

# PHOTOMASK

BACUS—The international technical group of SPIE dedicated to the advancement of photomask technology.

PUV20 - Photonics Best Student Oral

## Extreme-Ultraviolet Pellicle Durability Comparison for Better Lifetime

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### ABSTRACT

To accelerate extreme ultraviolet lithography manufacturing, a better pellicle which has a longer lifetime is required. Various materials and their combinations are suggested and implemented to extend the lifetime. Using finite element method, we analyzed the mechanical behavior of pellicle in terms of crack time when a pellicle begins to tear off. Without thermal property analysis, we were able to get relative crack times for various pellicle structures. Single walled carbon nanotube has the largest relative crack time but needed to be commercialization and multi-layer pSi core pellicle has longer lifetime than a single pSi core pellicle. Additionally, increasing Ru capping layer helps to strengthen the mechanical properties of the pSi core pellicle.

### 1. Introduction

The extreme-ultraviolet (EUV) lithography has been approaching for high volume manufacturing (HVM)<sup>[1]</sup>. However, various problems still have to be solved. One of the problems is that particles occur above the reticle in the lithography process. The particles affect the pattern and lower the yield. To overcome this problem, two-fold approach to eliminate reticle-front side defects was suggested<sup>[2]</sup>. One approach is to make clean vacuum system and the other is to protect the reticle with EUV pellicle. It is not yet clear what approach ultimately contributes to HVM acceleration. Therefore, both approaches of creating a clean system without pellicles and protecting the reticle with pellicle are still being studied<sup>[3]</sup>. Here, protecting the reticle with pellicle are considered in this paper.

In order to maintain and protect defect-free reticles an EUV pellicle has to be solved of various issues (e.g. over 90% single pass transmission, transmission uniformity, long lifetime and low reflectivity)<sup>[4]</sup>. One of these issues in EUV pellicle is to have an enough lifetime. In exposure process, however, thermal stress of particles on EUV pellicle can lead to pellicle deformation and to be broken<sup>[5]</sup>. Therefore, it is essential to strengthen EUV pellicle mechanical durability and to extend an EUV pellicle lifetime.

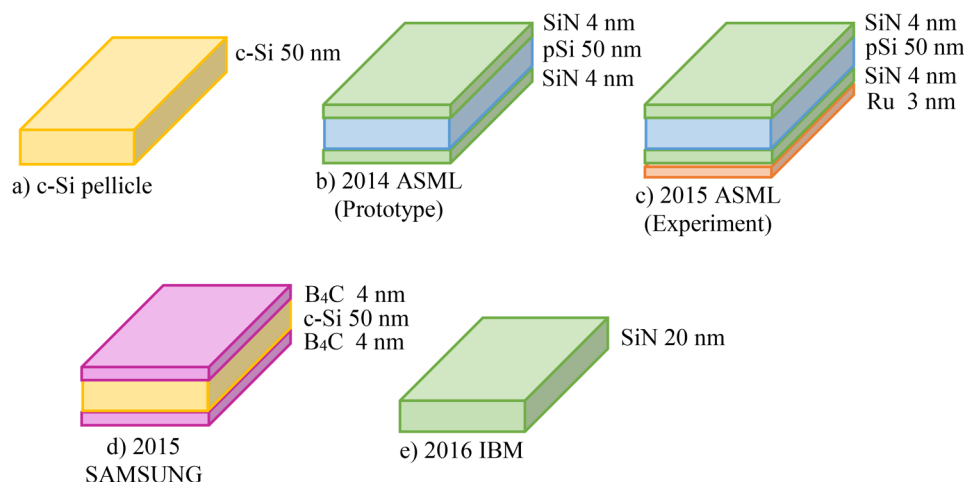


Figure 1. EUV pellicle structures that had been suggested.

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# EDITORIAL

## Impact of COVID-19 on the Semiconductor Industry

**Bala Thumma**, Synopsys, Inc.

The whole world has been impacted by COVID-19 over the last few months from China, moving through Asia, Europe, Americas, Australia, and Africa. The impact has been swift, significant, and unprecedented on many industries, economies, and has taken a significant toll on human life, especially the elderly and those with pre-existing medical conditions. The lockdowns, shelter-in-place orders, social distancing, are causing some of the businesses to shut down, increasing unemployment, and impacting the GDPs of countries across the world.

Semiconductor industry has been impacted by travel restrictions, supply chain interruptions, material and component shortages, employees unable to work because of health safety issues, reduced consumer demand, unemployment, and the slew of uncertainties around the world. In their recent report, Gartner estimates a \$55 billion decline in worldwide semiconductor revenue compared to their previous forecast. Certain segments are strong, especially memory and server segments, because of strong demand for cloud services, remote working, online access, distance learning, and internet services. This is more than offset negatively by the lack of consumers for smartphones, automobile, and electronic products in this environment.

One of the aspects in the semiconductor industry that makes it more resistant to the current situation is the cleanroom operations the manufacturing segment of the industry works in, which minimizes the risk of virus transmission. The strict guidelines already followed by the cleanrooms in the industry ensure that airborne particles and other contaminants like the COVID-19 cannot penetrate through. These steps safeguard workers who are already operating in safe environment when they are within the cleanrooms. Companies have been taking pro-active steps like restricted travel and movement of employees, reducing on-site workforce, implementing telecommuting, actively quarantining employees who might be affected, social distancing, providing protective masks and sanitizers, which have all been very effective in combating the spread of the virus.

Given the current situation around us, what should we be doing to get the industry and the economies around the world moving? This is a very difficult question. On the one hand, health and safety calls for extending lockdowns and shelter-in-place to contain the virus spread, and on the other hand, the longer the economy shuts down, the longer and more painful it will be for people to get back to work. As unemployment shoots up, some companies may not survive, and consumer confidence will be badly shaken causing hardships to a lot of people around the world. Confronted with this grim reality, countries worldwide must strike the right balance between safety and opening the economies. Hopefully right decisions will be made, and then we will start on a long road to recovery.



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**Table 1. EUV pellicle material properties.**

|                                     | Ru    | SiN  | c-Si  | B <sub>4</sub> C | p-Si | SiC    | SWCNT |
|-------------------------------------|-------|------|-------|------------------|------|--------|-------|
| Density (kg/cm <sup>3</sup> )       | 12410 | 3250 | 2300  | 2550             | 2328 | 3210   | 1600  |
| Young's modulus (Gpa)               | 454   | 325  | 190   | 472              | 170  | 401.38 | 3600  |
| Possion's ratio                     | 0.25  | 0.28 | 0.275 | 0.21             | 0.22 | 0.187  | 0.069 |
| Tensile ultimate strength (Gpa)     | 0.545 | 6.40 | 0.18  | 0.569            | 1.21 | 1.625  | 52    |
| Compressive ultimate strength (Gpa) | 0.415 | 7.10 | 3.46  | 5.687            | 1.48 | 1.395  | 150   |

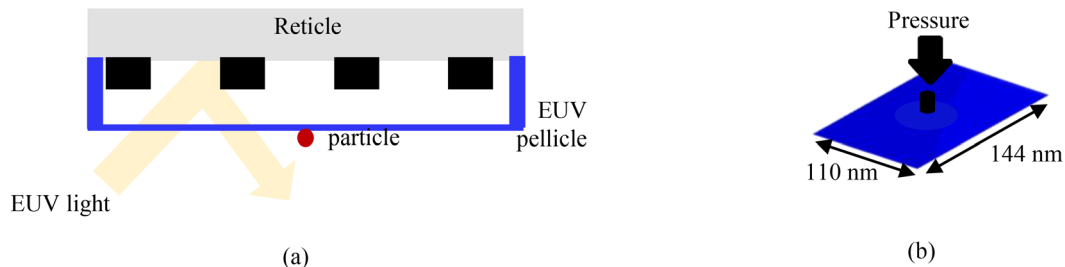


Figure 2. (a) A EUV reticle with a particle on top of a pellicle in exposure process, (b) EUV pellicle modeling and load condition as a constant pressure to a pellicle through a cylindrical particle.

Various EUV materials and structures had been suggested over the past years from single layer to multilayer. Here, we suggest the crack time through finite element method (FEM) and compared the crack times of some EUV pellicle structures. With these compared results we will suggest EUV pellicle materials and structures with enhanced mechanical durability for better lifetime of EUV pellicle. Keep in mind that the thermal properties are not included in this paper.

## 2. EUV Pellicle Structures with Various Materials

### 2.1 EUV pellicle material candidates

In order to solve the EUV pellicle issues, many materials have been considered as EUV pellicle material. Among them, few materials are chosen as EUV pellicle membrane materials satisfying the EUV pellicle conditions.

Over the past years, silicon nitride (SiN), poly-crystalline silicon (pSi) and single-crystalline silicon (c-Si) have been considered as candidates of EUV pellicle core (e.g., first generation candidates)<sup>[5]</sup>. Additionally, silicon carbide (SiC) and single walled carbon nanotube (SWCNT) are also being tested. With thin thickness, boron carbide (B<sub>4</sub>C) and ruthenium (Ru) are also considered as capping layers of EUV pellicle.

### 2.2 EUV pellicle structures

Various EUV pellicle structures have been suggested from single layer to multilayer. A multilayer pellicle is consisted of a core layer which has the largest thickness and is consisted of capping layers which protect a core layer. EUV pellicle structures presented so far are shown in Fig. 1.

In addition to EUV pellicle structures already presented so far, we simulated various pellicle structures from single layer to five layer with EUV pellicle materials. In this study, pSi, c-Si and SWCNT were only used as a core layer and Ru and B<sub>4</sub>C were only used as a capping layer of each EUV pellicle models. SiN and SiC were both used as core and capping layer.

## 3. Simulation with FEM

### 3.1 Simulation conditions with FEM

To simulate a mechanical strength for a given pellicle structure with FEM, material properties, modeling and load conditions are needed. In this study, we tried to compare EUV pellicle mechanical aspects. Therefore, tensile ultimate strength and compressive ultimate strength of each material based on thin film are needed. Properties of each material are shown in Table 1.

Particles can be deposited on the top of the pellicle in the lithography process. Accordingly, particles on the pellicle can act as load conditions during the process. Therefore, we made the 110 nm by 144 nm size pellicle membrane and gave a load condition as a constant pressure to a pellicle model through a cylindrical particle. We used a particle that has 10 $\mu$ m in diameter and 10 $\mu$ m in thickness. EUV pellicle modeling and particle are shown in Fig. 2

### 3.2 Definition of crack time with FEM

We gave a constant load condition of 100 MPa to see that all of our pellicle structures were broken. As a result, whenever we simulate each pellicle structure, we can see the time when pellicle starts to crack down. Therefore, we defined the time at which the pellicle cracking begins as a crack time. EUV pellicle with a relatively long crack time would have a long lifetime. Getting the crack time through a simulated EUV pellicle is shown in Fig. 3.

## 4. Results

### 4.1 Single core layer pellicle

By using EUV pellicle core material candidates (i.e. SWCNT, SiN, p-Si, c-Si and SiC), single layer EUV pellicles were modeled. Thickness is varied in unites of 10 nm. Consequently, we were able to obtain relative crack times of the structures with their thickness. Figure 4 shows the relative crack time with their thicknesses.

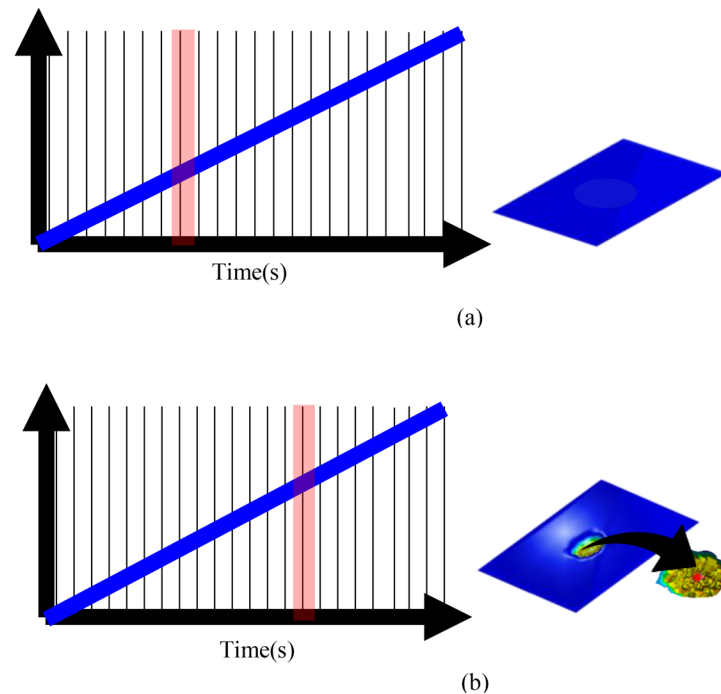


Figure 3. (a) No cracks in the EUV pellicle within the red mark time, (b) A EUV pellicle cracking begins in the red marking time and that is defined as the crack time in the EUV pellicle structure.

In Fig. 4, SWCNT shows relatively longer crack times and c-Si shows relatively smaller crack times for all thickness. The crack times of SiN and SiC are almost the same. The crack times are increased with larger thickness.

#### 4.2 EUV pellicle structures

As shown in Fig. 1, various EUV pellicle structures that had been already reported were simulated and obtained relative crack times.

The proposed EUV pellicle structures considered the various pellicle requirements. However, in our study we only considered the mechanical aspects of pellicle structures. Thus, it may not necessarily represent an increase in the mechanical aspect in Fig. 5. One thing to notice is that the crack time is increased with more capping layers and 4-layer ASML pellicle shows longer crack time.

#### 4.3 Core or capping material dependency of EUV multi-layer pellicle structures

As we mentioned above, multi-layer pellicle consists of core and capping layers. Therefore, it is necessary to study the core or capping material dependencies of EUV pellicle structures respectively. Figure 6 shows capping material dependency of three layer EUV pellicle and Fig. 7 shows core material dependency of three layer EUV pellicle. All of the structures of EUV pellicle that shown in Fig. 6 and Fig. 7 consist of a 50 nm core thickness and 4 nm capping thicknesses.

In the study of capping material dependency (i.e., Fig. 6), we fixed the pSi as a core and used Ru,  $B_4C$ , SiC and SiN as capping layer materials. Ru has maximum value of relative crack time and long lifetime in the order of  $B_4C$ , SiC and SiN. Thus, in terms of mechanical durability, Ru has a longer lifetime as a capping material than other capping materials.

In the core material dependency study, we used SWCNT, SiN, SiC and pSi as core layer materials with  $B_4C$  capping layers. In Fig. 7, SWCNT has the highest relative crack time compared to other pellicles and c-Si has the lowest relative crack time.

#### 4.4 From a single layer EUV pellicle to multi-layer EUV pellicle

To enhance the durability of EUV pellicle, it is essential to see if the lifetime of a pellicle structure extends as the number of layer increases. Therefore, EUV pellicles are simulated from a single layer EUV pellicle to multi-layer. Figure 8 shows the result.

The relative crack time of EUV pellicle has the lowest value when it consists of a single pSi core layer. As the number of capping layer increases, the relative crack time of EUV pellicle increases. In other words, an EUV pellicle can extend its mechanical lifetime if more capping layers are added.

#### 4.5 Five layer with pSi core pellicle capped with Ru and SiN

pSi core pellicles capped with Ru and SiN are currently known as best candidate for HVM, we tried to see which capping material has more impact on the EUV mechanical properties. We fixed a pSi core thickness and changed thickness of Ru or SiN.

As can be seen in Fig. 9, relative crack time of EUV pellicle increases as the capping Ru thickness increases although the SiN thickness decreases. We can see that the Ru capping thickness has more effect on the relative crack time of pSi core EUV pellicle.

### 5. Summary

For EUV high volume manufacturing, it is necessary to find more appropriate EUV pellicle structure. We studied various EUV pellicle structures to test the mechanical strength. The mechanical durability comparison of EUV pellicle structures for better lifetime can be obtained through relative crack time. Firstly, SWCNT has the strongest mechanical properties as a core layer and thus it has a potential for longer lifetime, but commercialization is not yet possible. Secondly, as the pellicle layer increases, crack time becomes longer and thus the mechanical properties become strong. Finally, increasing the thickness of Ru extends the crack time and thus the pellicle lifetime can be increased.

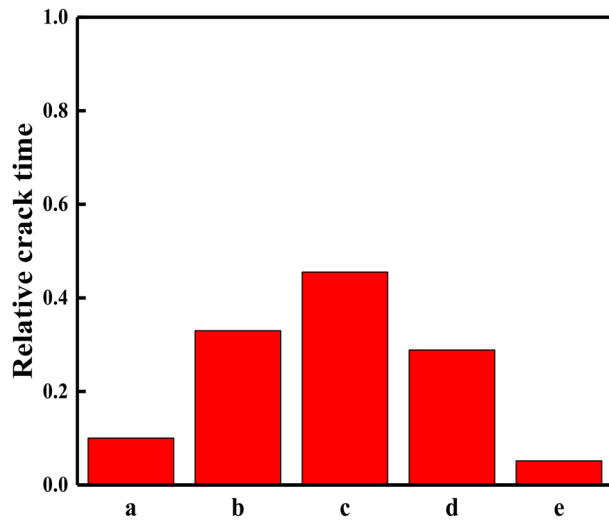


Figure 5. Relative crack time of reported EUV pellicle structures shown in Fig. 1.

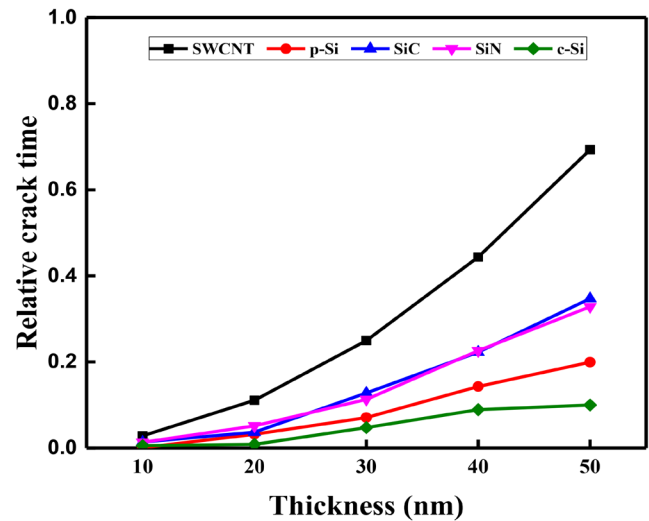


Figure 4. Relative crack time of SWCNT, SiC, SiN, pSi and c-Si single layer pellicles.

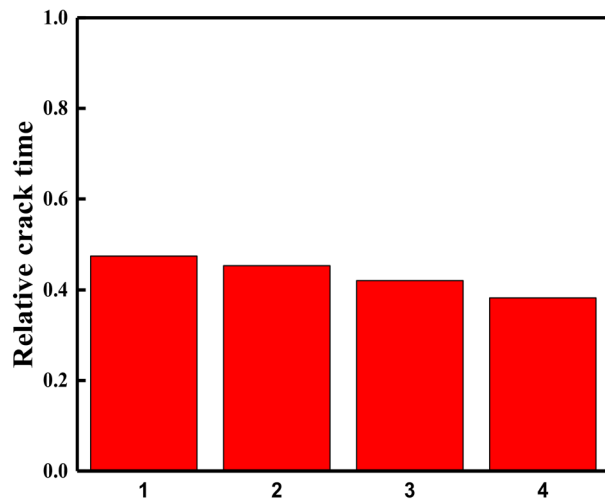
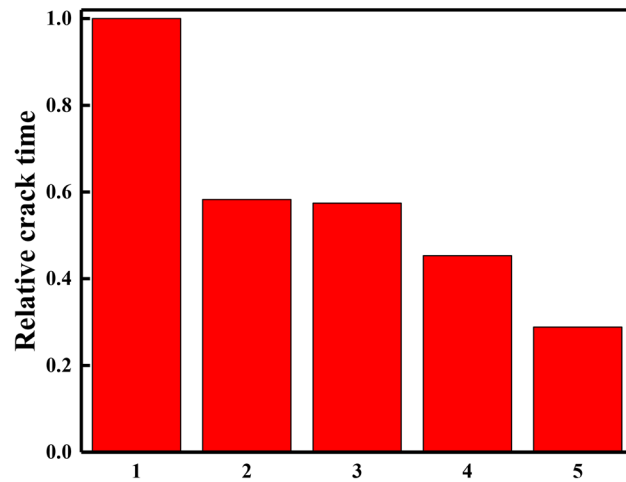


Figure 6. Relative crack time of multi-layer pellicle with different capping layers.

|         | 1   | 2                | 3   | 4   |
|---------|-----|------------------|-----|-----|
| 1 layer | Ru  | B <sub>4</sub> C | SiC | SiN |
| 2 layer | pSi | pSi              | pSi | pSi |
| 3 layer | Ru  | B <sub>4</sub> C | SiC | SiN |

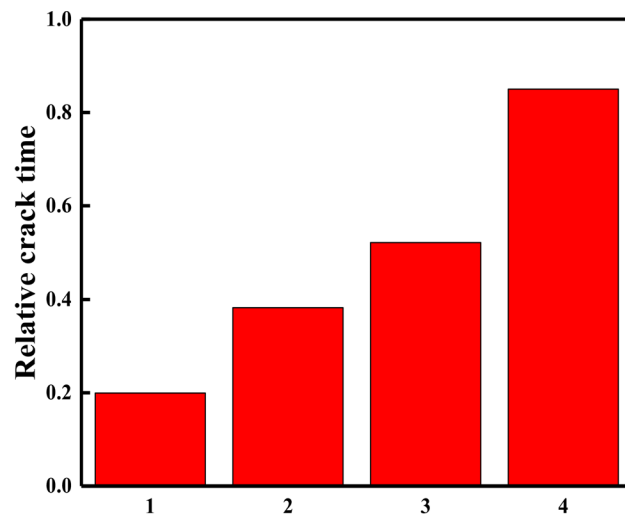
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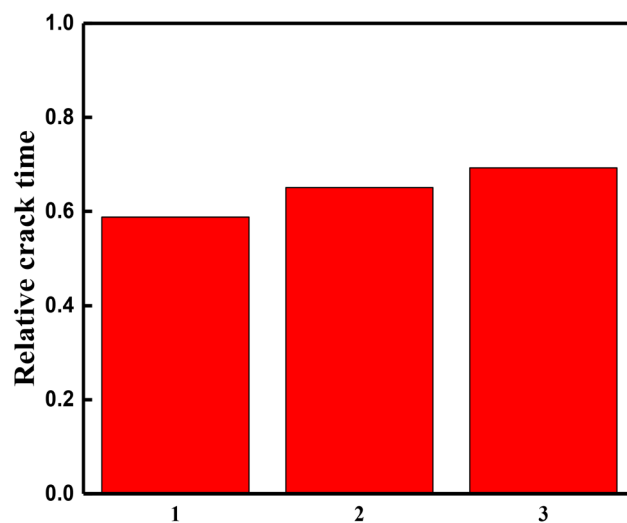
|         | 1                | 2                | 3                | 4                | 5                |
|---------|------------------|------------------|------------------|------------------|------------------|
| 1 layer | B <sub>4</sub> C | B <sub>4</sub> C | B <sub>4</sub> C | B <sub>4</sub> C | B <sub>4</sub> C |
| 2 layer | SWCNT            | SiN              | SiC              | pSi              | c-Si             |
| 3 layer | B <sub>4</sub> C | B <sub>4</sub> C | B <sub>4</sub> C | B <sub>4</sub> C | B <sub>4</sub> C |

Figure 7. Relative crack time of multi-layer pellicle with different core layers.



|         | 1          | 2          | 3          | 4          |
|---------|------------|------------|------------|------------|
| 1 layer | pSi, 50 nm | SiN, 4 nm  | SiN, 4 nm  | Ru, 3 nm   |
| 2 layer |            | pSi, 50 nm | pSi, 50 nm | SiN, 4 nm  |
| 3 layer |            | SiN, 4 nm  | SiN, 4 nm  | pSi, 50 nm |
| 4 layer |            |            | Ru, 3 nm   | SiN, 4 nm  |
| 5 layer |            |            |            | Ru, 3 nm   |

Figure 8. Relative crack time from a single pSi pellicle to multi-layer pSi core pellicles.



| Layer   | Structure | Thickness |       |       |
|---------|-----------|-----------|-------|-------|
|         |           | 1         | 2     | 3     |
| 1 layer | Ru        | 1 nm      | 2 nm  | 3 nm  |
| 2 layer | SiN       | 3 nm      | 2 nm  | 1 nm  |
| 3 layer | pSi       | 50 nm     | 50 nm | 50 nm |
| 4 layer | SiN       | 3 nm      | 2 nm  | 1 nm  |
| 5 layer | Ru        | 1 nm      | 2 nm  | 3 nm  |

Figure 9. Relative crack time of five layer with pSi core capped with Ru and SiN.





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# Industry Briefs

## ■ Samsung Announces Industry's First EUV DRAM with Shipment of First Million Modules

**Shannon Davis**, Semiconductor Digest

Samsung is the first to adopt EUV in DRAM production to overcome scaling challenges. It will be fully deployed in Samsung's future generations of DRAM, starting with its fourth-generation 10nm-class (D1a) or the highly-advanced 14nm-class. Samsung expects to begin volume production of D1a-based DDR5 and LPDDR5 next year, which would double manufacturing productivity of the 12-inch D1x wafers.

<https://www.semiconductor-digest.com/2020/03/26/samsung-announces-industrys-first-euv-dram-with-shipment-of-first-million-modules/>

## ■ Making Chips At 3nm And Beyond

**Mark LaPedus and Ed Sperling**, Semiconductor Engineering

Foundries are beginning to ramp up their new 5nm processes with 3nm in R&D. The big question is what comes after that. Work is well underway for the 2nm node and beyond, but there are numerous challenges as well as uncertainty on the horizon. There already are signs that the foundries have pushed out their 3nm production by a few months due to various technical issues and the unforeseen pandemic outbreak. At these nodes, chipmakers will likely require new equipment, such as the next version of extreme ultraviolet (EUV) lithography. New deposition, etch and inspection/metrology technologies are also in the works.

<https://semiengineering.com/making-chips-at-3nm-and-beyond/>

## ■ Gradual Rebound or Slight Dip – Two Scenarios for COVID-19 Impact to 2020 Global Silicon Wafer Market Sales

**Sungho Yoon**, Semi.org

Uncertainty has gripped the silicon wafer market as the COVID-19 pandemic threatens to upend growth projections for 2020. Declines in both shipments and revenue that plagued the silicon wafer market in 2019 had given way to optimism for 2020 with rising expectations for normalizing inventory levels, memory market improvements, data center market growth and the 5G market takeoff.

Over the past three months, silicon wafer shipments leveled off and the year-over-year (YoY) growth rate had started to rebound, SEMI reported in Silicon Wafer Market Monitor. Monthly shipments of 300mm polished wafers had been on the upswing since November 2019. Epitaxial wafer shipments had jumped sharply since the third quarter of 2019. And 200mm epitaxial wafer shipments were on the brink of recovering in February 2020 even as 200mm polished wafer shipments were stabilizing.

Then the COVID-19 outbreak struck.

<https://blog.semi.org/business-markets/gradual-rebound-or-slight-dip-two-scenarios-for-covid-19-impact-to-2020-global-silicon-wafer-market-sales>

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