Edward Snyder
Managing Director
Ph: 415.931.9955
esnyder@charterequityresearch.com

Jack Egan
Associate Analyst
Ph: 415.931.9955
jegan@charterequityresearch.com

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Cree Inc.

SiC Competitive Landscape

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Edward Snyder
Managing Director
Ph: 415.931.9955
esnyder@charterequityresearch.com

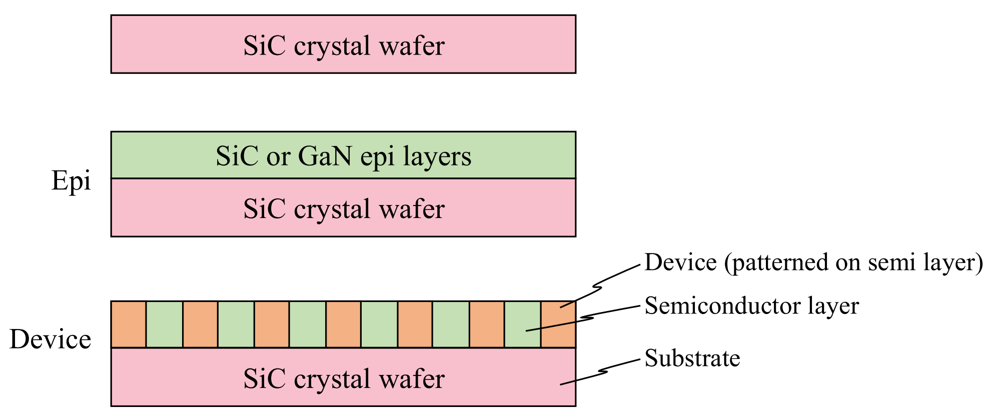
Jack Egan
Associate Analyst
Ph: 415.931.9955
jegan@charterequityresearch.com

Cree Inc.

(CREE: $113.81)

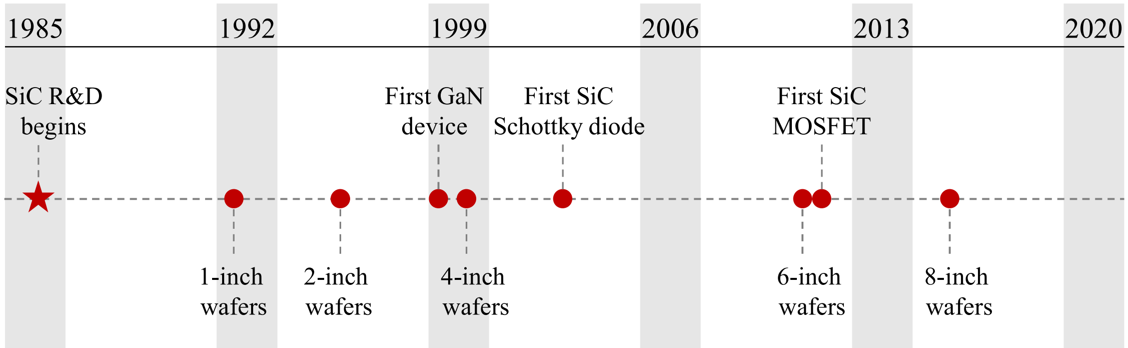
The silicon carbide competitive landscape.

In this, the 6th chapter of our Cree initiation, we provide a detailed analysis of the competitive landscape for silicon carbide (SiC). The technology maturation that spurred adoption of SiC among power device manufacturers also drove demand for wafers. This enticed a variety of companies to launch development programs to supply their own wafer needs or offer products on the merchant market. Unfortunately, material growth and wafer manufacturing are arguably the most difficult tasks in the SiC supply chain. A good many of the firms that endeavored to master them in the 1990s and early 2000s failed to produce viable products and were sold off to several of the current cast of wafer and device manufacturers. We delve into those stillborn efforts and the companies that acquired them as well as every other firm with a material share in any segment of the supply chain which includes bare substrates (referred to as "crystal wafers"), bare substrates with a silicon carbide or gallium nitride (GaN) semiconductor layer (referred to as epitaxial or "epi wafers"), and semiconductor components manufactured on epi wafers ("SiC devices" and "GaN devices"). For the purposes of our discussion all epi wafers and all devices (SiC or GaN) are on SiC crystal substrates.



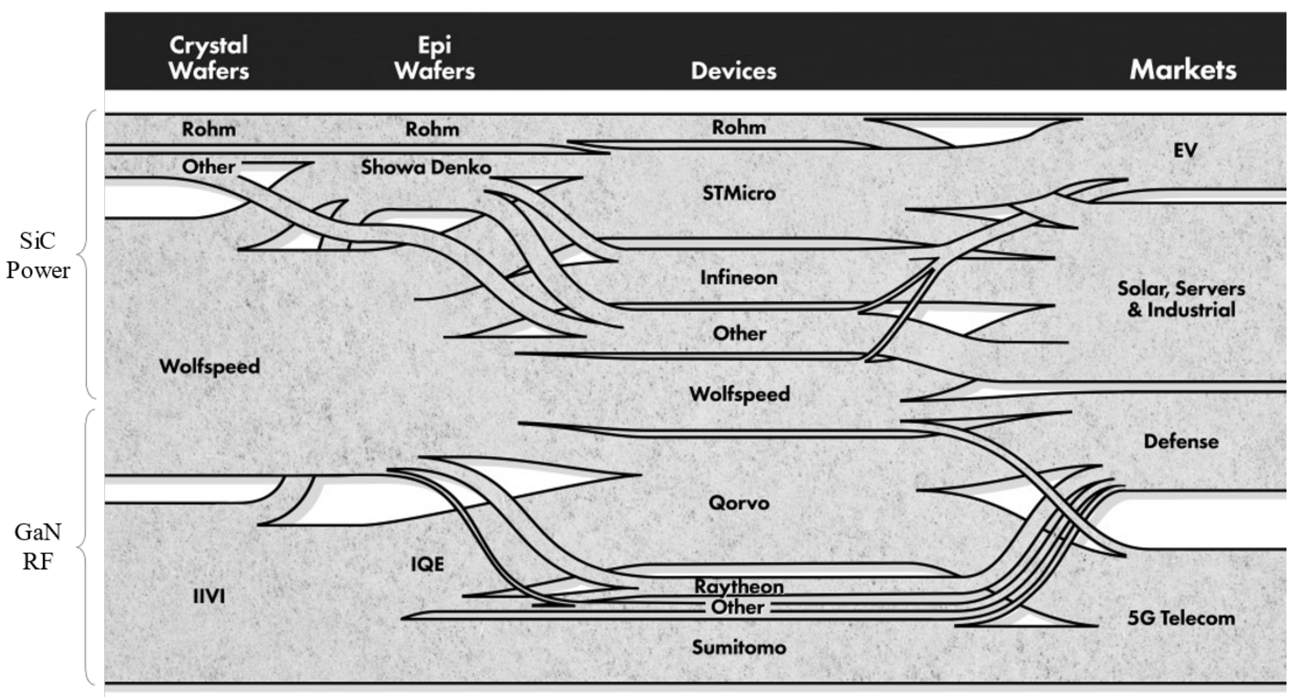
The enormous challenges of working with silicon carbide[1] required twenty years of research to overcome. Most of that was funded by the U.S. defense department which, with limited R&D resources, focused much of its attention on Cree, enabling it to become a pioneer in silicon carbide. Beginning in 1985, it spent decades furthering the science and in the process, obtained unparalleled insight into all forms and flavors of the technology. It was the first to offer 1-inch substrates[2] and by 1998 had already established a commanding lead in product breadth and quality in crystal wafers.

Cree SiC/GaN History



Between the effort required to master material growth and the lack of demand for $2K - $4K wafers, very few firms undertook the challenge of silicon carbide before 2010 and of those that did, only one survived. In fact, of the four firms producing crystal wafers in 1998 only Cree still exists; the other three struggled on for years only to be sold or given away to semiconductor manufacturers decades later. This paucity of suppliers created a "chicken and the egg" problem where costs were too high to entice OEMs to use the technology, but the lack of demand and technical challenges dissuaded suppliers from entering the market. If SiC was ever going to find its way out of the lab, Cree would have to supply it in all forms to all customers; crystal wafers, epi wafers and SiC and GaN devices. This necessarily meant it would be competing with some of its customers but that couldn't be avoided if it had any hope of jump starting the supply chain.

SiC and GaN Supply Chain

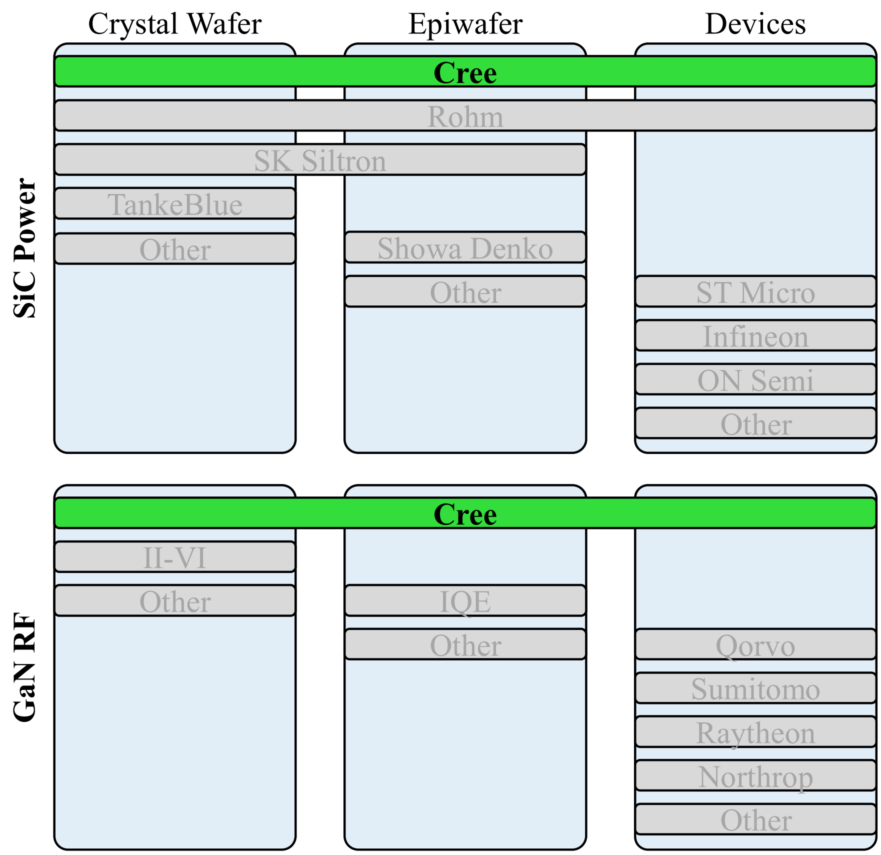


By 2015 costs declined enough for SiC devices to be used in industrial applications where high power and high performance are essential, and for defense OEMs to use GaN devices in radar and electronic warfare equipment. It was a start, but the reach of these products was limited by wafer cost which hovered around $1,000. That's declined to about $600 today for in the largest, long-term supply agreements but still remains far above the sub-$100 price of silicon wafers. Silicon carbide will never close the cost gap with silicon but it will never be rivaled by silicon in performance. Indeed, the massive advantage SiC enjoys in high power applications has legacy device manufacturers like ST Microelectronics, Infineon and ON Semiconductor hungry for more and casting about for any means of reducing wafer cost, including undertaking their own wafer programs. Aggressive plans notwithstanding, the road from research to production is just as difficult today, if not more so, because the quality and cost available from leading firms are vastly better than they were even ten years ago.

As a close reading of the history of the companies presented in this report will reveal, the best predictor of success is longevity or more specifically, experience. With a thirty-year head start, Cree holds a commanding lead over new entrants. It has a majority share in wafers, and once its new facility is completed, will become a larger device supplier. How that plays out with the customers it competes with remains to be seen but given the scarcity of high-quality wafers and the high elasticity of demand for devices, anything it can do to increase its scale and lower costs will accelerate the adoption of silicon carbide and increase demand for all suppliers in all markets.

Cree

Silicon Carbide Competitive Landscape



Cree is the only company competing in all segments of the SiC and GaN supply chain, largely because it started earlier and progressed faster than erstwhile competitors. A 1998 NASA SiC technology report[3] lists Cree as the leader with largest variety, highest quality, and longest history in SiC wafers. In fact, of the four firms listed in that report, Cree is the only one to survive to this day. The other three, Nippon Steel, SiCrystal, and Sterling all underwent M&A events to sell themselves or their growing silicon carbide operations.

CREE

	Established	1987
	SiC/GaN R&D	1985
	Products	SiC Wafers, SiC/GaN Devices
	Markets	Solar, Industrial, Radar, Telecom, EV
	Consolidated Revenue (2020)	$465M
	SiC Wafer Revenue 2020(e)	$279M
	SiC Device Revenue 2020(e)	$121M
Merchant Market	GaN Device Revenue 2020(e)	$65M
	Crystal/Epiwafers	51%
	SiC Devices	17%
	GaN Devices	8%

Cree's initial efforts in SiC in the 1980s were focused on mastering material growth which is the most difficult step in the path to producing devices. It launched wafer production in 1991, years before others entered the fray. SiCrystal (now Rohm) and Litton (now II-VI), which are its largest competitors in crystal wafers today, didn't begin development until 1994 and 1998, respectively. Cree's early start paid off in market share, giving it a top-three position in all categories of SiC products.

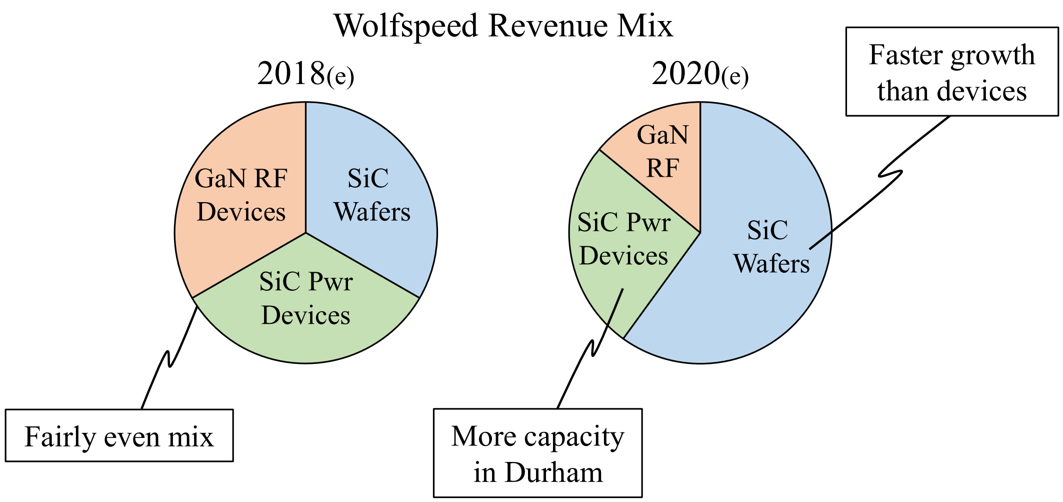
Market Share Leaders

	SiC Power			GaN RF		
Market Share	Crystal wafers	Epiwafers	Devices	Crystal wafers	Epiwafers	Devices
Leader	Cree	Cree	ST Micro	II-VI	IQE	Qorvo
#2	Rohm	Showa Denko	Infineon	Cree	Cree	Sumitomo
#3	TankeBlue	Rohm	Cree			Cree

Only company to compete in every step of SiC and GaN supply chains

Historically, Cree's sales were divided fairly evenly between materials (crystal and epitaxial wafers), SiC power devices (MOSFETs and Schottky diodes), and GaN RF devices (power amplifiers). Indeed, prior to CEO Gregg Lowe's arrival in 2017, the company was pricing epitaxial wafers at a premium to limit merchant market demand and ensure it had sufficient working capital to fulfill the needs of its LED business.

Once Lowe began shifting the company away from LEDs and lighting to Wolfspeed, he reduced wafer pricing to stimulate demand and increase Cree's presence in materials. By 2019, epi wafers accounted for the majority of Cree's merchant market wafer sales. The shift towards materials accelerated in May 2019 when the U.S. government banned sales to Huawei. Cut off from the big 5G buildout in China, Cree's GaN device sales suffered a steep decline and its revenue mix shifted further to materials.



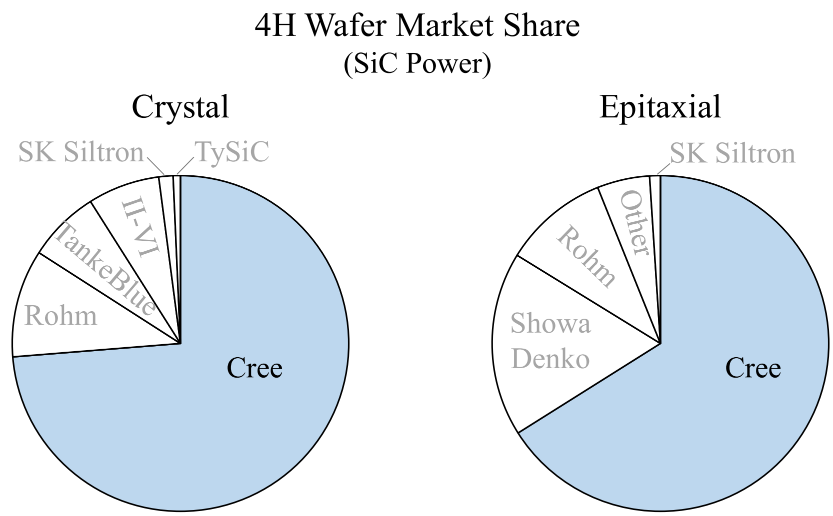
Silicon Carbide Wafers

Lower wafer pricing whet the industry's appetite and the ensuing rise in demand enabled Cree to become the leading supplier of crystal and epitaxial wafers for SiC power devices. As of 1Q21, we estimate materials (wafers) account for 60% of Cree's revenue, followed by SiC power devices (25%-30%) and GaN RF devices (10%-15%). This translates to about 50% share of the merchant market for materials (crystal and epitaxial wafers) and much higher share of total wafer production given a lot of the wafers it produces are consumed to fabricate its own SiC and GaN devices. Aggregating that with merchant market sales gives Cree a substantial scale advantage.

There are two primary crystal structures used for SiC wafers, 4H for low frequency power and 6H for high power RF. "4H" and "6H" refer to how the atoms are arranged which dictates the electrical and thermal properties of the wafer. The 6H crystal structure is similar to that of gallium nitride which simplifies deposition of a GaN epitaxial layer to the 6H substrate. Gallium nitride can operate at high frequencies and high power levels, making it a good match to the high power dissipation of 6H SiC wafers. GaN (6H) is used for radars, electronic warfare and communications in defense and for MiMo base stations in 5G infrastructure.

For low frequency, high power applications, a silicon carbide epitaxial layer is applied to the 4H SiC substrate. Electron mobility in silicon carbide is lower than in gallium nitride but for applications that don't operate at radio frequencies, SiC epi on a 4H SiC wafer provides the best thermal properties because they're the same crystal structure. SiC (4H) wafers are used in low frequency power applications, utility power inverters and electric vehicles. So while there are over 250 different crystal structures of silicon carbide, 4H for SiC power applications and 6H for GaN RF make up the vast majority of all crystal wafers because they provide the best balance of performance, cost, and ease of manufacturing.

Rohm, TankeBlue and SK Siltron are Cree's primary competitors in 4H crystal wafers, while Cree, Showa Denko, and to a lesser extent Rohm, all supply 4H epitaxial wafers. Rohm uses most of the wafers it produces for its own SiC power devices and therefore has little share of merchant market sales. It did sign a $120M wafer supply agreement with ST Micro (STM) in January 2020, but the lack of follow-on agreements suggests that was a one-off deal to ensure STM had a non-U.S. source for SiC wafers as a hedge against escalating trade tensions.



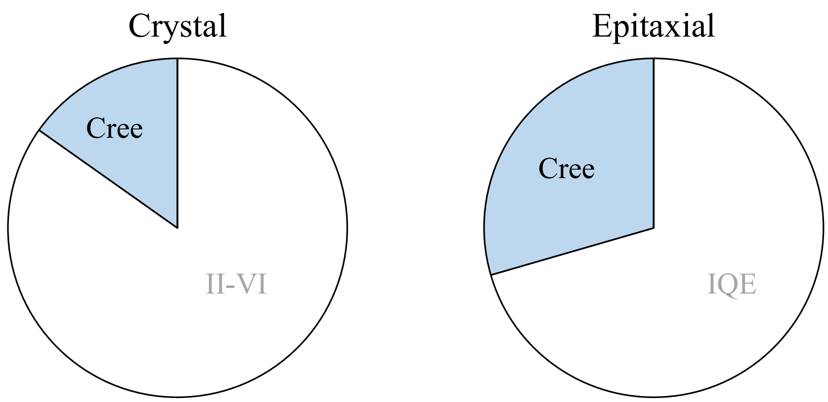
TankeBlue is a merchant market supplier to domestic Chinese device manufacturers. It is expanding capacity and expects to produce 120K wafers per year by 2022. That would give it the lead in 4H crystal wafers, but absent a substantial improvement in quality, the vast majority of its output will continue to be used to test and calibrate fab equipment rather than for devices.

SK Siltron purchased the SiC crystal and epitaxial wafer assets of Dow Corning in 2019 but has struggled to convert what was essentially an R&D effort into a production process. Dow Corning entered the SiC market with its 2003 purchase of Sterling Semiconductor but advancing to larger wafers proved challenging and the company lost market share to Cree, II-VI and Rohm/SiCrystal.

Showa Denko is located in Japan and focuses on applying semiconductor layers (epitaxy) to crystal wafers it purchases on the merchant market. It has signed an agreement to supply Denso with its SiC epitaxial wafers for electric vehicle products but is well behind Cree in terms of wafer capacity.

The process used to grow crystal wafers used for GaN RF devices (6H crystal) is quite a bit different and in many ways more arduous than for SiC power wafers (4H crystal). Therefore most firms focus on one or the other, with Cree as the only manufacturer to provide both. II-VI leads in 6H crystal wafers and IQE is the largest supplier of 6H epitaxial wafers. Cree is second largest in both products.

6H Wafer Market Share
(GaN RF)

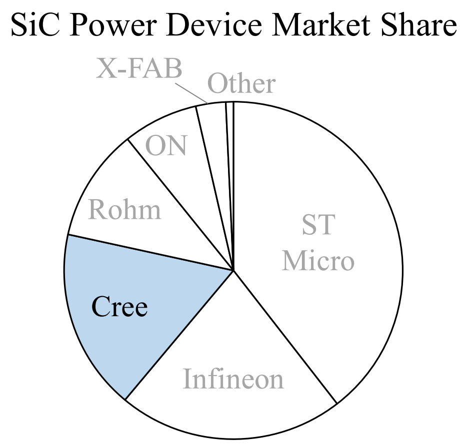


II-VI has long been a formidable competitor in 6H crystal wafers, evidenced by the $100M supply agreement it announced in December 2019. Its attempts to fabricate epitaxial wafers haven't gone as well and remains a work-in-progress. To help with that effort and expand into 4H crystal wafers, the company acquired Ascatron and INNOViON in 2020. That has given it a small slice of the market for 4H power wafers, but it has yet to yield a production epitaxial process or provide any significant diversification away from 6H RF wafers.

IQE purchases crystal wafers on the merchant market (primarily from II-VI), applies epitaxial layers, and sells those to GaN device manufacturers, just as Showa Denko does for 4H SiC epi wafers. IQE experienced strong growth in 2020 driven by the Chinese 5G buildout and increased use of GaN in defense radars. This, combined with Cree's focus on 4H SiC power business, suggest II-VI will remain firmly entrenched as the market leader in 6H crystal wafers and IQE as the number one in 6H epi wafers.

SiC Power Devices

In silicon carbide power devices (MOSFETs and Schottky diodes), Cree is the third-largest supplier behind ST Microelectronics and Infineon. Because Cree's facilities were initially devoted to research rather than production, tool layout, process control and floor space are not optimized for high volumes or high yields (see "CREE: The evolution and future of Cree's production operations" Charter Equity Research, November 19, 2020). To remedy this, the company is building a larger, state-of-the-art device fab in Mohawk Valley, New York. Slated to begin production in 2022, the new fab will be fully automated and use 8-inch wafers, giving it ample capacity for growth. The required investment is substantial, but it should provide Cree the necessary scale to compete against other leading power device manufacturers. In the meantime, to bolster capacity, the company replicated its Research Triangle Park SiC power device fab in its headquarters in Durham.



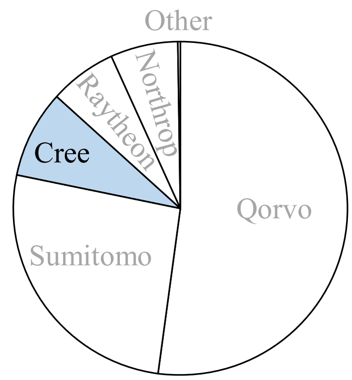
ST Microelectronics became the largest supplier of SiC devices when Tesla chose its SiC MOSFETs for the Tesla Model 3, one of the first electric vehicles to use silicon carbide and one of the best-selling EV models[4]. At 48 MOSFETs per vehicle, we expect most of ST Micro's SiC capacity is dedicated to Tesla which is responsible for the lion's share of the ~$275M it generated in SiC devices sales last year. STM expects that to increase to $475M-$500M in 2021. This will keep it in the #1 position ahead of Cree and Infineon, both of which we estimate generated SiC device revenue of $125M-$150M in 2020. Unlike at STM, the preponderance of SiC revenue for Cree and Infineon are from solar, industrial and datacenter markets.

Rohm is the fourth largest in SiC devices and in 1Q21 opened a new device fab to increase its scale. Even with the STM wafer supply agreement, we believe Rohm consumes most of the wafers it produces in the fabrication of its own devices. ON Semiconductor and X-FAB round out the competitive field with market shares of 7% and 3% respectively. We estimate the six leading suppliers of SiC devices manufacture more than 90% of the SiC devices sold on the merchant market today.

GaN RF Devices

The market and supply chain for GaN is smaller than for SiC power because the number of RF applications that benefit from GaN's power performance is smaller. GaN device manufacturers experienced a tailwind in 2020 from China's buildout of a nationwide 5G network and relentless growth in the use of GaN in radar and electronic warfare systems in the U.S. and its allies. We expect demand in defense will continue to increase over several more years but expect sales for 5G base stations to cool substantially. For Cree, the Huawei ban in May 2019 sapped demand for its GaN devices and likely contributed to the company's decision to focus more of its efforts and resources on the SiC power business. Qorvo's GaN business also declined materially, but after three quarters, the void left by Huawei had largely been filled by demand from Ericsson, ZTE and, to a lesser extent, Nokia. With a lower exposure to the telecom market, Cree did not experience a similar resurgence in GaN device sales, likely because many of its GaN devices are still produced on 4-inch wafers, which limits throughput, and increases per-device cost relative to Qorvo's 6-inch line.

GaN RF Device Market Share

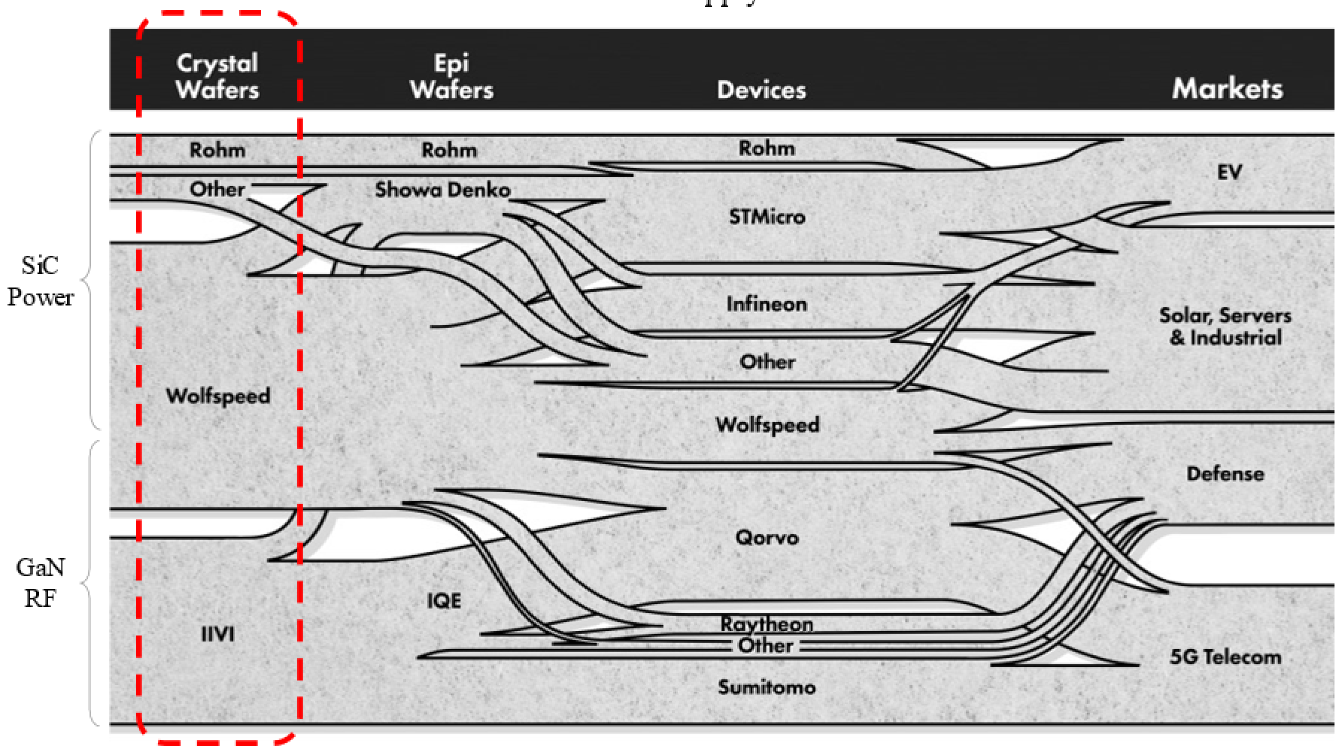


Qorvo is the largest manufacturer of GaN devices and supplies both the 5G telecom and military radar markets. RF Micro Devices and TriQuint, the two companies which merged to create Qorvo, had long running programs in GaN which gave Qorvo a lead from the day of the merger in 2015. Qorvo has also invested more heavily in GaN which is one of only two technologies consuming most of its CAPEX. Sumitomo is the second-largest supplier of GaN devices, virtually all of which were sold to Huawei prior to the U.S. ban. Post-ban we believe Sumitomo ramped capacity to fill the void left by Qorvo and Cree, which were precluded from selling to Huawei. Like Qorvo, it's also seeing higher demand from ZTE and Ericsson, which is fortunate given the Japanese constitution prevents domestic firms from supplying products for offensive military applications, so it sees little demand for GaN to defense. Sumitomo has its own GaN epitaxial process and buys the vast majority of its 6H crystal wafers from II-VI. The two companies signed an agreement in 2018 to collaborate on the development and production of 5G devices.

Cree's strong competitive position across the SiC and GaN markets was borne from its early focus on crystal and epitaxial SiC wafers, which provided the flexibility and visibility to pick which markets to pursue. Once the Mohawk Valley fab opens up in 2022, we expect sales of SiC wafers and power devices will increase and costs decline, given it will be running a fully automated fab on 8-inch wafers of its own production. The company is increasing its wafer capacity in tandem with the ramp of the new fab, so we anticipate sales of SiC power devices and wafers will grow at a similar clip in 2022 and 2023. Even though it's no longer a leader in GaN device sales, we don't believe Cree will exit the market given the lack of qualified suppliers and lucrative nature of the GaN defense segment. But by 2024, it would not be surprising to see the SiC power business (both wafers and devices) account for 85%-90% of Cree's total revenue with 6H GaN wafers and devices accounting for the remaining 10%-15%.

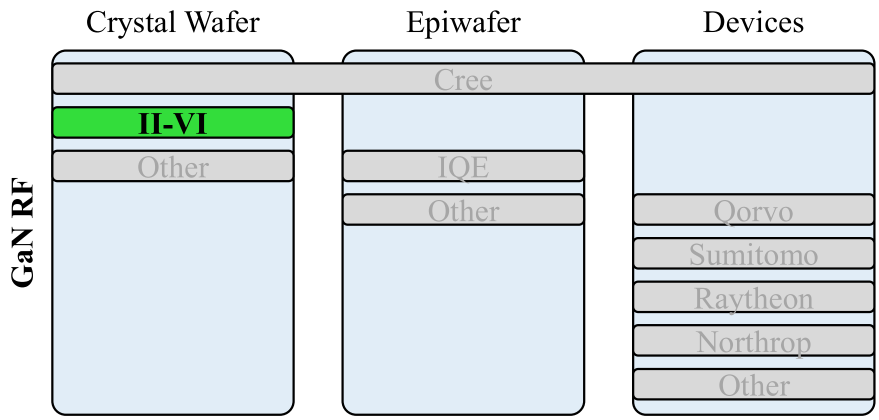
Crystal Wafers

SiC and GaN Supply Chain



II-VI

Silicon Carbide Competitive Landscape



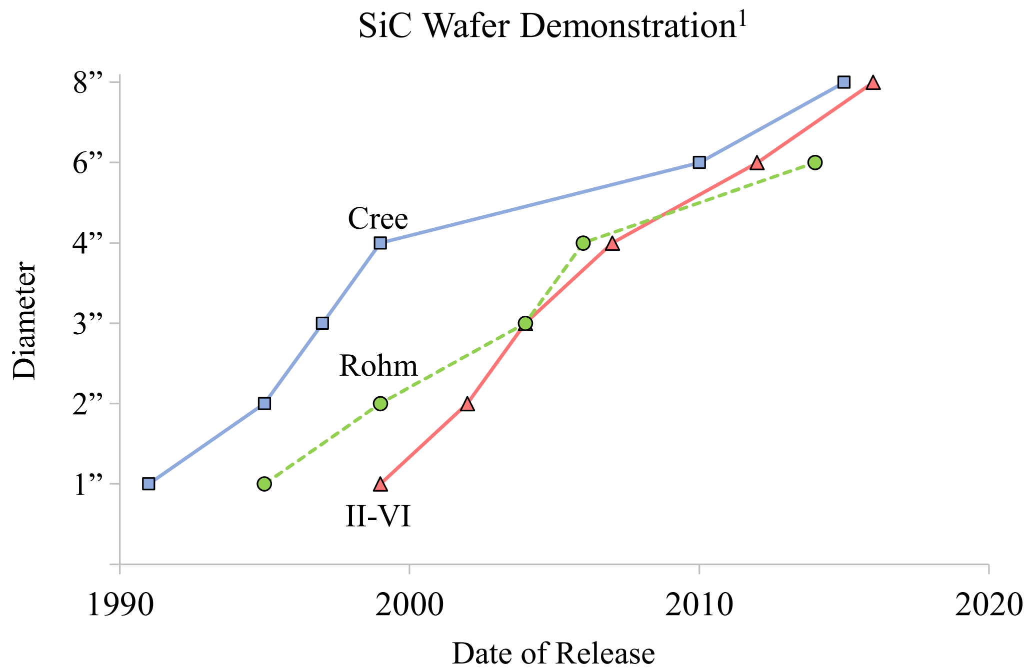
II-VI is the second-largest manufacturer of crystal SiC wafers and the largest merchant market supplier with about 40%-45% share. It was established in Saxonburg, PA in 1971 to manufacture materials and devices for the communications sector and commenced silicon carbide research in 1998. It does not manufacture SiC epi wafers or devices, only crystal wafers, which accounted for 5% of consolidated revenue in 2019 and approximately 4% in 2020.

II-VI

Established	1971
SiC R&D	1998
Products	SiC crystal wafers
Markets	Telecom, Radar
Consolidated Revenue (2020)	$2.9B
Wafer Revenue 2020(e)	$115M
Share of Merchant Mkt Crystal Wafer Sales	43%

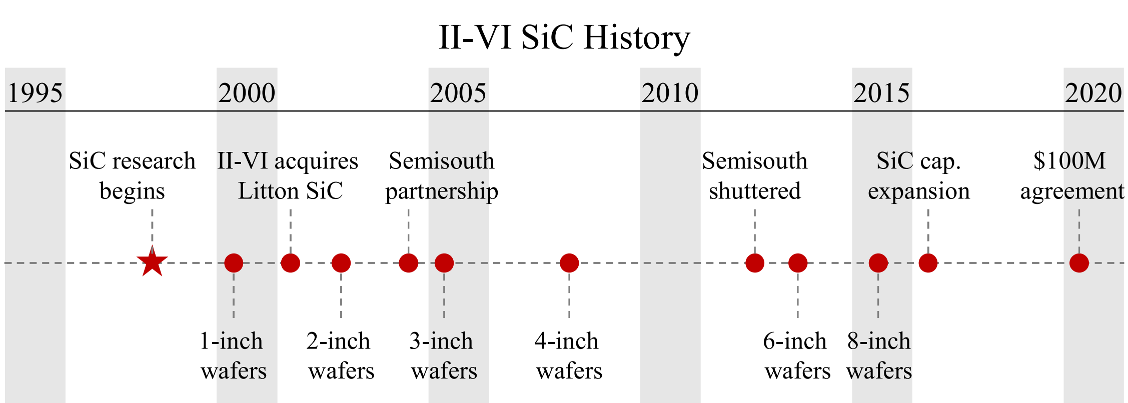
In 2001 it acquired the Litton Airtron SiC assets from Northrop Grumman to accelerate its efforts in SiC. Litton was involved in Office of Naval Research projects in the 1990s alongside other prominent suppliers such as Cree and Sterling Semiconductor (now SK Siltron). The acquisition doubled the size of II-VI's SiC program and added engineers experienced in developing 6H semi-insulating wafers for RF devices. Government sponsorship was essential because wafer sizes were still too small and yields too low for SiC to be viable in commercial production. In fact, throughout the 2000s, several firms abandoned work on silicon carbide when their efforts to develop larger wafers faltered.

This winnowed the field of competitors and focused more government resources on the efforts of the leading firms. II-VI has always lagged Cree in wafer size but by 2010 it narrowed the gap from ten years to two as Cree shifted its focus away from Wolfspeed to LEDs.

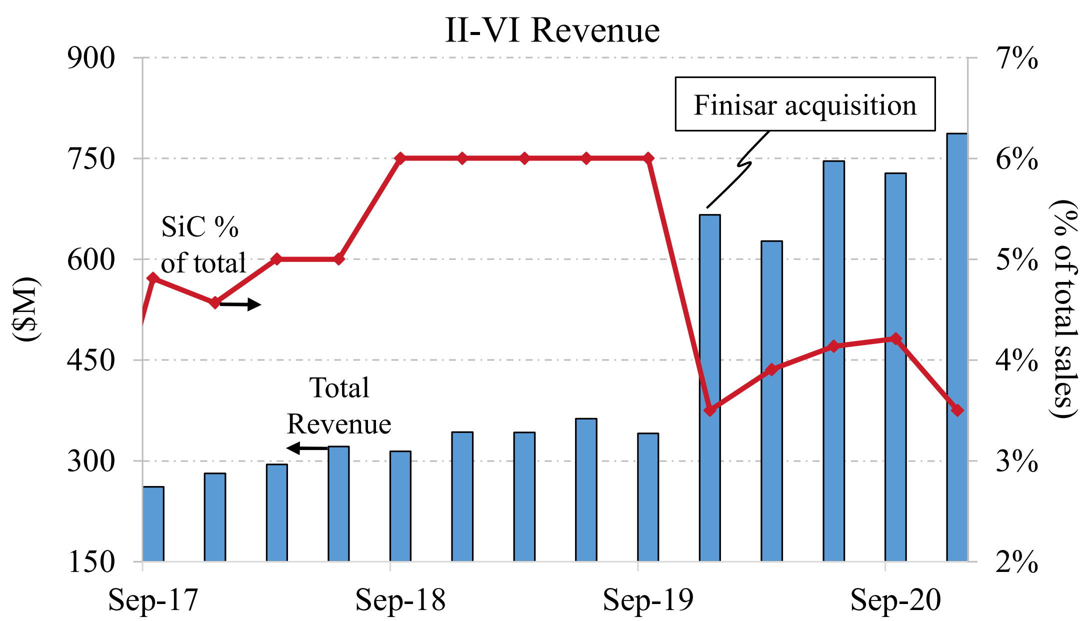


[1] New product announcements, not production

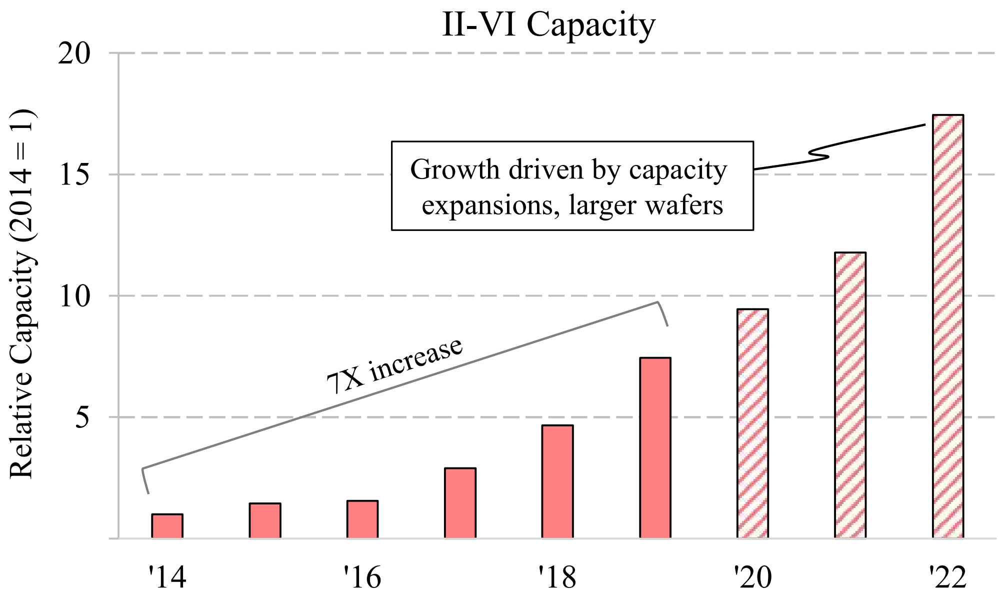
By focusing on just crystal wafers, II-VI accelerated development of larger wafer diameters. By contrast, Cree was spread across a much wider swath of silicon carbide materials including those for LEDs, RF (6H) and power (4H) applications, and produces both crystal and epitaxial wafers as well as devices. This gives Cree a larger role in the silicon carbide industry but allowed II-VI to close the gap in wafer sizes. II-VI has announced an increase in diameter every 2.7 years, whereas Cree and Rohm have introduced larger wafers every 4 and 4.6 years respectively. II-VI is now the leading supplier of SiC crystal wafers for RF devices.



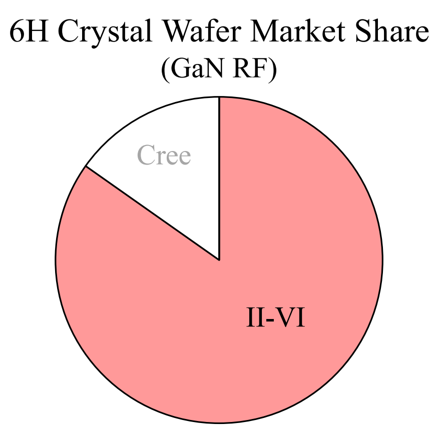
While it's succeeded in selling crystal wafers into the RF GaN market, II-VI does not have a production-scale epitaxial wafer operation. Crystal wafers have to be coated with a semiconductor layer before they can be used to fabricate semiconductor devices. II-VI has made several attempts to expand into epitaxial wafers, starting in 2003 when it partnered with SemiSouth, an early-stage epi wafer manufacturer, but a lack of progress ended that effort in 2012. It made another attempt in 2016 with the EpiWorks acquisition (a GaAs epitaxy company), but the stark technical differences between GaAs and GaN and the complexity of working with silicon carbide has rendered much of EpiWorks' knowledge in epitaxy impractical. Four years later, developmental work continues, and the company is still not in production with epi wafers. In August 2020 II-VI acquired Ascatron and INNOViON to develop a commercial epitaxial process but doesn't expect the effort to be viable for several years. As a result, II-VI must ship its SiC crystal wafers to Showa Denko and IQE, which add the semiconductor layers and sell the finished product to device manufacturers such as Sumitomo and Qorvo.



Despite lacking an internal epitaxy process, II-VI has experienced strong demand for wafers over the past several years. Its growth facilities were at or near full utilization for much of 2019 and into 2020 despite a 7X capacity increase from 2014 to 2019. The company plans to expand production by an additional 5x-10x over the next three to five years to meet growing demand in RF and expand into the market for SiC wafers used in power applications such as electric vehicles.

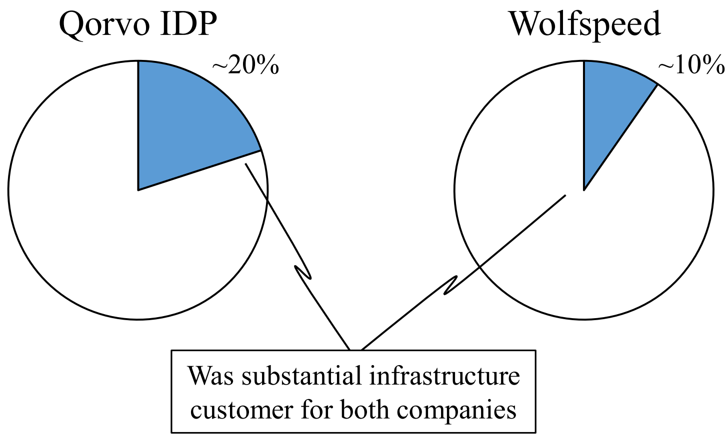


Telecom and defense are II-VI's primary RF markets and generated the vast majority of the $110M in SiC revenue recorded in CY20. II-VI's historical presence in communications devices and the expertise gained from the Litton acquisition nearly two decades ago have heavily influenced the direction of the company's operations. Management has announced its intention to pursue 4H wafers for EVs but the company has yet to enter production. Pivoting to the new technology would also open it to more competition[5] and introduce new technical challenges so we expect RF to generate the bulk of II-VI's SiC revenue for the foreseeable future.



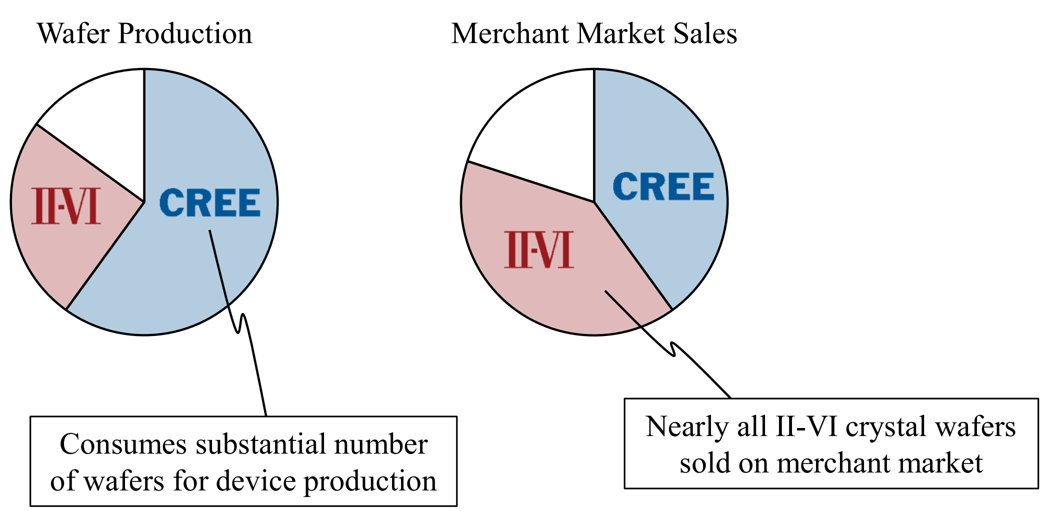
Within the broader RF landscape, radar in the U.S. and 5G deployments in China fueled the 30% growth in II-VI's SiC revenue in CY20. This was in spite of the Huawei ban, which has in fact been a tailwind for II-VI's SiC wafer business. When the ban went into effect, U.S. companies were cut off from selling 5G devices to the Chinese OEM, eliminating a large customer for the device operations of Cree and Qorvo virtually overnight. With the 5G rollout in full swing, Huawei was placed in an unenviable position since there are only three companies supplying it with these devices, two of which reside in the U.S.

Huawei Exposure
(5G infrastructure, March '19)



The exception is Japanese device manufacturer Sumitomo Electric Device Innovations (SEDI[6]). SEDI manufactures power amplifiers on silicon carbide wafers and has been a top-five wafer customer of II-VI since 2016. The two companies partnered to develop 5G power amplifiers in 2018 and six months after the Huawei ban in May 2019, II-VI announced a $100M wafer supply deal with an unnamed customer. This customer is almost certainly Sumitomo. Following the ban, Huawei's demand for 5G power amplifiers was routed from Qorvo and Cree to SEDI, prompting the company to sign a wafer contract with II-VI to ensure it could meet the sharply higher demand for devices. It is the first publicly announced deal for II-VI and unlikely to be the last considering the dearth of 6H wafer suppliers and increasing adoption of silicon carbide in telecom and defense.

Crystal Wafer Market Share
(4H power + 6H GaN RF)



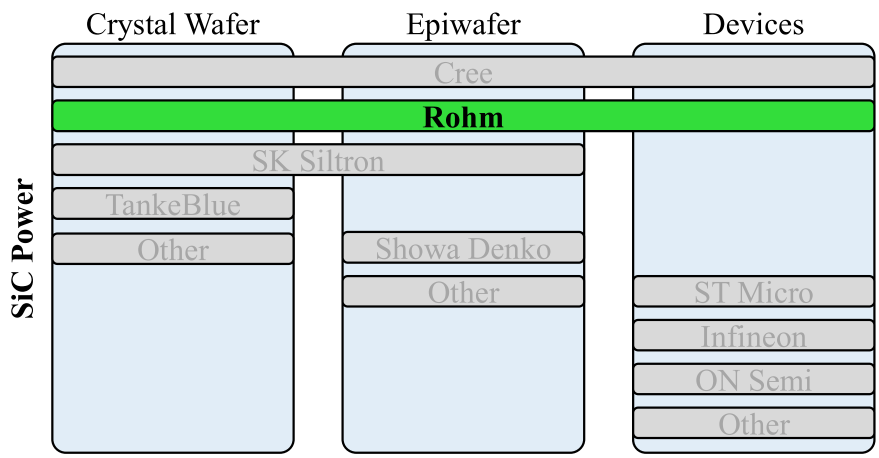
Recent demand trends and II-VI's relative advantage in 6H RF wafers suggest it will remain the primary supplier of wafers to telecom and defense. Demand in these markets will ebb and flow as more volatile revenue from the 5G buildout is supplemented by stable growth in defense. With so few competitors in 6H wafers, the company should have little trouble generating consistent year-over-year growth in SiC crystal wafer revenue.

While demand for RF wafers has remained strong for II-VI, management's recent prioritization of 4H wafers for power applications introduces uncertainty in direction of its wafer business. Competition in 4H is more intense than in RF and II-VI is well behind incumbent manufacturers in technology and scale. Cree and Rohm have decades of experience in 4H wafers and vertically integrated business models[7] which will put II-VI at a competitive disadvantage. These companies are still grappling with the technological complexity of SiC and low yields, which II-VI will likely experience when it reaches production of 4H wafers.

Even then, we don't believe II-VI will capture much market share from incumbent suppliers. Regardless of the company's resources and prior experience with 6H wafers, ramping 4H will take time, during which competitors' scale advantage will increase. The company may become a minor supplier of 4H wafers but not for several years. As such we expect II-VI to remain the primary supplier of 6H SiC wafers to the defense and telecom markets.

Rohm Semiconductor

Silicon Carbide Competitive Landscape



Rohm Semiconductor is a diversified device manufacturer based in Japan and the only fully vertically integrated SiC supplier other than Cree. It grows its own material and produces its own wafers which are used to feed its device fab. Having mastered all the steps of the silicon carbide process, the company could be a merchant market supplier of crystal and epitaxial wafers, but has instead focused exclusively on selling power devices. It did sign a wafer supply agreement (its first) with ST Microelectronics in January 2020 but hasn't followed that up with additional agreements with other vendors. It doesn't produce GaN and therefore has no share of the RF device (defense, 5G) market.

ROHM SEMICONDUCTOR

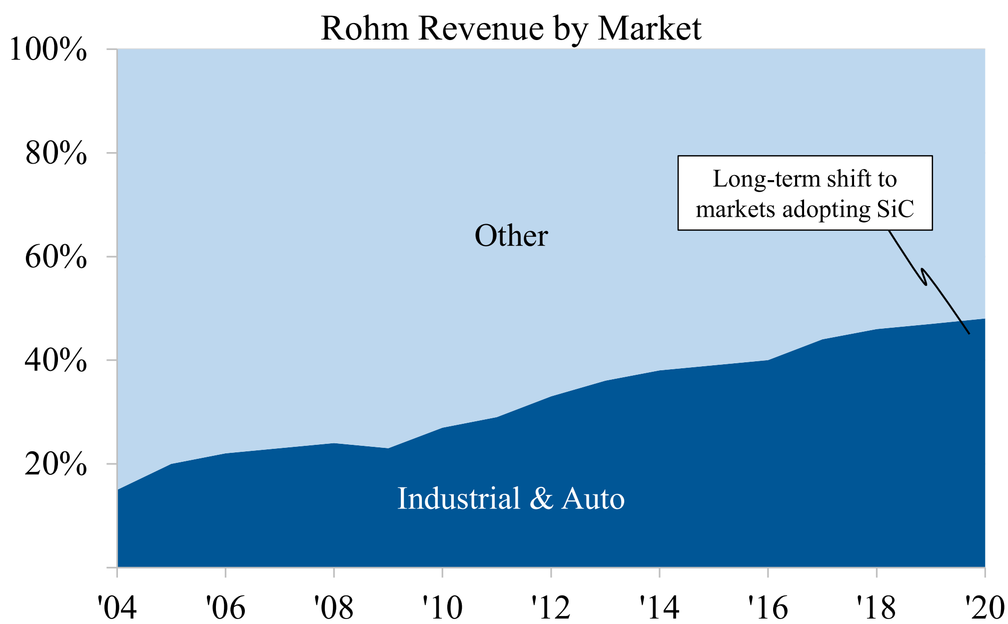
Established	1958
SiC R&D	2000
Products	SiC power devices
Markets	Solar, Industrial, EV
Consolidated Revenue (2020)	$3.2B
Device Revenue 2020(e)	$75M
Share of Merchant Mkt SiC Device Sales	10%

SiCrystal

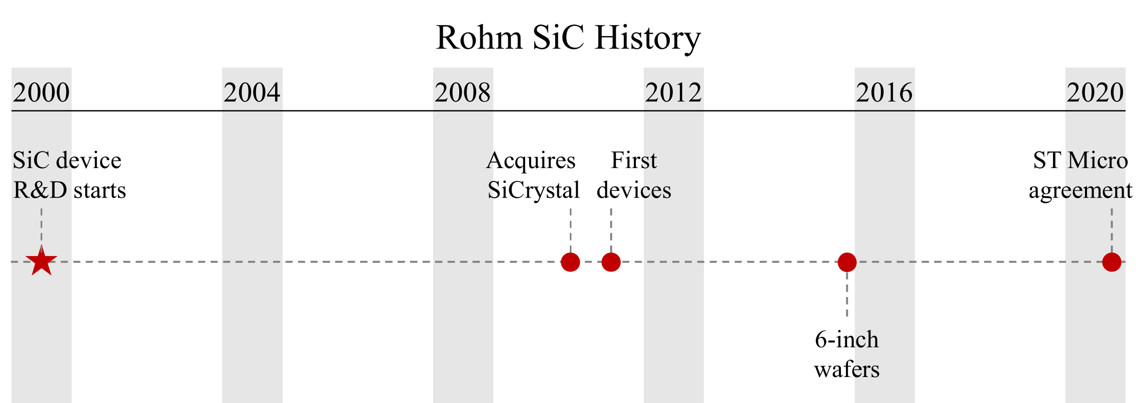
Established	1996
SiC R&D	1994
Products	SiC crystal and epiwafers
Markets	Solar, Industrial, EV
Consolidated Revenue (2020)	$3.2B
Wafer Revenue 2020(e)	$35M
Share of Merchant Mkt Crystal/Epi Wafer Sales*	6%

*Consumes most wafers internally for devices

SiC devices accounted for about $75M (2%) of Rohm's 2020 revenue, making it the fourth largest supplier behind ST Micro, Infineon, and Cree. The company has a sizable exposure to the automotive market but like all the other diversified semiconductor suppliers[8] except STM[9], it sees little SiC revenue from electric vehicles.



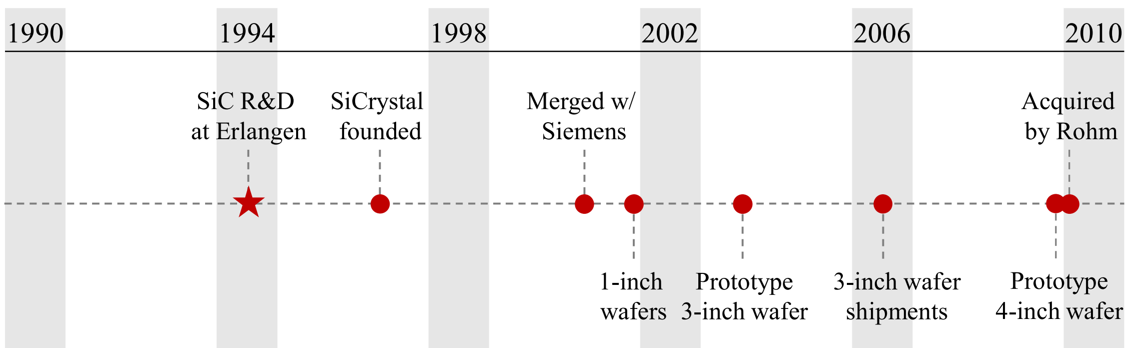
Rohm began developing silicon carbide in 2000 to bolster its position in power devices. In the early years of the 21st century SiC material was scarce, quality was low and costs were high. Cree was the largest supplier but was devoting most of its resources to LED and lighting and showed little interest in developing a robust SiC power supply chain or a merchant market wafer business. What wafers it did sell were only four inches in diameter and cost $1.5K - $4K each. High wafer cost stymied Rohm's ability to develop silicon carbide power devices, and forced it to develop its own boule, wafer, and epitaxial processes. To that end it began research on SiC epitaxial processes[10] in 2007 and acquired SiCrystal, one of only three companies producing commercial grade crystal wafers, in 2010.



SiCrystal originated in 1994 as a German government funded project for developing silicon carbide wafers. It incorporated in 1996 and began marketing its first SiC wafers

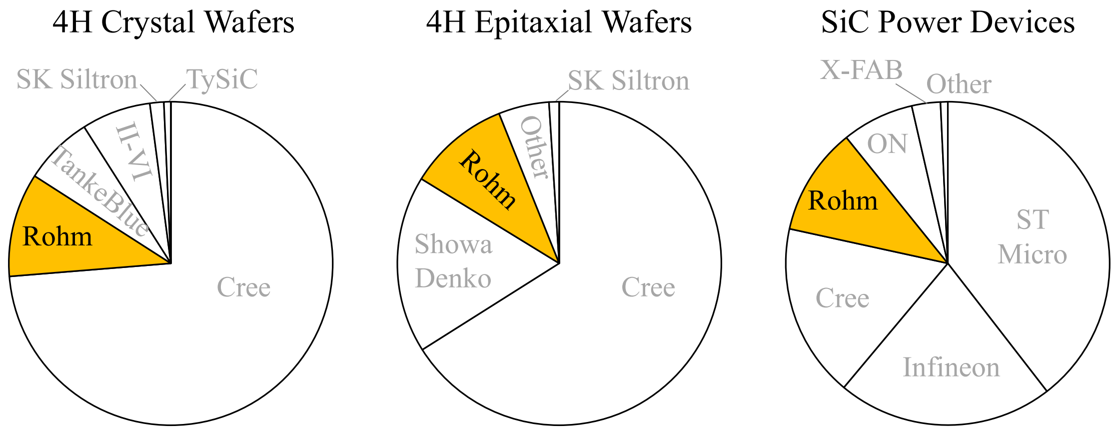
(6H) for LEDs[11,12] in 1997. In 2000 it merged with Siemens[13], which was working on SiC wafers for power applications (4H). The 4H crystal structure is easier to grow than 6H but the purity required for power devices is significantly more stringent than for LEDs so progress toward commercial quality 4H wafers was slow. By 2005 most of Siemens's/SiCrystal's output was still 6H on 4-inch wafers for LEDs. It was shipping 4H on 3-inch but production volumes didn't reach parity with 6H until just before SiCrystal was sold to Rohm in 2010. Indeed, it was likely the leap to 4-inch wafers which convinced Rohm that acquiring SiCrystal from Siemens was a more viable route to its own wafer fab than continuing with its struggling effort. Even on 4-inch diameters, Siemens's wafer costs were too high for it to consume or sell much of either 6H or 4H at the time Rohm acquired SiCrystal.

SiCrystal SiC History



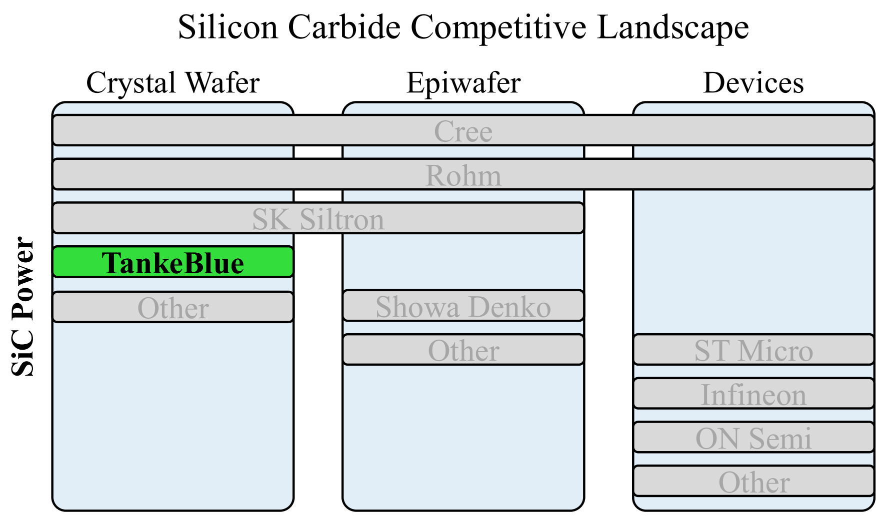
By 2015 Rohm began producing its first 6-inch wafers but didn't begin transitioning from 4-inch in earnest until 2017. In 2018, it projected a 7x increase in capacity in SiC devices by March 2019[14]. Historically, all of Rohm's wafer development was in support of its power device business so it didn't sell wafers on the merchant market. That changed in January 2020 when it signed a $120M wafer supply agreement with ST Micro, which we expect is generating $10M-$20M per year in total crystal and epitaxial wafer sales. It isn't clear if this is a one-off event spawned by Swiss-based ST Micro's concern over the stability of U.S. supply or a strategic expansion into the market for SiC wafers. The answer lies in the company's willingness to sign agreements with other power device manufacturers (Infineon, ON Semiconductor)[15]. By the date of this report, no others have been announced. The size of the ST Micro deal is dwarfed by Cree's $500M supply agreement with ST Micro and by the other $500M in agreements it has struck with other power device manufacturers.

Rohm Market Share



Rohm doesn't produce SiC wafers for RF so all of its SiC products are used in power devices, either Schottky diodes or MOSFETs. It launched production of both in 2010[16] which was late for Schottky diodes but ahead of most competitors in MOSFETs. In 2015 the company was first to market with a trench (vertical) version of the MOSFET that was touted to provide better performance[17]. In January 2021, Rohm opened a new device fab, which the company expects will increase SiC device throughput by 17X by 2025. No similar program has been announced for wafers which suggests the company's priority is to be a merchant market supplier of SiC power devices.

TankeBlue

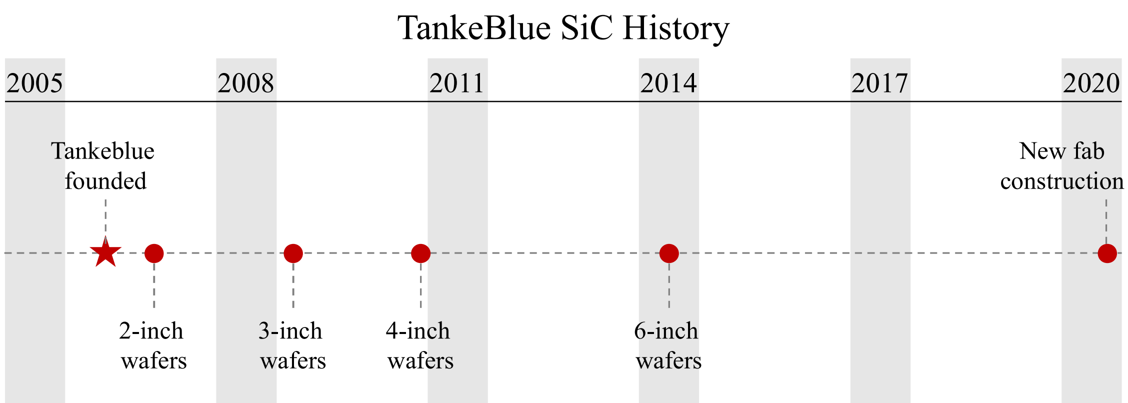


TankeBlue is a Chinese state-owned enterprise formed in 2006 to develop SiC crystal wafers based on research performed by the Institute of Physics at the Chinese Academy of Science. Although not prominent on the global market, the company is China's largest domestic manufacturer of 4H SiC crystal wafers with revenue of about $24M in 2019, with the company reporting strong growth in 2020. Virtually all of the company's wafers are sold to Chinese component manufacturers. Although it has a 6-inch process, the vast majority of its revenue derives from 4-inch wafers, all of which are 4H crystal structures for power applications.

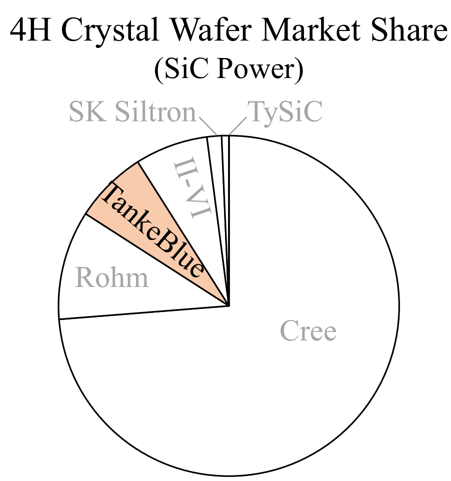
Established	2006
SiC R&D	2006
Products	SiC Crystal Wafers
Markets	Solar, Industrial, EV
Consolidated Revenue 2020(e)	$30M
Wafer Revenue 2020(e)	$30M
Share of Merchant Mkt Crystal Wafer Sales*	<5%

*Majority of wafers used for equipment testing

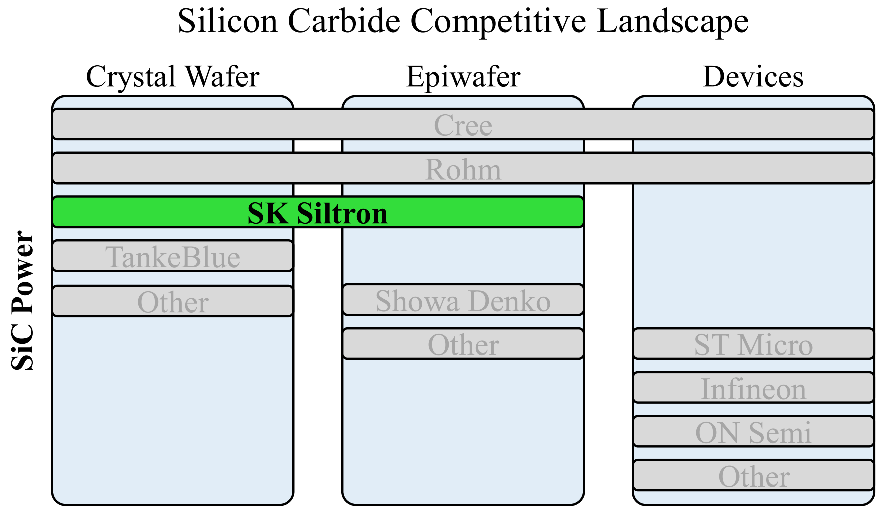
TankeBlue only produces wafer for power devices and does not produce semi-insulating wafers for RF applications. The company is developing 8-inch wafers but it remains a research project. The quality and performance of TankeBlue's wafers lag that of foreign suppliers so much (most) of its product is used to test wafer handling equipment, as sacrificial wafers for epitaxial development and for Schottky diodes. The company is developing wafers for MOSFETs but isn't likely to enter production with them in 2021. TankeBlue's headquarter facility is in Beijing and is devoted to slicing, polishing, cleaning and testing wafers from boules grown at this Shihezi facility.



It began construction on a new wafer growth facility in August 2020 and expects initial production in 2022. Once it ramps to full production, the new facility should expand its capacity to 120K although it isn't clear from company statements when it expects that to occur. As we've previously detailed, transitioning from wafer development to production is challenging and is reflected in TankeBlue's struggles with quality. With larger competitors supplying the market with higher quality wafers, we believe TankeBlue operates near break-even. The importance of silicon carbide in defense and industrial applications has made the creation of domestic sources a priority for the Chinese government, trumping the need for profit.



SK Siltron



SK Siltron[18] (SKS) (South Korea) is one of the top five global suppliers of silicon wafers[19], generating $1.5B in revenue in 2020. It had no experience in silicon carbide prior to its purchase of Dow Corning's SiC wafer fab in 2019 but intends to use its new asset to expand into the more lucrative markets for SiC crystal and epi wafers. Dow Corning struggled for more than 15 years to compete with the leading suppliers of silicon carbide but never garnered more than 5% market share. It developed wafers for both power (EV, industrial, power supply) and RF (radar, telecom) applications. Under SK Siltron, the silicon carbide group will primarily focus on 4H power wafers for electric vehicles[20]. We believe it will be several years before it becomes versant in the technology and several years beyond that before it will become competitive in the SiC wafer market.

SK siltron

Established	1983
SiC R&D	1996 (Sterling Semi)
Products	SiC crystal and epiwafers
Markets	Solar, Industrial, EV
Consolidated Revenue 2020(e)	$1.5B
Wafer Revenue 2020(e)	$5M
Share of Merchant Mkt Crystal Wafer Sales	<5%

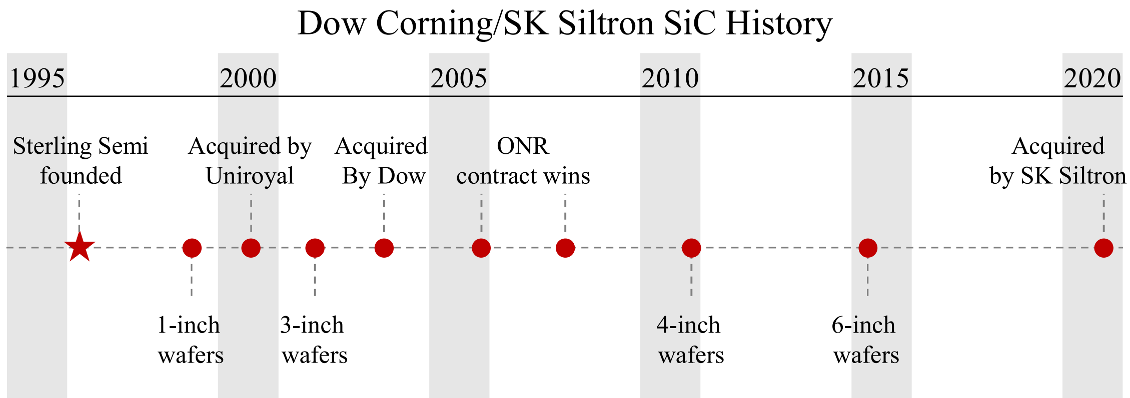
At $450M, SK Siltron's purchase of Dow's SiC group was the highest price paid for a silicon carbide wafer asset, exceeding Infineon's purchase of Siltectra by 3x. This is largely due to the fact that Dow's fab produced commercial grade wafers but also reflects the importance of silicon carbide to the future of SKS's wafer business. Because the most common semiconductor sold today is the silicon MOSFET and the second most common is the silicon IGBT[21], many of the wafers produced by SKS are consumed in the production of the very power devices that SiC will likely replace. Silicon carbide poses a serious threat to this market because MOSFETs fabricated on SiC far outperform MOSFETs or IGBTs on silicon. The disparity is so pronounced that all the large power device fabs and many of the wafer manufacturers that supply them have signed SiC supply agreements or acquired inchoate SiC product companies as a hedge against the rapid migration from silicon to silicon carbide in power devices.

Silicon Carbide M&A

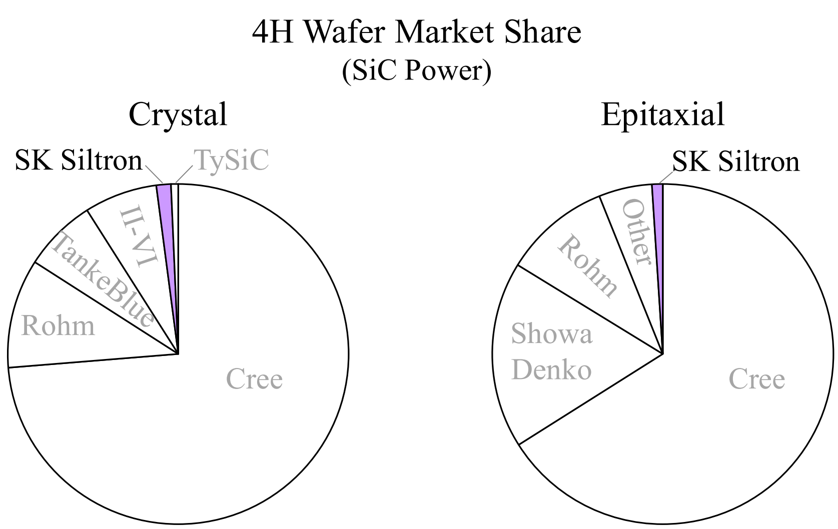
Acquirer	Target	Cost
SK Siltron	Dow Corning	$450M
Infineon	Siltectra	$146M
ST Micro	Norstel	$138M
Cree	Intrinsic	$46M
Soitec	EpiGaN	$35M
Dow Corning	Sterling	$11M

SK Siltron's purchase of Dow's fab represents the latest transaction in the long, convoluted history that began with Advanced Technology Materials (ATMI). In 1995 ATMI acquired Epitronics, a GaAs epitaxial manufacturer, in hopes of leveraging its knowledge and experience in GaAs to develop silicon carbide. The immense technical hurdles to growing SiC and the cost and difficultly of obtaining it on the merchant market led ATMI to shift its focus to GaN devices and transfer its nascent materials group to Sterling Semiconductor in 1998.

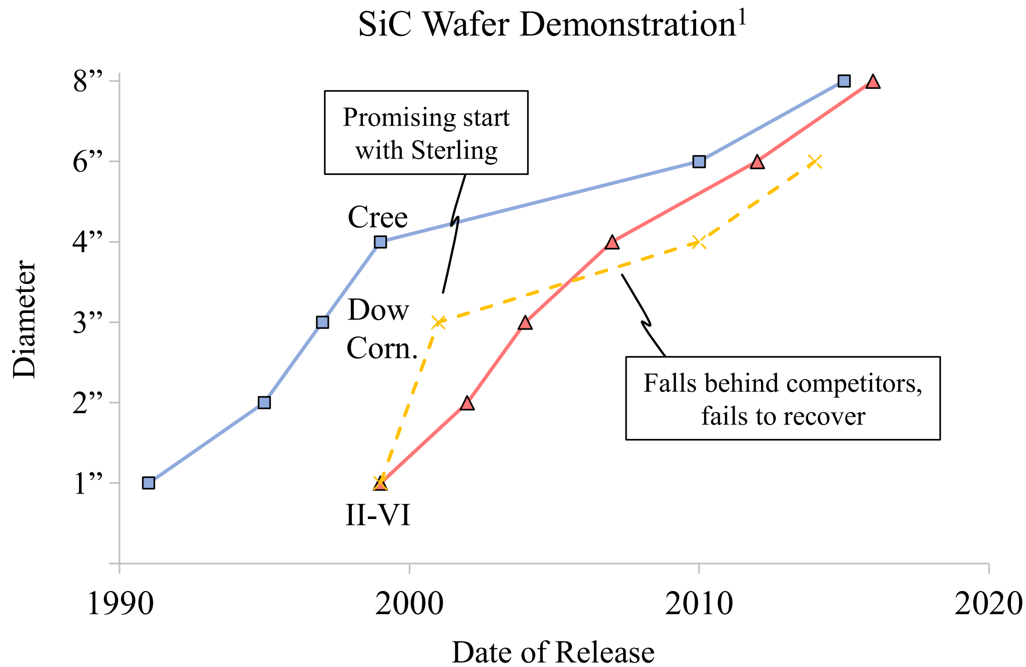
Sterling’s first years in SiC mirrored Cree’s experience with government funded research in material growth leveraged to develop wafers for light emitting diodes (LED). It produced its first 1-inch wafer in 1999 and won a DoD contract to improve the material quality the same year. Initially it divided research efforts between 4H (power) and 6H (RF, LED) wafers but shifted its focus to 6H once it was acquired by Uniroyal Technologies in 2000. After the acquisition, Sterling's wafers were used to feed Uniroyal's LED fab, but the arrangement was short-lived. By 2000 sapphire emerged as a lower cost material with comparable performance in LEDs and demand for Sterling's wafers declined. The dotcom bust pushed Uniroyal Technologies to the brink of insolvency[22], so to raise capital it agreed to sell Sterling for $13M to Umicore in early 2002. That deal fell through in June 2002 and Uniroyal filed for bankruptcy in August. After entering chapter 11, Uniroyal put Sterling on the block to generate capital but received only one bid from Dow Corning, which purchased the group in January 2003 for $11M.



For most of its history Sterling was a leading developer of SiC wafers, and often participated in research programs alongside Cree and SiCrystal (Rohm). That changed when Uniroyal Technologies acquired the company and diverted its efforts to 6H wafers for LEDs. From that point on Sterling fell behind and was never able regain parity with the leaders. Prior to 2010, 6H wafers (RF, LEDs) found little use outside government-funded research while 4H wafers (power devices) were in commercial production by 2004. Once Dow Corning gained control, Sterling's focus returned to 4H wafers but by then several new competitors had entered the market and the leaders were well ahead in size, quality and cost.



In 2005 and 2007, Dow won contracts with the Office of Naval Research to improve the quality and increase the size of its wafers from 3-inch to 4-inch but at that point II-VI was already producing 4-inch wafers and Cree was well on its way to 6-inch. Dow finally offered 4-inch crystal wafers in 2010 and an epitaxial version later that year. It didn't offer a 6-inch product until 2014, several years after competitors.

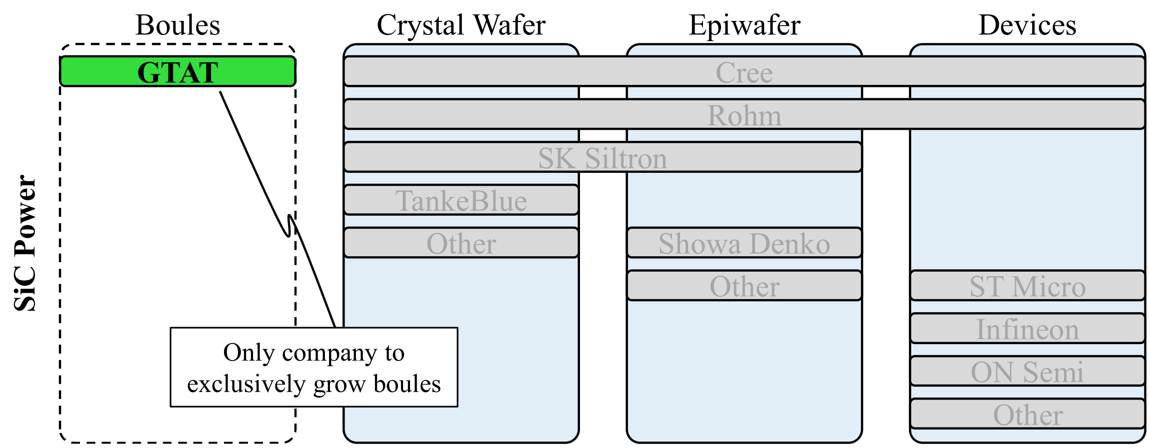


[1] New product announcements, not production

Demand for SiC wafers grew considerably throughout the 2010s but with Dow chronically behind in size, quality and cost, its market share never exceeded 5%. In 2019 it abandoned its efforts and sold Sterling to SK Siltron, which in March 2021 announced it'd be making substantial investments in its silicon carbide wafer capacity. SKS is well resourced but it's unlikely a new owner with no experience can quickly master the problems that plagued Dow Corning. The vast dissimilarities between silicon and silicon carbide foreclose much of SK Siltron's experience leaving it in a similar position as Dow when it acquired Sterling in 2003. The complexities of silicon carbide material growth are well established and will likely lead to a long learning curve for SKS, just as they have for every company that has undertaken the effort. Accordingly, we believe its market share in SiC wafers will remain below 5% for at least the next three years.

GT Advanced Technologies

Silicon Carbide Competitive Landscape



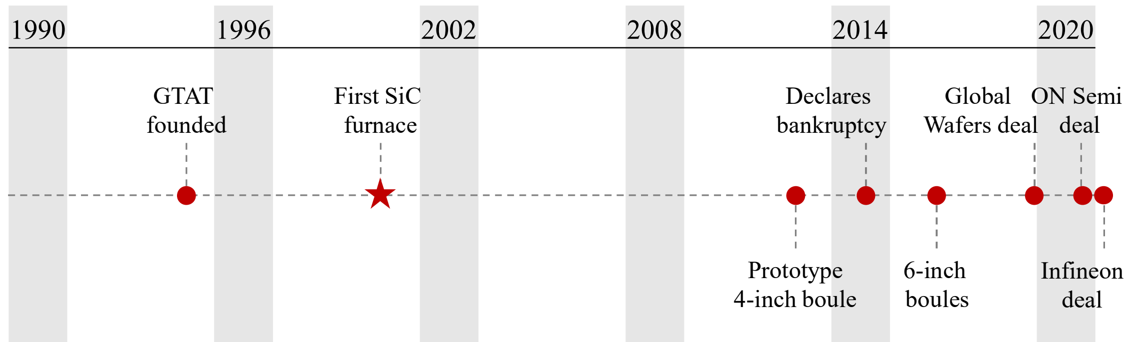
GT Advanced Technologies (GTAT) was founded in 1994 as a semiconductor equipment manufacturer specializing in furnaces for growing boules. It entered the materials market in 2010 with the purchase of a sapphire growth company called Crystal Systems. Three years later when it signed an agreement to mass produce sapphire screens for iPhone, material sales accounted for about 10% of revenue ($30M). Management expected that to increase to $500M - $600M with the new Apple business but the endeavor ended before it produced any revenue. GTAT's failure to meet quality and delivery targets led Apple to withhold a loan payment[23] in April 2014, and six months later GTAT declared bankruptcy.

GT ADVANCED TECHNOLOGIES

Established	1994
SiC R&D (furnaces*)	2000
Products	SiC Boules
Markets	Solar, Industrial, EV
Consolidated Revenue 2020(e)	$100M
Boule Revenue 2020(e)	$10M
Share of Merchant Mkt Crystal Wafer Sales	0%

*boule sales began in 2016

GT Advanced Technologies SiC History



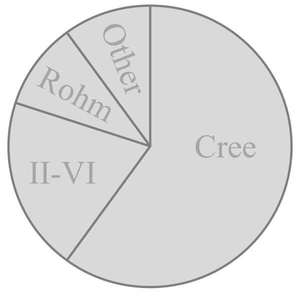
It emerged from bankruptcy in 2016 but endured shareholder and underwriter litigation for several more years. In December 2019, the company and former CEO consented to SEC antifraud charges for statements and actions during the Apple agreement. After exiting bankruptcy, GTAT began marketing itself as a source for SiC crystal material. As with sapphire, its experience in silicon carbide is in manufacturing furnaces, not growing materials.

Growing boules is arguably the most difficult step in the SiC supply chain. In fact the path to commercial grade SiC is so arduous that of the two dozen companies that have attempted it in the last 40 years, only three have more than 10% share and they account for over 90% of the market. More importantly, all three have spent more than 25 years perfecting their processes which necessarily involve customizing furnaces. Cree, which produces over 60% of the SiC crystal wafers used in device production today, designs and builds its own furnaces while II-VI (20% share of wafer production) and Rohm (10%) modify merchant market equipment. This is expensive and time consuming but it's the only proven path to growing boules of sufficient purity to generate high quality wafers.

The time and energy required to grow a SiC boule is substantial, but of equal or greater importance is process control. As we explain in detail in our "Silicon Carbide: Extremely hard and incredibly powerful" (March 31, 2020) publication, the multitude of problems encountered in the growth of silicon carbide impair yields to the point that most wafers from most firms are expensive or unusable or both. The inability to master the growth process has been the undoing of many SiC startups. Those that have succeeded did so after more than a decade developing custom processes, all of which are now trade secrets. By contrast, GTAT only entered the SiC market four years ago and all of its experience is in manufacturing merchant market furnaces, not boule growth, crystal wafer manufacturing, or epitaxial processes.

Crystal Wafer Market Share
(production)

GTAT (none)



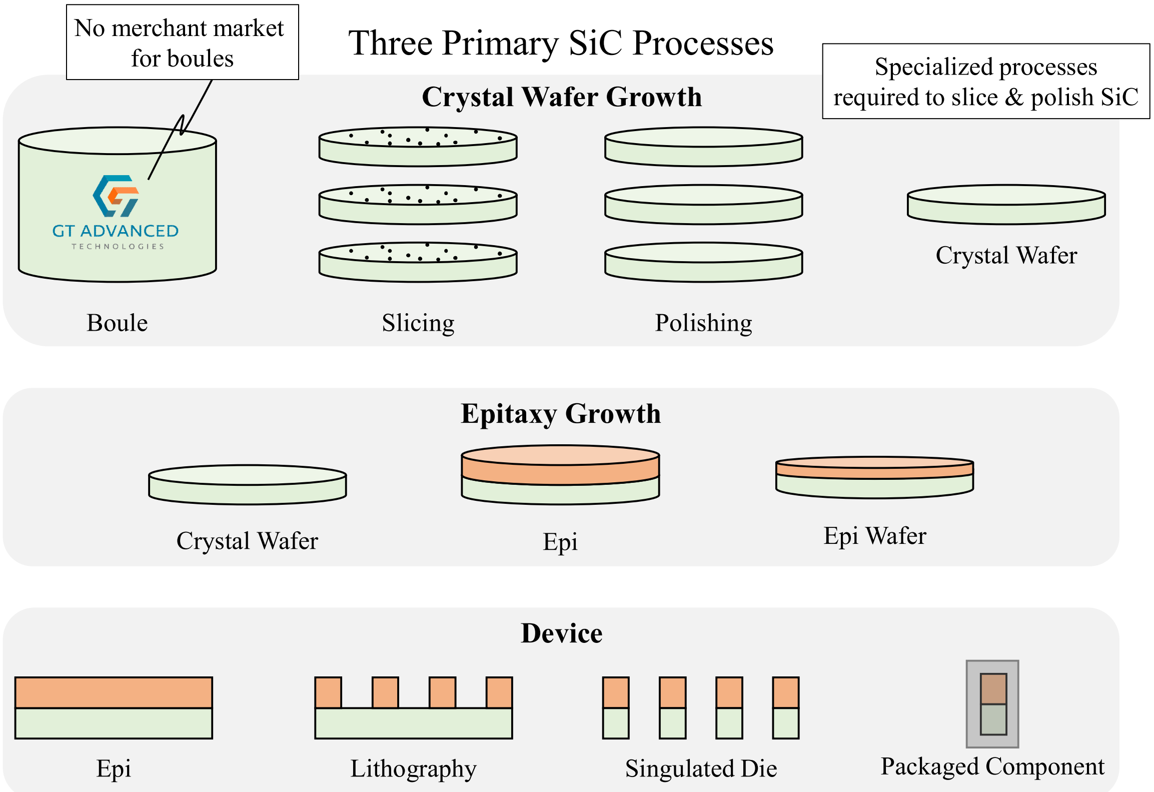
Cast in this light, the company's recent statements about the size and proficiency of its SiC material growth are problematic, particularly the CEO's November 2019 claims to be,

> *"…growing material at sizes and yields that nobody else, including the guys who've been doing for 20 years [are doing]."*
>
> *"We're operating at yields that are what we call silicon yields. In this industry that's very rare. Most people operate 30% yield, 60% yield, really high would be a 70% yield, we're far beyond that"*
>
> *"…yields for crystal growth…in the very, very high nineties"*

These assertions are difficult to reconcile with GTAT's lack of experience in silicon carbide and the fact that it doesn't produce wafers, only boules.

The slicing, polishing and epitaxial deposition operations required to turn a boule into a usable crystal wafer weigh heavily on material loss and yields, making it difficult to predict wafer costs based on boule yields. Indeed, many of the defects that impact wafer yields don't show up until the epitaxial layer is applied. This makes GTAT's statements about yields, and investors' correlation of those to Cree and II-VI, an apples-to-diamonds comparison[24].

The fact that GTAT plans on producing boules and not wafers will also make it difficult to find customers. The SiC supply chain doesn't include merchant market slice and polish operations so it will be difficult for GTAT to find companies that can perform those steps that don't already produce their own boules. Cree, II-VI and Rohm have their own slice and polish facilities but they grow their own material. Firms that add epitaxial layers such as Showa Denko (SiC epi) and IQE (GaN epi) buy wafers and therefore have no commercial facilities for slicing and polishing silicon carbide. Similarly major device manufacturers like ST Micro (SiC power) and Raytheon (GaN RF) purchase crystal and/or epitaxial wafers.

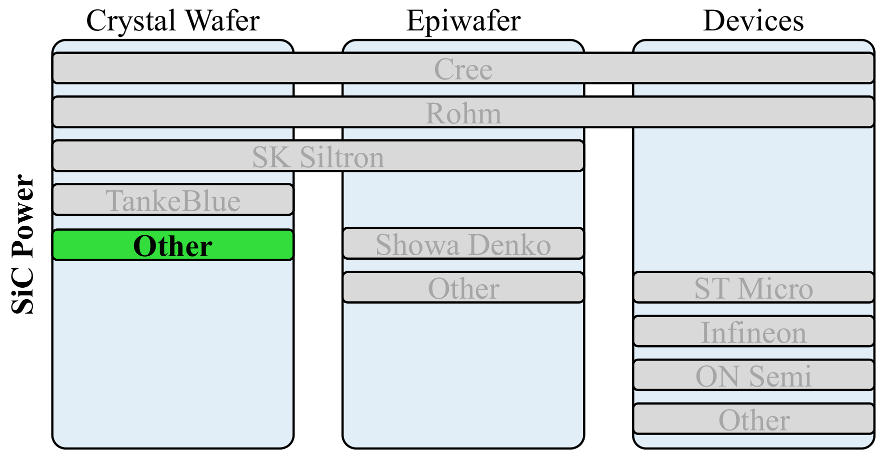


Infineon, GlobalWafers, and ON Semiconductor have signed supply agreements with GTAT, but we expect Infineon and ON Semi wanted a source of boules to test internal processes, whereas GlobalWafers has virtually zero presence in silicon carbide. Infineon is developing its experimental Cold Split process, gained through the 2018 acquisition of Siltectra, and needs boules for testing. ON Semiconductor is developing its own wafer production process and likely agreed to purchase boules from GTAT so it could test its slicing and polishing procedures without waiting until its crystal growth process is perfected. The devices Infineon and ON Semiconductor do produce are fabricated on wafers supplied by Cree, not GTAT, so as of yet, there is no reliable data on yields for GTAT's boules in commercial production. We therefore believe GTAT's assertion of 50K SiC wafers per year, and of going "*from having no factory to having the third largest crystal (SiC) factory in the world [in one year]*" are unrealistic. None of the commercial SiC devices produced this year or last use the company's material and its share of the SiC crystal wafer market is effectively zero.

The proof of GTAT's claims should be evident soon enough. If the spirit of management's statements are true, and GTAT is growing larger boules than Cree, II-VI and Rohm, with high-90% yields at "*cycle times less than half, closer to a third of the cycle times of the other industry leaders in less than a sixth of the power, less than half the footprint…*" the cost and quality of the material GTAT supplies to Infineon, ON, and GlobalWafers will be far superior to what competitors are receiving from incumbent suppliers. As a result, we should see Infineon and ON gain substantial market share at the expense of STM and Cree. If instead, GTATs comments are more in the mold of those made about its sapphire capabilities during its short relationship with Apple, we expect little penetration of the SiC device market by GlobalFoundries, for Infineon to maintain its current market share, and for ON Semiconductor to show slow but steady growth as it competes with incumbent device manufacturers using wafers purchased from Cree.

Soitec

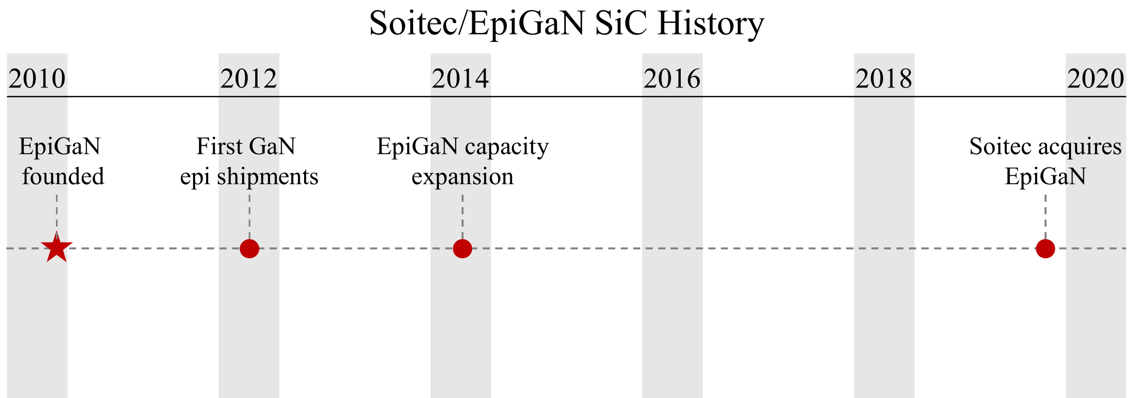
Silicon Carbide Competitive Landscape



Soitec manufactures and is a merchant market supplier of silicon on insulator (SOI) wafers used extensively in RF components for handsets. Because performance of SOI is superior to other materials for low-power RF devices but varies significantly with temperature, it's necessary to bond a thin layer of the material to a more stable, inexpensive substrate such as silicon. The process for accomplishing this is called Smart Cut and is used to produce all the company's SOI wafers. Soitec also markets Smart Cut as a method for developing specialized engineered substrates for other applications.

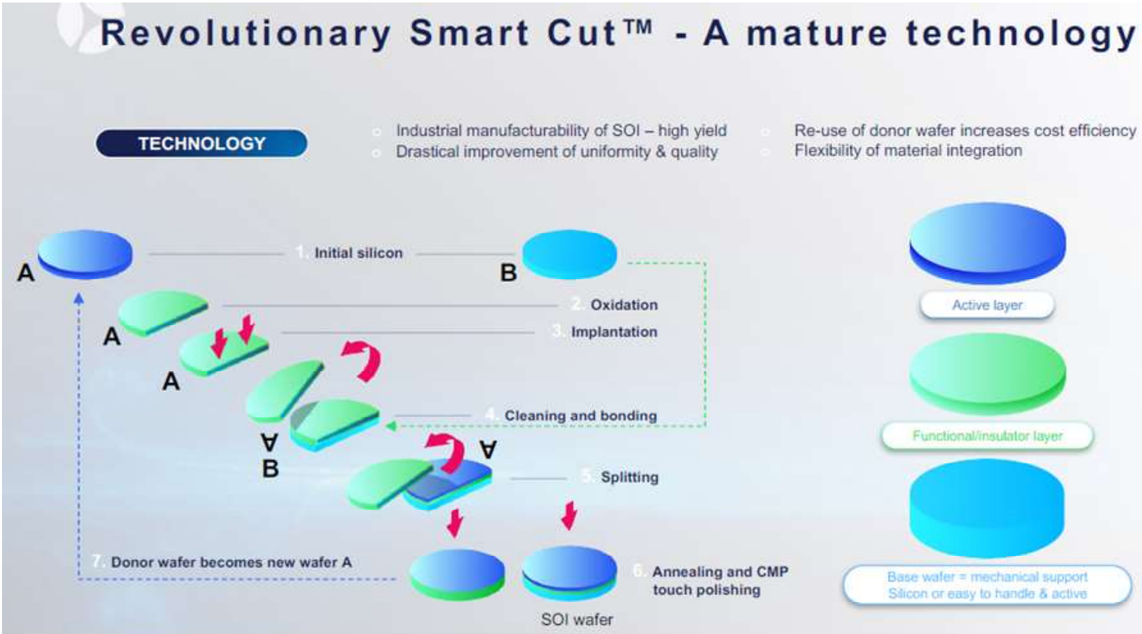
soitec

Established	1992
GaN R&D	2010 (EpiGaN)
Products	GaN Epiwafers
Markets	Telecom
Consolidated Revenue 2020	$723M
Wafer Revenue 2020(e)	de minimis
Share of Merchant Mkt Epiwafer Sales	0%



Soitec is now looking to use Smart Cut to reduce the cost of silicon carbide wafers. It began working on SiC with its purchase of EpiGaN in 2019. As its name implies, EpiGaN developed methods for depositing GaN epitaxial layers on silicon and silicon carbide wafers. It was founded in 2010 and was still in "startup" mode when it was acquired in May 2019. Soitec followed that acquisition by launching a joint development program with Applied Materials in November 2019. The effort will combine Soitec's Smart Cut process with Applied Materials' technology and equipment to produce engineered SiC substrates. The initial goal was to have a wafer fabrication operation by early 2020[25] but more recent statements suggest production won't begin until 2023.

If successful, Smart Cut for SiC will enable the company to enter the merchant market with low-cost crystal wafers or GaN wafers using EpiGaN's epitaxial process. Accomplishing this requires it purchase high-quality SiC wafers from Cree and II-VI, slice them into many thin layers, and deposit those layers on lower cost, handle substrates[26]. Smart Cut is in production on SOI today but getting it to work with silicon carbide will be difficult because several of the properties that make SiC an excellent material for high power devices are incompatible with steps of the Smart Cut process.



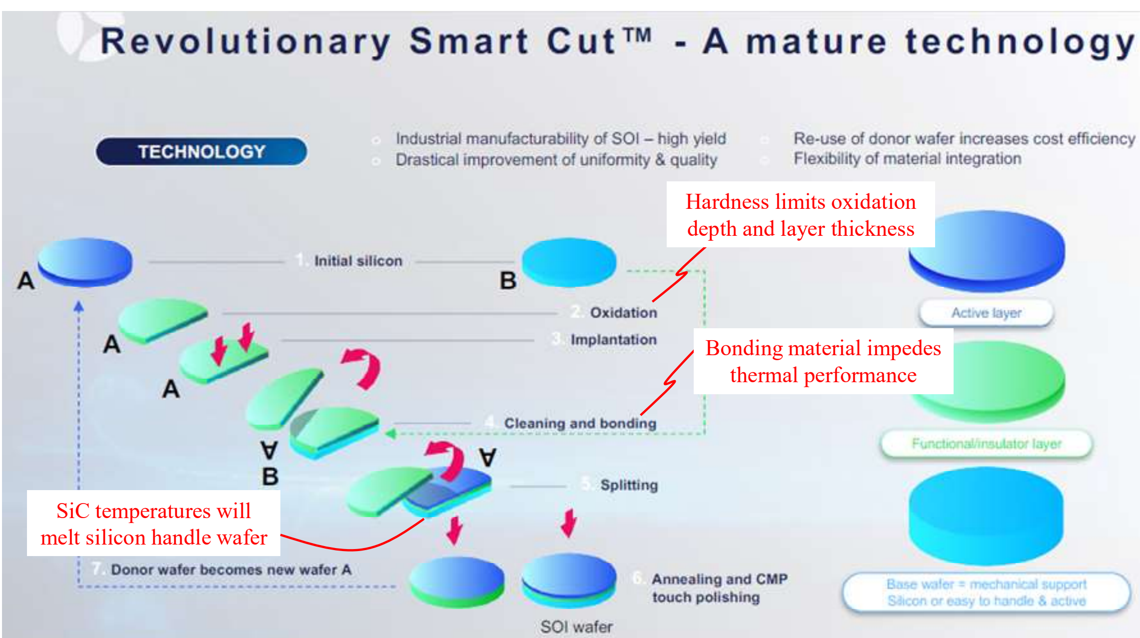
To cleave a thin layer from the donor wafer, Smart Cut bombards the top surface with oxygen to implant ions to a specific depth, usually about 1 – 2 microns. It then flips the wafer over and bonds the ion implanted surface to the top of a "handle" substrate. Once the two wafers are joined, the donor is "snapped" off halfway through the ion layer, leaving an engineered wafer that combines a thin, precisely defined layer of SOI and a low-cost, stable silicon substrate.

The point of Smart Cut is to improve performance, not reduce cost. Neither SOI nor crystal silicon are expensive so adding process steps to divide an inexpensive wafer into thin layers doesn't impact BOM cost enough to justify the effort. It does however improve performance. The temperature and RF characteristics of a thin, precisely controlled layer of SOI is substantially better than of a thick wafer. Bonding that layer to a silicon handle substrate doesn't impair performance or add appreciably to the cost so engineered SOI-on-Si wafers are economically viable. That isn't the case for other materials, however. Materials that contain a lot of defects or are poor matches to silicon have not worked well with Smart Cut. A decade-long effort with Sumitomo to develop a cost-efficient means of producing GaN crystal wafers, similar to SiC crystal wafers, from GaN boules was plagued with problems. Like silicon carbide, defects in crystal GaN occur across the surface and penetrate down into the material. Slicing an ingot into thin layers exposes defects that aren't visible on the surface. GaN is also used for high-power devices so the handle wafer has to be thermally matched and conduct heat well. Attempts to use different materials for the handle wafer provided futile, and after more than ten years, the effort was shuttered.

By almost any measure, silicon carbide is on the opposite end of the performance universe from SOI. It was developed for large, high-power semiconductors fabricated on thermally efficient substrates that conduct heat away from the semiconductor. Smart Cut is used to fabricate small, thin, low-power devices on an electrical and thermally insulating handle substrate. Virtually nothing it's designed to do is a good fit for SiC power devices. Indeed, fabricating high power, high frequency devices on any material other than silicon carbide reduces performance appreciably so using Smart Cut to bond a thin layer of SiC to a non-SiC substrate incurs a steep performance penalty. It is also more expensive because the defects it exposes lower yields.

The extreme hardness of SiC also poses problems for Smart Cut. Silicon carbide is more than five times harder than silicon, which makes slicing thin layers from a thick crystal wafer substantially more difficult. The ion implantation process used by Smart Cut to create a 1.5 micron layer in SOI only penetrates about 0.4 microns in SiC. This is too thin for power components like MOSFETs which require 2 – 3 microns or for RF power transistors which require 1 micron. Thicker layers could be produced, but the size and energy required for the implanter would be substantially larger and the cost materially higher. Given the entire purpose of using Smart Cut on SiC wafers is to reduce cost, anything that increases the cost of Smart Cut or reduces yields and performance is counterproductive. This is especially true if the wafers are too thin to be used for power devices (MOSFETs, diodes), which is the largest market for silicon carbide wafers.

Today, Smart Cut is only used in production on silicon-based substrates, primarily high-frequency SOI and piezoelectric (filters) devices operating at relatively low power levels. It seems the further it moves away from this sweet spot, the less useful it becomes.



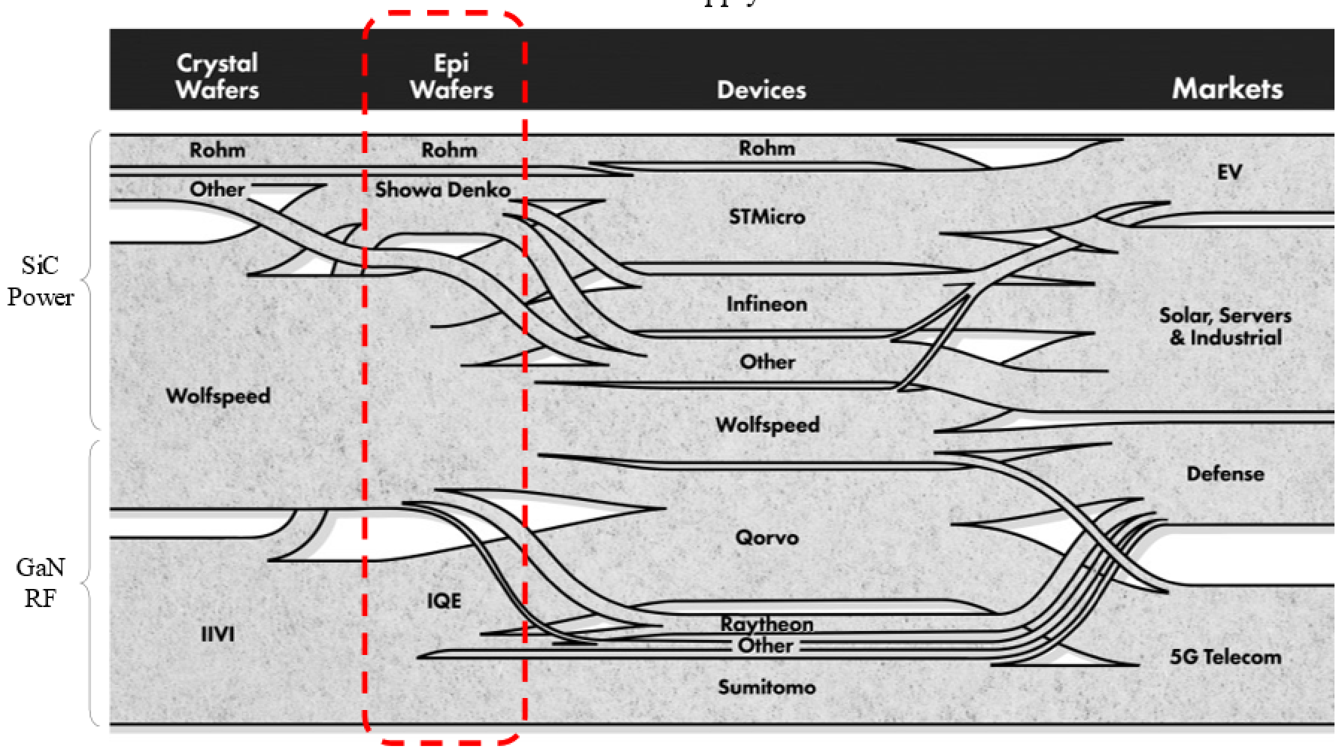
The "glue" used to bond the thin cleaved wafer to the donor substrate creates another hurdle. The silicon dioxide used by Smart Cut to bond the donor wafer to the handle substrate is a thermal and electrical insulator. Neither of those characteristics are well suited for the types of devices fabricated on silicon carbide. The MOSFETs and RF transistors driving demand for SiC generate copious amounts of heat. Normally that heat is whisked away by the SiC substrate which has a thermal conductivity similar to aluminum. Silicon dioxide's thermal conductivity is more than 200 times lower, or expressed another way, the resistance to heat flow is 200 times higher, so using it to bond SiC to a handle substrate significantly reduces the power rating of whatever device is fabricated on the engineered wafer. Silicon dioxide is also an electrical insulator so none of the devices fabricated on the SiC layer could penetrate into the handle substrate, even if it were highly conductive material like heavily doped silicon. The cleaved SiC donor layer would have to be thick enough to accommodate large vertical devices, making ion implantation even more problematic.

The high temperatures used to process SiC wafers are perhaps the biggest impediment to using Smart Cut. The shortest path to applying Smart Cut to SiC would be to reuse as much of the process and materials currently in production with SOI. That isn't possible though because all the products generated by Smart Cut use silicon as the handle substrate which has a melting point below the temperatures used to process silicon carbide wafers. If used as the handle substrate, a silicon wafer would liquefy when the epitaxial layer is applied to the SiC wafer. A higher temperature material such as sapphire could be used but it's substantially more expensive than silicon and its thermal and material properties are poorly suited for the types of devices fabricated on SiC. It has been suggested that low-quality, low-cost silicon carbide wafers could be used as the handle substrate. Doing so would minimize thermal and electrical mismatch problems but increase cost which defeats the purpose of applying Smart Cut to SiC.

Many of the problems of applying Smart Cut to silicon carbide can be avoided by using low-quality, low-cost SiC wafers for the handle substrate. Thousands of these wafers are produced every year by firms struggling to perfect their growth process. High defect densities render them unusable for anything but test substrates, but even low-quality SiC wafers conduct heat more efficiently than silicon and will withstand the temperature of epitaxial and annealing processes used to manufacture GaN wafers. Unfortunately, the difference in cost between a bad SiC wafer and a good SiC wafer is probably not large enough to justify the expensive of Smart Cut. Moreover as Cree and II-VI increase wafer diameters, improve yields and expand production, high-performance wafer ASPs decline, further narrowing the premium Soitec is aiming to exploit. In addition as TankeBlue and other suppliers improve their growth processes, the cost of low-quality wafers increase. With the ceiling dropping and the floor rising, the margin stack required to pay for Smart Cut on SiC will be trampled if it hasn't been flattened already. Indeed, we expect the volume pricing Cree and II-VI provide to their largest customers (ST Microelectronics, Infineon, Sumitomo, Qorvo) is substantially lower than what Soitec would receive for the few wafers it would sell. It's also likely the wafer transfer price between Cree and Wolfspeed is lower than the volume pricing it provides its largest customers, and far below what Soitec would pay. Even if Soitec could overcome the technical problems of applying Smart Cut to SiC, we don't believe there'd be enough margin to justify the effort.

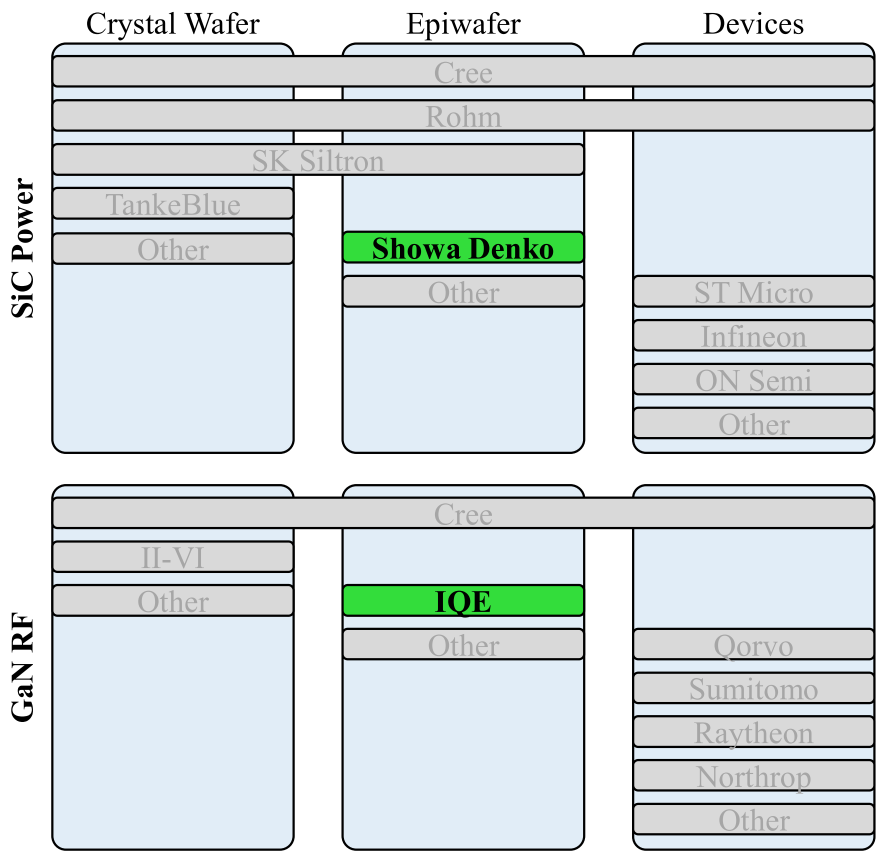
Epitaxial Wafers

SiC and GaN Supply Chain



IQE & Showa Denko

Silicon Carbide Competitive Landscape



In the silicon carbide supply chain, Showa Denko and IQE are merchant market suppliers of epitaxial wafers. They purchase crystal wafers, add semiconductor layers to create epitaxial wafers, and sell those to component suppliers who use them to manufacture devices. The need for merchant market epitaxy is driven by the technological complexity of SiC, which prevents most crystal wafer manufacturers from developing production epitaxy processes[27]. It also lowers working capital requirements for component suppliers like ST Micro, Infineon and Qorvo. Rather than stock the wide variety of epi wafers required to fab the different devices they supply, they can purchase built-to-order wafers. Even Cree and Rohm, which produce their own SiC epi, use merchant market epi wafers to supplement internal capacity during periods of high demand.

SHOWA DENKO

Established	1939
SiC R&D	2005
Products	SiC Epiwafers
Markets	Solar, Industrial, EV
Consolidated Revenue	$9.1B
Wafer Revenue 2020(e)	$35M
Share of Merchant Mkt Epiwafer Sales	10%

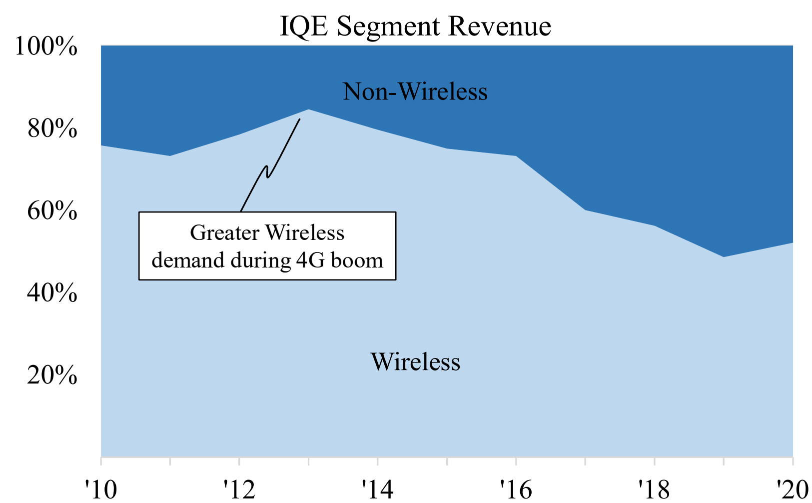
IQE

Established	1988
GaN R&D	Early 2000s
Products	GaN epiwafers
Markets	Telecom, Radar
Consolidated Revenue	$212M
Wafer Revenue 2020(e)	$50M
Share of Merchant Mkt Epiwafer Sales	15%

The arduous process of developing SiC and GaN epitaxy processes motivated crystal wafer supplier II-VI to acquire two SiC epitaxy companies[28] in 2020. The effort required to perfect and bring those processes to production[29] has kept II-VI relying on IQE and Showa Denko for epi services. Between the scale advantage of working with multiple crystal wafer manufacturers and supplying multiple device fabs and good visibility into industry trends and requirements in SiC epi, we believe IQE's and Showa Denko's share will increase as use of SiC expands.

IQE

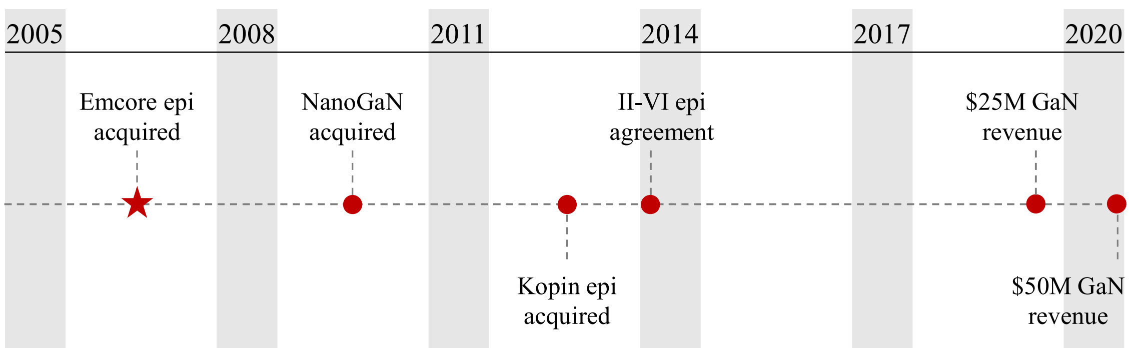
IQE is based in the United Kingdom and produces a variety of epitaxial wafers using compound semiconductor materials[30]. Revenue is divided between Photonics, which includes wafers for lasers and optical sensors, and Wireless, which supplies GaAs and GaN epi wafers for devices used in handsets and base stations, respectively. Robust demand for GaAs during the 4G boom in 2013 drove Wireless to more than 80% of total revenue, while the rise of PON and optical interconnects in cloud data centers pushed that down to 52% by 2020.



The company was established as Epitaxial Product International in 1988 and rebranded as IQE in 1999 after a merger with U.S. based Quantum Epitaxial Designs (QED). Epitaxial Product International produced epi wafers for optoelectronics whereas QED's targeted radio frequency applications. Combining markets, geographies and technologies[31] enabled the merged company to gain scale rapidly, leading to an IPO shortly after the merger. Consolidated revenue grew from $25M in 2005 to $117M in 2012.

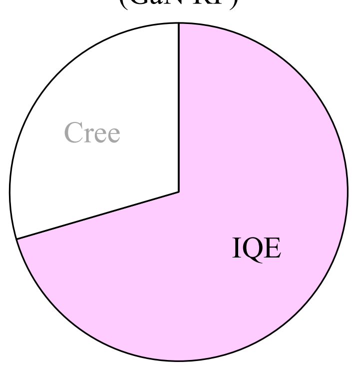
IQE developed an internal GaN epitaxy process in the early 2000s and bolstered its GaN operations through the acquisitions of Emcore's GaN epitaxy business (2006), NanoGaN (2009), and Kopin's GaN epitaxy business (2012). Other than government-funded projects, demand for GaN devices remained low until about 2014 when the increase in wafer diameters and higher yields reduced substrate cost sufficiently for device manufacturers to use SiC for high-performance applications.

IQE GaN History



The largest suppliers of GaN epitaxial wafers are IQE followed by Cree. In 2019, IQE generated $25M in GaN sales (15% of total revenue), which increased to $50M in 2020 on strong demand from 5G deployments in China. Cree supplies GaN epi wafers on the merchant market but consumes much of its output in the production of its own devices[32]. Although it prioritizes SiC power over GaN, the lack of qualified epitaxial wafer suppliers suggests it will remain IQE's largest competitor for the foreseeable future.

6H Epiwafer Market Share
(GaN RF)



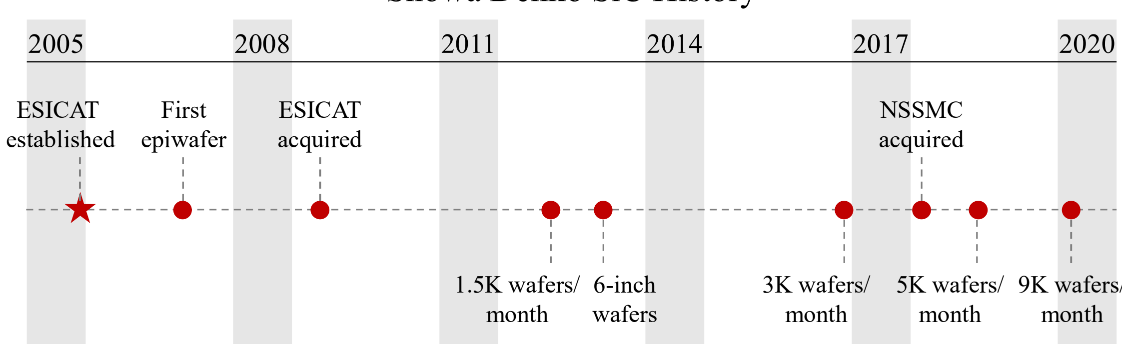
There are a variety of smaller firms striving for a place in the GaN epi market but as of yet, their share is immaterial. EpiGaN was a small competitor in GaN until it was acquired by Soitec in 2019. Soitec touted it as a leading European supplier of epi wafers[33], but the €30M price tag suggests EpiGaN was still in "startup mode" despite nearly 10 years of effort. Soitec is experimenting with methods of manufacturing silicon carbide wafers (see the "Soitec" section for details), none of which have usable yield results thus far. Should it succeed we expect its next step would be to use EpiGaN to develop a production GaN epitaxy process, allowing it to enter the merchant market for GaN epi wafers. We believe it's unlikely to pose a competitive threat to IQE or Cree in the foreseeable future.

Showa Denko

Showa Denko was established in 1939 and has become a leading Japanese chemical manufacturer. Revenue exceeded $9B in 2020, divided between Materials[34] (31%), Petrochemicals (20%), Chemicals (16%), Electronics (10%), Inorganics (9%), Aluminum (8%), and Other (11%). Generous cash flow from the chemical business enabled Showa Denko to become one of the few non-semiconductor companies to develop silicon carbide epitaxial wafers. It began research into silicon carbide in 2005, the same year it established the ESICAT joint venture with multiple Japanese research institutes to accelerate the development of SiC epitaxy processes. Prototype wafer sales began in 2006 and in 2008 Showa Denko acquired all of ESICAT. It transitioned from 4-inch to 6-inch diameters in 2012 and began a capacity expansion program in 2016 that increased throughput from 3,000 wafers per month to over 9,000 by 2019.

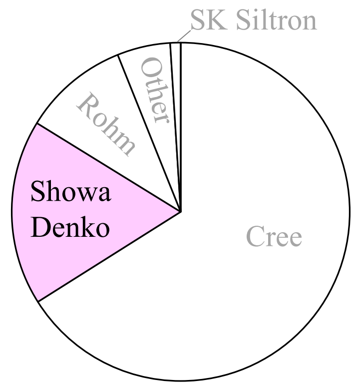
With SiC epi in production, Showa Denko moved to acquire crystal wafer growth technology in 2017 by purchasing the crystal wafer assets of Nippon Steel-Sumitomo Metal Corporation (NSSMC). After nearly a decade of investment, NSSMC had failed to gain market share and didn't believe further investments would bear results so it essentially handed the division to Showa Denko. NSSMC was well behind Cree, II-VI and Rohm in performance and yields (cost) in SiC crystal wafers and as the market for SiC power devices gained momentum beginning in 2019, the gap increased. We believe Showa Denko has yet to perfect NSSMC's process and will need to devote years and substantial R&D and CAPEX to compete with Cree and Rohm in the crystal wafer merchant market.

Showa Denko SiC History



It's a different story in SiC epitaxial wafers where the company has become the second-largest merchant market supplier and manufacturer behind Cree. It purchases the majority of its crystal wafers from Cree but also buys wafers from smaller suppliers such as Dow Corning (now SK Siltron) and TankeBlue. We estimate Showa Denko generated $30M-$40M of silicon carbide epi wafer sales in 2020, accounting for less than 1% of consolidated revenue. In fact, the business is such a small component of consolidated results it was included in the "Other" segment until being transferred to the Electronics segment in 2019. The company derives most of its SiC revenue from the industrial market but is targeting EVs. In December 2020 it signed an agreement to supply Japanese automotive company Denso with SiC materials for electric vehicles. Excluding Tesla, demand for SiC power devices by automotive OEMs isn't expected to become material until 2022[35].

4H Epiwafer Market Share
(SiC Power)



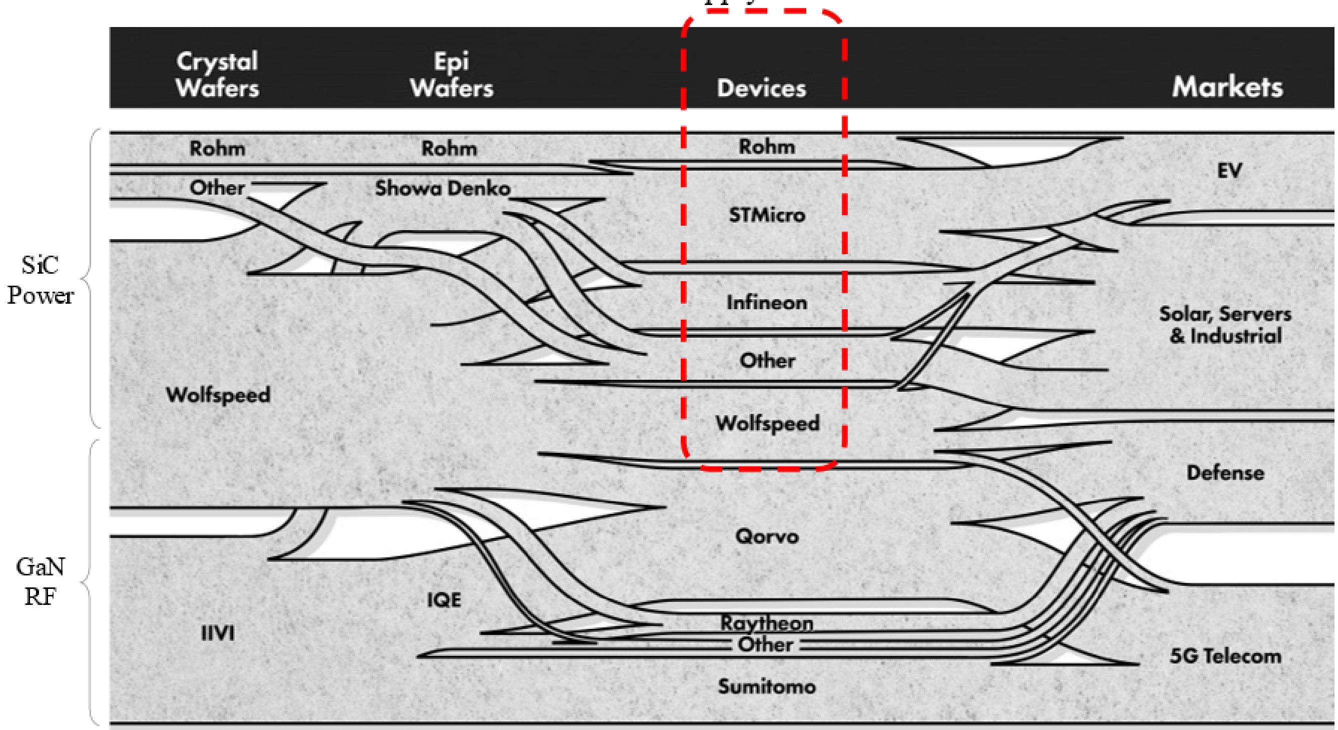
In the SiC epi wafer merchant market, Showa Denko is the second-largest supplier behind Cree. Cree has a substantial scale advantage but consumes many of its epi wafers internally for SiC power device fabrication. Moreover a large portion of its wafer capacity is dedicated to long-term supply agreements with power device companies. With many of Cree's wafers reserved for internal production and long-term supply agreements, Showa Denko can absorb the demand which Cree can't fulfill.

Rohm Semiconductor is the third-largest manufacturer of SiC epitaxial wafers, but virtually all of its production is consumed in the production of its own devices. Other than the $120M wafer supply agreement with ST Microelectronics in January 2020, it has not participated in the SiC epi wafer merchant market. It is unclear whether the agreement with ST was Rohm's first step or its only supply agreement, but the lack of additional announcement leads us to believe it was a one-off event (See our note "ST Micro/Rohm wafer deal has little impact on Cree." January 22, 2020).

Similar to Showa Denko, EpiWorld sells SiC epitaxial wafers on the merchant market and does not compete in crystal wafers or devices. It is the 3rd largest supplier of silicon carbide epi wafers following Cree and Showa Denko. It primarily serves its domestic Chinese market and claims to produce over 60,000 wafers per year, but its wafers are rarely used outside China. We expect that is largely due to low yields. The high cost of silicon carbide precludes its use in low-performance applications, so it is difficult for companies struggling with quality to gain market share because there is no low-end market for SiC devices. Incumbent wafer and device manufacturers usually require many years to improve wafer yields to the point where they're viable in production. Showa Denko spent more than 15 years developing a production SiC epi process and is still working on crystal wafer growth, three years after acquiring NSSMC and 13 years after NSSMC began work. EpiWorld was established in 2011, so we expect it is years away from achieving high enough quality to challenge Showa Denko's or Cree.

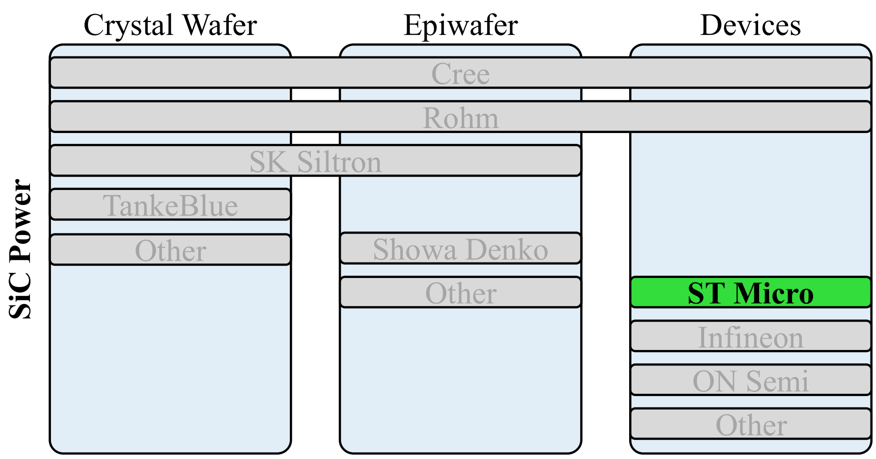
SiC Power Devices

SiC and GaN Supply Chain



ST Microelectronics

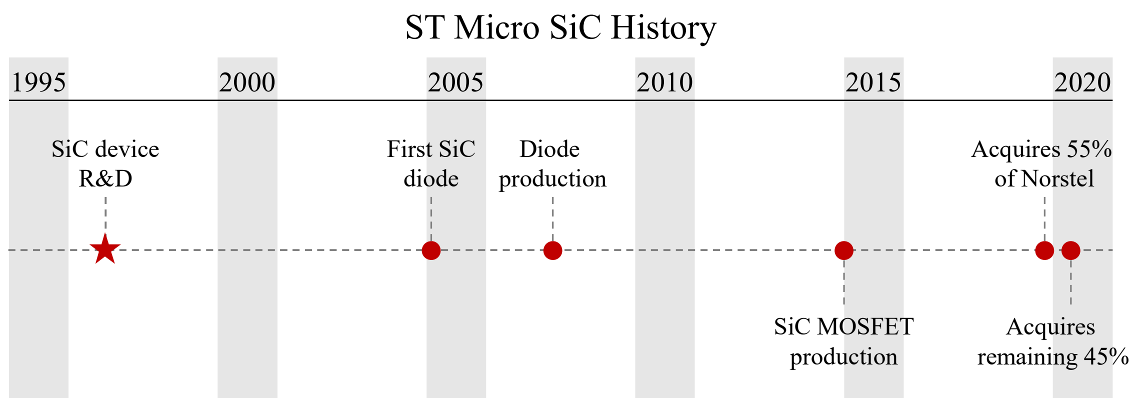
Silicon Carbide Competitive Landscape



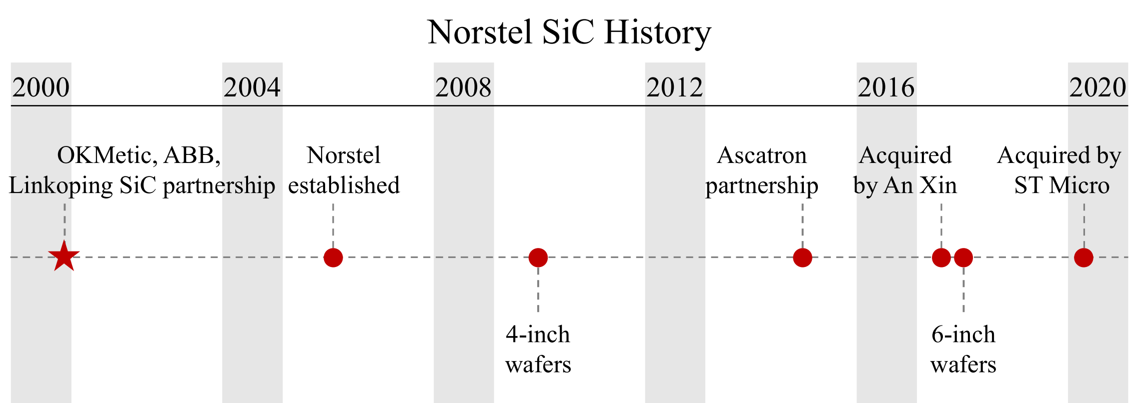
ST Microelectronics (STM) is the largest supplier of SiC power devices, most of which were MOSFETs used in the inverter of Tesla's Model 3 BEV (battery electric vehicle). SiC devices sales accounted for \$100M in 2018, growing to \$250M-\$275M in 2020. The sales into industrial applications and growth in demand for Model 3 will drive SiC revenue to \$475M-\$500M in 2021. Its silicon carbide power devices are fabricated at the company's Catania, Italy factory which sources the vast majority of its crystal and epitaxial wafers from Cree. STM signed a wafer supply agreement with Rohm in January 2020 for \$120M, but it appears to be a one-off transaction to hedge against trade tensions. It is dwarfed by the \$500M in existing supply agreements with Cree.

Established	1987
SiC R&D	1996
Products	SiC Power Devices
Markets	Solar, Industrial, EV
Consolidated Revenue	\$10B
SiC Device Revenue 2020(e)	\$275M
Share of Merchant Mkt SiC Device Sales	40%

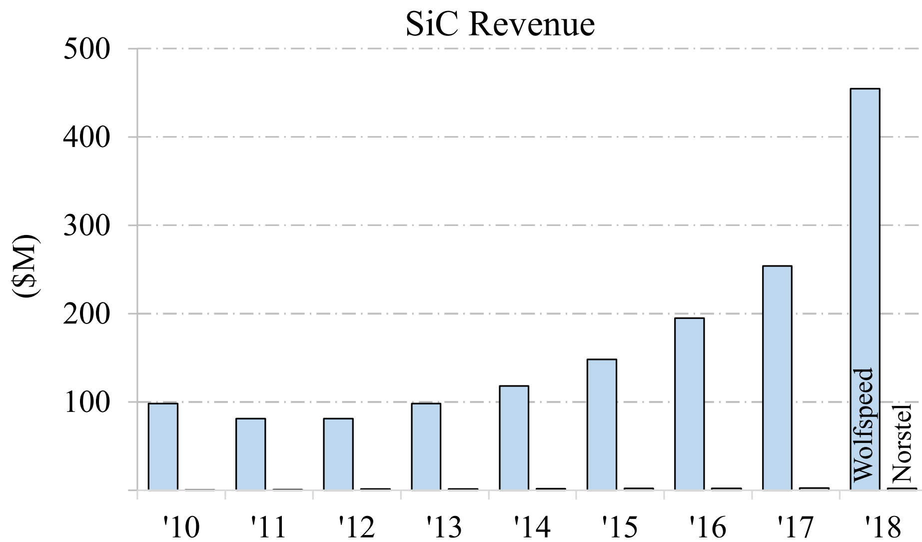
The rapid growth in its SiC device sales has management eager to expand the base and lower the cost of its SiC wafer supply. That's easier said than done, as the hurdles to improving material growth have ruined the fortunes of most firms that endeavored to try. Included in that list is Norstel which, after 15 years of effort, many rounds of funding, several partnerships, and an acquisition by a Chinese PE firm, was purchased by STM in 2019.



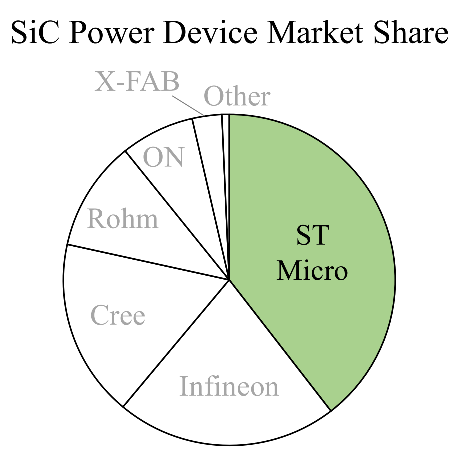
Norstel was formed in 2005 in Sweden to 'industrialize' an unusual SiC growth process. Developed by Okmetic (a small private research firm), Sweden's Linkoping University, and ABB Corporate Research, the process uses high temperature chemical vapor deposition (HTCVD) to increase precision and reduce defects in silicon carbide boules. The company obtained private and Swedish government funding to build a SiC wafer facility in Norrkoping, Sweden in 2006.



Lab results were promising but moving the process to production proved difficult. Unlike the physical vapor transport (PVT) method employed by all the leading SiC wafer suppliers, HTCVD was slow and delicate. Six years after its formation, Norstel could produce 2, 3 and 4-inch wafers but it wasn't selling many. Revenue increased from \$700K in 2011 to \$1.8M in 2014, most of which was government funded research. In 2014 the company partnered with Ascatron, a Swedish SiC epitaxial firm in an attempt to lower costs but after posting less than \$2M in revenue in 2016, sold itself to An Xin, a Chinese PE fund, in 2017.

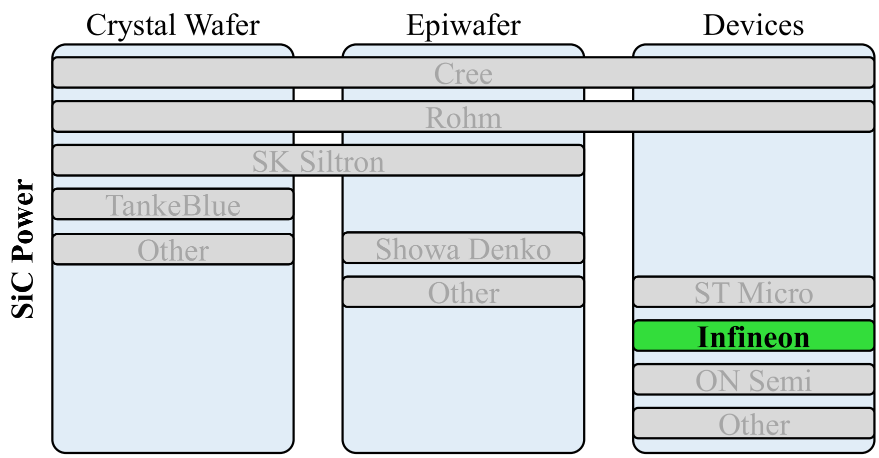


When the Chinese PE fund realized it couldn't take Norstel's technology out of Sweden it sold the company to ST Microelectronics in 2019. By that time ST Micro had already expanded its supply agreements with Cree from $250M to over $500M and would add another $120M with Rohm a month later. With $620M in wafers lined up over the next several years, STM is in the SiC business to stay, so $138M for Norstel and the possibility of someday having its own SiC growth capability seems a reasonable price for a call option with no expiration date.



Infineon

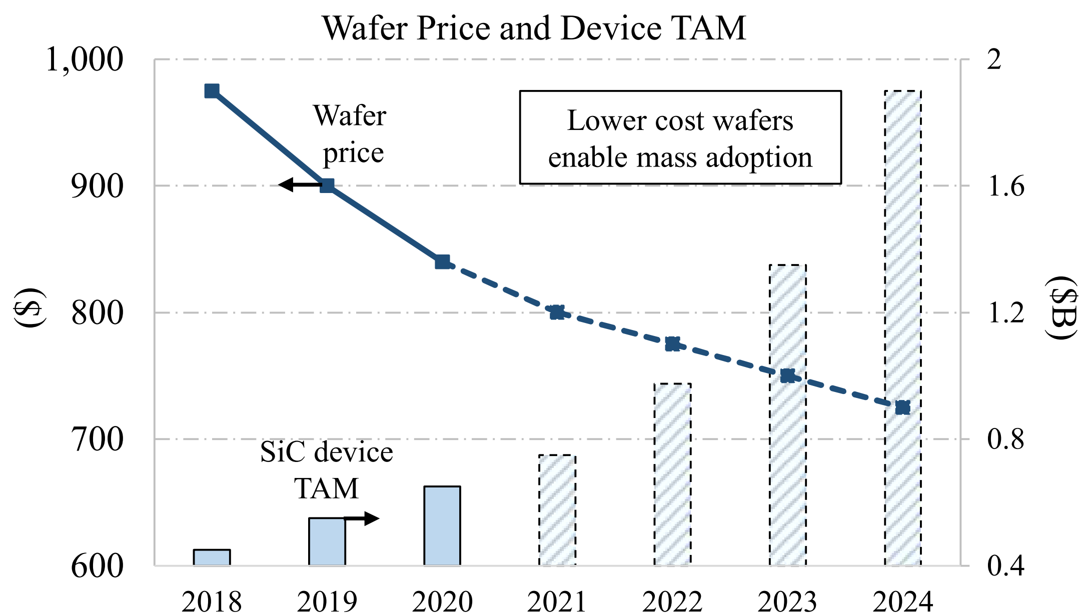
Silicon Carbide Competitive Landscape



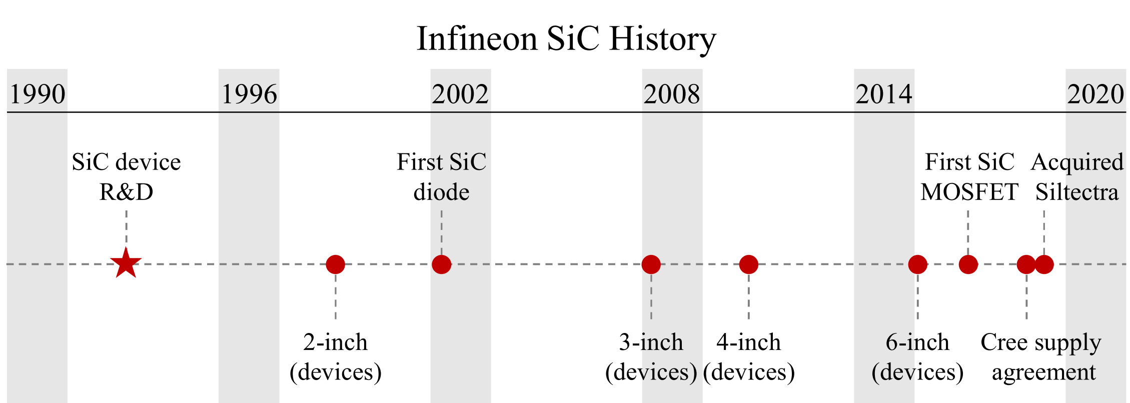
Infineon is the second-largest manufacturer of silicon carbide power devices with \$125M-\$150M of revenue (~2% of consolidated) in 2020 for about 20%-25% share of the SiC power device merchant market. Infineon was originally the semiconductor arm of Siemens before it was spun out in 2000 and has since grown to become a leading global supplier of power semiconductors[36]. It is headquartered in Germany and only sells devices and has no crystal or epitaxial wafers. Development of SiC power devices commenced in 1992 and Infineon demonstrated the industry's first silicon carbide Schottky diode in 2001. Diodes entered production in 2004 and experienced some traction in the 2000s, but high cost limited adoption to a handful of high-end markets such as utility-scale solar inverters.

Established	1999
SiC R&D	1992 (Siemens)
Products	SiC Power Devices
Markets	Solar, Industrial, EV
Consolidated Revenue	\$9B
SiC Device Revenue 2020(e)	\$150M
Share of Merchant Mkt SiC Device Sales	22%

Infineon trailed competitors in MOSFETs which didn't enter production until 2016, while Cree and Rohm released first-generation MOSFETs in 2011. Infineon never had an internal wafer source, a problem it tried to remedy by purchasing Cree's Wolfspeed division in 2016. When that deal was blocked by U.S. regulators[37] in 2018, Infineon and Cree signed a $100M SiC wafer supply agreement.

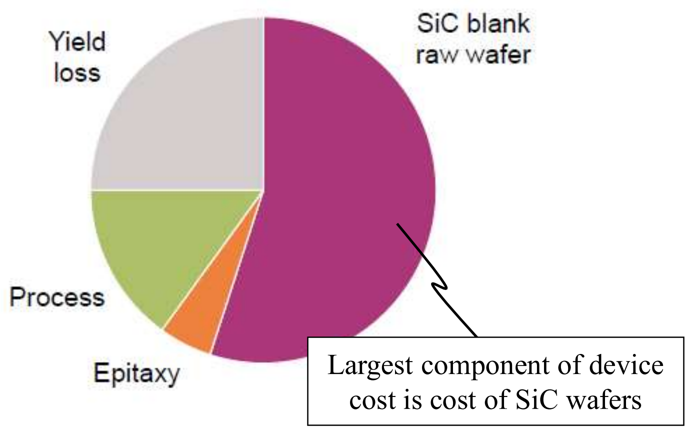


Securing a supply of SiC wafers allowed Infineon to push more aggressively into the power device market which management expects to grow from $500M in 2019 to nearly $2B by 2024. With such a pronounced performance advantage over silicon, cost is the only roadblock to mass adoption of SiC devices. Indeed more than half the cost of a SiC MOSFET can be attributed to the wafer so to further its efforts to lower its BOM cost, Infineon acquired wafer splitting startup Siltectra for $140M in 2018.

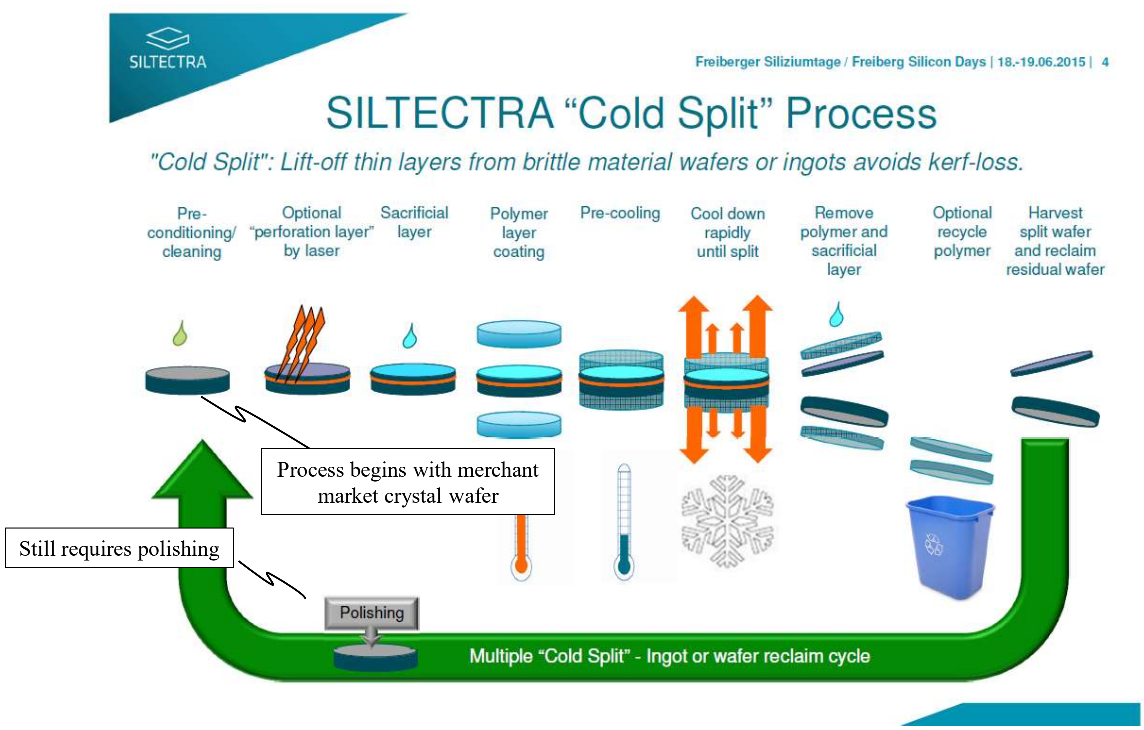


Siltectra was founded in Germany in 2010 with a seed investment from a German VC fund. Siltectra doesn't grow silicon carbide but uses its Cold Split process to slice wafers it purchases on the merchant market. Instead of sawing boules into wafers, Cold Split uses extreme temperature changes to cleave individual wafers from a boule without material loss.

SiC MOSFET Cost Breakdown

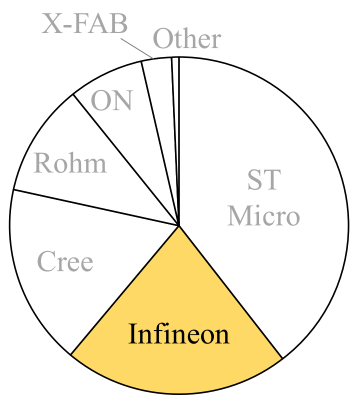


Cold Split has successfully been applied to other materials such as silicon but the extreme hardness of silicon carbide introduces unique challenges. Siltectra began testing the Cold Split process on silicon carbide in 2016 and planned to ramp production in October 2018 but was acquired by Infineon in late 2018. With a price tag of less than 2% of annual revenue, the Siltectra acquisition carries an attractive risk/reward profile and little downside to Infineon's device business. Infineon doesn't expect the Cold Split process to be commercially viable until 2022 at the earliest.



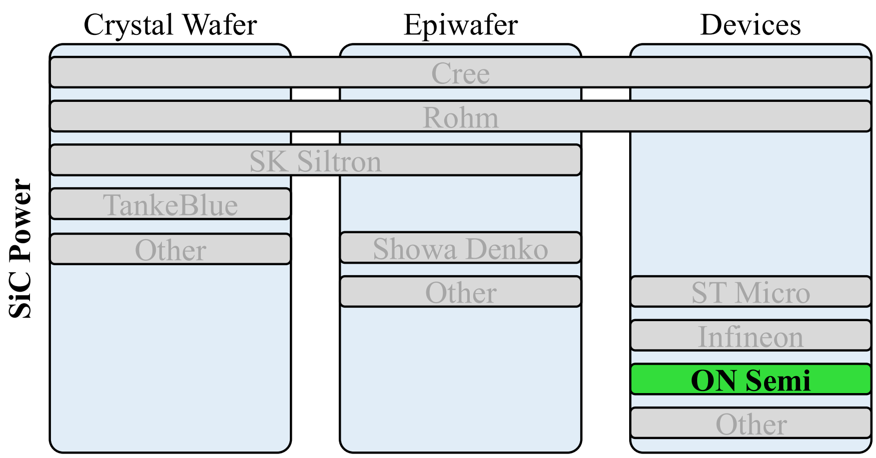
Even with Siltectra, Infineon doesn't have an internal source for silicon carbide so it must continue buying SiC wafers from Cree regardless of the success or failure of Cold Split.

SiC Power Device Market Share



ON Semiconductor

Silicon Carbide Competitive Landscape



ON Semiconductor was established in 1999 when it was spun out of Motorola. It manufactures mixed signal and power semiconductor devices and posted $5.3B in revenue in 2020, divided between Automotive (32%), Industrial (25%), Communications (20%), Consumer (11%), and Computing (12%). The company began manufacturing silicon carbide power devices in 2017 and by 2020 we estimate sales totaled $40M-$50M, or less than 1% of consolidated revenue. Devices are primarily sold into the industrial power control, datacenter power supply, and solar inverter markets. Like nearly all SiC power device manufacturers, ON emphasizes electric vehicles for long term growth. Although sales of EV products were immaterial to revenue in 2020, it believes the TAM for that market will more than double from $500M in 2020 to $1.2B by 2025.

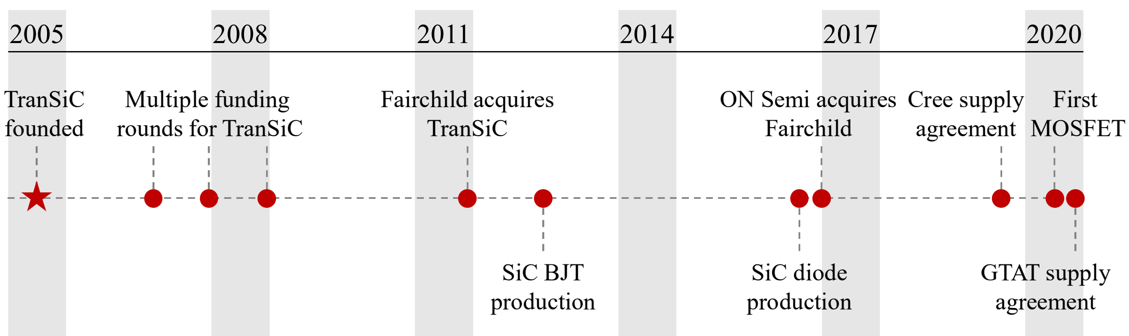
ON Semiconductor®

Established	1999
SiC R&D	2005 (TranSiC)
Products	SiC Power Devices
Markets	Solar, Industrial, EV
Consolidated Revenue	$5B
SiC Device Revenue 2020(e)	$50M
Share of Merchant Mkt SiC Device Sales	7%

ON Semi did not develop silicon carbide internally but entered the market through its acquisition of Fairchild Semiconductor in 2016. Fairchild began working on silicon carbide after it purchased a Swedish startup, TranSiC, for $17M in 2011.

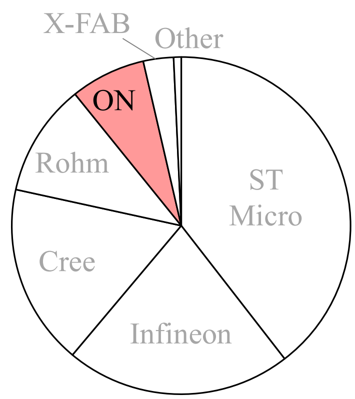
TranSiC's history is similar to that of Norstel (see section on STM), another government sponsored startup in Sweden. It originated in the early 2000s as a university project to develop silicon carbide power devices for industrial applications and hybrid vehicles[38] at Sweden's Royal Institute of Technology. In 2005 it was spun out of the University as TranSiC and received funding from Sweden's state-sponsored departments of innovation (VINNOVA) and energy (Energimyndighet). It unveiled its first prototype device in 2006. The company received additional capital from Volvo and venture capital fund Midroc New Technology. In 2007 it received another round of financing from Sweden's innovation and energy departments to further its work on an epitaxy process and improve device packaging. It's last round of funding, led by Volvo, Midroc and Industrifonden, a Swedish venture capital fund, came a year later (2008) and was ostensibly used to transition to product qualification.

ON Semiconductor SiC History



It's unlikely TranSiC generated any commercial product revenue by the time Fairchild acquired it in 2011 and ON has not produced SiC devices using TranSiC's process to date. Aside from the normal difficulties of working with silicon carbide, TranSiC faced additional hurdles based on the type of device it decided to pursue. Unlike all other SiC device manufacturers which produced MOSFETs and Schottky diodes, TranSiC spent its energy trying to fabricate bipolar junction transistors (BJT). The benefits of BJTs are not well suited to the high-power applications that favor silicon carbide[39] and many of its drawbacks are exacerbated. BJTs generally find use at low and medium power levels where there's little advantage to using SiC. Fairchild continued TranSiC's efforts and released a commercial BJT in 2012, but once ON Semi acquired Fairchild, it appears work on SiC BJTs was discontinued[40] in favor of Schottky diodes and MOSFETs.

SiC Power Device Market Share

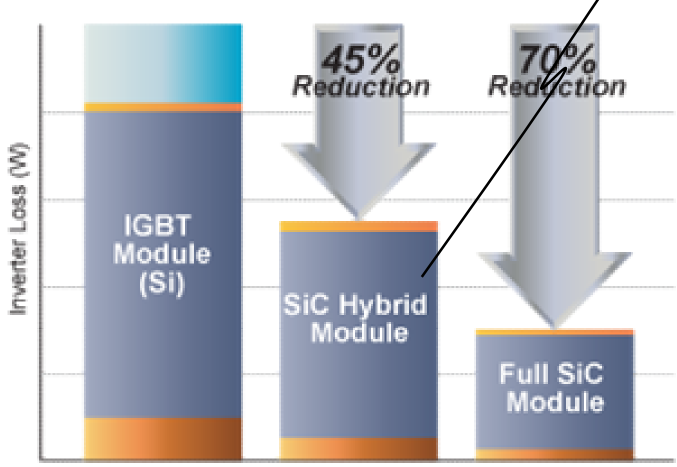


Today, the majority of silicon carbide devices sold by ON Semi are Schottky diodes, as it did not release its first SiC MOSFET until 2020, nearly a decade after Cree and Rohm. ON Semi announced its first SiC revenue from the automotive sector in 2H18 although the revenue was likely small as the only mass market EV using SiC in 2018 was the Tesla Model 3, all of which was supplied by ST Micro. The vast majority of ON's SiC diodes are used in industrial power control, datacenter power supply, and solar inverter applications.

Its late entry into SiC MOSFETs suggests that for the foreseeable future, most of ON Semi's silicon carbide revenue will derive from Schottky diodes. Although diodes are not as lucrative as MOSFETs, their lower ASPs allows them to be more widely employed in hybrid modules, which pair SiC Schottky diodes with legacy silicon transistors (IGBTs) to improve power performance at a lower cost than a SiC MOSFET.

SiC Module Efficiency

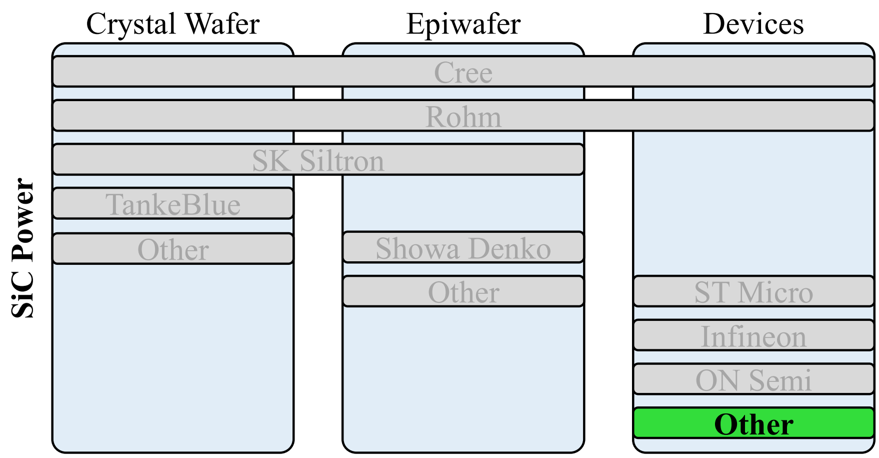
Hybrid modules provide significant gains over silicon



ON Semiconductor buys most of its silicon carbide crystal and epitaxial wafers from Cree. The two companies inked an $85M long-term wafer supply agreement in August 2019. ON is developing an internal process for crystal wafer growth[41] although it's unlikely it will be production-ready for several years. In March 2020 ON agreed to buy up to $50M of silicon carbide boules from GT Advanced Technologies (GTAT) over a five-year span. A bevy of bullish statements from GTAT management in 2019 (for details see GTAT section), as it rebounded from its Apple debacle, have not been followed up by results, leaving us doubtful it has much if any role to play in the SiC supply chain. The GTAT supply agreement is for silicon carbide boules, which must be sliced, polished and have an epitaxial layer deposited before ON, or any other component manufacturer can use them to fabricate devices. Slicing and polishing silicon carbide boules is not trivial (for details see our note "CREE: Silicon Carbide: Extremely hard and incredibly powerful" March 31, 2020) and significantly more difficult than with silicon. Moreover there are no merchant market vendors for slicing and polishing SiC wafers so the steps have to be developed internally. We expect ON signed the boule supply agreement with GTAT to aid in this effort and to complement its work on bringing the TranSiC/Fairchild crystal wafer growth process to fruition, an effort that will require years to complete in our opinion.

X-FAB

Silicon Carbide Competitive Landscape

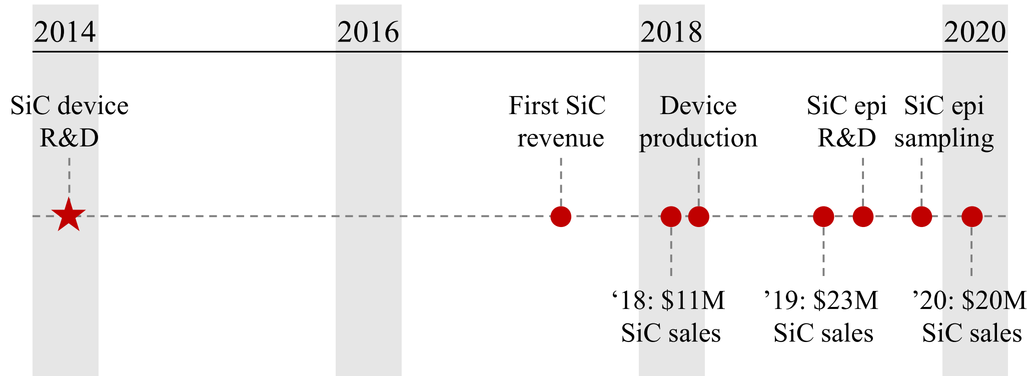


X-FAB is a Belgium based foundry specializing in mixed signal semiconductors combining high voltage power devices with sensors, memory and control functions capable of operating at temperatures required in automotive applications. It reported $478M in revenue for 2020, half of which derived from automotive products, 23% from consumers, 20% from industrial and 7% from medical. The company had 22 customers exiting 2020 and CMOS, SOI, MEMS and SiC device fabs in Germany, France, Malaysia, and the United States. In 2014 it received funding from Power America[42] to begin conversion of some of its 6-inch CMOS equipment in its Lubbock, Texas facility[43] for use as a SiC device foundry. It took three years for that effort to bear results[44] but in 2017 it reported $4.5M in revenue for SiC devices, two thirds of which was for research and prototyping. That rose to $23M in 2019, or about 6% of consolidated sales, and dropped to about $20M in 2020 due to COVID.

Established	1992
SiC R&D	2014
Products	SiC Power Devices, Epi
Markets	Solar, Industrial, EV
Consolidated Revenue	$478M
SiC Device Revenue 2020(e)	$20M
Share of Merchant Mkt SiC Device Sales	3%

Being a device foundry, X-FAB doesn't provide packaging, assembly, or test, so the devices it fabricates are delivered to customers as full wafers (not singulated). The conversion of these to packaged components increase their value by 3x so the $23M in SiC wafer revenue X-FAB logged in 2019 is equivalent to about $70M in SiC device sales, making X-FAB one of the top six SiC device manufacturers.

X-FAB SiC History

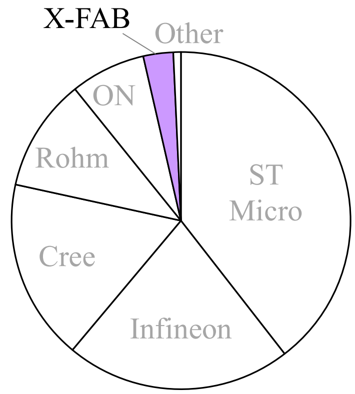


Having developed epitaxial processes for silicon, the company was intent on doing the same for silicon carbide and therefore began developing a SiC epitaxy process in early 2019 with the goal of production by year-end 2019. The effort provided more difficult than expected and the company was still qualifying the process with customers at year end 2020. Nevertheless, management expects to be in production in 2021 and believes developing its own process is essential to reducing its inventory and improving throughput and margins[45].

Like nearly all SiC power device manufacturers, X-FAB holds out electric vehicles as the ultimate growth market but derives the vast majority of its SiC revenue from industrial applications such as power inverters for solar, motor controls, train electromotive and computer power supplies. Of its 22 SiC customers (2020), most were Asian fabless semiconductor companies, primarily Chinese firms servicing solar, industrial and to a lesser extent EV markets in China.

As the only pure-play device foundry in the SiC food chain, X-FAB is the natural home for small, fabless device companies as well as large IDMs and OEMs trying to develop silicon carbide products. Without its own wafer growth operations or a direct channel to industrial and EV markets, the company relies on Cree, TankeBlue and II-VI for supply (wafers) and its fabless component manufacturers for demand. Its success in SiC power will depend on its customers' ability to compete with wafer suppliers with their own device capabilities (Cree, Rohm) and device manufacturers trying to develop their own wafer growth operations (ST Microelectronics, Infineon and ON Semiconductor). As such it will always be squeezed on cost by the vertically integrated suppliers and price by the largest SiC device fabs.

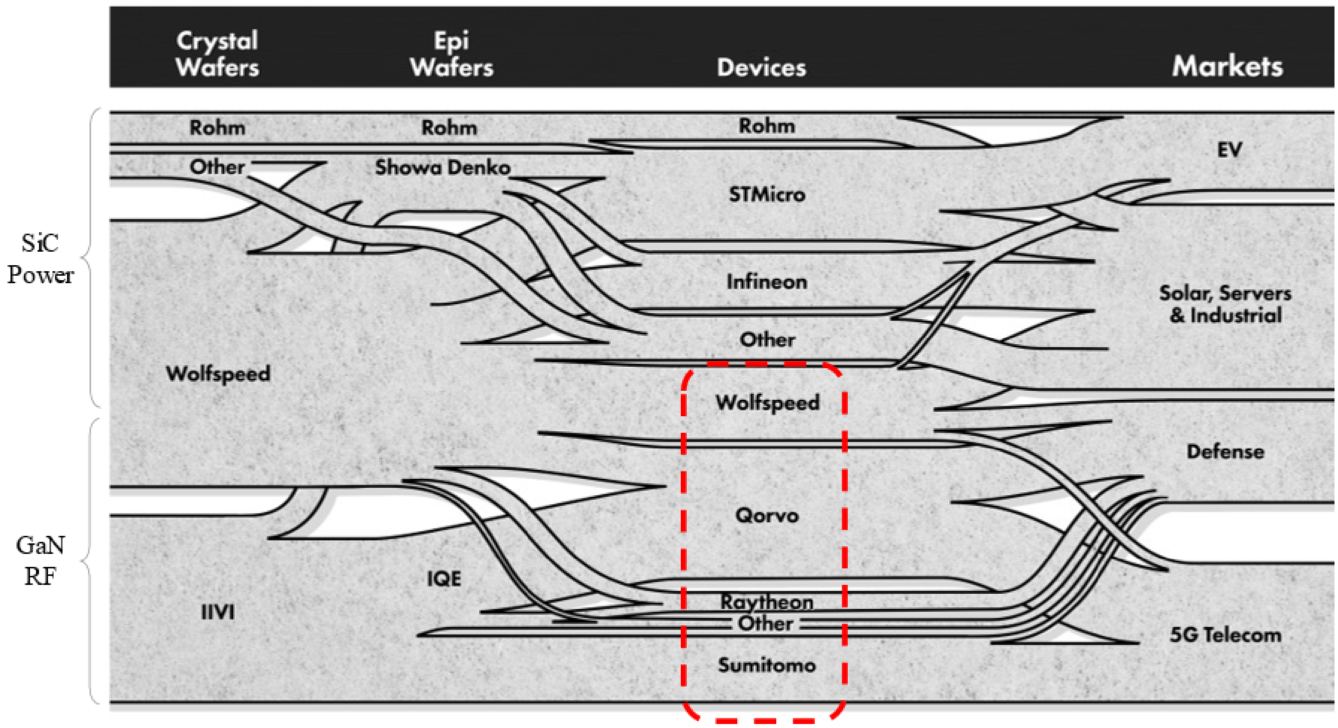
SiC Power Device Market Share



A good example of this is ST Microelectronics. At about ten times the size of X-FAB's SiC sales, STM has a substantial scale advantage that almost certainly translates to lower wafer costs in its supply agreements with Cree. The gap between what it pays for a 6-inch wafer and what X-FAB pays will likely increase as STM uses its much larger channel into the power device market to expand the breadth and depth of its SiC device sales faster than X-FAB. At the same time, Cree is seeing wafer costs to its internal device group decline as the aggregate demand of the $1B in supply agreements it has executed with device manufacturers runs through its wafer growth facility in Durham, North Carolina. Moreover once its large, automated 200mm device fab is completed in 2022, production costs and ASPs of its SiC power products will likely decline, increasing the competitive pressure on all silicon carbide foundries. Neither STM nor Cree provide foundry services in SiC and while Qorvo and Northrop do, it's a de minimis component of consolidated revenue and immaterial to industry device sales. This leaves room for X-FAB which is likely to see its SiC revenue increase in 2021 as it perfects its SiC epi process and the industry recovers from COVID.

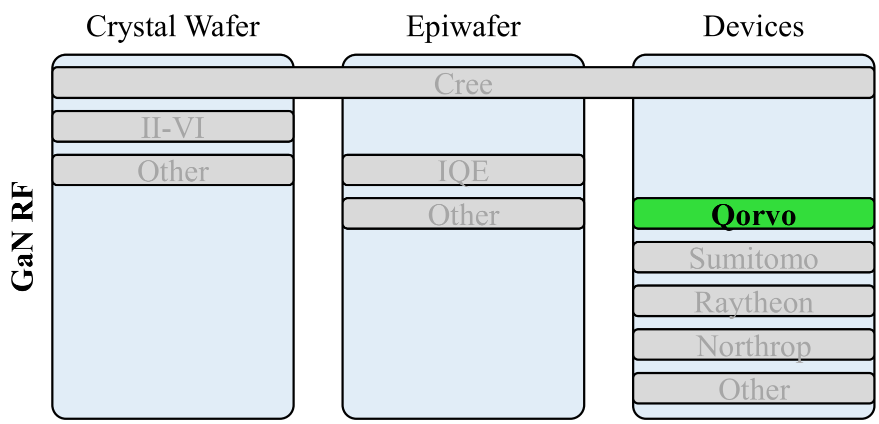
GaN RF Devices

SiC and GaN Supply Chain



Qorvo

Silicon Carbide Competitive Landscape

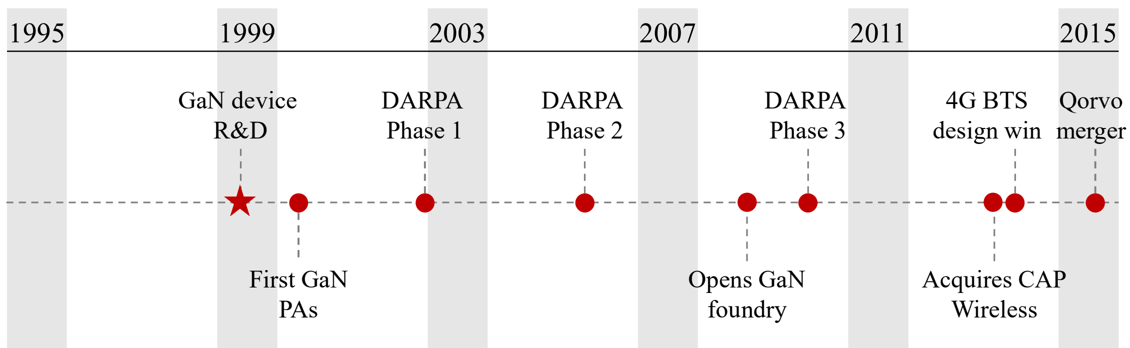


Qorvo is the largest supplier of GaN devices for defense and the second largest for telecom (5G base stations). It doesn't manufacture or participate in the market for SiC power, whether it be devices, crystal or epitaxial wafers. The company attained its lead in GaN devices through the combined efforts of RF Micro Devices (RFMD) and TriQuint, the firms that merged to form Qorvo in 2015. Of the two, TriQuint had a longer history and larger presence in GaN.

Established	2015
GaN R&D	1999 (TQNT)
Products	GaN RF Devices
Markets	Telecom, Radar
Consolidated Revenue	$4B
GaN Device Revenue 2020(e)	$400M
Share of Merchant Mkt GaN Device Sales	50%

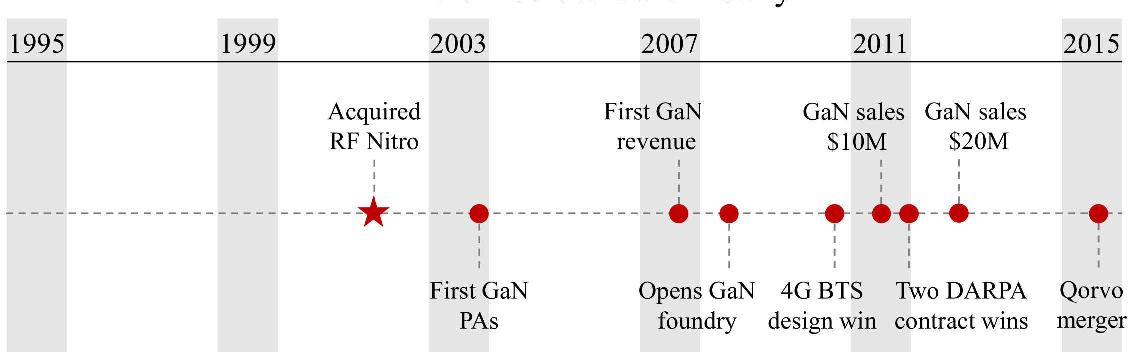
TriQuint was founded in 1985 to produce high-frequency semiconductors, making it an ideal candidate for early GaN research contracts. It received its first funding from Lockheed Martin[46] in 1999, with further funding in 2002 from DARPA's wide bandgap semiconductor program. DARPA's strategy was to fund process development to field viable silicon carbide devices for radar and electronic warfare (EW) systems. It divided its efforts across three tracks with Raytheon working in the low frequencies (radar), TriQuint in the high frequencies (satellite, space) and Cree in broadband (electronic warfare). This put TriQuint on the path to $30M in contracts over the next eight years and allowed it to develop power amplifiers (PAs) and monolithic microwave integrated circuits (MMICs) for satellite and space applications. By 2010 its GaN fab processes were mature enough to offer foundry services and a year later it entered volume device production. At the same time, Raytheon's progress in GaN-based radars whet the defense department's appetite for more, opening the way for TriQuint to move into low frequency and broadband GaN products for air and missile defense, ship borne radar and electronic warfare systems[47]. That, combined with its original work in space systems and adoption of GaN power amplifiers by cable equipment OEMs for DOCSIS 3.0 and 3.1, we believe drove GaN revenue growth to about $75M in 2015.

TriQuint GaN History

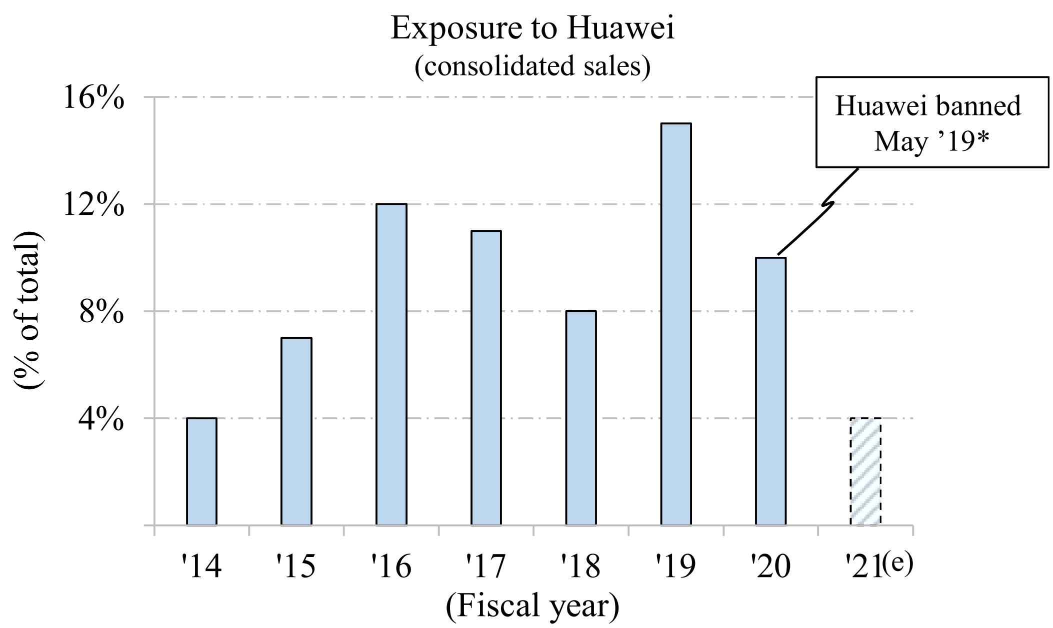


RF Micro Devices' entry into GaN didn't occur until its acquisition of RF Nitro in 2001 and its contribution to Qorvo's GaN business after the merger was more modest than TriQuint's. With a smaller exposure to defense, RFMD wasn't a prime candidate for government contracts and without that funding, progress toward usable GaN devices was slower. As a result, the company didn't demonstrate its first GaN PA until 2004, three years after the RF Nitro acquisition. A year later it had a GaN fab up and running at its Greensboro, North Carolina site and logged its first GaN revenue two years later (2007). Revenue grew to $10M in 2011, and doubled in 2012 with 50% from military radar, 25% from cable infrastructure[48] and 25% from government foundry[49] contracts.

RF Micro Devices GaN History

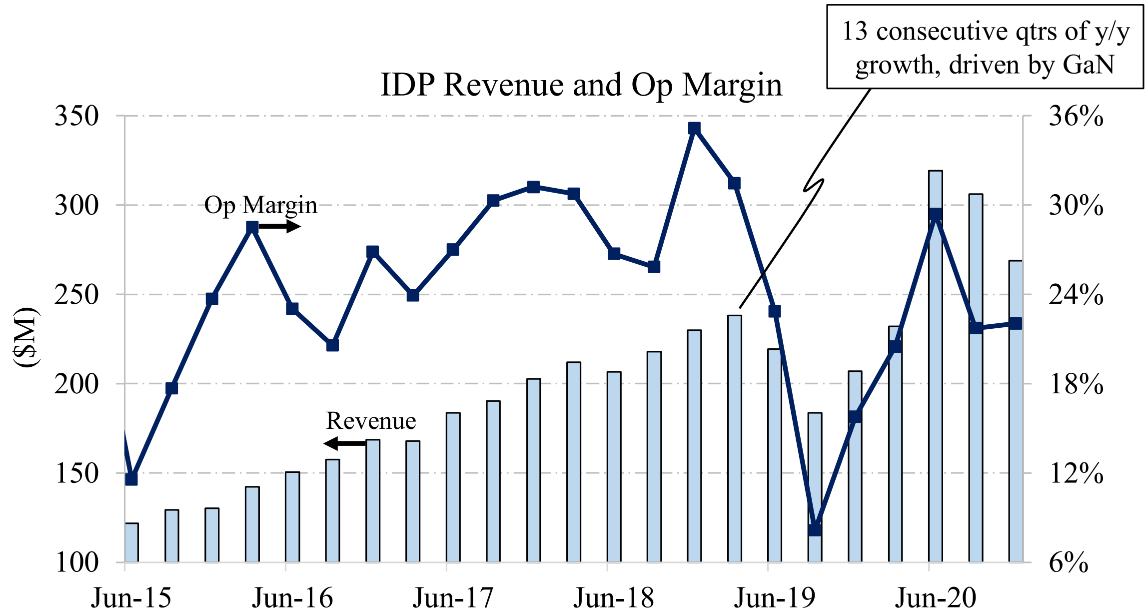


After the merger, Qorvo organized all GaN products under its Infrastructure and Defense Products (IDP) group in Richardson, Texas. Early sales to cable infrastructure were soon eclipsed by defense as deployment of GaN radars and electronic warfare systems gained momentum in the U.S. Raytheon and Northrop Grumman are among Qorvo's largest defense customers even though both OEMs have their own GaN fabs[50] which are used for R&D and low volume production. For large contracts they source most of their GaN devices from Qorvo, which enjoys a substantial cost advantage given it also supplies Lockheed, Britain's BAE systems, Israel's ELTA, and a variety of other radar/EW OEMs as well as cable and telecom equipment manufacturers. Indeed, Qorvo is the largest provider of GaN devices into defense, selling more than all military and space OEMs combined. Between the maturity of its process and scale of its manufacturing, GaN is highly accretive to IDP and corporate gross margins. This helped elevate IDP's operating margin from the low 20% range after the merger in 2015, to the low 30% range in 2017.

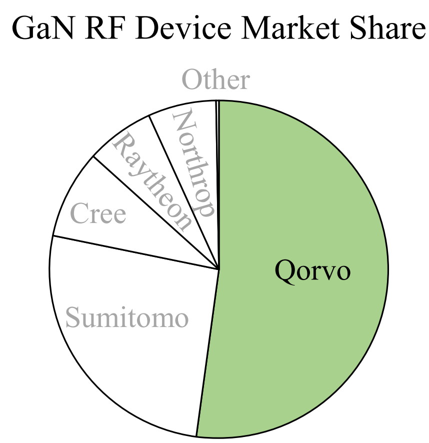


*Post-ban, Qorvo continued Mobile sales to Huawei

Once China began nationwide deployment of 5G MiMo base stations, GaN sales to telecom exceeded even defense, lifting IDP revenue to $240M and operating margin to 32% in March 2019, which also marked the 13th consecutive quarter of y/y revenue growth. Most of those base stations were produced by Huawei, whose close ties to China's military led to U.S. government sanctions in May 2019. That ended all Qorvo's GaN sales to the OEM which accounted for $170M in revenue in the June 2019 quarter. The revenue and margin trough of September 2019 was quickly filled with steady but widespread growth in GaN radar systems and ZTE's share gains in 5G base stations at Huawei's expense.

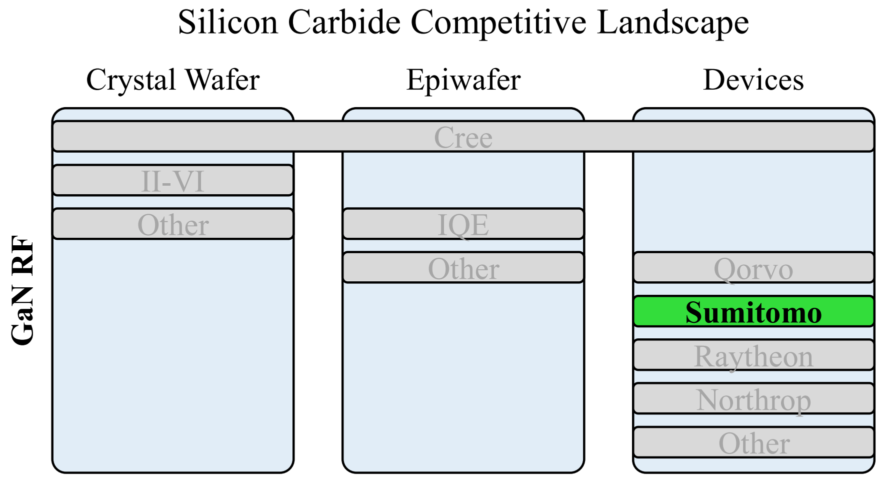


By June 2020, IDP was back to posting record revenue thanks to robust sales of WiFi 6 equipment to consumers stuck at home during the COVID-19 pandemic. The surge in sales of connectivity products drove GaN as percent of revenue below its late 2018 peak, which has kept IDP operating margins below 30%.

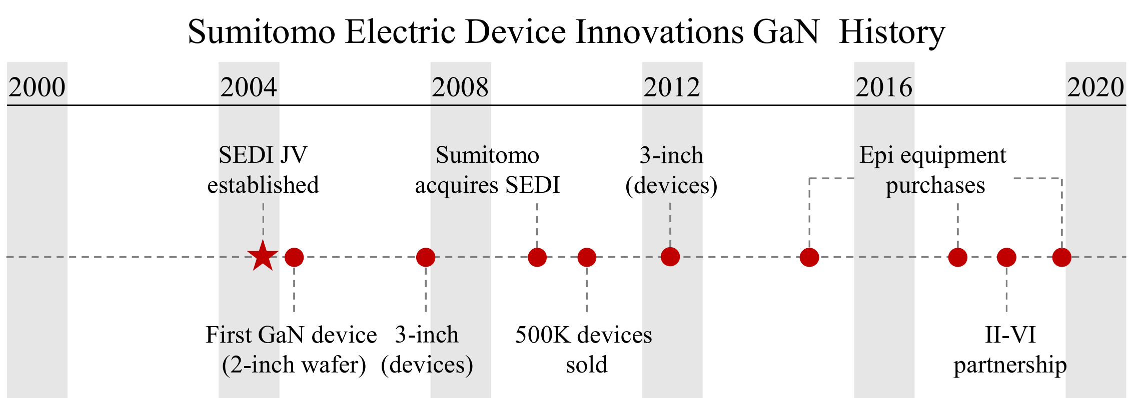


With GaN being required in all new U.S. radar and EW systems we expect consistent growth in revenue and margins for IDP's defense business. That will be modulated heavily by 5G base station deployments with spurts of growth when the mix favors MiMo systems, which are GaN-centric, and ebb when it shifts to U.S. C-band deployments, which will be more heavily weighted to macro base stations.

Sumitomo Electric Device Innovations



Sumitomo Electric Device Innovations (SEDI), a subsidiary of Sumitomo Electric Industries in Japan, is the second-largest manufacturer of GaN RF devices and the largest supplier of GaN power amplifiers used in China's deployment of 5G. SEDI was formed in 2004 as a joint venture between Fujitsu and Sumitomo Electric Industries, two companies with fledgling GaN operations, and was originally called Eudyna. The joint venture prioritized early-stage GaN research in an effort to complement the existing GaAs and optical businesses of the parent companies. Combining the resources of Fujitsu and Sumitomo accelerated product development and Eudyna released its first prototype GaN device less than one year after its formation. Adoption was slow as devices were expensive and performance was better suited to next gen 4G equipment, not the 2G and 3G equipment in use before 2010.

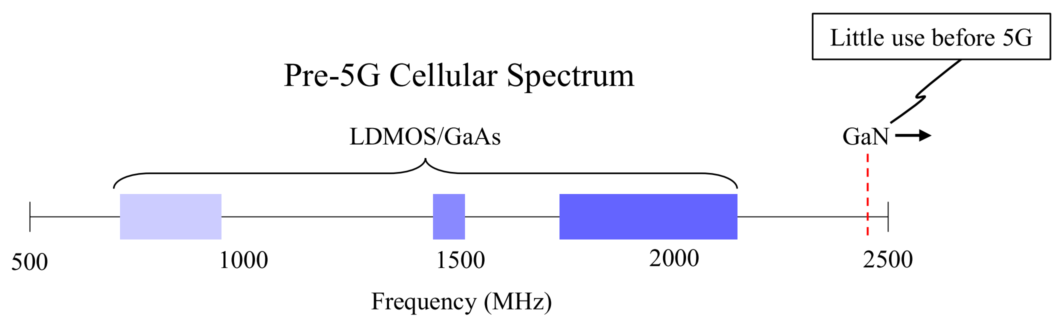


Eudyna made significant investments in GaN during the 2000s although the TAM for GaN was small. Most devices were sold into radar applications in the U.S. as nearly all U.S. GaN companies (Cree, TriQuint/Qorvo, Northrop Grumman, Raytheon) developed the technology at the behest of the U.S. Department of Defense for radar projects. Telecom was the only RF market SEDI could realistically supply as the Japan Arms Export Ban prohibited Japanese companies from exporting defense equipment from 1976-2014, disincentivizing the development of GaN for radar. With U.S. competitors occupied with military projects, Eudyna established itself as the leader in telecom and the company logged $300M in total revenue in 2008, although the vast majority was attributed to optical and GaAs devices.

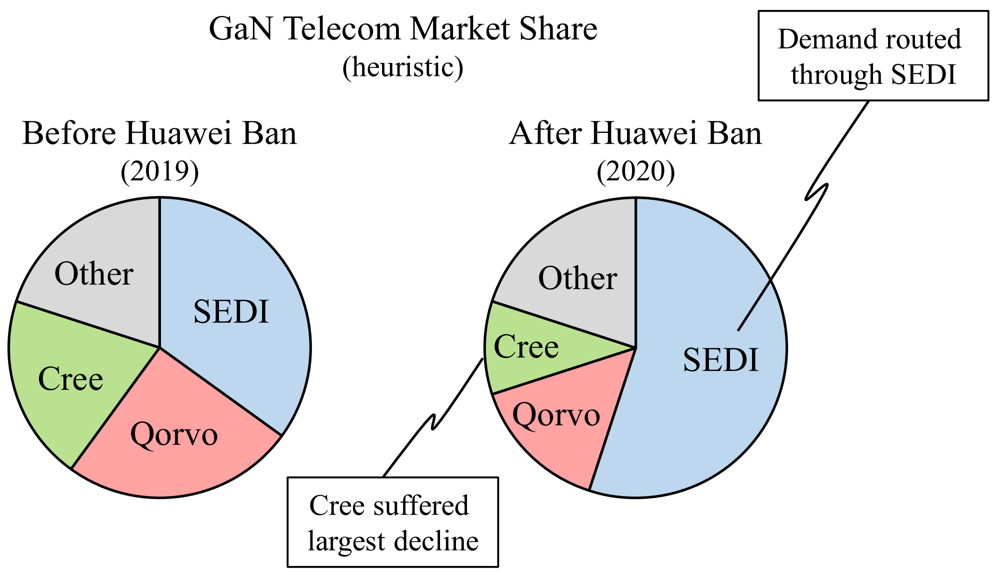
SUMITOMO ELECTRIC DEVICE INNOVATIONS, INC.

Established	2004 (JV)
GaN R&D	1990s
Products	GaN RF devices
Markets	Telecom
Consolidated Revenue	$26B
GaN Device Revenue 2020(e)	$200M-$250M
Share of Merchant Mkt GaN Device Sales	25%

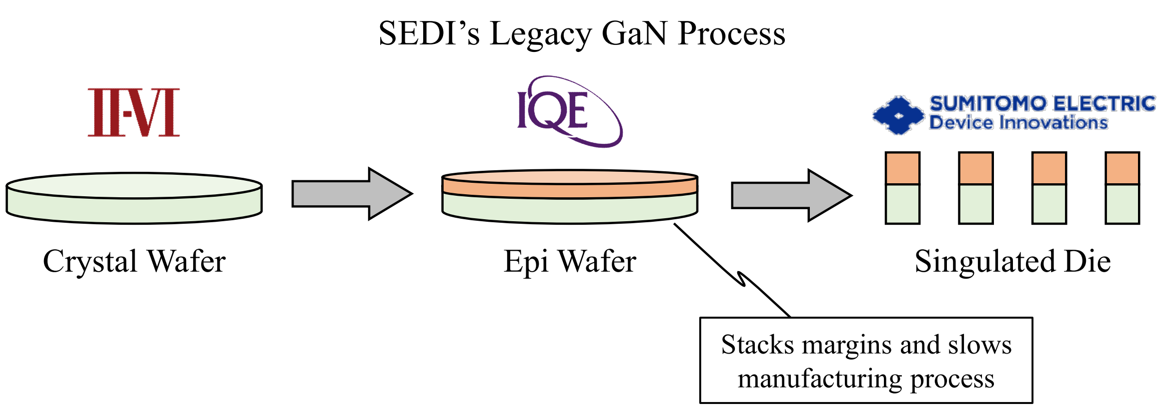
Eudyna's efforts in GaN began to yield results once LTE rollouts began in 2009. That year, to take advantage of growing momentum in 4G deployments, Sumitomo Electric Industries acquired Fujitsu's stake in Eudyna and renamed the business Sumitomo Electric Device Innovations. Huawei, the first major telecom OEM to employ GaN, named SEDI as one of its top suppliers in 2009, by which time it had cumulative sales of 500K GaN devices. Unit sales continued to grow but because GaN is optimized for radio frequencies well above the cellular spectrum, most sales were probably for R&D on 5G base stations at Huawei.



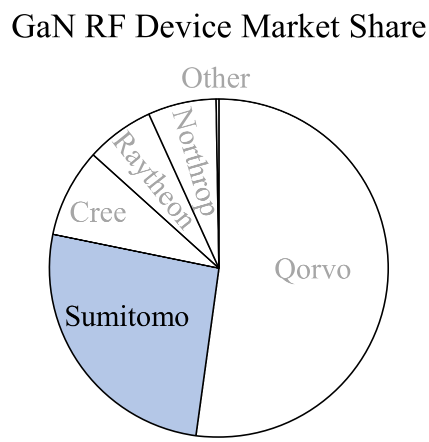
SEDI fabricates GaN power amplifiers on silicon carbide crystal wafers, but doesn't have an internal source of wafers and therefore purchases them from U.S. vendors, primarily II-VI. Since 2016 SEDI has been a top-five customer of II-VI, the leading producer of 6H crystal wafers used in RF applications. The two companies entered a partnership in 2018 to develop a vertically-integrated platform for 5G GaN devices, which has likely accelerated since the Huawei ban in May 2019. The Chinese OEM purchased GaN devices from Qorvo and Cree in addition to SEDI but once the ban was enacted and American companies could no longer ship to Huawei, all of Huawei's GaN needs were filled by SEDI. Six months after the ban, II-VI announced a $100M SiC crystal wafer supply agreement with an unnamed 5G telecom customer, and just two days later SEDI purchased equipment to create epitaxial wafers from crystal wafers. The timing of these developments suggests SEDI ramped device production to meet sharply higher demand from Huawei and therefore needed to purchase more crystal wafers from II-VI.



SEDI's acquisition of epitaxial equipment in December 2019 was not its first, as the company made similar purchases in 2014 and 2017 in its efforts to vertically integrate its GaN device business. We believe SEDI originally purchased most of its epi wafers from Cree and IQE but has produced more of its own as its epitaxial process improved.



If SEDI can properly scale its epitaxial wafer operations, its telecom business could pull further ahead of U.S. competitors. It led Cree and Qorvo in telecom for years and increased that lead following the Huawei ban. Even if restrictions on Huawei are eased, Cree has prioritized its SiC power device business whereas Qorvo began focusing on other applications (radar) and other telecom OEMs (ZTE, Ericsson) since the Huawei ban. U.S. device manufacturers witnessed firsthand the risk in supplying Huawei and as a result SEDI will almost certainly remain entrenched as Huawei's primary supplier and the largest GaN device manufacturer for telecom applications, at least until the Chinese 5G buildout slows.

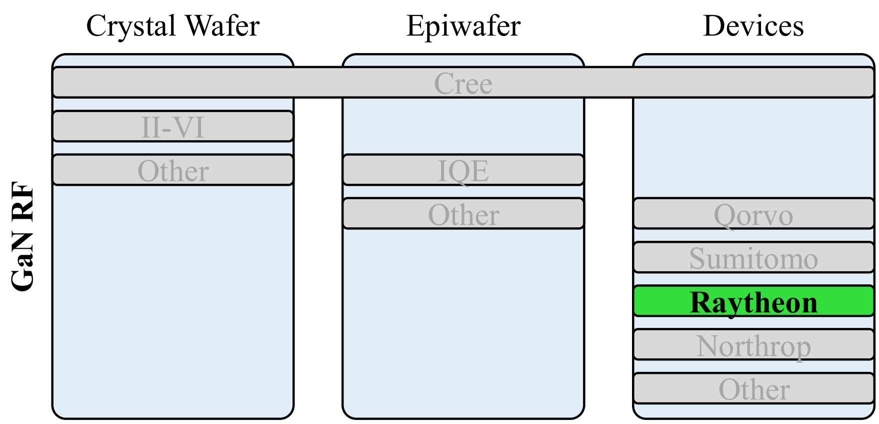


For the greater RF GaN market, we expect moderate growth in the coming years. In 2018 the Chinese government mandated the roll-out of a nationwide 5G network regardless of cost. Deployments were initially concentrated in urban areas with most base stations configured with MiMo systems, which use a large number of GaN power amplifiers. With most of the major urban areas covered, the build has moved to suburban and rural regions which are more heavily weighted to macro base stations. This reduces demand for GaN. Deployment of C-band systems in the U.S. will offset some of this decline but unlike in China, U.S. carriers are concerned with ROI and are therefore not inclined to widespread deployment of expensive MiMo systems. We expect a modest increase in sales to U.S. carriers to moderate but not offset declining demand in China. The ban in sales to Huawei have cut off Cree and Qorvo from demand for GaN in China and has therefore insulated them somewhat from the correction that will like hit Sumitomo the hardest.

Since GaN outperforms silicon and GaAs in nearly every area other than cost, the technology will not disappear once China halts its 5G rollout. GaN will never reach price parity with legacy materials but the cost/performance ratio has risen substantially over the past decade and will continue to increase as device manufacturers scale and the material costs (crystal/epitaxial wafers) decline.

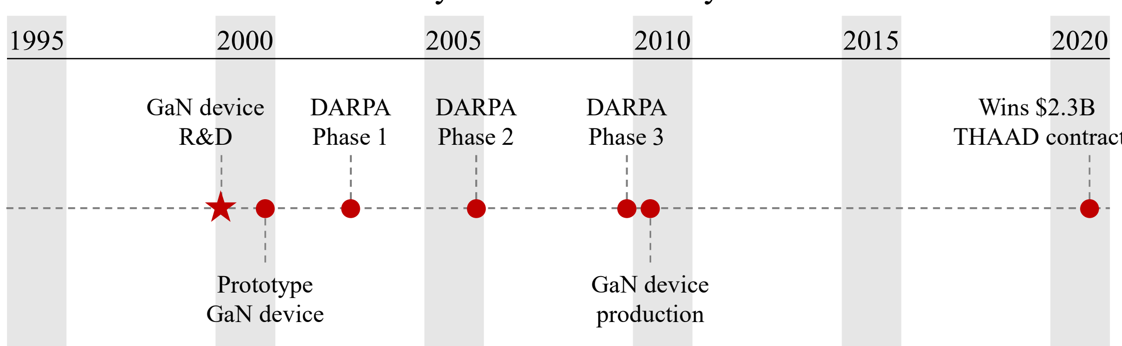
Raytheon Technologies

Silicon Carbide Competitive Landscape

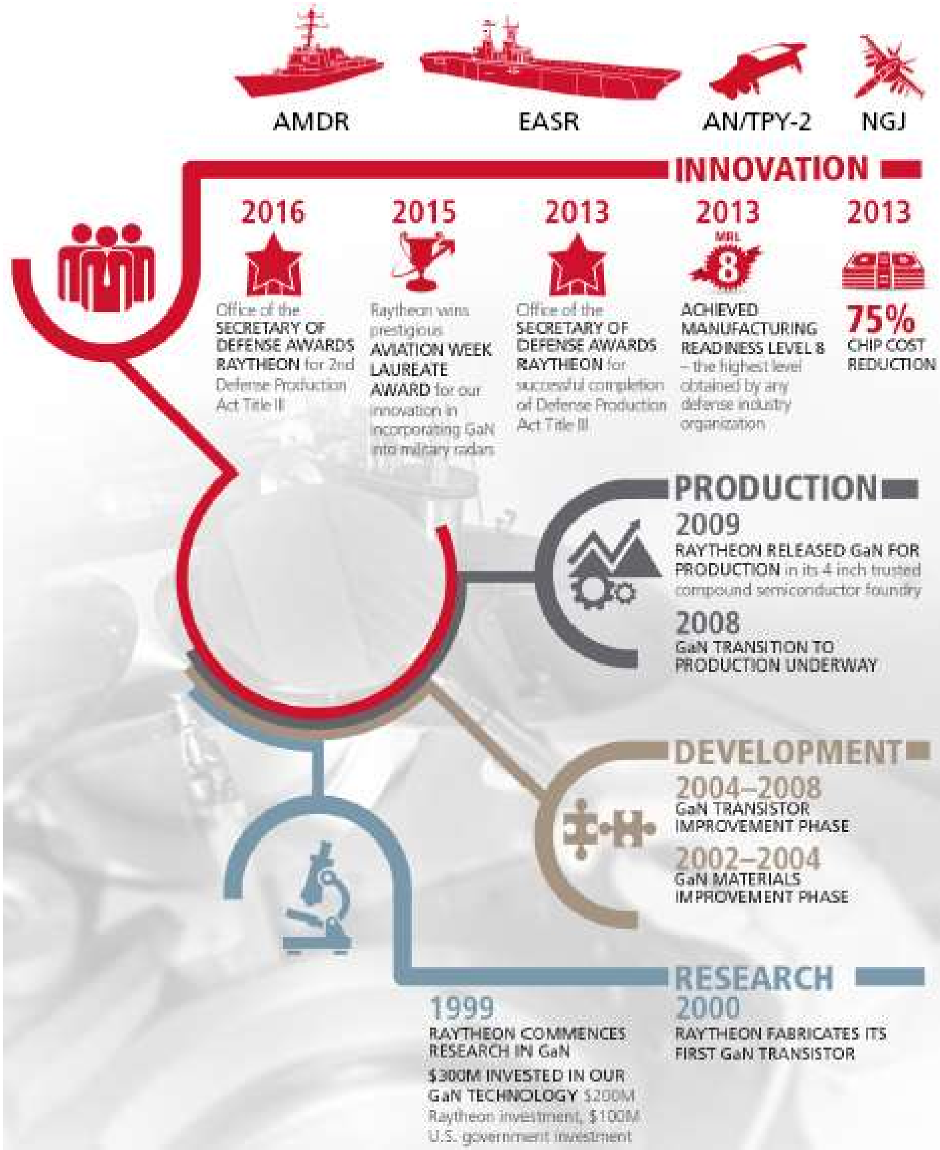


Specializing in missiles, radar, and electronic warfare equipment, Raytheon is the fourth largest U.S. defense contractor by revenue. Although it sometimes partners with rivals such as Boeing and Lockheed on large programs, it's the sole source for many of the most sophisticated radars, nearly all of which use GaN. Having developed everything from wafers to systems, Raytheon is one of the very few defense OEMs vertically integrated in GaN. This gives it a big advantage in competing for large radar projects, especially those for missile defense which benefits the most from GaN.

Raytheon GaN History



Raytheon GaN History



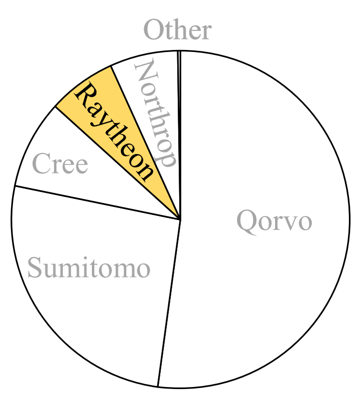
Raytheon's history in SiC doesn't stretch as far back as Cree's but it did begin research well before most semiconductor device manufacturers and long before other defense system OEMs. The company fabricated its first GaN transistor in 2000. This was a proof-of-concept device to demonstrate the performance advantages of GaN over GaAs and as such was not for production. The company spent the next four years ('00 - '04) refining its process to raise yields to the point they'd be viable in production. It took another four years ('04 - '08) to do the same for GaN devices, primarily transistors in monolithic microwave integrated circuits. By 2008 material and device yields were high enough to begin the transition to production, which was completed in 2009. Since then Raytheon has incorporated GaN into virtually all its electronic warfare, communications, and radar systems. Its biggest wins are for air and missile defense radars on land and sea, but it was also awarded an airborne electronic warfare system using GaN.

Raytheon

Established	1922
GaN R&D	1999
Products	GaN RF devices
Markets	Radar
Consolidated Revenue	$57B
GaN Device Revenue 2020(e)	$50M
Share of Merchant Mkt GaN Device Sales	7%

All of Raytheon's SiC production is consumed by its systems group, so it is not a merchant market supplier of SiC in any form. Developing its own wafers provided insights that improved its GaN devices but the scale of its SiC operations are too small to be cost competitive in wafers with Cree or II-VI or in devices with Qorvo. To remedy this, Raytheon buys SiC wafers from Cree and II-VI and sources GaN devices for large defense programs from Qorvo. This makes its GaN operations a pseudo-competitor on internal programs and its systems division a large customer of Qorvo's GaN devices.

GaN RF Device Market Share



After years of development, the first wave of SiC based radars are now being deployed and performance results have convinced the Department of Defense to incorporate GaN in all new systems. Like all defense OEMs, Raytheon can't source GaN devices from non-U.S. manufacturers so its growing appetite for devices is flowing through as higher demand at Qorvo. This is one of the primary factors fueling the two-year growth profile in the defense segment of Qorvo's Industrial Defense Product (IDP) group. Given the decade long production runs for some of these systems, we expect consistent stable growth in IDP's defense segment and SiC wafer sales to Raytheon at II-VI and, to a lesser extent, Cree.

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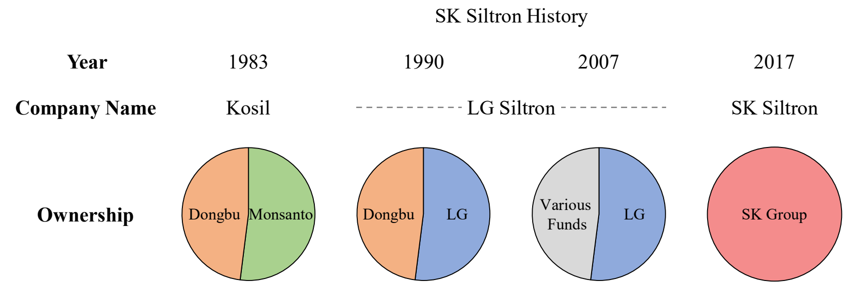
[1] For a detailed discussion of the technical challenges to manufacturing silicon carbide see our publication "CREE: Silicon Carbide: Extremely hard and incredibly powerful." Charter Equity Research, March 31, 2020.
[2] "After years of further development of the sublimation growth process, Cree Research became the first company to sell 2.5 cm diameter semiconductor wafers of 6H-SiC", SiC Technology (1998), NASA Lewis Research Center, Philip G. Neudeck. Pg 13.
[3] "SiC Technology (1998)", NASA Lewis Research Center, page 15.
[4] Tesla does not share unit volumes by model but by year-end 2020, the Model 3 was estimated to have surpassed 800,000 cumulative unit sales, overtaking the Nissan Leaf for the best-selling global plugin electric vehicle model.
[5] Companies which only produce wafers for power switching applications include Rohm, TankeBlue, SK Siltron, TySiC, and internal projects owned by large device manufacturers. While most internal wafer growth projects have immaterial volume, the parent companies (Infineon, ST Micro) have substantial resources at hand, providing a longer runway for startups to reach production.
[6] SEDI is not to be confused with Sumitomo Electric Device Innovations USA (SEDU), a manufacturer of optical devices and modules which are primarily sold in the U.S.
[7] Vertical integration provides direct feedback from device production to wafer/epi wafer operations, allowing wafer processes to be adjusted quickly for internal use and external wafer sales.
[8] The largest semiconductor suppliers to automotive applications are NXP, Infineon, Texas Instruments and ST Microelectronics. With the exception of ST Microelectronics, which supplies SiC MOSFETs to Tesla, none of these companies have material SiC device sales into electric vehicles.
[9] ST Micro is the sole supplier for SiC MOSFETs the Tesla Model 3, the first mass-produced EV to use silicon carbide. Each Model 3 inverter holds 48 ST Micro MOSFETs.
[10] Alongside Tokyo Electron and Kyoto University, Rohm set out to develop epitaxial equipment and processes for mass production in 2007. SiCrystal, purchased in 2009, had its own epitaxial processes but had made substantially more headway into bare crystal wafers. Rohm claimed its epitaxial process was used for devices in 2008 so SiCrystal's research on epitaxy likely augmented the progress Rohm had already made.
[11] The 6H crystal structure is primarily associated with RF devices but can be used for any GaN devices, such as blue and white LEDs. Some LED companies used silicon carbide crystal wafers but most switched to sapphire in the late-1990s as it delivered similar performance at a substantially lower cost. When Cree sold its LED business in 2020, it was virtually the only company using SiC for LEDs.
[12] Source: http://www.wtec.org/loyola/ttec/hte_e/report/hte-europe.pdf (page 60, 3rd paragraph)
[13] In 2000, SiCrystal merged with Freitronics, a Siemens-owned SiC wafer startup, giving Siemens a majority stake until Rohm acquired the shares in 2009.
[14] Rohm published the capacity expansion projections in its March 2018 presentation but hasn't produced an update. However other manufacturers such as II-VI have achieved similar growth.
[15] ST Micro has entered $620M worth of public SiC wafer agreements ($500M with Cree, $120M with Rohm) plus the acquisition of Norstel in 2019, whereas Infineon has agreed to purchase $100M of wafers from Cree, and ON Semiconductor entered an $85M agreement with Cree and agreed to purchase "up to" $50M of SiC boules from GT Advanced Technologies.
[16] Rohm press release, *ROHM Now Offers the Industry's Largest Lineup of Automotive-Grade SiC MOSFETs*, March 20, 2019: "In December 2010 ROHM was the first in the world to succeed in mass producing SiC MOSFET..."
[17] Rohm press release, *New 4th Generation SiC MOSFETs Featuring the Industry's Lowest ON Resistance*, June 17, 2020: "In 2015, ROHM began mass production of the industry-first trench-type SiC MOSFETs utilizing an original structure."
[18] Originally called Kosil, SK Siltron was established in 1983 as a joint venture between Monsanto and South Korea-based Dongbu to develop silicon wafers. In 1990 Monsanto sold its stake to LG, which renamed the company LG Siltron, and in 2007 a consortium of South Korean funds acquired Dongbu's stake in the company. By year-end 2017, SK Group had acquired LG's stake and the remaining equity from the various funds in order to provide its chipmaking arm SK Hynix an internal source of wafers. The business was later renamed SK Siltron. It purchased Dow Corning's SiC wafer business in 2019 for $450M to expand outside the commoditized market for silicon.



[19] Bare silicon wafer leaders include Shin-Etsu Handotai, SUMCO, Siltronic, SK Siltron, and GlobalWafers.

[20] Following the acquisition SK Siltron suggested it would sell wafers into both SiC power and GaN RF markets (5G) but as of April 2021, its website only displays 4H wafers (for power switching devices) and its target markets are Transportation (EV), Industrial, and Energy.

[21] IGBT: Insulated Gate Bipolar Transistors are high-power semiconductors that can handle more power than a similar size MOSFET but operate at lower frequencies (slower switching speeds).

[22] At the end of the March 2002 quarter, Uniroyal had less than $1M cash on its balance sheet and reported a net loss of $39M on $4.5M in revenue in the prior six months.

[23] After loaning the company $578M and buying an Arizona facility to house the production line, Apple abandoned its work with GTAT, complaining of poor quality and the lack of progress on production. In December 2019, after bankruptcy, shareholder and underwriter litigation, GTAT and its CEO consented to SEC orders finding they violated antifraud provision.

[24] Until its 2020 wafer supply agreement with ST Microelectronics, Rohm had not sold wafers on the merchant market and had not made any claims about wafer yields.

[25] "The (Smart Cut SiC) line is expected to be operational by the first half of 2020, with the goal of producing silicon carbide wafer samples using Soitec's Smart Cut technology in the second half of 2020.", Soitec Press Release, *Soitec announces joint development program with Applied Materials on next-generation silicon carbide substrates,* November 18, 2019.

[26] "Supply of silicon carbide is a huge challenge but with Smart Cut we could take a silicon carbide crystal, cut a thin layer and transfer this onto a [receiving] substrate and in this way generate a much bigger supply...", Thomas Piliszczuk, Head of Strategy, Soitec, CompoundSemiconductor, *Soitec: Beyond Silicon-on-Insulator,* June, 2019.

[27] Cree and Rohm are the only two crystal wafers manufacturers with their own epitaxial processes. II-VI, TankeBlue, TySiC, as well as all the inchoate efforts such as Norstel and Siltectra do not have in-house epitaxy.

[28] In August 2020 II-VI acquired two companies, Ascatron and INNOViON, for undisclosed amounts. Ascatron is a Swedish manufacturer of silicon carbide epitaxial wafers and power devices and INNOViON is a leading provider of ion implantation services for silicon and compound semiconductors like SiC.

[29] Silicon carbide crystals are grown at 2,500 degrees Fahrenheit, a temperature which would melt virtually all other semiconductor materials. Once the growth process is done and the crystal solidifies, it is one of the hardest materials on Earth, and the difficulties encountered during slicing and polishing the wafer chew into yields. After a crystal wafer has been sliced and polished, epitaxy is performed at a similarly high temperature, which can warp the crystal wafer. .

[30] Compound semiconductors are produced by combining two elements, like silicon carbide and gallium nitride. These materials are more expensive and defect-prone than silicon but can operate at higher frequencies and power levels, depending on the material. IQE Full Year 2018 Results: "Compound semiconductors such as GaAs and InP can operate at speeds that are several orders of magnitudes higher than is possible using silicon alone … Compound semiconductors including silicon carbide (SiC) and GaN are capable of operating at high powers (high voltages and current levels) and are highly efficient at converting different types of power and at high frequencies."

[31] Epitaxial Products International used the metal organic chemical vapor deposition (MOCVD) process to manufacture its epi wafers whereas QED used molecular beam epitaxy (MBE). MBE allows for more precise control in adding epitaxial layers but is expensive, whereas MOCVD offers less precision at a lower

cost. Having both processes allowed IQE to target a broader customer base and become a one-stop shop for epi wafers in RF. Source: https://link.springer.com/chapter/10.1007/978-3-319-48933-9_14
[32] Most of Cree's production (crystal, epi, devices) is focused on the SiC power market, as reflected in the fact that 75% of the $1B in long-term wafer supply agreements it signed are with SiC power device manufacturers. Cree is expanding wafer capacity, but the expansion is concentrated on wafers used in SiC power applications, which will be used to feed its new internal device fab starting in 2022.
[33] Soitec press release, *Soitec expands its engineered substrate portfolio into GaN (Gallium Nitride) with the acquisition of EpiGaN*, May 13, 2019: "Soitec … announced today that it has entered into a definitive agreement to acquire EpiGaN, a leading European supplier of GaN epitaxial wafer (epi-wafer) materials."
[34] Showa Denko acquired Hitachi Chemical in April 2020 which was consolidated as the Materials segment. Silicon carbide epitaxial wafer sales are included in the Electronics segment.
[35] Cree CEO Gregg Lowe, September 2020 conference call: "we're starting to ramp some of these [EV] products in 2022, we'd see a really a steeper ramp in 2024, 2025 … So the automotive ones are typically three to four years out."; Helmut Gassel, Infineon Chief Marketing Officer, June 2020 conference call: "In Automotive, yes, we have design wins … they haven't really ramped into production yet, but they will be ramping as of [2021] in Silicon Carbide in Automotive."
[36] In a December 2018 presentation, Infineon claimed 18.6% of the $18.5B market for power discretes and modules, trailed by ON Semi (9%) and ST Micro (5.1%).
[37] Infineon's acquisition of Cree was blocked on national security grounds as GaN power amplifiers are used in radar. However we believe the U.S. government's substantial investments into the early development of SiC and GaN also contributed to this decision. Nearly all major U.S. suppliers of SiC and GaN (Cree, Qorvo, Raytheon, Sterling [now SK Siltron]) were funded by the government early on when the technology was far from profitable and the government likely didn't want its investments to be all for naught. Once the deal was blocked, Infineon's priorities shifted to SiC power devices and it sold its RF GaN device business to Cree, in addition to the $100M wafer supply deal.
[38] Most vehicle models planning to adopt silicon carbide are fully electric, but TranSiC concentrated on the use of SiC in mild hybrid cars, the power requirements of which are not nearly as high as battery electric or plugin hybrid vehicles.
[39] For a better understanding of the strengthens and weakness of the different types of devices used with silicon carbide see our note on the topic "CREE: Silicon Carbide: Extremely hard and incredibly powerful." Charter Equity Research, March 31, 2020.
[40] As of 2021, ON Semi does not sell silicon carbide bipolar junction transistors.
[41] ON Semiconductor blog post, *ON Semiconductor's World-Class Wide Bandgap Product Supply Chain,* June 24th, 2020: "ON Semiconductor has positioned itself to ensure wafer supply by signing two Long Term Supply Agreements (LTSA), continuously evaluating new substrate manufacturers, as well as developing substrates internally."
[42] Power America is a collaborative effort between various U.S. government labs, universities, OEMs, and semiconductor manufacturers to showcase, educate and further research into wide bandgap semiconductors (silicon carbide). Cree and X-FAB provide foundry services for Power America research projects, funded by industry participants and government labs.
[43] X-FAB purchased the Lubbock fab from Texas Instruments (TI) in 1998. It was a 150mm, 0.6 micron FLASH memory fab that TI idled rather than continue investing in and trying to compete with Micron, Intel, Samsung and Japanese foundries that had come to dominate the technology. Once X-FAB started operations it began replicating the CMOS lines operating in its German facility to Texas. By 2018 the Lubbock facility was a fully loaded CMOS foundry.
[44] We expect the long gestation of X-FAB's first SiC line was due to the lack of affordable merchant market SiC power wafers prior to 2018. Cree was still devoting most of its resources to the LED market and restructuring its SiC strategy after its attempt to sell Wolfspeed to Infineon was shuttered by government security concerns. II-VI had yet to offer SiC power wafers, Rohm was not selling crystal or epitaxial wafers on the merchant market, and none of the other struggling wafer operations (Dow, Norstel, Siltectra, TankeBlue) had viable products, in fact many were looking for cash infusions or an acquisition by better funded device companies. The change in Cree's management in late 2017 brought a greater focus on merchant market wafer sales, resulting in price reductions on crystal and epitaxial wafers. This led a slew of power device manufacturers to sign long-term supply agreements, including X-FAB, which inked an

$86M deal with Cree on October 16, 2018 for crystal and epitaxial wafers for power devices targeting the industrial market.

[45] Silicon carbide device yields would improve with a better understanding of how SiC epi impacts wafer yields (a complex interaction with silicon carbide). Inventory costs would also decline given the company would no longer have to stock different grades of epi wafers for different power levels (6.5Kv, 3.3Kv, 1.7Kv, 1.2Kv, 650v). It could also source lower cost crystal wafers for lower performance devices instead of being locked into the high performance wafers Cree uses for its epi process. Having its own SiC epi process would allow X-FAB to purchase bare substrates (crystal wafers) instead of the more expensive epi wafers it currently requires.

[46] In multiple press releases, TriQuint mentioned it had been sponsored by Lockheed Martin at the onset of its GaN research although the company didn't disclose the amount or specific purpose of the funding.

[47] Notes from November 2019 call with James Klein on Defense. James said TriQuint's original mandate for GaN from the DoD was high and wide frequencies, specifically X, Ku, Ka, and W bands and any version of broadband and EW, well beyond 2 – 18 GHz and covering many octaves. He said TriQuint only entered low frequency, high power 10 years ago (2011). This is a little different from what James told us in our on-site summer 2015 meeting in Texas. At that meeting James said government funding for GaN research was originally divided into three tracks based on frequency. Cree was focused on EW (broadband), TriQuint on high-frequencies and Raytheon on low frequencies (S, L band radars).

[48] Cable infrastructure was one of the first segments to adopt GaN but didn't experience the same growth as radar or telecom. In 2018, Qorvo estimated the TAM for GaN-based cable TV products was well below $50M and would remain essentially flat through 2022.

[49] RFMD opened its GaN foundry to external customers in June 2009 where it would fabricate devices designed by other companies.

[50] Raytheon and Northrop Grumman participated in the DARPA project in the 2000s alongside Cree and Qorvo and both OEMs built their own device fabs which they use for R&D and low volume production. For large systems they purchase GaN devices from Qorvo and, to a lesser extent, Cree, both of which enjoy cost and scale advantages.