Discover

2021 Scientific Report

Entegris

Advancing the World's Technologies Through Science and Innovation

Materials Science and Analytics

- Separation science
- Membrane science and engineering
- Polymer characterization and development
- Interfacial science
- Source of contamination analysis

Advanced Materials

- Materials synthesis and tailored formulation
- Precision gas mixtures
- Specialty coatings
- Graphite, SiC, and engineered carbon
- Surface prep and clean
- Liquid and gas storage and transport

Microcontamination Control

- Leading-edge liquid filtration and purification
- Gas purification at parts-per-trillion (ppt) levels
- AMC solutions for advanced fabs
- Wafer and reticle handling
- Fluid management, sensing, and control

Manufacturing Excellence

- Ultraclean component and materials manufacturing
- Rapid prototyping and customization
- Leading-edge quality control with integrated SPC
- Broad global manufacturing footprint

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Welcome to Our 2021 Scientific Report

At Entegris, innovation is more than a business imperative. It is an existential mandate central to our corporate PACE values and our commitment to social responsibility. We want innovation at Entegris to align with our value proposition for our customers and to create broad economic value, wider access to technology, and to improve the lives of people around the world. As we innovate, we will strive toward excellence, realizing that excellence is a journey. It requires setting high standards for ourselves and pushing the limits of what is deemed possible.

Among the most important questions we ask ourselves is: Where will our next new ideas come from?

While there is no single answer to this question, at the heart of our innovation is the inspiration that comes from a close collaboration with our customers – the world's leading manufacturers in highly complex industries. We focus our collective mindset as an organization on helping these customers develop solutions that power the transformation of our cities, transportation, and healthcare as well as the way we work, learn, and live our lives. You may know Entegris best for our innovations in the semiconductor market where we use our expertise in materials science to solve advanced technology problems. The laptop, tablet, or phone on which you may be reading this report was likely produced in a factory enabled by Entegris innovations.

To deliver on the promise of novel solutions to help our customers advance their manufacturing processes and improve the performance of their products, we invest in a network of industry -leading technology centers. We locate these tech centers near where our global customers operate and where the next generation of advanced technologies will be developed. This geographic proximity makes it possible for our engineers and scientists to engage more effectively with our customers. It creates a shared sense of purpose and facilitates more open collaboration that translates into shorter development cycles, accelerated ramps to high-volume manufacturing, higher yields, and, ultimately, solutions that address our customers' challenges in real time.

In addition, Entegris employees around the world contribute to advanced research in collaboration with world-renowned research institutes like Belgium's imec and France's CEA-LETI. And in 2020, we launched a joint research laboratory with A*STAR's Singapore Institute of Manufacturing Technology (SIMTech) to explore additive manufacturing and state-of-the-art modeling and simulation techniques for new product development efforts. By contributing to leading-edge research, we not only create new value, capabilities, and innovative approaches for Entegris but also for the industries we serve.

Our differentiated technologies, development speed, and unique rigor in our development process also have opened up opportunities for us to contribute breakthrough research in our core semiconductor market and to create value in new areas. Over the years, we have worked closely with leaders in the semiconductor industry and research consortia to advance EUV lithography through the R&D process to its current expansion into high-volume production. Today we're witnessing radical innovations in the development, qualification, and delivery of vaccines to fight the COVID-19 pandemic around the world. Clean, robust, and reliable solutions developed by Entegris are helping make it possible to manufacture and safely distribute these vaccines. We are also witnessing exciting achievements in science and engineering beyond our planet. Entegris has contributed to advances in optics used in space with technology for the GEMS (Geostationary Environment Monitoring Spectrometer) satellite that is being deployed to monitor our planet's atmosphere. And closer to home, there is a commitment to preserve and protect our planet by introducing new technologies that enable reductions in our carbon footprint. Entegris capabilities and innovative solutions can support the demand for these technologies, particularly as the automotive industry evolves toward more electrified and autonomous fleets.

This inaugural Entegris Scientific Report showcases our approach to innovations that are addressing complex challenges in materials science that impact our daily lives. In a year that has been so difficult for so many, we are excited to have supported the massive effort to produce the digital solutions needed to safely work and learn from home, and we are proud to have contributed to the efforts of vaccine manufacturers who have provided hope for brighter days ahead. These efforts are among the many contributions of the dedicated team members throughout our global organization who overcome obstacles to tackle hard problems and to create the innovations that we rely upon today and those that will continue to improve and transform our lives in the future.

Sincerely,

Bertrand Loy
President and
Chief Executive Officer

James A. O'Neill, Ph.D.
Senior Vice President and
Chief Technology Officer

ENABLING THE SMARTPHONE EVOLUTION

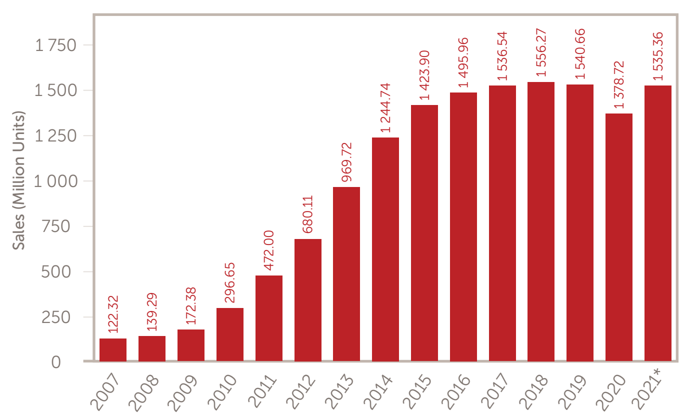
10 Years on the Leading Edge of Technology

Authors: James A. O'Neill, Ph.D.
Wenge Yang, Ph.D.

Semiconductor Innovations Power Smartphone Technology

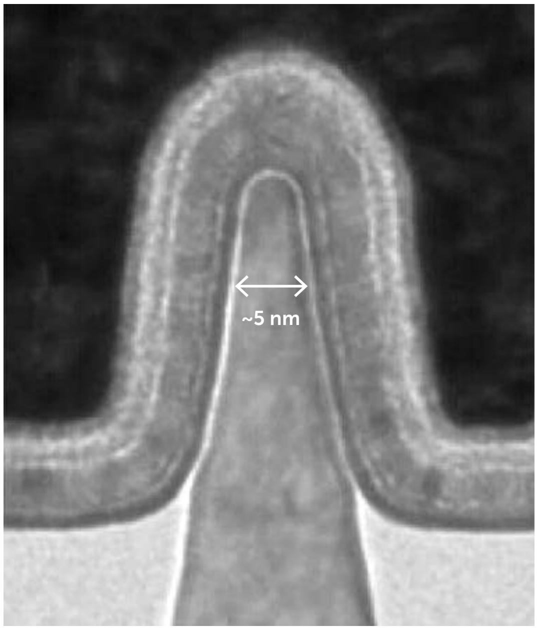
While internet connected mobile devices have been in use since the late 1990s, the smartphone as we know it today was first introduced in 2007 with the announcement of the Apple iPhone.® Since then, the smartphone has become more than just a useful communication gadget; it is unarguably an extraordinarily influential piece of transformational technology that has put everything from banking to navigation in our pocket.[1] Smartphone technology has become ubiquitous around the world with an estimated 1.5B units sold per year (Figure 1), making mobile technology a major driver of semiconductor chip manufacturing volumes. Each year sees the introduction of new smartphone capabilities, from biometric advancements like voice, facial, and fingerprint recognition, to improved geo-positioning accuracy, enhanced mobile security, augmented and virtual reality (AR/VR), and artificial intelligence (AI). These new capabilities generate ever-increasing data volumes and drive the need to process, store, and communicate that data. Smartphone technology pushes the frontier of logic processor performance, achievable memory density, and modem speed. In response, increasingly complex chip designs and more challenging device architectures are required to meet high performance and low power needs, as well as increasing data demands. Who doesn't want a device that can run twelve apps simultaneously and requires charging only once a week?

Number of Smartphones Sold to End Users Worldwide
From 2007 to 2021



**Forecast*
Source: Gartner, Statista

Figure 1.



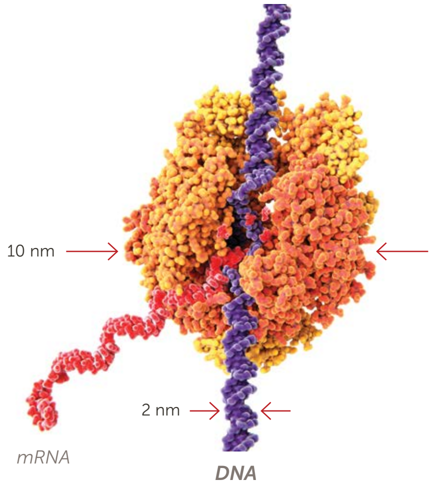


*Figure 2. Limiting dimensions on today's leading-edge logic chips are comparable to a single strand of DNA.**

Historically, improvements in speed and density have been achieved by miniaturizing features on a chip through advancements in photolithography. Yet the limiting dimensions on today's leading-edge logic chips are approximately five nanometers: that's roughly 40 atomic diameters (Figure 2). The industry is now faced with the enormous challenge of engineering materials at nearly atomic scale dimensions, and continued optics-based miniaturization is increasingly difficult. Therefore, other innovations are needed such as new device architectures that are no longer limited to the plane of the wafer but rise into the vertical dimension (Figure 3). Such structures in turn require new materials with increasingly stringent performance requirements to enable their fabrication.

This innovation pushes the frontier of semiconductor fabrication capabilities at the world's most advanced chip manufacturers. It also introduces a significant amount of complexity into the fabrication process, making manufacturing yield ramps more difficult to achieve in the timeframe at which new technology nodes are introduced. For semiconductor manufacturers that supply smartphone companies, cycles of learning and speed to yield are key. Therefore, semiconductor process engineers place enormous emphasis on introducing performance-enabling materials and controlling defects throughout their manufacturing process. This article will examine the role Entegris plays in enabling both performance and yield through the introduction of advanced high-purity materials, and the ability to ensure the integrity of those materials from the point where they are manufactured to where they are used on the wafer. We will examine key elements of the smartphone platform and illustrate where Entegris materials play an enabling role.

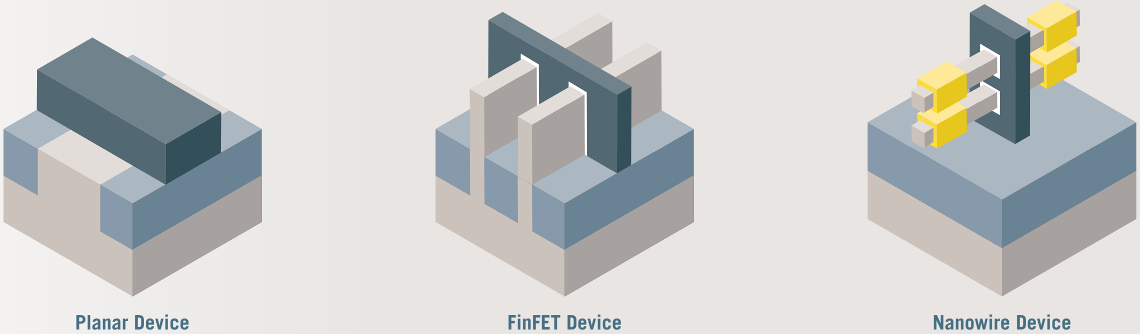


Figure 3.

Advancements in Logic Technology

The unrelenting demand for processor performance by smartphone platforms rapidly motivated the need to integrate multiple application processing cores (APUs), processing cores (CPUs), graphics processing units (GPUs), and cache memory to enable mobile computing functions into a single chip. By 2010, leading smartphone providers started to design their own logic processors rather than relying on chip designs provided by traditional logic IDMs. The initial technology was fabricated in a 45 nm node manufacturing process by leading chip foundries. The relationship between design shop and fab strengthened over the next 10 years as new chip designs challenged the limits of existing fabrication process capabilities, and guided, in large part, the advancement of the logic process technology roadmap (Figure 4). Over time, there developed a close interplay between how far design limits could be pushed within the capabilities of a given fabrication process technology. Today's most advanced logic processor used in a smartphone platform is fabricated with 5 nm node process technology and contains 16 billion transistors on a piece of silicon the size of a thumbnail.[2] This dimensional scaling has been enabled by continued enhancements in lithographic multi-patterning techniques using 193 nm immersion scanners, and more recently, extreme ultraviolet lithography (EUV) has been introduced to extend the reach of optical scaling capabilities to pitches of approximately 26 nm.

However, further performance improvements have required additional innovations such as the introduction of new device architectures like FinFETs that bring the active region of the transistor out of the plane of the silicon wafer into the vertical dimension. This innovation allows for better device performance at lower standby power (lower subthreshold leakage) as compared to planar devices – an advantage for high performance mobile devices. However, making three-dimensional structures on a wafer introduces new challenges to the fabrication process such as the need to engineer films over high aspect ratio structures. This places new requirements on the performance of the materials used in the fabrication process such as enhanced selectivity or extreme conformality. For example, thickness variations in the hafnium oxide (HfO_2) gate dielectric film over a fin structure in today's FinFET transistor will detrimentally affect device leakage which has an exponential dependence on film thickness. Additionally, any variations across the chip will broaden the threshold voltage (Vt) distribution making it difficult to turn off the more than 16 billion transistors simultaneously.

Logic Process Technology Roadmap

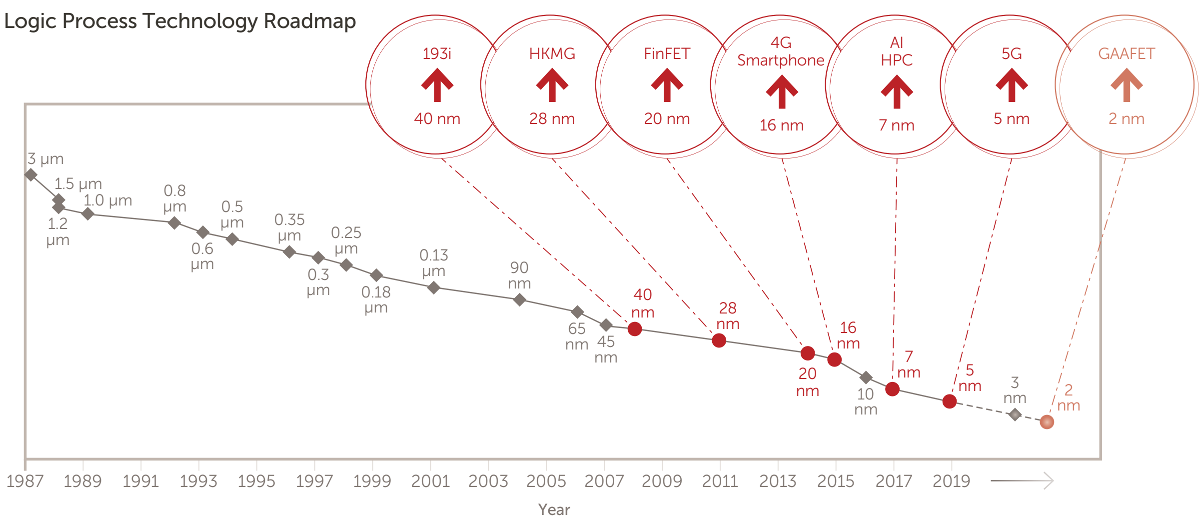


Figure 4.

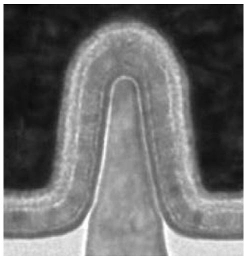


*Figure 5.**

Atomic layer deposition (ALD) processes are now used in an increasing number of critical deposition steps in the manufacturing sequence to address the need for conformality (Figure 5). Such processes deposit material a few atomic layers at a time in a sequential manner until the desired film thickness is achieved. Not only is extreme conformality needed over very high aspect ratio structures, but also critical films such as the HfO_2 gate dielectric must have extremely low levels of impurities. Entegris has patent pending technologies surrounding this capability. Such performance requirements limit the number of metalorganic candidate precursors that can be used in this ALD process, so hafnium halide precursors have been adopted instead. Historically, process engineers have preferred precursors which are gases or liquids at room temperature due to their ease of handling and delivery. However, the preferred precursor for the HfO_2 high-k gate dielectric is a solid at room temperature. This material introduces new challenges in process defectivity and deposition rate due to its corrosivity, its low vapor pressure, and its tendency to entrain particulates from the reservoir of powdered $HfCl_4$. For this reason, great effort is made to engineer a delivery system that ensures low defectivity and maximizes the amount of vapor delivered to the wafer surface (Figure 6).

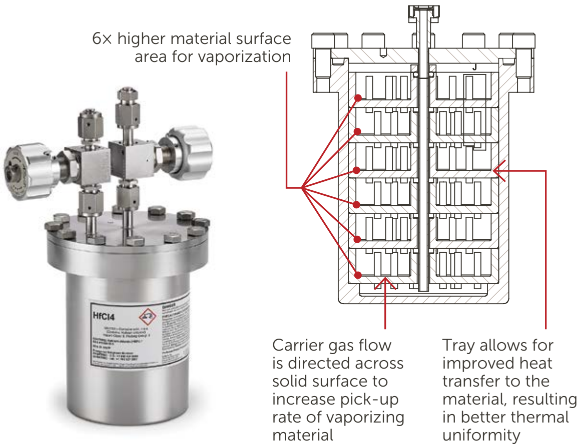
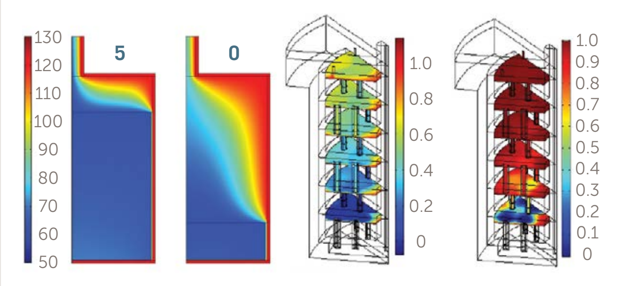


Figure 6. Entegris ProE-Vap solid precursor delivery vessel.



Specifically engineered surfaces within the vessel prevent corrosion and the introduction of additional defects and ensure maximum entrainment of precursor vapor to the wafer.

In addition, inline particle filters are added to avoid entrainment of small particles of $HfCl_4$ powder into the chamber. Today, Entegris' patented ProE-Vap® system is the leading technology for solid precursor delivery used in critical processes for logic chips found in most advanced smartphone platforms.

Advancements in Memory Technology

As impressive as the advancement in logic technology designs have been over the last 20 years, advancements in memory/storage technology found in smartphone platforms are equally notable. Smartphones available around the year 2000 typically came with 8 to 16 GB of storage while 512 GB to 1 TB of storage is available on today's phones. Significant improvements in camera technology and the proliferation of video usage have been major drivers for this need for increased storage. Smartphones use dedicated NAND flash technology for storage because hard disk drives (HDD) would not survive the rough handling that phones are subject to daily. As in logic chips, lithographic miniaturization is the means by which memory density was achieved in 2D flash NAND devices; however, miniaturization of the memory cell below roughly 20 nm node is difficult due to the need to store sufficient charge for reliable bit information. Therefore, facing limitations in size reduction, 2D NAND has evolved into 3D structures with layers of storage cells stacked on top of each other to increase storage density (Figure 7).[3]

3D NAND Roadmap

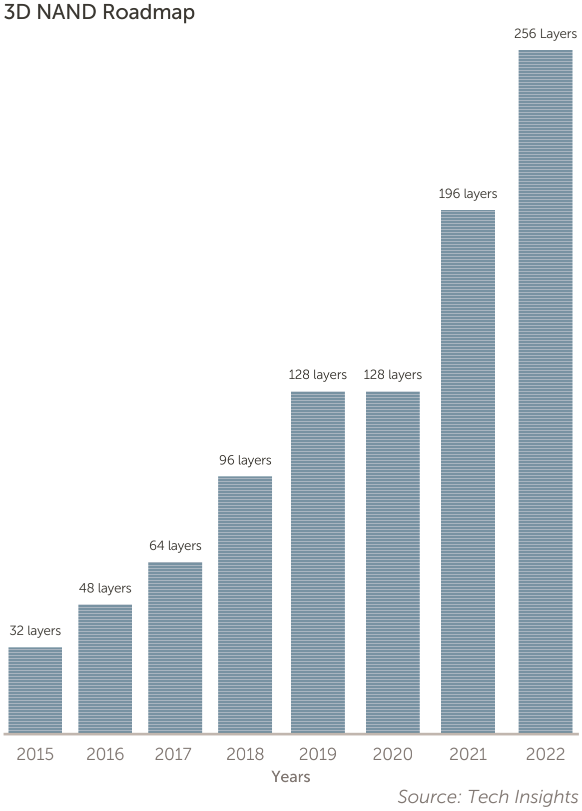


Figure 7.

Today's smartphones with 512 GB of storage are based on 3D flash NAND chips with more than 100 layers. Evolution of NAND flash technology into the vertical direction in general, and such extreme levels of stacking, in particular, has introduced additional challenges to the process used to make these memory chips. Specifically, the high aspect ratio of features that interconnect each of the storage nodes in the device requires materials with unique process capabilities. A particular challenge solved by Entegris patent pending technology is the selective removal of silicon nitride films in a tall SiN/SiO stack in a process used to form the channels where the conductive word-line metal will be deposited. This process requires that the amount of material removed at the top of the stack be the same as that at the bottom, and defects resulting from residuals in the etching process be minimized (Figure 8). Any process selected for this critical step in the 3D NAND build must demonstrate extreme selectivity, low defectivity, and uniformity across the array placing stringent requirements on the behavior of the etch formulation as well as any filtration used to eliminate defects. Advanced chemistries developed for this process typically consist of a complex mixture of additives in a base etching solution. In addition, advanced filters useful for removing small defects typically consist of polymeric membranes that have been chemically modified to functionalize the surface for the removal of targeted defects. Entegris has patented technology surrounding the functionalization of polymer mebranes. However, a complex chemical formulation in the presence of a chemically modified polymer membrane requires a deep understanding of the interplay between filter and formulation. Without this, the membrane could remove critical additives in the formulation, rendering it less effective. Equally problematic is if the etch formulation attacks the functionalization on the membrane, creating a source of defectivity. The most successful selective etch formulations used in the fabrication of advanced 3D NAND chips found in advanced smartphone platforms consist of carefully engineered chemistries with filter membranes that have been specifically developed to work with them; that is, a complete formulation/filtration system is required to fabricate these advanced devices.

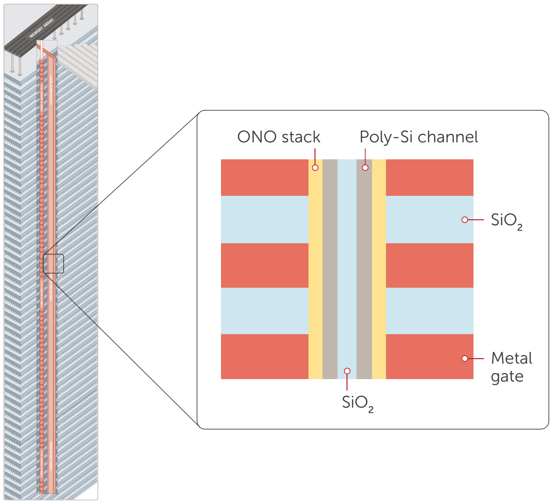


Figure 8.

To accelerate the development of complex chemical systems like those used in the 3D NAND application, computational techniques are increasingly used to provide additional insight. One such model simulates the behavior of complicated chemical formulations within nanoconfined spaces such as narrow etched channels or the pores of a polymer filter membrane. Such models reveal that differences in the diffusion rate of components along various directions of a confined space result in changes in their relative concentration at different positions in the structure. It also shows that the composition of the formulation in a confined space is quite different from that in the bulk solution (Figure 9). This unexpected insight accelerates the rate of learning and allows the formulation to be tuned for the specific application.

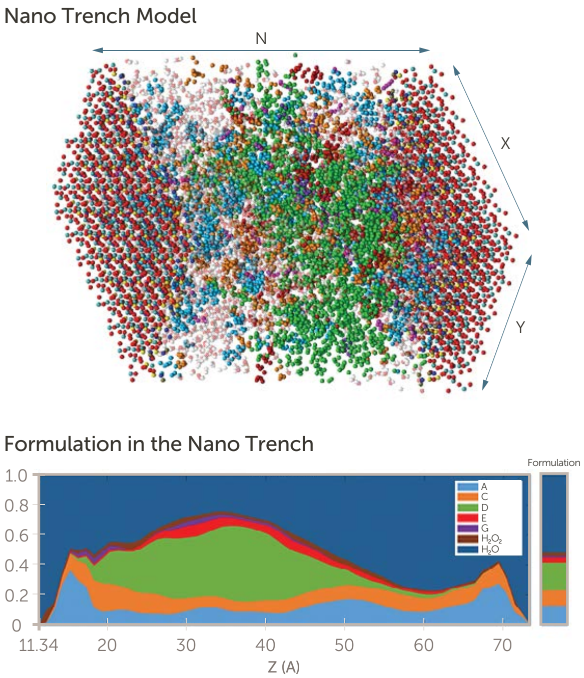


Figure 9. New modeling approaches are increasingly used in developing advanced semiconductor chemicals in today's leading-edge nodes.

Advancements in Radio Frequency (RF) Technology

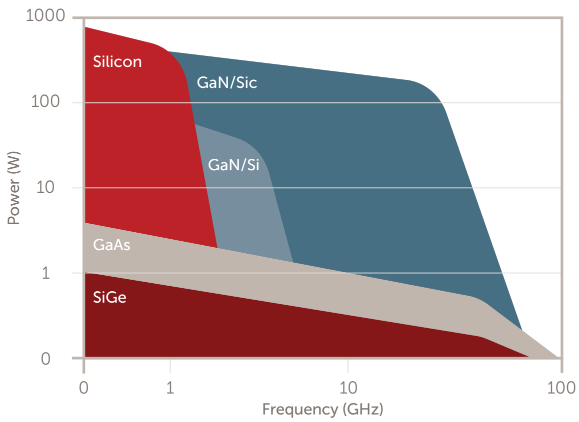
As wireless technology advanced, RF ICs also evolved to handle increasing speed and power needs. This is particularly true in the most recent transition from 4G to 5G technology, and research for 6G has already started. Table 1 lists the evolution of wireless technology in terms of operating frequency and download speed. It is clear that higher frequency bands are needed as the industry moves from one generation to the next to improve transmission speed. For 5G, the industry will eventually move to microwave frequencies of up to 100 GHz to achieve gigabyte per second download speeds.[4]

For RF ICs to handle the demands of the cellular network, operating frequency and power range are two critical parameters that determine the type of devices that can be used. While the migration of RF technology to higher frequencies has been slow in the past due to the capability of silicon-based MOS devices, 5G becomes a trigger for the adoption of wide band-gap RF devices such as gallium nitride (GaN) on Silicon or GaN on SiC substrates. The reason for this significant change in device material is the need for much higher operating power and frequency of 5G technology. Figure 10 shows the various categories of RF devices based on their operating power and frequency window. This chart shows that while Silicon LDMOS (laterally diffused MOSFETS) can handle high power RF transmission up to 1 GHz microwave frequency, to achieve true 5G performance of 25 – 100 GHz while handling increasing power demands requires GaN devices, either on a silicon substrate for low power region, or GaN on SiC in both the high power and high frequency regimes.

					5G		
	1G	**2G**	**3G**	**4G**	**Low-band**	**Mid-band**	**mmWave**
Frequency	30 KHz	200 KHz	1.25 – 5 MHz	20 – 100 MHz	600 – 850 MHz	2.5 – 3.7 GHz	25 – 100 GHz
Download speed	50 Kbps	250 Kbps	3 Mbps	50 Mbps	50 – 250 Mbps	100 – 900 Mbps	1 – 10 Gbps

Table 1. Cellular network technology evolution on operating frequency and download speed.

Comparing Power and Frequency of Different Materials



Source: Analog Devices

Figure 10.

RF GaN technology is a perfect technology for 5G. Compared to high-frequency processes such as gallium arsenide and indium phosphide, GaN devices output more power. Compared to power processes such as LDCMOS and silicon carbide (SiC), GaN has better frequency characteristics. GaN RF devices also carry several distinctive advantages over other types of semiconductor RF ICs in size, power density, thermal performance, and efficiency. Within GaN devices, GaN/SiC has better power and frequency performance due to better thermal conductivity and lattice matching with the underlying substrate.[5]

One of the biggest challenges of making GaN devices is the difficulty of processing hard GaN materials and if used, the underlying SiC substrate. GaN and SiC are both much harder than silicon wafers, making polishing these materials to make substrates for RF semiconductors the key step in adopting these materials. Entegris' Specialty Chemicals and Engineered Materials division is a leader in the design and production of chemical mechanical planarization (CMP) slurries used for polishing ultra-hard materials such as SiC and GaN. Through careful engineering of the abrasive particle and the additives to the slurry, Entegris' patented technology can increase polishing rates of hard materials like GaN and SiC by 50% while minimizing surface roughness and defectivity. Such Entegris technology is critical in enabling 5G technology for mobile devices for the next five to 10 years.

Using Chemistry and Advanced Materials to Enable the Future

Mobile technology, as epitomized by the smartphone, is the most ubiquitous manifestation of advanced semiconductor technology in the hands of the everyday user. This technology is charged to deliver functions that test the limit of the most advanced production facilities ever built, and the most complex chip designs ever created. Structures that perform the role of switching the transistor have been miniaturized to dimensions on the order of a strand of DNA, and billions of these transistors are contained within each of the roughly 500 chips on a wafer, produced at the rate of tens of thousands of wafers each month, making the transistor the most produced invention ever built. All this capability is built on a foundation of high-performance materials; it is the content in your smartphone that you can't even see. It is safe to say that chemistry and the engineered materials it has enabled is what makes the advancement of mobile technologies like the smartphone possible. Entegris contributes in this environment through high performance materials – capable of being engineered at atomic scale dimensions – with accompanying technology that ensures the integrity of the material from the point where it is manufactured to the point where it is used on the wafer. Without such materials, none of the functions behind the touchscreen would work.

References

[1] https://www.semantics3.com/blog/evolution-of-the-mobile-phone-industry-2/

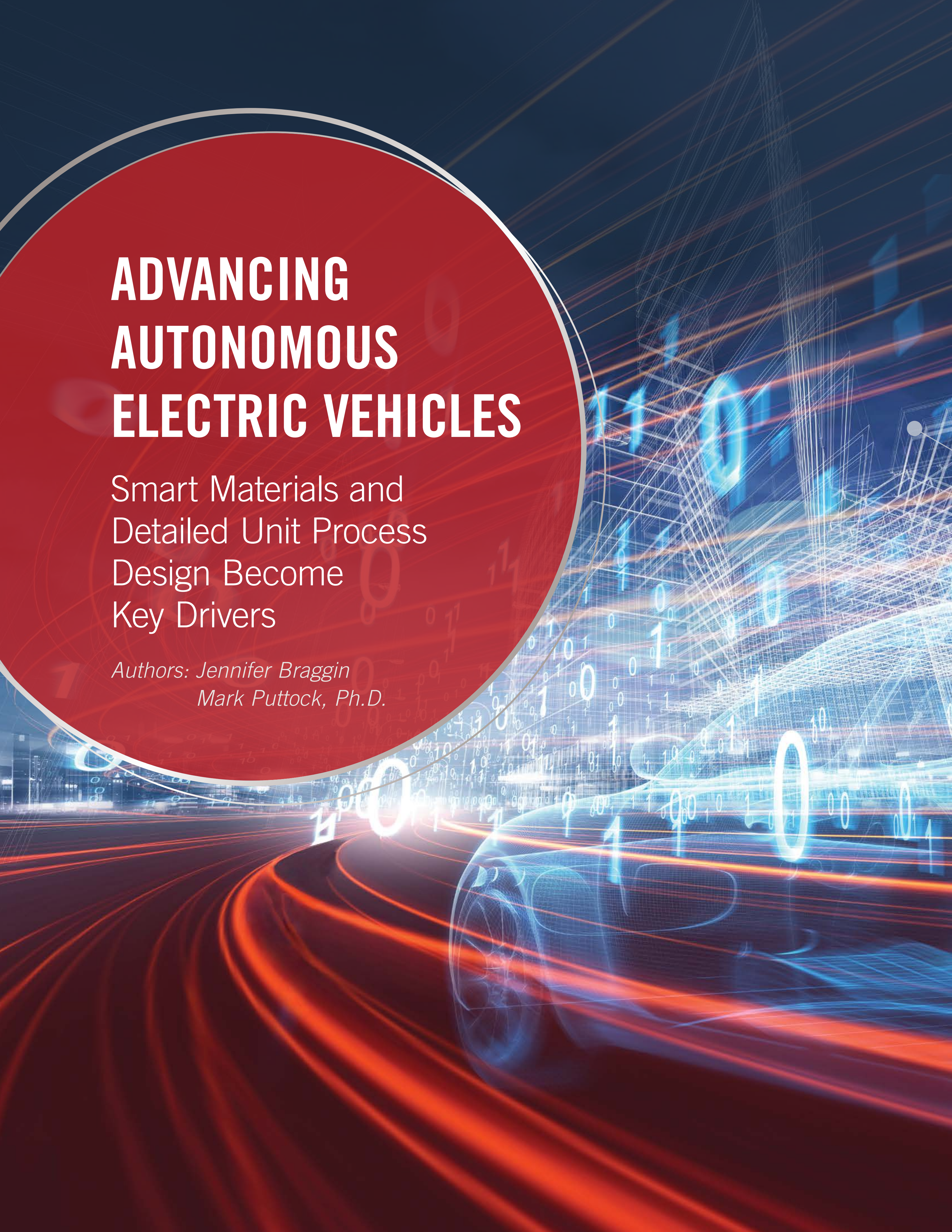
[2] https://www.pcmag.com/news/what-is-the-apple-m1-chip

[3] https://semiengineering.com/3d-nand-race-faces-huge-tech-and-cost-challenges/

[4] https://semiengineering.com/gan-versus-silicon-for-5g/

[5] https://www.microwavejournal.com/articles/34896-gan-and-gaas-5g-brings-thriving-business-opportunities

[*] Used with permission – C. Auth *et al.*, "A 22nm high performance and low-power CMOS technology featuring fully-depleted tri-gate transistors, self-aligned contacts and high density MIM capacitors," *2012 Symposium on VLSI Technology (VLSIT)*, 2012, pp. 131-132, doi: 10.1109/VLSIT.2012.6242496.



ADVANCING AUTONOMOUS ELECTRIC VEHICLES

Smart Materials and Detailed Unit Process Design Become Key Drivers

Authors: Jennifer Braggin
Mark Puttock, Ph.D.

Back to the Future

An increasing number of car manufacturers are pursuing two new technologies in parallel – *fully* electric and autonomous vehicles. In doing so they are introducing consumers to an exciting new future. That future holds the promise of new modes of transportation that directly address climate change, equity, and safety.

Introducing these new technologies in parallel presents an incredible opportunity for the semiconductor industry. For electric vehicles, the materials landscape is very broad. Wide band gap devices are at the heart of electric and hybrid vehicles being used for power distribution, vehicle charging, high intensity headlights, and light detection and ranging (LIDAR). For autonomous vehicles, silicon-based semiconductor technologies are being utilized in an increasing number of applications in the car, and the designs of these devices are pushed to their limits. Silicon-based technologies are used in powertrain, networking, infotainment, communications (5G), and most importantly, safety systems. As more complex devices designed for artificial intelligence (AI) are integrated into safety systems, there is much more opportunity for innovation and risk.

Semiconductors Power Today's Automobiles

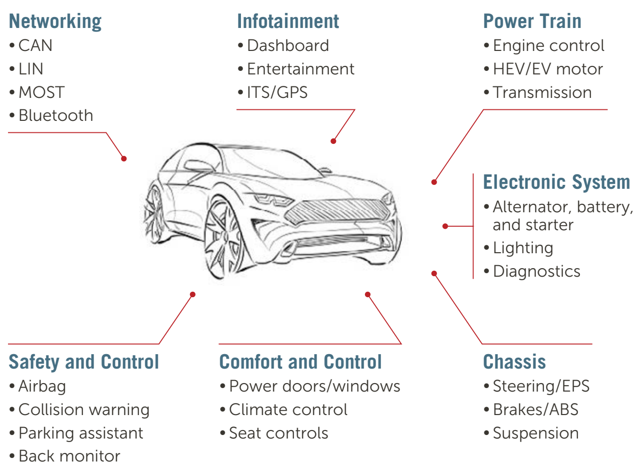


Figure 1. Semiconductor content in modern automobiles.

Concerns regarding these new technologies come from the different expectations and requirements placed on automotive electronics when compared to consumer electronics (Table 1). Most people only expect their mobile phone to last a few years, whereas they expect their car to operate for 10 – 15 years. These high expectations and requirements mandate a fundamental change in how automotive electronics are designed for functional safety. Functional safety, as defined by ISO 26262, means that autonomous cars perform their tasks exactly when the tasks are supposed to be performed. In most cases, however, the devices that power these tasks may have latent defects which, over the life of the devices, may interfere with normal operation.

To build an understanding of functional safety starting with the manufacture of semiconductor devices, the Automotive Electronics Council (AEC) recently updated a version of the Automotive Zero Defects Framework AEC-Q004.[1] This document identifies opportunities for members of the semiconductor supply chain to achieve the "zero defect strategy," which targets zero *system-level* failures. Areas of interest in the document provide the best practices in manufacturing, test, reliability, and continuous improvement methods. However, the document does not go so far as to prescribe how to apply these best practices and ultimately falls short of giving the members of the supply chain useful guidelines to achieve zero system-level failures. This topic was recently addressed by Volkswagen in a paper at the International Integrated Reliability Workshop, highlighting the need for collaboration across the semiconductor and automotive supply chains to identify opportunities for improvements specifically focused on contamination control.[2]

Another source of concern is introduced as semiconductor manufacturers rapidly introduce new materials into the chip fabrication process to accommodate new technologies long before ramping to full yield and monitoring reliability becomes an issue. Figure 2 highlights the number of new materials introduced over time. Those in the newest classification (in light gray) include several materials that have yet to go into mass production but are being investigated.

With the rapid demand for new materials, Entegris is poised to be able to provide innovative solutions to enable a more electrified, automated driving experience.

				Rh, Ir, Mo, MoS (2D), Graphene, CNT, V, NiAl, IGZO, Yttrium, Metal mix Ru/Co/Mo, HfO(Zr) memory
			La (HKMG), Cu reflow, aC HM (B doped), sSOI/GeOI, III-V IL, Ge IL, Ge, InGaAs, InSb, GaN, STO, Ru	La (HKMG), Cu reflow, aC HM (B doped), sSOI/GeOI, III-V IL, Ge IL, Ge, InGaAs, InSb, GaN, STO, Ru
		Metal oxides (memory), GST, CuMn, Co, Air, SiC, LT SiO, LaO, SiCO	Metal oxides (memory), GST, EUV PR, Co, Air, SiC, LT SiO, LaO, SiCO	Metal oxides (memory), GST, EUV MO PR. SnO, Co, Air, SiC, LT SiO, LaO, SiCO
	SiCN, TiAlC MG, AlO, Hf(Si)O, ZrO, pSiOC, SOI, SiGe(B)	SiCN, TiAlC MG, AlO, Hf(Si)O, ZrO, pSiOC, SOI, SiGe(B)	SiCN, TiAlC MG, AlO, Hf(Si)O, ZrO, pSiOC, SOI, SiGe(B)	SiCN, TiAlC MG, AlO, Hf(Si)O, ZrO, pSiOC, SOI, SiGe(B)
SOG, TaO, SiOC, Ta/TaN, Cu SiOF, TiSi, PtSi, ITO, WSi, W, TiW, TiN, P, B, Ge dopants, Al, BPSG, SiO, SiN, resist, Si	SOG, TaO, SiOC, Ta/TaN, Cu SiOF, TiSi, PtSi, ITO, WSi, W, TiW, TiN, P, B, Ge dopants, Al, BPSG, SiO, SiN, resist, Si	SOG, TaO, SiOC, Ta/TaN, Cu SiOF, TiSi, PtSi, ITO, WSi, W, TiW, TiN, P, B, Ge dopants, Al, BPSG, SiO, SiN, resist, Si	SOG, TaO, SiOC, Ta/TaN, Cu SiOF, TiSi, PtSi, ITO, WSi, W, TiW, TiN, P, B, Ge dopants, Al, BPSG, SiO, SiN, resist, Si	SOG, TaO, SiOC, Ta/TaN, Cu SiOF, TiSi, PtSi, ITO, WSi, W, TiW, TiN, P, B, Ge dopants, Al, BPSG, SiO, SiN, resist, Si
2000	**2010**	**2015**	**2020**	**2025 Potential**

Figure 2. The rapid increase of materials used in semiconductor manufacturing.

Automotive IC Requirements Versus Mobile

	AUTOMOTIVE	MOBILE
Process	>180 nm – 7 nm	>28 nm – 7 nm
Frequencies	>30 MHz – 5.9 GHz	>900 MHz – 2.7 GHz
Voltages	-1 V – >60 V	0.5 V – 1.8 V
Temperatures	-40 – 155°C	0 – 40°C
Operation lifetime	10 – 15 years	1 – 3 years
Target field failure rates	Target zero failure	<10%

Table 1. Source: Synopsys, Deloitte analysis.

Designing Materials for Power Devices

Wide band gap devices are very attractive to the automotive market. SiC devices have reduced power loss, high speed switching operation, the ability to operate at high temperatures, and improved heat-dissipation techniques over standard Si devices (Figure 3). GaN devices are desirable to the automotive industry because they have small on-state resistance, very low conduction loss, fast switching speed, and high electron mobility. These factors allow SiC and GaN devices to be smaller, which saves space and reduces the need for heat sinks, conserving total power.

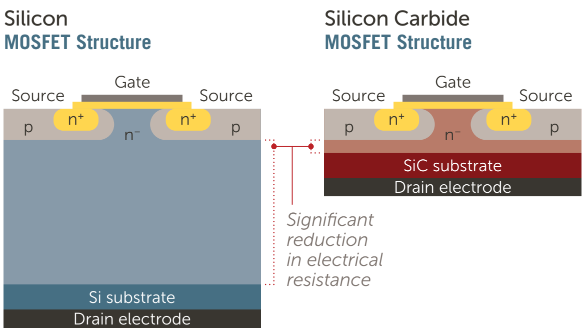


Figure 3. A comparison of the footprint of the same inverters using Si and SiC technologies.

These performance benefits come from the inherent material properties of SiC or GaN, which can be difficult to produce at large scale, and today are generally manufactured at substrate sizes of 200 mm and below. Because these devices have not been produced in nearly the high volumes of standard silicon devices, nor have they been on the market for very long, it is difficult to understand how reliable they will be.[3] Focusing early on smart materials design, particularly the SiC and GaN materials, can be one way to build in long-term materials reliability.

Physical vapor transport (PVT) is one method for growing SiC crystals as boules. In this method, SiC powders are applied to a seed material and are heated above 2,000°C within a graphite crucible. The purity of the resulting substrate is highly dependent on the purity of the SiC powder and the cleanliness of the graphite crucible. SiC wafers can also be produced using high temperature chemical vapor deposition (HT CVD), whereby precursor materials, such as SiH_4 and hydrocarbon gases, are fed into a chamber at temperatures above 2,000°C. The crystal slowly grows, similar to an epitaxial process. What most impacts the success of this process is the ability to have precise, pure gas supply and temperature control within the chamber. Entegris produces gas delivery systems with improved safety functionalities that aid in this process.

GaN substrates can be made using different methods. In hydride vapor phase epitaxy (HVPE), GaN is grown by a reaction between GaCl and NH_3. This is the primary method of making GaN substrates. GaN substrates can also be made using a hetero-epitaxial growth method where the GaN layers are grown on sapphire, diamond, SiC, AlN, or Si substrates. Growing GaN on SiC or Si reduces production costs. GaN substrate manufacturers can benefit from many of the Entegris technologies already mentioned, as they are similar for this process.

Once the substrate has been sawed into individual wafers, it is ground down at the edges and polished into a flat, uniform substrate. The polishing step in particular is very important. SiC substrates polish at 8 – 10x lower rate of standard Si substrates. Therefore, careful design of the slurry materials for polishing is required. Entegris' slurry business is a market leader in the design and production of chemical mechanical planarization (CMP) slurries for polishing ultra-hard surface materials such as SiC and GaN into epitaxial-ready condition. The materials designed for these processes require that specialized chemistry and engineered particles be combined to soften hard surfaces, increase removal rates, decrease abrasive mechanical action, and remove surface defects.

What makes polishing these substrates so difficult is that the wide bandgap materials are not just hard, but they are also chemically inert. This results in poor chemical-mechanical action during polishing. In addition, the hard particles traditionally used for silicon device polishing steps cause significant surface and sub-surface damage on these substrates, and soft particles result in very slow polish rates and long polishing times.

Therefore, the design of the slurry must be very deliberate. Entegris combines a unique suite of surface-engineered particles (Figure 4) with proprietary chemicals to achieve enhanced removal rate, surface finish, and defectivity.

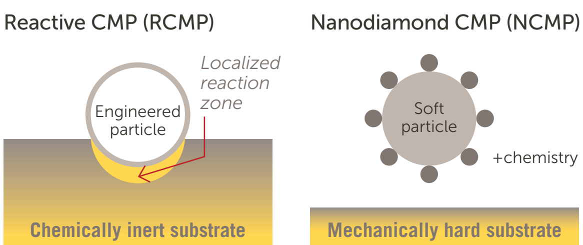


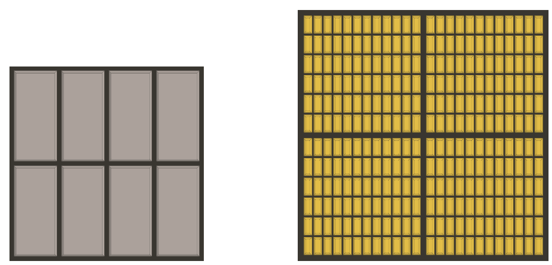
Figure 4. Innovative abrasives used in the design of slurries for wide bandgap materials.

The creation of wide bandgap devices can also benefit from several Entegris technologies. Much like with standard Si devices, several epitaxy, deposition, and etch processes are required. Entegris' Specialty Gas business creates pure, safe GaCl (+NH_3) and $AlCl_3$ gases for epitaxial growth. Entegris also creates plasma enhanced chemical vapor deposition (PECVD) materials, such as oxides and nitrides, which are critical for passivation layers. Ensuring the materials are pure and delivered safely is the first step in reducing reliability risk for devices in the field.

Anticipating Autonomy Risks with Materials Design for Sub-N7 Designs

Where materials design will have a significant impact on power devices for the electrification of transportation, so will it have a significant impact on vehicle autonomy. More AI specific designs, including graphics processing units (GPUs), field-programmable gate arrays (FPGAs), and application-specific integrated circuits (ASICs), are being developed because they are significantly more efficient and faster than today's designs for training and inference for AI specific algorithms (Figure 5). As a result, these chips are more energy efficient and cost effective in complex systems that are required for highly parallel computations required of autonomous vehicles.[4]

CPU vs. GPU Chips



CENTRAL PROCESSING UNIT (CPU)

- Multiple cores
- Optimized for single tasks
- General purpose computing
- Slow to build and train models for machine learning (ML)
- Low compute density

GRAPHICS PROCESSING UNIT (GPU)

- 3 orders of magnitude more cores than a CPU
- Optimized for many concurrent tasks
- Optimization of specialized computing
- Fast to build and train models for ML (machine learning)
- High compute density

Figure 5. Comparing a central processing unit (CPU) with a GPU, whereby GPUs are being leveraged for AI applications.

With new applications will come a host of novel materials required for manufacturing (Figure 3) that could introduce new challenges. One process that is extensively used in both advanced Si and GaN device manufacturing is atomic layer deposition (ALD). ALD provides atomic level control of deposition. For GaN devices, ALD is used to create gate dielectric materials. Entegris has been working with semiconductor manufacturers for years to deliver clean ALD sources that can enable these new technologies.

In addition, there will be many new materials introduced, which means there will be a need for tailored chemistries for cleaning. Entegris' chemists have expertise in formulating selective wet etching chemistries for cleaning applications as they evolve with each new technology node.

Another materials change facing Si devices will be the metallization layers. As feature sizes shrink, metal line resistivity increases dramatically as copper grain sizes become as wide as the patterns themselves. In addition, as the lines narrow, the proportion of liner and barrier materials increases, which also increases resistivity. Therefore, new metallurgies are being implemented and explored to continue shrinking Si devices. This means transitioning from tungsten (W) and copper (Cu) to cobalt (Co), molybdenum (Mo), and ruthenium (Ru). These transitions require several process changes in addition to the material changes. Entegris has been a pioneer in creating precursors for the materials that enable these new metallurgies.

Changing the metal is one step in transforming the process. Cleaning the surface after the CMP process is also critical and requires specialized chemistries. Entegris has developed formulations for use with Co, whereby etchants dissolve Co oxides and organic additives remove organic residues remaining from the process. Corrosion inhibitors are also added to control galvanic corrosion during cleaning.

Summary

By addressing the opportunities presented by the new AEC-Q004 Automotive Zero Defects Framework, car manufacturers are moving to drive semiconductor manufacturers to identify areas for improvement that will address yield and long-term reliability. These are more important now than ever as SiC, GaN, and Artificial Intelligence devices are concurrently being introduced into the automotive supply chain. As semiconductor manufacturers work to push the limits of their ability to introduce new materials and new processes into their factories, it will be difficult to ramp yield and improve reliability without the support of the automotive system designers and suppliers in both industries.

A holistic approach to designing and implementing smart materials begins by having all interested parties engaged in solving the problems that directly impact yield and reliability. And this is just one piece of the puzzle. Engaging the entire supply chain in discussions around materials, contamination control, and materials handling will accelerate the speed at which issues get addressed. Ensuring that automotive manufacturers, suppliers, and semiconductor manufacturers have close communication and a thorough understanding of the challenges is just the first step. Entegris participates in these collaborations and will continue to design and deliver innovative materials, contamination control, and materials handling solutions to enable our automated and electrified future.

References

[1] AEC-Q004, *Automotive Zero Defects Framework,* Automotive Electronics Council, 26 February (2020); http://www.aecouncil.com/Documents/AEC_Q004_Rev-.pdf.

[2] Aal, A., Braggin, J., Amade, A., and Puttock, M., *Addressing weak links in automotive reliability – semiconductor contamination control, inspection, and test,* IEEE International Integrated Reliability Workshop, (2020).

[3] Lapedus, M., *Improving Reliability for GaN and SiC,* Semiconductor Engineering, 18 June (2020); https://semiengineering.com/improving-reliability-for-gan-and-sic/.

[4] Khan, S.M, Mann, A., *AI Chips: What they are and why they matter,* Center for Security and Emerging Technology, (2020); https://cset.georgetown.edu/publication/ai-chips-what-they-are-and-why-they-matter/.

FROM PROTOTYPES TO HIGH VOLUME MANUFACTURING

Entegris' AM Journey

Authors: Montray C. Leavy, Ph.D.
Subhash Guddati

An Innovative Approach to Next Generation Product Development

Remaining competitive in the era of Industry 4.0 requires businesses to look at new ways to offer superior products and solutions at attractive prices (Figure 1). To achieve this goal, industries are keen to innovate and make fundamental changes to the way they design and fabricate products. One such innovation is additive manufacturing (AM) also known as 3D printing. AM offers several advantages to traditional manufacturing including freedom of design, waste and inventory reduction, ease of manufacturing complex geometries, reduced product development cycle times, and on-demand production of custom parts. It also enables the transformation from conventional centralized production to a customized, networked, distributed production system. For example, the U.S. Navy is exploring the use of shipboard AM to increase self-sufficiency by fabricating replacement parts on-demand thereby reducing the need to carry a heavy inventory of assorted hardware at sea.[1] In short, AM is a game changer for the manufacturing sector. This article covers the basics of 3D printing, the role of modeling and simulation in AM, and how Entegris has adopted AM into its new product development process.

As defined by ASTM international (ASTM 2792-12), additive manufacturing is a process of joining materials to make parts from computer-aided design (CAD) models, usually layer upon layer, as opposed to material removal methods like machining or milling.[2] 3D printing technologies are broken into seven categories based on the material and the method by which it is applied (Table 1).

Advantages of 3D Printing

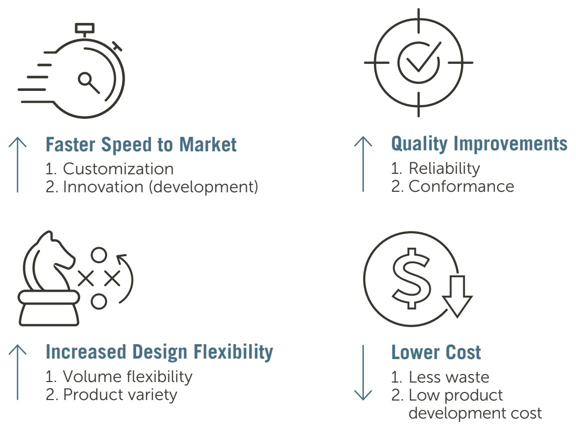
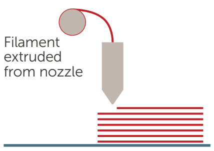
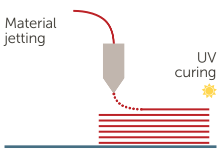
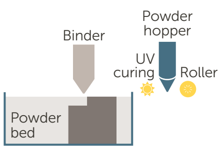
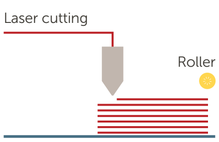
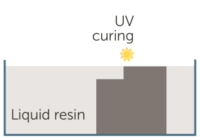
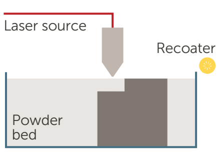
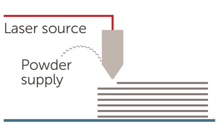


Figure 1.

Summary of Existing 3D Printing Processes

PROCESS TYPE	PROCESS DEFINITION	MATERIAL	BENEFITS	LIMITATION
Material extrusion 	Material in filament form is extruded through a nozzle where it is heated and deposited layer by layer to form the part.	Polymer Metals Ceramics	• Capital and operation cost is low • Process can print metals and ceramics by binding with polymers and extruding into filament	• Layer lines are visible and affect the surface finish • Printhead clogging and warpage for larger prints
Material jetting 	Droplets of build material are selectively deposited and solidified layer by layer.	Photo-polymer Wax	• Achieve outstanding accuracy and surface finishes • Printed parts have homogeneous mechanical and thermal properties	• Only limited materials can be printed • Printed parts are structurally weak and are not suitable for functional applications
Binder jetting 	A liquid binding agent is selectively deposited to join powder materials layer by layer.	Metal Polymer Ceramic	• Wide range of materials such as metals, polymers, and ceramics can be printed • No deformation of parts as no thermal process is involved during printing	• Less accurate due to shrinkage of part • Not currently able to print high density parts
Sheet lamination 	Sheets of material are bonded to form an object by stacking layer by layer.	Hybrids Metal Ceramic	• Process can print bimetallic or multi-material components • Faster print time but requires post processing to achieve the final shape and size	• Hollow or parts with internal features are challenging to produce • Generates more material waste when compared to other AM methods
Vat photopolymerization 	Generates parts by selectively curing a liquid photopolymer resin layer by layer using light.	Photo-polymer Ceramics	• Good accuracy and high surface finish • Process can print metals and ceramics by mixing with photopolymer resins	• Limited to photo resins material only • Lack of strength and durability of the printed parts • Still affected by UV light
Powder bed fusion 	Part is formed by selectively melting or fusing successive layers of powder using thermal energy.	Metal Polymer	• Powder recycling is feasible with proper control • Process can print functional critical parts with high density and surface quality	• Thermal distortion and warping issues due to use of high thermal energy for printing • Powder cost is very high and without recycling the powder it will be an expensive process
Directed energy deposition 	Focused thermal energy is used to fuse materials by melting as they are being deposited. The feedstock can be in powder or wire form.	Metal	• Capability to build larger parts • Suitable for repair or reconditioning of an existing part	• Printing resolution is low which results in poorer surface finish and requires secondary processing • Not suitable to print overhang or conformally cooled channel parts as support structures can't be used for printing

Source: Synopsys, Detroit analysis

3D Printing Process Flow

Figure 2. Typical process flow in 3D printing.

3D Printing at Entegris

In recent years, Entegris has been using 3D printing technology for polymer-based materials to produce protypes, jigs, and fixtures to support the development of new product designs. 3D printing not only provides an alternative to conventional manufacturing by being a cost-effective substitute for low volume high mix products, but also has accelerated product development cycles by enabling rapid prototyping required for functional testing of critical designs.

Beyond polymer-based materials, Entegris also has active development programs, some of which are patent pending, in porous metals, ceramics, and advanced materials like zeolites and metal-organic frameworks (MOFs). Each of these materials has its own challenges in the design and process phases of development: customized designs that consist of complex shapes, buried structures such as conformal cooling channels, and materials of construction that cannot be processed with conventional fabrication techniques. In addition, Entegris has fabricated parts with specific density and gradient porosity that can only be achieved with 3D printing.

Generally, 3D printed parts require several post processing operations like de-powdering, machining, heat treatment, and polishing to obtain the required surface finish. Figure 3 illustrates 3D printed parts before and after going through various post-printing processes.

As printed condition

After post processing

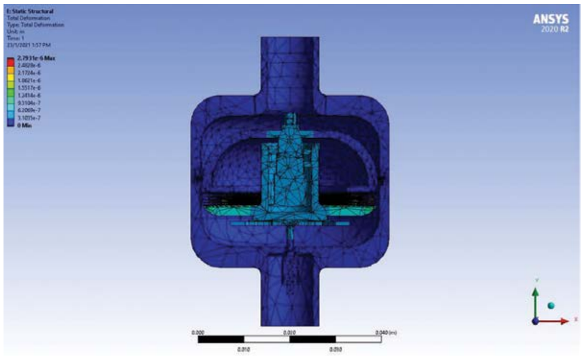
Figure 3. Parts before and after finishing processes.

Role of Modeling and Simulation in 3D Printing

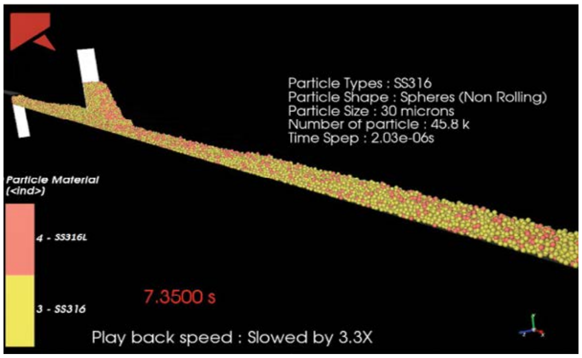
Typically, finite element modeling (FEM) and computational fluid dynamics (CFD) simulations are used in the design phase of product development to evaluate a product's performance and functionality. Recent advances in 3D printing-specific simulation software now make it possible to visualize complex thermomechanical phenomena during printing. Results from these simulations can be used to predict distortion, stress, microstructural characteristics, and thermal strain. Entegris is integrating these simulation tools into its product development processes to overcome the current challenges and restrictions associated with conventional manufacturing and various aspects of 3D printing processes (Figure 4). Specifically, we have used modeling to evaluate the printability of complex designs, the flow of material in a printer's powder bed, and the heat flow and distortion of a part during its fabrication.

Fully Leverage the Advantages

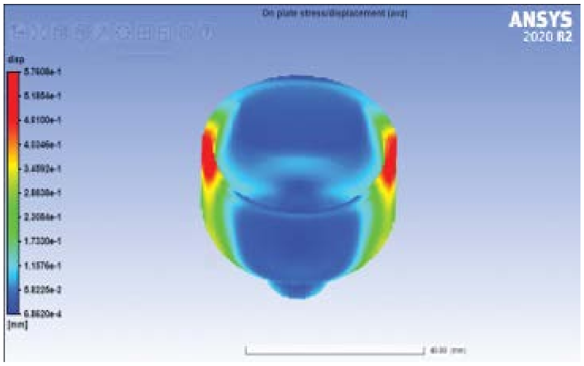
To fully leverage the advantages that AM offers in producing complex geometries and reducing component weight while maintaining structural integrity, design for additive manufacturing (DFAM) is often employed. DFAM[3] methods take advantage of the enormous design freedom this technology provides and can be employed to leverage multiscale structures for weight reduction, topology optimization, and part consolidation. Figure 5 illustrates an example of topology optimization where the mass of an existing component is reduced by 47% resulting in a lighter weight, more cost-effective component with superior thermal performance in the high temperature environment where it is used.



Design simultion



Powder bed flow simultion



SLM process simulation

Figure 4. Modeling and simulations.

Original Design
Mass: 114.23 g

Lattice Design
Mass: 85.3 g
(25% ↓)

Topology Optimization
Mass: 60.4 g
(47% ↓)

Figure 5. Topology optimization.

Entegris Collaborates in the Additive Manufacturing Ecosystem

To fully leverage the benefits and determine the optimal way to incorporate AM into our technology ecosystem, Entegris is strategically collaborating with key universities and research institutes. We recently launched a joint research laboratory with the Agency for Science, Technology, and Research's (A*STAR) Singapore Institute of Manufacturing Technology (SIMTech) dedicated to the development and enhancement of Entegris products leveraging additive manufacturing technologies coupled with state-of-the-art modeling and simulation techniques. Activities of this joint development focus on metal and ceramic component development, the redesign of novel metal-based products, and the characterization of various metal powders. Such research is intended to identify ways to overcome the current design constraints in traditional manufacturing and lead to innovations in 3D printing that benefit a wide range of applications in the semiconductor, aerospace, medical, and energy industries.

References

[1] https://www.navsea.navy.mil/Media/News/SavedNewsModule/Article/2366654/nswc-philadelphia-division-supports-additive-manufacturing-in-the-fleet/

[2] https://www.astm.org/industry/additive-manufacturing-overview.html#:~:text=Additive%20Manufacturing%20Standards%20Drive%20Innovation,piece%20of%20material%2C%20often%20metal

[3] https://en.wikipedia.org/wiki/Design_for_additive_manufacturing

STATE-OF-THE-ART SPACE OPTICS

Innovative Materials for a Challenging Environment

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Troy Scoggins, Ph.D.

Optics in Space

The standard for astronomical space imaging was set with the 1990 launch of the Hubble Space Telescope. Since its famous optical correction in 1993, scientists have used Hubble's 2.4 m telescope to gather images from distances up to 13.4 billion light years[1] and have contributed data to more than 13,000 journal articles,[2] making Hubble one of the most productive science missions ever launched. In October 2021, the telescope is set to be supplanted by the NASA/ESA/CSA James Webb mission. Webb's 6.5 m primary mirror will collect images across a wide EM spectrum, and its ability to gather exponentially more light will lead to ever greater discoveries.

While astronomical missions have provided insight to fundamental physics, of growing global concern is atmospheric pollution that causes a variety of negative health conditions in both developed and developing nations. The World Health Organization (WHO) estimates that in 2016, 91% of the world's population lived in areas where air quality guideline levels were not met, and outdoor air pollution caused 4.2 million premature deaths each year, most in developing countries.[3] Consequently, remote sensing is an important tool that government agencies use for assessing the effectiveness of policies designed to reduce air pollution. Space-based optical systems are ideal for monitoring air pollution and environmental quality on a global scale.

Commercial applications of earth imaging are also growing, along with the number of companies supplying those images. Google Maps, Apple Maps, and Life360 are familiar consumer applications enabled by satellite imaging. Companies providing the imaging also support commercial farming, energy, mining, finance, and information businesses.

Finally, communication is a growing application of space-based optics. A new breed of companies are developing launch capability and satellite networks to support the growing demand for low-latency internet. To support gigabit data capacity at low power, communication between satellites is planned to be enabled through high-frequency lasers, and receivers of those lasers will require optical collectors.[4] Several companies are working to economically manufacture thousands of telescopes to optical standards that can withstand the low earth orbit (LEO) environment.

Each of the missions listed above is optimally located in one of a handful of orbits. These orbits present different environmental challenges to reliable operation. Objects in LEO experience high velocity travel through a thin atmosphere, and multiple cycles through sunlight and darkness per day. In geostationary equatorial orbit (GEO), satellites are further from Earth and synchronized with its rotation, and therefore see only one sun cycle per day. However, these satellites are exposed to higher radiation. Polar orbits exist at altitudes between LEO and GEO and travel roughly from north to south. The trade-off between mission performance, reliability, and cost, determine where to locate a satellite or constellation, and these factors impact the choice of materials to be used.

Space-Based Optics Materials

Two figures of merit define the trade space when considering material choices in the design of optics. For scanning systems, the mechanical figure of merit E/ρ (elastic modulus by density, or specific stiffness) determines how rapidly mirrors can be accelerated, decelerated, and fixed for imaging. In systems that see thermal cycles, thermal diffusivity/CTE expresses how much deformation will be induced in an instrument during solar transits.

Historically, instrument designers began with readily available materials such as carbon fiber, titanium, steel, aluminum, and glass which could be easily fashioned into appropriate shapes, then add design complexity to compensate for limitations in material properties and manufacturing capabilities. These compensation schemes were necessary when systems were composed of different materials, and typically took the form of flexures and alignment options. These added features drove up integration costs and lengthened assembly cycles.

Low-volume, high-performance instruments like Hubble and James Webb demand perfect design and flexible fabrication and assembly, driving up cost and delaying the fabrication schedule. As the market for space optical instrumentation grows, standardization and high-volume manufacturing are generating innovation, leading to quality improvements at reduced cost. Optics integrators are interested in designing high-volume instruments using monolithic material systems for optimal performance combined with "snap-together" interchangeable components to reduce integration cost.

Figure of Merit Comparison

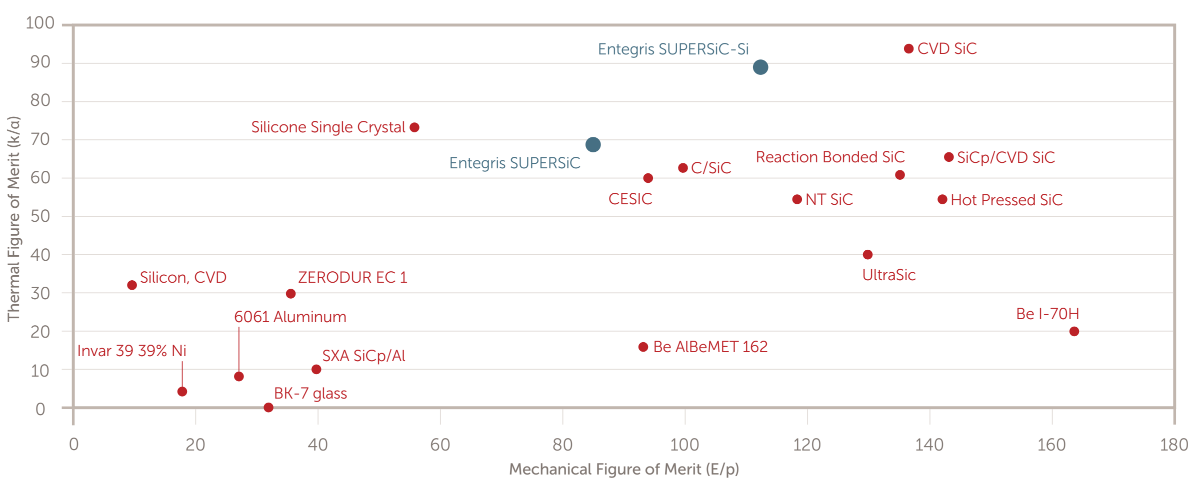


Figure 1. Figures of merit for satellite materials.

Surveying the material landscape to support these emerging requirements, silicon carbide (SiC) stands out as the leading candidate. For decades, SiC has been promoted for its outstanding performance,[5, 6, 7, 8] but limitations in manufacturability have kept costs high. Various forms of SiC have been evaluated for use in space optical systems, including powder forming, green sintering, chemical vapor deposition, and chemical vapor conversion processes.[5] Powder-based processes include slip casting of SiC slurries, sintered SiC pre-forms and cold isostatic pressing of SiC powder. Each technology entails shaping and then sintering to form the final silicon carbide article. Finished substrates made using these technologies have high density and strength, but their performance is limited by up to 20% sintering shrinkage, large minimum cross-section, and draft angle requirements. Chemical vapor deposition results in a very strong, high density, highly polishable material with excellent properties, but with high cost and limited design flexibility. The Entegris chemical vapor conversion process involves producing a special form of graphite designed specifically for conversion, and machining that graphite into light-weight shapes needed for optical structures. This process produces net-shaped, complex components at low cost because machining is performed in the graphite state. Mature joining technologies enable even greater shape-making capability and performance. This combination provides a cost-effective path to monolithic system architecture and ideal thermal matching, minimizing image distortion in any thermal environment.

While bulk mechanical stability is important, the critical optical surface also requires fidelity to figure down to fractions of the wavelength of light to achieve image quality and high resolution. To realize a reflective surface, a fully dense material must be applied to the mirror substrate. The combination of a porous or densified silicon carbide with a fully dense polycrystalline CVD SiC coating provides a substrate which can be optically polished, with a near perfectly matched thermal expansion coefficient. CVD SiC surfaces have been successfully polished to λ/50 (λ=632 nm) figure error,[9] yielding excellent image quality over a wide temperature range.[10]

Optics Materials

MATERIAL	DENSITY (ρ)	ELASTIC MODULUS (E)	THERMAL EXPANSION @ CA 293K (α)	THERMAL CONDUCTIVITY (κ)	MECHANICAL FoM (E/ρ)	THERMAL FoM (κ/α)
Borosilicate[7]	2.23 g/cc	63 GPa	3.3×10^{-6}/K	1.14[2] W/m•K	28 kN•m/g	0.36
Sintered SiC[11]	3.1 – 3.19 g/cc	420 GPa	2.0×10^{-6}/K	180 W/m•K	133 kN•m/g	90
CVD SiC	3.21 g/cc	466 GPa	2.2×10^{-6}/K	280 W/m•K	142 kN•m/g	65
Reaction Bonded SiC	2.89 g/cc	391 GPa	2.4×10^{-6}/K	155 W/m•K	135 kN•m/g	65
Entegris SUPERSiC®	2.55 g/cc	248 GPa	2.0×10^{-6}/K	158 W/m•K	97 kN•m/g	79
Entegris SUPERSiC®-Si	3.05 g/cc	330 GPa	2.3×10^{-6}/K	204 W/m•K	110 kN•m/g	88
Beryllium	1.85 g/cc	287 GPa	11.3×10^{-6}/K	190 W/m•K	155 kN•m/g	17
Zerodur®[12]	2.53 g/cc	91 GPa	-0.09×10^{-6}/K	1.64 W/m•K	36 kN•m/g	18
Aluminum	2.7 g/cc	68 GPa	23.6×10^{-6}/K	170 W/m•K	25 kN•m/g	7

Table 1.

Example Missions

GEOSTATIONARY ENVIRONMENTAL MONITORING SPECTROMETER

Space-based instruments offer an unparalleled technology for global scale environmental monitoring. The United States, Republic of Korea, and the European Union are developing a constellation of satellites aimed at monitoring atmospheric pollutants; the Tropospheric Emissions: Monitoring of Pollution (TEMPO), the Geostationary Environment Monitoring Spectrometer (GEMS), and the Sentinel 4 (S4), respectively. Ball Aerospace developed both the TEMPO and GEMS as "co-development" satellites. These instruments will be deployed over the United States, and much of Asia and Europe to monitor several species including nitrogen and sulfur oxides, ozone and light aldehydes, and atmospheric aerosols.[13]

The National Institute of Environmental Research, Republic of Korea launched the GEMS onboard the GK-2B satellite in late 2019. This spectrometer operates in the 300-500 nm range with spectral resolution of 0.2 nm.[6] Entegris SUPERSiC® lies at the heart of the fully deployed and operational GEMS and TEMPO satellite spectrometers as the primary collectors.

MULTISLIT OPTIMIZED SPECTROMETER (MOS)

A second proposed mission which incorporates SUPERSiC® material technology takes even greater advantage of the benefits of silicon carbide, being composed of multiple mirrors and a full structure bonded and assembled from silicon infiltrated SUPERSiC-Si. The NASA/Ball Aerospace Multislit Optimized Spectrometer (MOS) is a hyperspectral multiplexing instrument designed to remotely monitor coastal areas multiple times per day from a GEO orbit, while providing high resolution imagery in a challenging signal-to-noise ratio environment. The instrument was manufactured as a bench combined with six walls, all formed from Entegris SUPERSiC-Si and bonded into a rigid, lightweight structure with mounts and windows to accommodate instrumentation. The highly efficient architecture combines multiple slits into a single instrument, reducing the required aperture, volume, and weight to achieve the mission. Structural, thermal, and optical performance (STOP) analysis of the instrument successfully demonstrated excellent thermal stability. Vibration testing to launch loads is expected to move the spectrometer subassembly to a technology readiness level of 6 (TRL6). Design analysis indicates that the weight of a four-slit system can be reduced by two thirds when compared to a single-slit spectrometer. Optimal lightweight design, combined with world-class thermal stability will enable this compact instrument to achieve its mission while being launched as a hosted payload alongside a geostationary communications satellite, greatly reducing total cost.[14]

Figure 2. GEO-KOMPSAT 2B.[15]

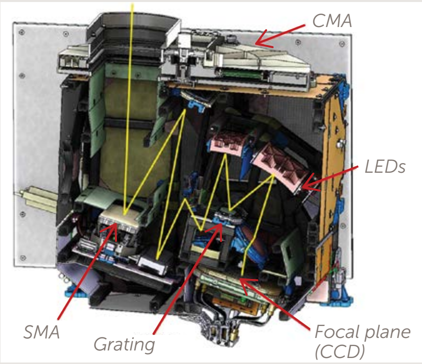


Figure 3. GEMS instrument x-section.[6]

Figure 4. GEMS scan mirror.[16]

Conclusion

Optical systems in space are becoming increasingly useful tools across a wide range of applications. As access to space becomes more affordable, increasing numbers of environmental, scientific, and commercial instruments are being envisioned and deployed. The missions those instruments pursue drive ever-increasing demands for image quality and economy, while the environments they inhabit challenge those demands. New materials, material combinations, and manufacturing techniques are being developed to meet those challenges, with variants of silicon carbide showing great promise for achieving performance and cost targets. Early mission successes using Entegris' SUPERSiC® portend a bright future for the technology.

References

[1] P. Oesch, B Robertson, UCSC; A. Field, Space Telescope Science Institute; https://www.nasa.gov/feature/goddard/2016/hubble-team-breaks-cosmic-distance-record.

[2] Iman Ghosh; *Exploring the Expanse: 30 Years of Hubble Discoveries;* Visual Capitalist, April 24, 2020; https://www.visualcapitalist.com/30-years-hubble-discoveries.

[3] https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health.

[4] spie.org, *Lasers Harken a Data Revolution for Space,* Johnson-Groh, 2021; https://spie.org/news/photonics-focus/janfeb-2021/lasers-harken-data-revolution-for-space?SSO=1.

[5] John S. Johnson, Kevin D. Grobsky, and Don Bray *Rapid fabrication of lightweight silicon-carbide mirrors,* Proc. SPIE 4771, Optomechanical Design and Engineering 2002, (9 September 2002).

[6] Won Jun Choi, Kyung-Jung Moon, Jongmin Yoon, Ara Cho, Sang-kyun Kim, Seounghoon Lee, Dai, ho Ko, Jhoon Kim, Myung Hwan Ahn, Deok-Rae Kim, Sang-Min Kim, Ji-Young Kim, Dennis Nicks, Jeong-Su Kim, *Introducing the geostationary environment monitoring spectrometer,* J. Appl. Remote Sens. 12(4), 044005 (2018).

[7] L. Feinberg et al., *Space telescope design considerations,* Opt. Eng. 51(1), 011006 (2012).

[8] Fang Jiang, Yan Liu, Yong Yang, Zheng-Ren Huang, Dan Li, Gui-ling Liu, Xue-Jain Liu; *Research Progress of Optical Fabrication and Surface Microstructure Modification of SiC,* Journal of Nanomaterials, Volume 2012, Article ID 984048.

[9] J. Kong and K. Young, *Super Polishing of SiC Aspheric Optics,* in Imaging and Applied Optics Technical Papers, OSA Technical Digest (online) (Optical Society of America, 2012), paper OW1D.3.

[10] Jitendra S. Goela, Michael A. Pickering, Raymond L. Taylor, Brian W. Murray, and Arthur Lompado, *Properties of chemical-vapor-deposited silicon carbide for optics applications in severe environments,* Appl. Opt. 30, 3166-3175 (1991).

[11] NASA Science: Solar System Exploration; Feb 24, 2009; https://solarsystem.nasa.gov/news/307/galileos-observations-of-the-moon-jupiter-venus-and-the-sun/.

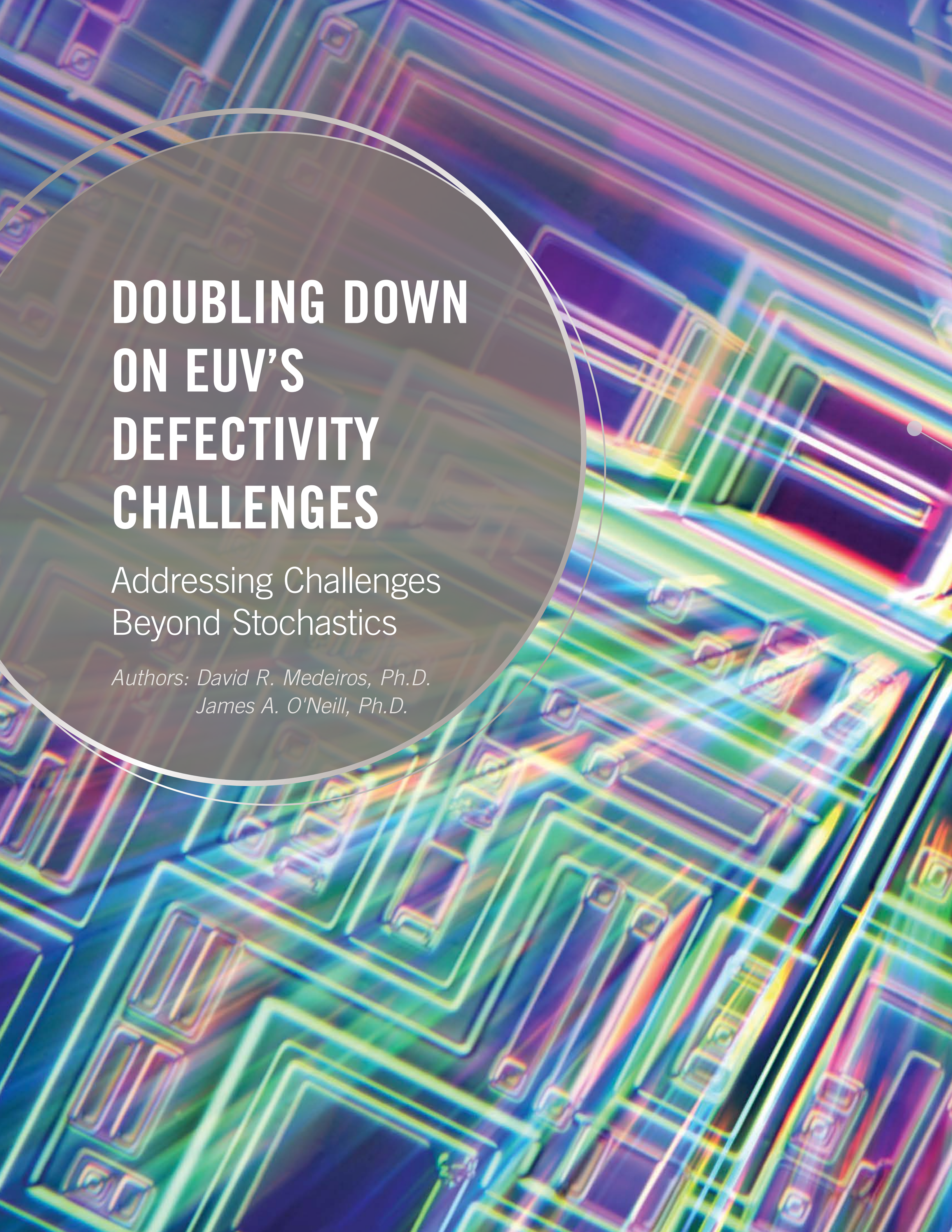
[12] Zerodur® is a registered trademark of Schott Glass Co.

[13] 33rd Space Symposium, Technical Track, Colorado Springs, Colorado, United States of America Presented on April 3, 2017.

[14] William S. Good, Tim Valle, Curtiss O. Davis, Nicholas Tufillaro, Peter Spuhler, Chuck Hardsety, Conor Staples, *Miltislit optimized spectrometer: flight-like environment test results,* Proceedings of SPIE, Volume 9222.

[15] Korea Aerospace Research Institute (KARI); https://www.kari.re.kr/eng.do.

[16] Used with permission; Ball Aerospace; https://www.ball.com/aerospace/programs/gems.



DOUBLING DOWN ON EUV'S DEFECTIVITY CHALLENGES

Addressing Challenges Beyond Stochastics

Authors: David R. Medeiros, Ph.D.
James A. O'Neill, Ph.D.

Background

Beyond the "traditional" challenges posed by node-to-node density scaling, including finer resolution, tighter process tolerances, ever-narrowing control over sources of defectivity, and a general reduction in all sources of variability, the rapid adoption of EUV technology for patterning in the sub-7 nm era imposes at least two additional hurdles. These include the impacts of sub-optimal pellicles for photomasks and the increased influence of stochastic error in the imaging process. To augment the progress in developing solutions to mitigate these added challenges, it is also necessary to "over-achieve" on the standard sources of variability, especially defectivity that can be mitigated. Most notably, cleanliness in mask storage and handling must be taken to a new level as some manufacturers enter high-volume manufacturing without pellicles while technologists continue to pursue better candidate pellicle materials. Similarly, the cleanliness of all chemicals used in resist processing must also be improved via filtration and purification as chemical suppliers drive to innovative, unconventional solutions like metal oxide resists that help address stochastic variation. Even more disruptive is the advent of dry resists that avoid all liquid processing in both coating and development, overcoming the stochastic defects and diffusion-based limitations of conventional materials. A holistic view of lithographic defectivity illustrates the challenges and opportunities the long-awaited EUV era provides.

The Convergence of the EUV and Automotive Eras

Despite the nay-sayers who have repeatedly declared "Moore's Law is dead!", semiconductor manufacturers have made progress to create ever-smaller circuitry. As the industry advances into the single-digit nodes, among the technical breakthroughs that have brought about this near continuum of device scaling are new metallurgy, innovative gate stack materials, novel device architectures, and increasingly complex patterning schemes. All have enabled the continuation of Moore's Law.[1] Despite the advancements, some fundamental challenges continuously present themselves and only become exacerbated at the smallest dimensions, perhaps most notably, variability. Process inhomogeneities, temporal fluctuations in tool performance, and, of course, random defectivity from undesired species, are perpetual hurdles that need to be addressed before achieving and sustaining robust manufacturing yields. Defectivity is especially challenging in the patterning area where the onset of EUV lithography has enabled the progression to sub-30 nm pitch features, albeit with the onset of increased impact of stochastic imaging defects. Such defects, attributable to the random nature of traditional multi-component chemically amplified resists and the relatively low photon flux for a given exposure dose inherent with exposure at this high energy wavelength of 13.5 nm (~92 eV), present an added obstacle to be addressed while simultaneously maintaining critical dimension precision and image placement, or overlay, control.

Therefore, it is natural to look to drive all other "conventional" sources of defectivity – those not attributable to the stochastic nature of the imaging process – to as low a level as possible, and nominally to zero. In fact, in all practicality, the industry needs to drive beyond current defect detection limits to attain the levels being driven by the most stringent reliability specifications, namely those of the automotive industry. The "zero defects" target has become more than an aspirational mantra as we consider the implications and requirements of automation-assistance in current vehicles and the ultimate move toward fully autonomous driving.[2,3] Instead, zero defects have become an expectation of the end-user and a requirement for the industry. As such, the expectation for both the semiconductor manufacturer as well as the supplier of all comprising materials is to eliminate, in their entirety, all extrinsic defects. The onus on the materials supplier is accordingly also being cascaded to their suppliers, creating a high-value quality supply chain environment.

The Evolution of EUV

Extreme ultraviolet (EUV) lithography has been in the development phase for decades and was perpetually cast as the "next generation lithography," or NGL, solution to enable extension of scaling consistent with Moore's Law. However, this revolutionary technology was beset with significant technical challenges that delayed the adoption for high volume manufacturing until relatively recently. The challenges posed by EUV included 1) the availability of a reliable high-power source of 13.5 nm photons, 2) suitably robust resist materials that could achieve the resolution, image quality, and photo speed requirements, and 3) advances in mask making and characterization, to name the most evident. The results of the combined efforts of the industry have resulted in the adoption of EUV for the 7, 5, and 3 nm logic nodes and beyond by some of the industry's leading semiconductor chip manufacturers as well as adoption more recently for advanced DRAM applications. The accelerated pace at which EUV is being inserted into high-volume manufacturing, as shown in Figure 1, poses new challenges, especially considering that the dimensions of the next targeted nodes are beginning to approach the limits of single exposure for EUV. Double-patterning EUV may be required as a bridging solution until high numerical aperture (NA) EUV is available for deployment in high volume manufacturing in ~2025.

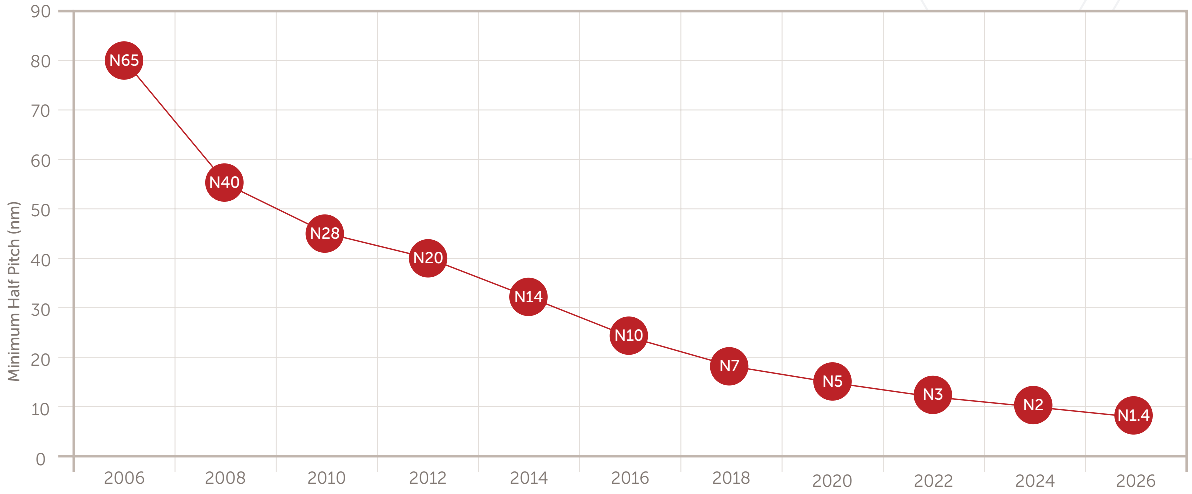


Figure 1. Approximate scaling roadmap of advanced logic offerings showing sustainment of Moore's Law through the 1.4x node (N1.4).

Thus, we are currently experiencing a confluence of two paradigm shifts in the semiconductor industry:

1. the unprecedented demand for the tightest reliability tolerances driven by automotive specifications, which mandate the zero-defect initiative, and
2. the long-awaited adoption of EUV lithography for high-volume manufacturing in advanced logic and DRAM nodes.

When coupled with the ever-increasing overall demand for semiconductors resulting from the digital transformation currently so prevalent in virtually all aspects of society, these dramatic shifts significantly raise the bar for reduction of all sources of variability and more robust defectivity mitigation strategies.

EUV Stochastics

As the industry progresses toward ever-smaller features, of particular concern are stochastic defects inherent in EUV imaging. Stochastic defects are broadly defined as random errors that are induced by the imaging process itself.[4] That is, they are to be differentiated from traditional causal sources of patterning defects such as those induced by microcontamination in photoresist or other processing media, airborne contaminants that can compromise imaging, particulates or haze in photomasks, and aberrations in the optical path or topography or backside contamination induced focus or overlay shifts. Stochastic defects are instead classified as a printing failure that is unexpected due to the random nature of the imaging process. While there is inherent randomness in all lithographic imaging processes, such as the composition of multicomponent photoresists and the diffusion and reaction propagation that ensue upon exposure, the high-energy nature of EUV photons make this technology more susceptible to stochastics. This is especially important when the feature size being imaged approximates the sphere of influence of individual photon-initiated events.

Relative to photons of 193 nm wavelength as in ArF immersion lithography, EUV photons are more than 14 times more energetic. This means that for a comparable dose and an equivalent volume element, or voxel, of imaging material, there are ~14.3 fewer photons. The scarcity of photons as nodes scale to finer dimensions is illustrated in Figure 2. This graph plots the calculated photons for a voxel representative of a typical line-end of a patterned line/space at the minimum feature size for each node, each at a constant aspect ratio of 2.2 and an exposure dose of 30 mJ/cm². Thus, as we scale from the 7 nm node (N7) to the 1.4 nm node (N1.4), we are reliant on less than half as many photons to define the patterned line-end. Therefore, as scaling proceeds, imaging is significantly more susceptible to the impact of an errant photon inducing unwanted photochemistry or conversely, not interfering the desired photochemical event. A more rigorous treatment of "photon counting" and the confluent effect of the randomness inherent in multicomponent chemically amplified resists (CARs) is available in the literature.[5]

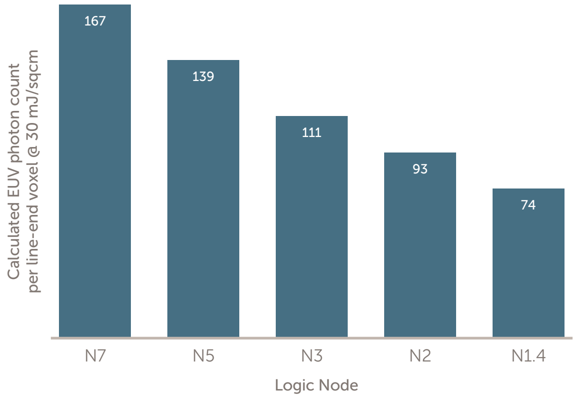


Figure 2. Calculated EUV photon count per line-end voxel for logic nodes at targeted minimum feature size with a constant aspect ratio (2.2) and exposure dose (30 mJ/cm²).

However, stochastic effects are only one source of defectivity in EUV lithography. EUV is susceptible to all the traditional sources of defectivity and, again, by nature of the scaling, the historical node-to-node improvements need to be advanced at an even higher rate to attain defect densities necessary for high-yielding processes. Additionally, the industry is also approaching another inflection point, in that detection limits of defects, both from their source or how they manifest on the wafer, are being pushed to the full capability. With the growing importance of long-term reliability in semiconductors, such as those used in control and navigation in autonomous driving or in medical diagnostics and treatment, latent defectivity that is not detectable by conventional metrology techniques or yield screening is becoming increasingly intolerable. It is necessary to no longer scale defect densities at the historical trends but rather to over-achieve on these traditional sources to account for the advent of the impact of stochastics, as well as the limits of conventional detection techniques. By exploring the current trends of mitigation against resist-based, airborne, and mask-originated defect sources, approaches for "non-linear" defect control are proposed to extend EUV lithography to 2 nm node and beyond.

Addressing Resist Defectivity Through Advanced Filtration

For multiple generations of technology, the importance of tight control over resist contamination via point-of-use (POU) filtration and the subsequent impact on improved device yield has been an area of high activity in semiconductor manufacturing. Continuous improvement in separation media, porosity scaling, and keen insight into the interactions with photochemistry, have led to sub-1 nm filtration of highly engineered membrane materials that afford the high yielding processes the industry has come to expect and rely upon.[6,7] Figure 3 shows the various mechanisms of defect entrapment that have been engineered into advanced filtration solutions for final POU photoresist filtration. Furthermore, the importance of filtration and purification of the upstream components of the photoresist formulation and the tight tolerances for unwanted metallic species or other impurities have proven to make the difference in the materials selection for high-performance applications.

Bottom antireflective coatings, or BARCs, have long been a mainstay for reflectivity control for KrF and ArF/ArFi patterning. Additionally, the ubiquitous use of multilayer patterning to allow for thin film imaging with both ArFi and EUV lithography have brought about a deluge of new materials, each requiring filtration solutions. Whether they are spin-on-carbons (SOCs), spin-on-hardmasks (SOHs), and organic planarizing layers (OPLs), or spin-on-glasses (SOGs) and silicon-containing antireflective coatings (SiARCs), or conventional organic BARCs, each innovative material introduced to solve a patterning challenge, in turn, introduces a potential source of defectivity and, thereby, requires a filtration solution. While with older generations of technology, traditional scaling of pore size leading to more effective sieving provided suitable filtration solutions, advanced nodes require tailoring of membranes to accommodate specific contaminants, whether they're metallic species, inorganic anions, or organics such as oligomers or high molecular weight fractions of resist polymers. Customization by nature of membrane composition, or specialized surface modification, allows for selective removals of the undesirable species.[7] Increasingly, resist suppliers and end-users are moving toward serial filtration involving specifically selected media and porosity in discrete filter housings to allow for maximum efficacy of all unwanted contaminants. The drive toward a true "zero defects" state for patterning requires that all sources be addressed.[8] The growing trend toward filter customization to address specific species is expected to grow in coming years.

Metal Oxide Resists: A Remedy for Stochastics?

In the last decade, entirely new resist systems have been developed to both avoid some of the random nature of the multicomponent CARs, while simultaneously increasing the photochemical capture of the scarce EUV photons by taking advantage of materials with a high absorbance cross section at 13.5 nm.[9] Through several generations of development of metal oxide resists, or MORs, high resolution with low degree of variability has been demonstrated. These systems employ a spin-cast film of nanoparticles of metal oxide precursor comprising a photosensitive ligand. Upon exposure, this photosensitive ligand is cleaved to leave hydroxyl moieties that subsequently condense to form a metal oxide network, rendering the exposed film insoluble in developer. Thus, a negative tone image is formed, with the unexposed regions being readily soluble. The discrete nature of the elements of the MOR allow for high resolution, and the strong absorbance of the metallic species afford an enhanced capture and, in turn, relatively low photospeed. Of course, as with CARs, MORs also require a suitable filtration scheme as they too are subject to extrinsic defectivity. It's been found that careful selection of the membrane, porosity, and specific surface modification can afford defectivity comparable to that of CARs.

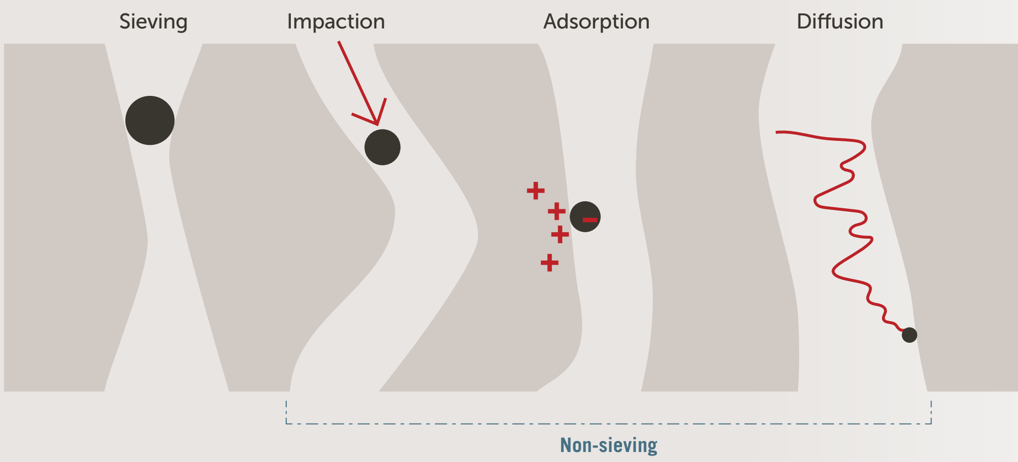


Figure 3. Retention mechanisms employed in resist filtration via targeted membrane selection. (Used with permission.[7])

An alternative approach to MORs that take advantage of the discrete nature of the MO precursor and the high absorbance cross section are the recently reported dry resist systems.[10] Researchers have taken a novel approach and completely removed all solution-based processing from the lithographic process. That is, rather than a spin-cast film, the resist is applied via a "dry" chemical vapor deposition (CVD). Instead of a solution-based developer, the three-dimensional image is created directly via dry reactive ion etching (RIE). The benefit of the "all-dry" process is the avoidance of the diffusional effects that can be a source of variability in conventional photolithographic processing. While such systems are relatively new to the industry, they are garnering significant interest to help address stochastics, particular for sub-3 nm nodes.

Mask Contamination: The Killer Defect

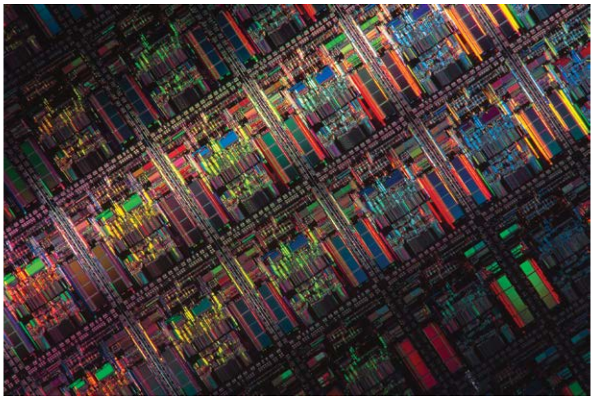
As problematic to yield as resist contamination can be, defects borne from particles or degradation of a photomask, or reticle, can be catastrophic, since a single "killer" repeater defect can cause a non-yielding chip in each impacted field on multiple wafers or multiple lots of wafers. The economic impact of a single defect cannot be overstated. Therefore, chip manufacturers go to great lengths to ensure that reticles remain in pristine condition throughout their useful lifetime in the fab, including during transport to the fab and through multiple lithography scanners. Again, the stakes for EUV are even higher than with DUV lithography, as not only are the critical dimensions of the printed features smaller, only recently have manufacturing-worthy pellicles been introduced to high volume manufacturing. Preventing contamination of reticles is highly dependent on the protocols for transport, inspection, cleaning, and usage within the factory as well as the storage containers in which they are housed when not in use. The use of a dual-pod system comprised of an inner metal pod that securely holds the reticle in place providing protection from shock during movement, and a plastic outer pod that interfaces with existing factory infrastructure, has proven to be the industry-standard ensuring long usable lifetimes for these expensive reticles.[11] This pod-within-a-pod design provides a highly effective barrier to particulates, airborne contamination, moisture, electrostatic discharge, and other sources of potential contamination or degradation. The form factor of dual-pod system is available for both reticles that use pellicles as well as those that do not.

While reticle pods are essential for extended lifetime and storage of EUV photomasks, pellicles form the last line of defense. The challenge for selecting a material of construction for an EUV pellicle requires that the material be highly transparent at 13.5 nm, durable enough to withstand repeated exposure on 92eV photons without perturbation of its optical and mechanical properties, and able to be fabricated into a uniform film capable of mounting onto a full area of a reticle. Recall as well that as EUV masks are reflective, the radiation passes through the pellicle twice, in contrast to transmissive DUV masks, where light passes through just once. Development of polysilicon pellicles has reached a state where it provides upwards of 90% transmission of EUV and suitable durability, and manufacturability is considered a viable solution for high volume manufacturing. Polysilicon pellicles are being readily adopted for use in today's 0.33 NA EUV systems. However, the source power scaling roadmap suggests the need to raise source output to >500 W, and a new material will be required to withstand cumulative exposure doses in the ranges being projected.

Researchers at imec have reported on the use of carbon nanotubes (CNTs) for a next generation EUV pellicle.[12] CNTs can be made into a relatively high porosity film of considerable strength that has proven to effectively prevent particulates from reaching the reticle surface. The high porosity affords excellent transmission at 13.5 nm, exceeding 95%.[12] While CNTs have the mechanical integrity and optical properties to make them strong candidates, they do experience a degree of degradation in the presence of the low levels of hydrogen gas in the EUV system. As such, current focus is on post-processing of CNTs to make them a viable candidate for high NA EUV.

Conclusions

The near simultaneous adoption of EUV lithography for advanced node semiconductor manufacturing and the advent of the automotive specifications for reliability and zero defects have posed an extreme set of challenges for variability reduction and contamination control. Stochastic imaging defects become impactful at fine critical dimensions and with the use of high energy EUV, driving a required "over-achievement" in other sources of defectivity. Advances are required in resist filtration, stochastic-tolerant resist systems, and mask defect prevention, all of which need to seamlessly dovetail into the EUV ecosystem, which is highly dependent on these solutions. A comprehensive approach as afforded by the extensive portfolio of Entegris offerings is necessary to enable implementation of high NA EUV systems with high power sources to further sustain scaling at a historical pace and meet the needs of the automotive era.



References

[1] *International Roadmap for Devices and Systems (IRDS™) 2020 Edition,* IEEE publication (2020)

[2] *Automotive Zero Defects Framework,* Automotive Electronics Council: AEC-Q004, (2020)

[3] A. Aal, J. Braggin, A. Amade, M. Puttock, *Addressing Weak Links in Automotive Reliability Semiconductor Contamination Control, Inspection and Test,* 2020 IEEE International Integrated Reliability Workshop (IIRW), (2020)

[4] P. DeBisschop and E. Hendrickx, *Stochastic Printing Failures in EUV Lithography,* Proc. SPIE, 10957 (2018)

[5] W. D. Hinsberg, G. M. Wallraff, M. I. Sanchez, N. Megiddo, O. Kostko, *Contribution of EUV resist counting statistics to stochastic printing failures,* J. of Micro/Nanopatterning, Materials and Metrology, 20, (2021)

[6] *EUV Enablement: Solving Defect Challenges in the EUV Process,* Entegris white paper, (2020)

[7] Kohyama, F. Kaneko, A. Gjoka, J. Jaber, *Bridging the Defect Gap in EUV Photoresist,* Proc. SPIE, 10960, (2019)

[8] B. Tufts, *Trends and Observations in Materials Quality at Advanced Process Nodes,* Strategic Materials Conference Korea (2021)

[9] J. Stowers, J. Anderson, B. Cardineau, B. Clark, P. DeSchepper, J. Edson, M. Greer, K. Jiang, M. Kocsis, S. Meyers, A. Telecky, A. Grenville, D. DeSimone, W. Gillijns, G. Vandenberghe, *Metal Oxide EUV Photoresist Performance for N7 Relevant Patterns and Processes,* 9779, (2016)

[10] R. Wise, *Breaking Stochastic Tradeoffs with a Dry Deposited and Dry Developed EUV Photoresist System,* Proc. SPIE, 11612, (2021)

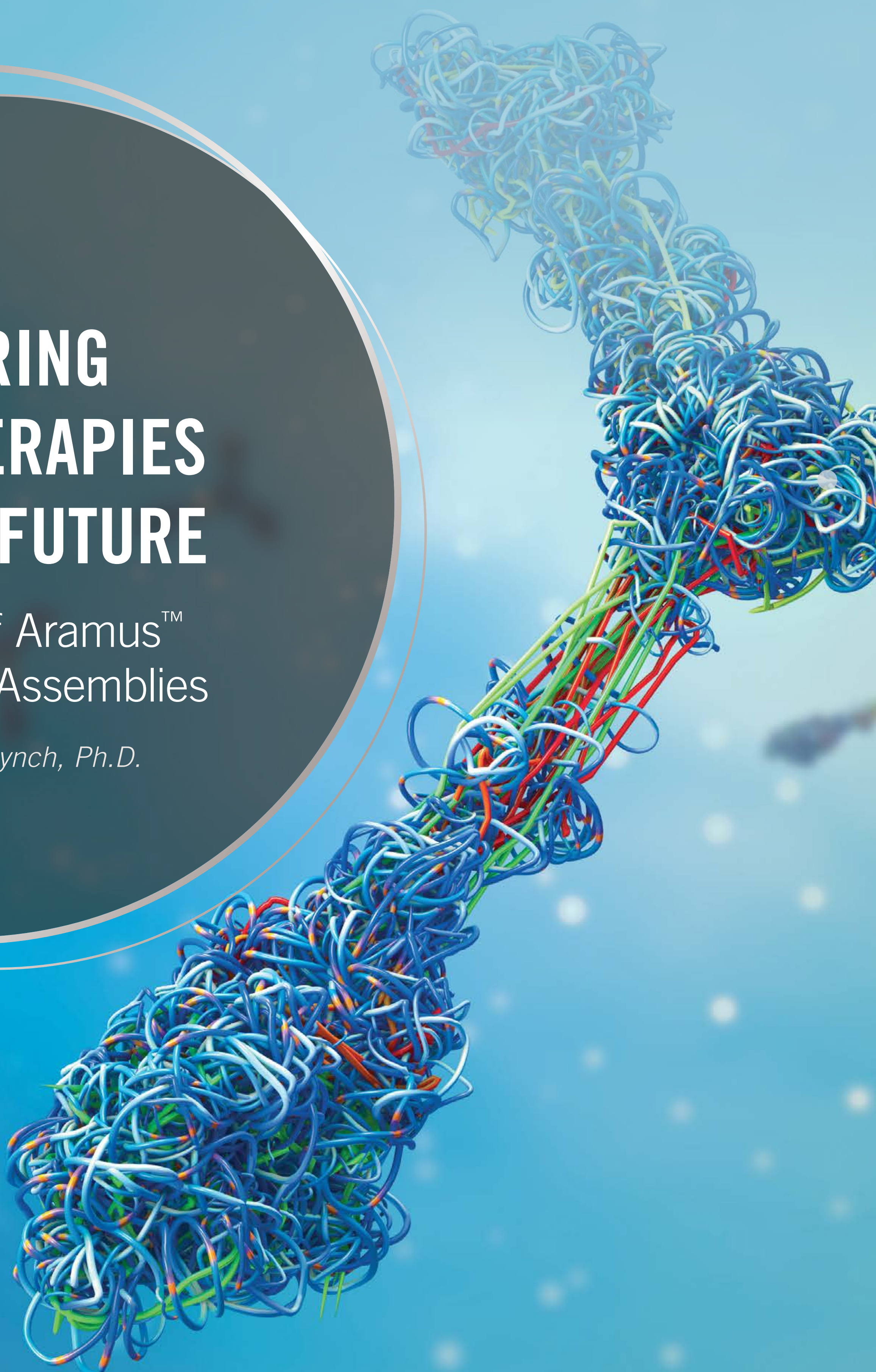
[11] *Enabling Advanced Lithography: The Challenges of Storing and Transporting EUV Reticles,* Entegris white paper, (2019)

[12] E. Gallagher, M. Y. Timmermans, I. Pollentier, J.U. Lee, M. Mariano, C. Adelmann, C. Huyghebaert, F. Scholze, C. Lambis, *CNTs in the Context of EUV Pellicle History,* Proc. SPIE, 10583, (2018)

DELIVERING THE THERAPIES OF THE FUTURE

The Role of Aramus™ Single-use Assemblies

Author: John B. Lynch, Ph.D.



COVID-19 Accelerates Expansion into Life Sciences

Several years ago, Entegris' leadership team recognized the potential application of its process capabilities developed for leading semiconductor manufacturers to the life sciences industry. Both industries require some of the most advanced manufacturing capabilities in the world. Both industries require high-purity specialty chemicals and materials; specially designed systems for fluid management, storage, and transport; and the strict control of particles to prevent contamination.

For different reasons, both industries have an intense focus on eliminating process variation during production. In the case of semiconductors, manufacturers need to ensure the reliability and performance of the integrated circuits they produce while also achieving high yields. In life sciences, the objective is to increase efficacy and to prevent toxic side effects. In life sciences, validation also is critical.

While the desired results differ, process control is the means for achieving the necessary results in both industries, especially in the life sciences segment of bioprocessing where the process is the product.

Aramus 2D single-use assembly.

Entegris' World-Class Technologies Include:

Liquid Packaging

We provide innovative, safe, high-purity liquid packaging and delivery systems, designed to maintain the safety, reliability, and integrity of biopharmaceutical products. Along with liner-based systems that ensure safe transport, containment, and dispense of process fluids, we offer a number of containment solutions for stationary and mid-range mobile applications.

Single-Use Assemblies

Our single-use assemblies provide purity with faster time-to-market while protecting process quality, efficacy, and efficiency. From the early stages of R&D to the final filling stage, we deliver high performing, inert, and low extractables and leachables (E&L) solutions for single-use and full-scale processes. Our solutions make it possible to safely transport, store, and dispense reagents and solvents for DNA, peptide and protein synthesis, active pharmaceutical ingredient (API) manufacture, and fermentation.

Fluid Management

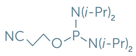
For decades, we have been ensuring materials integrity with quality fluid management systems and related services to the semiconductor and chemical processing industries. With this expertise, we offer nonmetallic solutions that meet the needs of biopharmaceutical as well as bulk and finishing pharmaceutical industries, specifically for steam-in-place (SIP) and clean-in-place (CIP) applications.

Filtration and Purification

Our advanced materials technologies enable us to deliver high-purity and validated products that achieve reliable performance. We manufacture leading-edge polymeric membranes and sterile filtration cartridges for a wide range of life sciences and pharmaceutical applications including buffer and intermediate filtration.

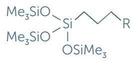
Particle Characterization

Subvisible particle detection is a critical challenge faced by companies developing and manufacturing parenteral drugs. Our particle characterization solutions enable customers to perform single or automated tests on parenteral drugs following USP <788>, therapeutic proteins per USP <787>, ophthalmic solutions per USP <789>, and lipid emulsion per USP <729>.



Organophosphorus and Fine Chemicals

For small molecule and oligonucleotide based pharmaceutical actives, we excel in the development, scale-up, and manufacture of high-quality intermediates, phosphorylating agents, key synthesis reagents, phosphine ligands, and catalysts. We provide creative solutions including options for custom synthesis, specifications, packaging, and delivery logistics.



R = halogens, NH_2, amides, NCO, acryloxy

Organosilanes and Other Specialty Chemicals

Utilizing our 40 years of specialty chemical expertise, we partner with a range of companies from novel contact lens manufacturers to wound care companies to prominent global life sciences businesses. Our best-in-class chemical competencies include unique monomers and polymers, organosilicon compounds and methacrylates, and stable isotope labeling. Custom synthesis is available and we can tailor chemicals to a customer's exact specifications.

It is this rigorous focus on process capabilities in the fabrication of semiconductors that created an opportunity for Entegris in the production of pharmaceuticals for the life sciences industry. Today, Entegris is playing a crucial role in the development and manufacture of therapies for COVID-19 and is a key supplier of the Aramus™ single-use high purity assemblies to some of the major companies working on and distributing vaccines.

Like Entegris' semiconductor customers, our pharmaceutical customers rely on our state-of-the-art global supply chain. We leverage our global infrastructure with regional R&D and manufacturing facilities to address specific customer needs with customized applications and solutions. Through a highly collaborative customer engagement model, we gain a clear understanding of each customer's unique challenges. From small to large molecule drug manufacturing, we work to reduce the risks associated with a complex manufacturing process and to deliver world-class quality with reliable batch-to-batch consistency.

Biotherapeutics and Bulk Drug Storage and Transport

The dominance of biologics on the top pharmaceutical drug blockbuster list is evidence of the therapeutic success and rapid growth of biologics.[1] The COVID-19 pandemic is a powerful example of how important biotherapeutics are for treatment of the virus and, ultimately, prevention through the availability of vaccines.

The overall process to produce biotherapeutics has three main steps:

1. Upstream, which includes growing the therapeutic in a bioreactor
2. Downstream, which includes several purification steps
3. Final fill, in which the bulk drug is transferred into vials or syringes for distribution of the actual drug product

Biopharmaceutical therapy development and manufacture is proliferating because of scale-up in biosimilars and scale-out in emerging cell and gene therapies. This requires successful distribution between process sites from where purification is completed to the site where final fill of the drug product is performed. These steps are often decentralized for added manufacturing flexibility, since final fill and finish processes are not bound by time-dependent active pharmaceutical ingredient (API) product factors and can therefore be utilized at a higher rate than API production processes.

As the global clinical pipeline expands with more complex and temperature-sensitive products, the distribution of high-value APIs between development sites, clinical sites, and drug manufacturers for further processing will become a more relied upon paradigm. This is the case in the ongoing race to develop treatments for COVID-19, which requires a temperature-controlled distribution network that can quickly scale up to meet huge demands. Over the 2018 – 2024 period, cold chain products are expected to grow at nearly twofold the rate of non-cold chain.[2] As cold chain grows, effectively managing and mitigating its associated risks will be critical.

Cold chain consists of the freezing of heat labile APIs to below subzero temperatures for storing and transporting the frozen product followed by thawing for subsequent manufacturing and production. The current implementation of single-use technologies (SUT) is reducing operating costs and mitigating the contamination risk of traditional stainless-steel freezing tanks and bottles through batch flexibility, lower storage density, and controlled freezing – all in a sterile closed system. However, under frozen temperature, these polyolefin single-use components are brittle and prone to failure that can lead to product loss and contamination.

In addition, transport presents significant risk – it is the only part of the production process that is outside of the manufacturer's process control. Even within the cold chain end-to-end process (Figure 1), the frozen distribution of product is where significant failure can occur from various unknown mechanical and thermal shocks experienced along its route. Mechanical damage typically results in 3–5% product loss from bag breakage in frozen bulk drug cold chain handling, and most pharmaceutical end users see temperature excursions in their shipments. Forty-three percent of those end users see excursions that exceed four degrees, which is enough to harm their product.[3]

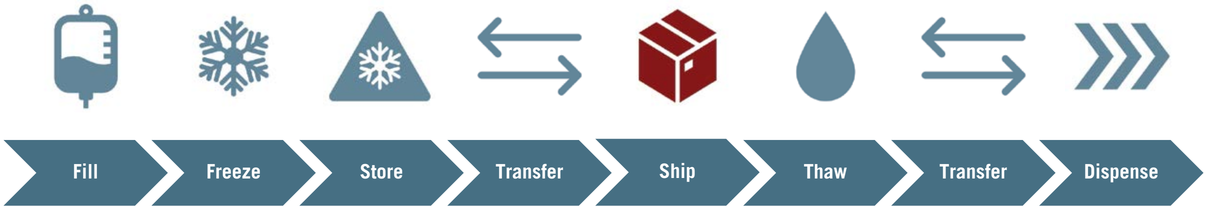


Figure 1.

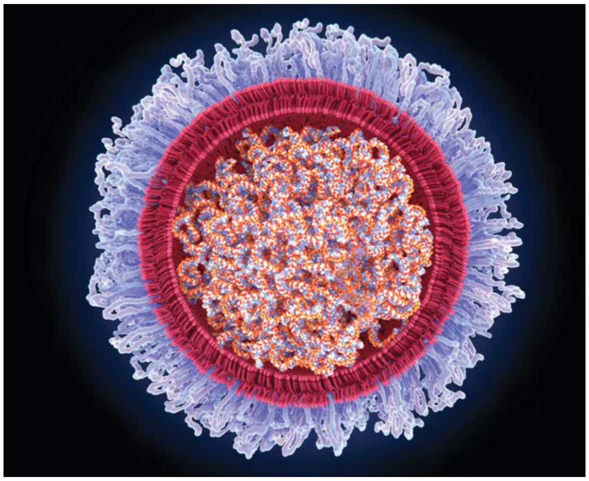
To further quantify this impact, the industry sees a $35 billion loss annually from failures in temperature-controlled logistics.[4] It is vital then, to have a single-use product packaging system that functions under these conditions. However, these systems are often not appropriately qualified to avoid failure or maintain temperature because their challenging distribution environments are not fully understood. Fortunately, the risks of single-use bags in frozen shipping can be mitigated by following the approach of:

- Employing sensors for monitoring critical shipment parameters
- Utilizing more suitable low-temperature materials and packaging
- Qualifying and evaluating through simulated standards and testing in real-world transit lanes

Implementing these guidelines increases visibility into the distribution lane, incorporates robust materials, and qualifies them against relevant metrics to ensure consistent product quality in cold chain.

Collaborating with Life Sciences Customers to Deliver the Therapies of the Future

Entegris' innovation, manufacturing excellence, and commitment to quality and leadership in purity are valued in the life sciences industry's race to deliver a global supply of vaccines for COVID-19. Similarly, we expect our high-purity bags like the Aramus assemblies that are ideal for freezing, transporting, storing, and thawing drug substances will be key to the therapies of the future.



COVID-19 mRNA vaccine.

These will include biologics and cell therapies as well as traditional and mRNA vaccines. We are excited and optimistic about the role that our broad portfolio will play as we continue to collaborate and partner with customers to solve the most demanding manufacturing challenges in the evolving life sciences industry.

References

[1] Stephanie Yip, *Top 10 Best-Selling Drugs of 2019,* https://pharmaintelligence.informa.com/resources/product-content/top-10-best-selling-drugs-of-2019.

[2] Basta N., Lipowicz M., *2020 Biopharma Cold Chain Sourcebook,* 11th Edition, Pharmaceutical Commerce.

[3] *2019 Biopharma Cold Chain Logistics Survey,* Pelican Biothermal.

[4] QVIA Institute for Human Data Science.

Innovation Through Creativity and Collaboration

~2,600
registered, live patents

~1,100
pending patent applications

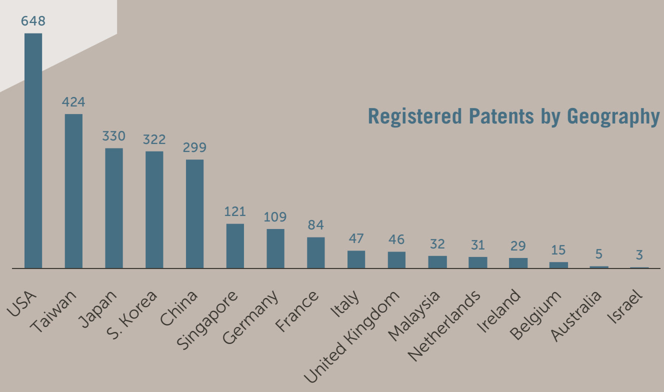
~29
Third party collaborators, some intellectual property is exchanged

200 inventors from **7** countries contributed to portfolio in 2020

Actively license and monetize dynamic global patent portfolio

Entegris

Patent Portfolio



Global R&D and Tech Centers for Collaborative Customer Engagement

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Dr. O'Neill joined Entegris in 2012 and now serves as chief technology officer. In that role, he leads Entegris' innovation process directing the development of new products and a global network of technology centers where Entegris' engineers and scientists collaborate with customers to develop solutions to their most advanced technical challenges. Prior to Entegris, Jim led several semiconductor technology development programs at IBM.

Wenge Yang, Ph.D. | Vice President, Market Strategy

Article: Enabling the Smartphone Evolution – 10 years on the Leading Edge of Technology

Dr. Yang joined Entegris in 2012 to lead the company's market strategy. In his role, he is responsible for product and market strategy, market research and market trend analysis, strategic marketing, and maintenance of the company's strategic technology roadmap. Prior to joining Entegris, Wenge was an equity research analyst at Citigroup covering the semiconductor equipment and materials sector. He also served in various executive roles at Advanced Micro Devices and Tokyo Electron.

Jennifer Braggin | Divisional Communications Manager – Microcontamination Control

Article: Advancing Autonomous Electric Vehicles – Smart Materials and Detailed Unit Process Design Become Key Drivers

While holding various roles in technical marketing and engineering management at several companies, Ms. Braggin's career has focused on improving manufacturing yields, enhancing training efforts, and communicating technical achievements to international customers and partners. A life-long learner, Jennifer is also a lecturer at the Gordon Institute at Tufts University where she oversees the engineering management minor and teaches engineering management and leadership courses.

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Article: Advancing Autonomous Electric Vehicles – Smart Materials and Detailed Unit Process Design Become Key Drivers

Dr. Puttock has worked in the semiconductor industry over 30 years. With a broad understanding of technology trends, Mark collaborates with Entegris' global product development teams to develop timely and differentiated new materials and components for the world's leading semiconductor manufacturers.

Montray C. Leavy, Ph.D. | Deputy Chief Technology Officer

Article: From Prototype to High Volume Manufacturing – Entegris' AM Journey

Dr. Leavy is based in Singapore and leads the advanced technology engagement team, which is responsible for creating and implementing technology roadmaps while ensuring alignment with customers' new product initiatives and industry trends. The team also identifies and implements new technologies and capabilities to achieve Entegris' future technology objectives. Earlier in his career, Montray served as vice president of account technology at ATMI where he delivered tailored materials solutions for customers' most critical technology processes.

Subhash Guddati | Technology Director, ATE, Office of the CTO

Article: From Prototype to High Volume Manufacturing – Entegris' AM Journey

Mr. Guddati has 18 years of experience in product development, process improvement, and program management in R&D and manufacturing environments. He has notable achievements in data storage (hard disk drives) and additive manufacturing. Subhash has a keen eye for integrating emerging technologies like additive manufacturing, digital threads, and blockchain technologies for product development and manufacturing processes. His current responsibilities focus on expanding Entegris' R&D capabilities in Singapore.

Wayne Hambek | Director, Industrial Project Management – Specialty Chemicals and Engineered Materials

Article: State-of-the-Art Space Optics – Innovative Materials for a Challenging Environment

Mr. Hambek has been involved in developing new products and new markets for Entegris' SCEM division for over eighteen years. He has successfully introduced products in diverse fields including jet engine components, biomedical implants, and alternative energy and has been instrumental in the optics community's development of best-in-class components and systems. Wayne serves as one of three Entegris representatives to the Center for Freeform Optics, a government-university-industry collaboration focused on advancing state-of-the-art optics technology.

Troy Scoggins, Ph.D. | Director, Technology – Specialty Chemicals and Engineered Materials

Article: State-of-the-Art Space Optics – Innovative Materials for a Challenging Environment

Dr. Scoggins has over 23 years of experience with Entegris in scientific and technical leadership roles focused on silicon carbide and graphite technologies as well as semiconductor gas purification. In 2009, he was named director of the technical development organization for Entegris' POCO Materials. Troy's role was recently expanded to include responsibilities in the SCEM division associated with portfolio management, computational modeling, and cross-divisional programs.

David R. Medeiros, Ph.D. | Senior Director, Engineering, Office of the CTO

Article: Doubling Down on EUV's Defectivity Challenges – Addressing Challenges Beyond Stochastics

Dr. Medeiros joined Entegris in spring 2021 with over 30 years in the semiconductor industry, primarily in patterning technology. He is leveraging his extensive experience leading R&D, high-volume manufacturing, and central planning teams as well as his deep knowledge of chemistry and organic materials to develop a comprehensive lithography strategy for Entegris that is highly focused on the rapidly expanding area of EUV technology.

John B. Lynch, Ph.D. | Vice President Life Sciences

Article: The Race for COVID-19 Vaccines – The Role of Aramus Single-use Assemblies

Dr. Lynch has a passion for leveraging science and technology to improve health and wellbeing. He has more than 30 years of scientific, technical, and business leadership experience focused on innovation and growth in the life sciences and other markets. John has served as vice president of life sciences at Entegris since 2019, after joining the company in 2017 with responsibility for new market business development.

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