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Graphene: The next S-curve for semiconductors?

Slowing productivity improvements and rising costs for silicon have business leaders evaluating other materials.

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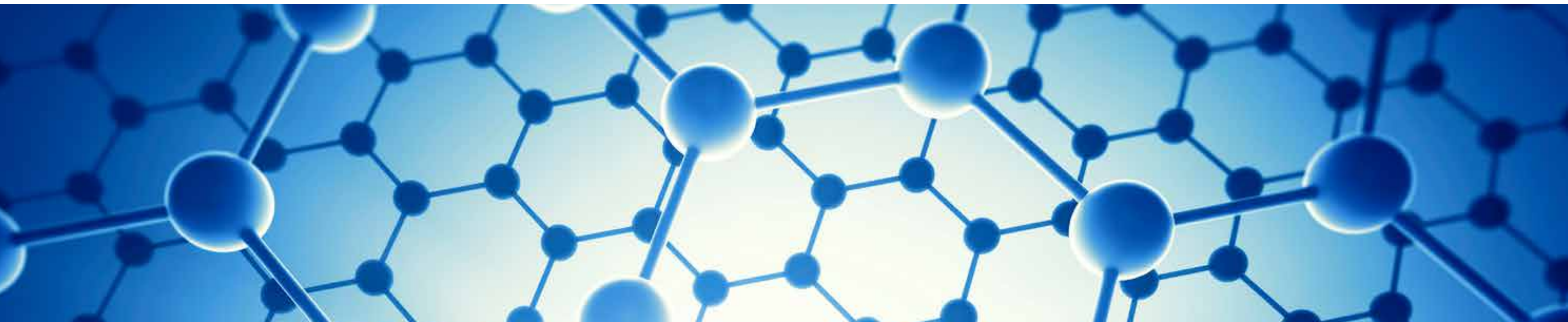

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The path from breakthrough discovery to transformational industry applications can be a long, circuitous one. Often the first rush of possibility is followed by decades of development, refinement, and experimentation. Even then, there are no guarantees. Labs around the world are littered with once-promising technologies that never found commercial use in the market. This precedent puts executives in a difficult position when determining where and when to invest in emerging innovations. For every company that places the right bet on emerging digital technologies, there are dozens of competitors that completely miss the wave and must play catch up. Time will tell whether Kodak's recent entrance into Bitcoin mining, for example, is an isolated move or part of a prescient long-term strategy.[1]

Semiconductor companies find themselves in a tricky position. Regular innovation with silicon allowed the industry to generate consistent profits and consistent, impressive performance improvements for decades. More recently, companies are experiencing increased difficulty wringing more value out of silicon. This slowdown has left companies to determine what will replace silicon and when. Graphene, for example, has been heralded as a miracle material with the potential to equal or surpass silicon's performance. However, the material's commercialization could be up to 25 years away and will require substantial investment in both R&D and capital costs to bring it into production. With so much spending currently allocated to silicon, executives must determine the right moment to shift gears toward the next material—even when the outcome is far from guaranteed.

The challenge extends well beyond graphene; as semiconductor companies seek to identify and harness the next wave of innovation, executives must adopt a different approach. The ability to understand how seemingly disparate developments can create new business models and applications requires a more expansive perspective focused on connecting the dots and exploring new ways to apply knowledge and insights. Semiconductor executives should use this lens to shape a long-term strategy to extract value out of existing materials and technologies while monitoring nascent innovations. This mind-set will better position companies to survive both known and unknown challenges in the coming years.

Silicon: Head winds ahead?

Silicon, the primary material used in the semiconductor industry, has historically kept pace with Moore's law by providing previously unimaginable progress. Disruptive and transformational technologies—advanced analytics, augmented reality, autonomous vehicles, digital, and the Internet of Things (IoT)—have been made possible by a singular element that is the namesake for the richest 50 square miles in the world. Still, serious questions are being raised about the future of silicon and its ability to continue to support innovation: three leading indicators tell the story.

Slowing performance improvements lead to pricing pressures

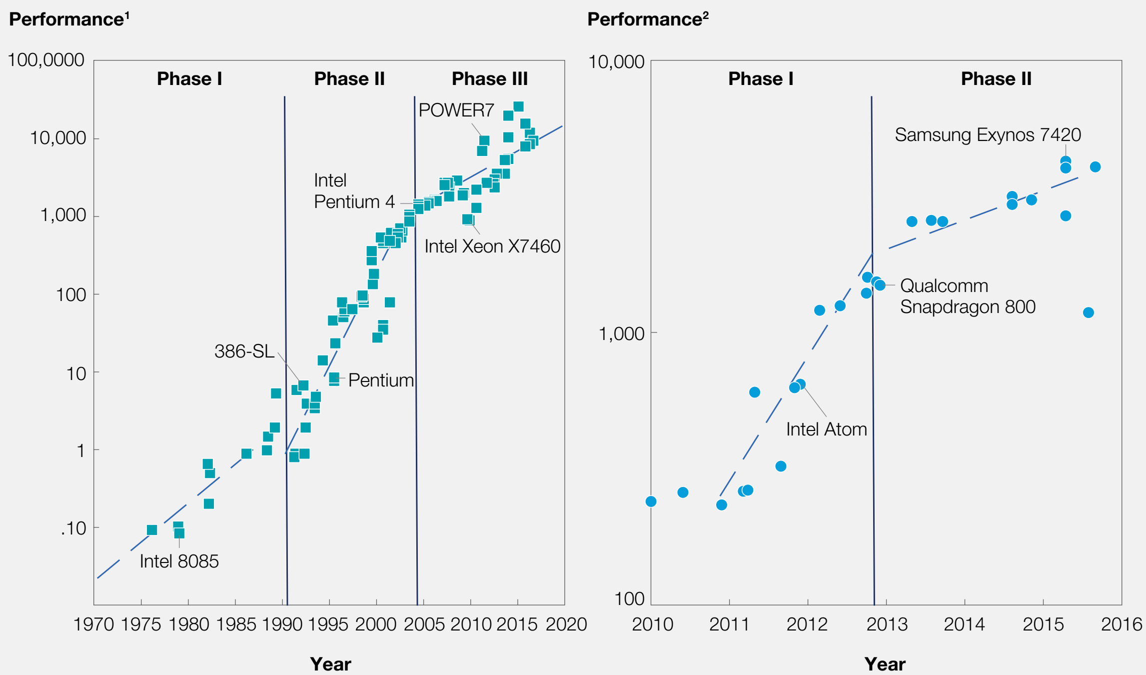
Silicon offered designers and engineers a canvas that gave rise to sustained advancements in capacity and performance. A look at data from the 1970s illustrates these exponential performance improvements. However, in recent years the pace has slowed considerably. PC processing power has leveled off and increases in smartphone processor performance have begun to slow—in short, silicon is becoming mortal (Exhibit 1). These trends mean companies that built competitive advantages on continued innovation have seen their lead start to erode as other companies catch up.

Trendsetters are struggling to widen the performance improvement lead over competitors, so their ability to capture premium pricing before the rest of the market catches up is impeded. Our analysis indicates once multiple competitors enter the market, prices fall 10 to 15 percent.

Exhibit 1 **Performance improvement is slowing down**

Rate of x86 PC central processing unit performance improvement has plateaued

. . . and performance improvements in smart-phone processors are also slowing down.



[1] Indexed to standard microprocessor in 1990.
[2] Android multicore CPU benchmark.

Source: Geekbench Android benchmark; Standard Performance Evaluation Corporation CPU benchmarks 1995, 2000, 2006

Escalating capital and R&D costs

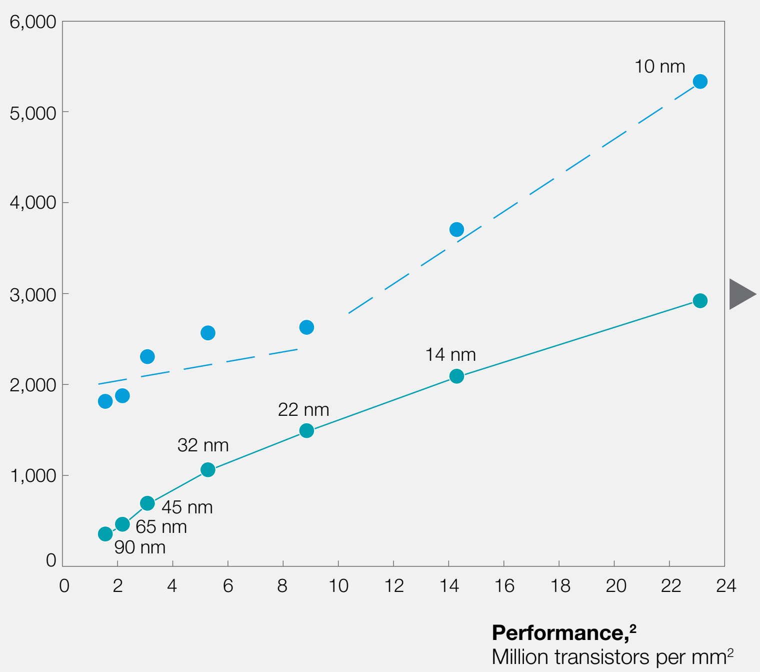
Costs for semiconductor companies continue to rise as they move to next-generation fabs. To achieve performance gains, we estimate companies must increase capital spending by as much as 40 percent (given requirements for new equipment) and R&D spending by 150 percent to achieve the same throughput (Exhibit 2). The primary cause of escalating capital costs is manufacturing equipment, which has increased by about $2 billion since the industry made the transition to multipatterning. Not surprisingly, integrated device manufacturers have rapidly boosted their R&D investments for leading node technology.

Feeling physical limitations of silicon

Separate from the commercial challenges, silicon's continued growth is also uncertain because innovation has caught up to the material's physical limitations. For example, node length is approaching the conducting channel width where performance is severely inhibited: silicon transistors will stop performing due to quantum effects of small dimensions such as tunneling, leakages, and heat

Exhibit 2 Escalating capital requirements and R&D investment may inhibit further innovation

Capex and R&D cost per performance for new fab node since 2004



Cost of capital to build fabs have accelerated after 22nm[3] transition, while R&D cost continues to rise

Capital cost
Building a 14nm costs ~40% more than the previous generation fabs

- Longer to process because of multipatterning
- Requires 1.4X times the equipment to get the same throughput

R&D cost
Transitioning to 11nm is expected to require 1.5X R&D resources

- Simple scaling no longer holds and more complex innovation is required

[1] Assuming a 300mm wafer fab with 30,000 wafer monthly capacity.
[2] Performance is calculated based on transistor density at each node reported for Intel products.
[3] Nanometers.

Source: iSuppli; press search; SEMI World Fab Watch

Graphene by the numbers

2004—First isolation of graphene by University of Manchester's Andre Geim and Konstantin Novoselov

1 atom—The thickness of a layer of graphene

€1 billion—Amount of money the European Union committed to establish the Graphene Flagship in 2013[2]

142—Number of graphene producers across 27 countries[3]

Patents by country from 2004 to Q1 2017[4]

China	South Korea	United States	Japan	Taiwan
15,375	6,024	4,328	1,471	681

issues. Limitations in lithography, instrumentation, and fabricating nanosized structures will also hinder advancements.

These three trends raise a critical question for semiconductor companies: how much should they continue to invest in silicon rather than supporting the development of innovative materials that could produce a step change in performance and sustain revenue growth?

Why graphene could be a game changer

The industry is experimenting with several exotic new materials, including silicene, germanene, and black phosphorous, but graphene is touted as having the greatest potential (Exhibit 3). The discovery of an atom-thick layer of graphene by two researchers at the University of Manchester in England in 2004, stoked expectations that it could become a superior replacement for silicon (see sidebar, “Graphene by the numbers”). Graphene’s properties

Exhibit 3 **New materials have highest potential to spur next-generation technology that could help sustain innovation**

■ Highest long-term potential

		Development	Examples	Key advantages	Key disadvantages
22 nm	Traditional scaling	Alternative computing platforms	• Graphics processing unit-based computing • Field-programmable gate array-based computing	• Large performance gains for specific applications	• Requires paradigm shift for OS developers to run on these platforms
10 nm	Limits of CMOS	Application-specific designs	• Apple’s A9 chip	• Large performance gains for specific applications	• Expensive to execute for small volumes
	Quantum effects	Advanced designs for silicon	• Resistive random-access memory • 3-D geometries • Fin Field Effect Transistor • III-V semiconductors	• Affected over 50+ years of silicon-based electronics development	• Requires more complex designs and fab
Atomic	Atomic limit	Exotic new materials	• Graphene • MoS2,[1] silicene, germanene, and black phosphorus	• Supports new generation of electronics	• R&D and capex intensive • Risk of unknown hurdles at scale-up

[1] Molybdenum disulfide.

Source: Expert interviews

have companies across industries salivating: its mobility is estimated to be 250 times that of silicon and its flexibility and other properties make it ideal for a range of applications, from battery technology to optoelectronics such as touch screens. Recent patents, academic papers, and research publications testify to the widespread interest in graphene.

Despite this promise, adoption of graphene has been elusive. So what is holding it back? We have identified four limitations, two technical and two industrial. On the technical side, band-gap engineering remains a major hurdle: without a band gap, graphene switches cannot turn off. Over the past decade, researchers have focused on addressing this issue but have yet to crack the code. In addition, graphene fabrication must generate quality crystals and be compatible with existing complementary metal-oxide semiconductor (CMOS) devices. On the industrial side, a large amount of capital is required in fabs, but semiconductor companies have most of their resources tied to current fab improvement plans. Further, an integrated value chain (including manufacturing midstream retooling) exists for silicon, but billions in investments are needed to re-create one for graphene.

Given these uncertainties, we predict graphene adoption and market growth to come in three phases—enhancer, silicon replacement, and revolutionary electronics (Exhibit 4).

In the near-term, we expect graphene to be used as an enhancer for silicon, with protective layers of graphene used to improve the reliability and performance of interconnects. Currently, 14-nanometer tantalum-nitride metal barriers are used on copper interconnects to prevent diffusion into the silicon. At gaps of less than ten nanometers, diffusion becomes a major cause of device failure—one defect per part billion results in a failure rate of around 30 percent. Graphene barriers offer several advantages over other alternatives such as ruthenium and cobalt, including better protection abilities at just one-eighth the size and with interconnect speeds around 30 percent faster.

The primary reasons for graphene's lack of adoption are twofold. The requirements for graphene's transfer and coating process need to be fully developed and integrated within fabrication steps. In addition, the cost of graphene must decrease significantly to enable commercial mass production. We predict it will take at least five to ten years to resolve these issues for graphene to become a viable silicon alternative.

Over the next 10 to 25 years, graphene could replace silicon as the primary material in semiconductors, assuming research discovers methods to overcome its band-gap limitations. Even then, graphene will be used in applications where its technical merits (such as high speed, low-loss requirements, small scale, and flexibility) are better suited for electronic

Graphene fabrication must generate quality crystals and be compatible with existing complementary metal-oxide semiconductor (CMOS) devices.

Exhibit 4 **We expect graphene adoption and market growth to come in three phases**

Phases of graphene adoption

	Enhancer	Silicon replacement	Revolutionary electronics
Primary function	Provides incremental performance improvement to leading edge devices, eg: • Improvement in speed over copper • Longer transistor lifetime by preventing ion-diffusion	Transformative change in miniaturization of CMOS by replacing silicon with graphene as primary active material: • Improvement in feature size	• All graphene devices make one-layer lithography a reality • Novel devices based on principles beyond CMOS technology (eg, spintronic, valleytronics, quantum-computing platforms)
Primary devices and applications	• Leading-edge CPUs and memory • Niche applications such as radio frequency analog	• Next-generation CPUs and memory such as ReRAM	• New and undiscovered applications
Critical assumptions	• Seamless CMOS integration	• Band-gap engineering • Large-area crystal growth	• R&D proof of principle
	5–10 years	10–25 years	25+ years

applications than alternative materials (Exhibit 5). Our analysis calculates the total addressable market for graphene at $190 billion across data processing, wireless communications, and consumer electronics.

Adoption is expected to follow an S-curve trend similar to other technologies, with the time frame for implementation most closely mimicking wafer adoption. Overall, optimistic scenarios show market value potential for graphene semiconductors to be around $70 billion by 2030.

How should leading semiconductors players proceed?

History has revealed that some technologies take a long time to commercialize but can rapidly transform industries once they hit the market. In our experience, companies with a track record of casting a wide net to discover the next transformative technology tend to be more prepared to withstand industry disruptions.

Exhibit 5 **Total serviceable market for graphene-based electronics is calculated to be ~$190B based on demand for high-performance applications**

Application	Device type	Market size, $B	Serviceable market, %	Serviceable market, $B
Data processing	NAND	14	88	13
	DRAM	22	98	22
	MPU	34	99	34
	Logic ASIC	19	29	6
	Total	**89**		**74**
Wireless communica-tions	NAND	14	77	11
	DRAM	17	75	13
	Logic ASIC	31	79	25
	Analog ASIC	13	68	9
	Optical	10	57	6
	Total	**85**	74	**63**
Consumer electronics	**Logic ASIC**	**12**		**5**
			Other	**46**

- Data processing and wireless communications represent +70% of serviceable market due to their demand for high performance, with a strong presence from **enterprise server, PC, and smartphone markets.**
- **Memory, MPU, and logic ASIC** are important components in these devices and represent the majority of the market.
- **Video game consoles** represent the majority of consumer electronics.

Source: IHS Technology; Expert interviews

Graphene's promise is counterbalanced by the severe technical and commercial challenges discussed, which could impede its use as a silicon replacement. Therefore, when evaluating graphene's true potential, semiconductor executives should use a structured innovation approach to evaluate their options. The innovation X-ray consists of ten questions across three categories—innovation strategy, technology disruption, and innovation practices (Exhibit 6). Addressing these questions can help business leaders get a better sense of their organization's capabilities when pursuing innovation and support the exploration of different scenarios with or without graphene adoption. The result is a

Exhibit 6 **Innovation X-ray consists of ten questions for turbocharging your structured approach**

What are the outcomes from your innovation strategy?	• How much of your company's financial performance is affected, and could be **affected, by new products and materials?** (eg, revenue and profit generated) • What does your **customer base say about your status as an innovator?** (eg, customer assessment of your innovation, share of revenue from new customers and geographies) • How innovative has your **R&D and product development** been? (eg, time to market and quantity and quality of patents compared with peers)
What are the oppor-tunities and risks from technology disruptions?	• What opportunities and risks do we see across the value chain related to **markets and products, business models, and operations?** • What opportunities and risks do **disruptive technologies** create in your **value chain?** • What strategies should you adopt for playing in the **ecosystem** and choosing your **tech stack** portfolio?
What innovation practices do you have in place?	• How does your company stack up against peers in **prioritizing innovation in corporate and business-unit strategy?** (eg, through incubators, corporate venture capital, accelerators) • How does your organization compare to peers in creating an **innovative environment?** (eg, through breakout structures, agile tribes, etc) • Has your company created the **technology capabilities and infrastructures** to enable innovation? (eg, through partnerships with platform developers) • Has your company fostered an **innovative culture?**

strategy that prepares organizations for dramatic, technology-driven industry change.

■ ■ ■

After a long and productive run with silicon, executives are beginning to contemplate what might replace it and provide a similar S-curve of innovation. Graphene's characteristics have stoked the imagination, but to date its physical limitations have kept it from being named silicon's heir apparent. The recent history of technological innovation suggests the landscape could change rapidly—thus, executives should consider graphene as a serious contender. Regardless of the eventual outcome, semiconductor businesses can position themselves to weather technological disruption, and come out ahead, by embracing a mind-set focused on structured innovation. A world of many unknowns demands it. ■

[1] MacKenzie Sigalos, "This $3,400 bitcoin-mining machine is a cornerstone of Kodak's crypto pivot," CNBC, January 10, 2018, cnbc.com.

[2] Jeffrey Draa, "Is the U.S. lagging behind the rest of the world in graphene research?" Grolltex, April 16, 2017, grolltex.com.

[3] Tom Eldridge, "Is China still leading the graphene race?" Nanotechnology Now, January 5, 2017, nanotech-now.com.

[4] "China dominates graphene-related filing activity globally with more than 50% of total patents filed between 2004 and 2017 Q1," AcceleratingBiz, last updated December 4, 2017, acceleratingbiz.com.

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