thank the GLOBALFOUNDRIES Inc., Advanced Mask Technology Center GmbH & Co.KG and Toppan Printing Co., Ltd. management and technical teams for their support of this project.

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# Industry Briefs

## Nanoimprint Lithography Adopted for DFB Lasers

Compound semiconductor wafer supplier IQE plc (Cardiff, Wales) has announced that its NanoImprint Lithography ("NIL") technology has been production qualified by a leading supplier of Distributed Feedback ("DFB") lasers into the telecoms industry, and the first production order has been received. The supplier has found that using NIL gratings provides greater precision and dimensional control (which have resulted in higher performance in side mode suppression ratio (SMSR), a key performance measure of DFB lasers), better pitch and duty cycle uniformity, and narrower lasing wavelength within the wafer for the customer as compared to conventional interference holography. DFB lasers are high power edge-emitting lasers used as transmission components for high-speed data communications across national fiber optic networks. Increasing demand for DFB lasers is likely to be driven by 5G and IoT deployment, IQE claims. See news report at bit.ly/NILforDFB and company press release at bit.ly/NIL4DFB

## US Tariffs on Chinese Imports includes Mask and Reticle Tools

A press release by the U.S. Office of the United States Trade Representative at discusses the new trade tariffs poised to be imposed on China by the U.S. on June 15th, 2018 and approved by President Trump; the tariffs are of "25 percent on approximately $50 billion worth of Chinese imports containing industrially significant technologies, including those related to China's 'Made in China 2025' industrial policy." One item listed is "machines and apparatus for the manufacture of masks and reticles" See USTR press release at bit.ly/USTRChineseTariffs

## History Walk: Federico Faggin: The Real Silicon Man

Faggin seems to have been at the heart of many of the early advances in microprocessors. He played a big part in the development of MOS processors during the transition from TTL to CMOS. He was co-creator of the first commercially available processor, the 4004, as well as the 8080. And he was a co-founder of Zilog, which brought out the much-loved Z80 CPU. From there he moved on to neural networking chips, image sensors, and is active today in the scientific study of consciousness. It's time then that we had a closer look at a man who's very core must surely be made of silicon. The Z80, as well as the Z8 microcontroller conceived of by Faggin are still in production today. See news report at bit.ly/FedericoFagginSiliconMan

## VLSI Symposia: Samsung use EUV for 7 nm Process

Samsung unveiled its upcoming 7nm FinFET technology at the VLSI Symposia recently. Samsung is expected to be the first of the major semiconductor manufacturers to employ Extreme Ultra Violet (EUV) lithography for the process – EUV provides improved pattern uniformity and lower manufacturing costs compared to standard extreme-scaling multi-patterning processes. Samsung uses EUV with additional front-end scaling, special designs, and a single diffusion layer to produce the smallest FinFET transistors with a fin pitch of 27 and gate pitch 54 nm. Power consumption is reduced to around 50 to 60% of current 10 nm technology. See news report at bit.ly/Samsung7nmEUV

## China's Semi Capex Forecast to be Larger than Europe and Japan Combined in 2018

IC Insights forecasts that China-headquartered companies will spend $11.0 billion in semiconductor industry capex in 2018, which would represent 10.6% of the expected worldwide outlays of $103.5 billion. Not only would this amount be 5x what the Chinese companies spent only three years earlier in 2015, but it would also exceed the combined semiconductor industry capital spending of Japan- and Europe-headquartered companies this year. See news report at bit.ly/ChinaSemiCapex

## Pied Piper of Albany Found Guilty on all Counts

Alain Kaloyeros, who lured SEMATECH to Albany in 1987, was convicted of all charges Thursday in his bid-rigging trial, marking the downfall of a success story who left war-torn Lebanon to become the face of the nanotechnology industry in New York state. A federal jury in Manhattan found Kaloyeros and three co-defendants, all prominent upstate development executives, guilty on all counts in the latest successful prosecution of political corruption. See news report at bit.ly/PiedPiperGuilty In the late 1980's Kaloyeros wooed Sematech executives like a suitor: first the trip to Lake George for a scenic powwow with the Semiconductor Industry Association, then a campus tour, then lots of quality time with the governor. See 2002 profile at nyti.ms/2002Profile

## AI Becomes the New Moore's Law: Execs, Engineers Point to New Path

Moore's Law is dead, long live AI. That's the semiconductor industry's new rallying cry, sounded at a daylong symposium sponsored by Applied Materials at Semicon West. "The time of the node train is coming to an end.;There needs to be greater collaboration from materials to devices — hardware, software and systems" in new avenues, said Steve Ghanayem, former head of Applied's transistor and interconnect group now scouting for acquisitions and alliances to take the company in directions beyond Moore's Law.

In a keynote, CEO Gary Dickerson said Applied will announce soon new transistor materials that will reduce leakage current by three orders of magnitude. The news is nearly as big for chip makers as was Intel's advance in high-k metal gates in 2007. But today such advances are increasingly relevant only for an increasingly small group of designs and companies. See https://www.eetimes.com/document.asp?doc_id=1333471

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## 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.

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### 2018

**SPIE Photomask Technology + EUV Lithography**

17-20 September 2018
Monterey Convention Center
Monterey, California

www.spie.org/puv

### 2019

**Photomask Japan**

16-18 April 2019
PACIFICO Yokohama
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