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2024

COMPANY OF THE YEAR

IN THE GLOBAL GAN SEMICONDUCTORS INDUSTRY

QROMIS

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2024 BEST PRACTICES AWARD

Best Practices Criteria for World-Class Performance

Frost & Sullivan applies a rigorous analytical process to evaluate multiple nominees for each Award category before determining the final Award recipient. The process involves a detailed evaluation of best practices criteria across two dimensions for each nominated company. Qromis, Inc. excels in many of the criteria in the GaN semiconductors space.

AWARD CRITERIA

Technology Leverage	*Customer Impact*
Commitment to Innovation	Price/Performance Value
Commitment to Creativity	Customer Purchase Experience
Stage Gate Efficiency	Customer Ownership Experience
Commercialization Success	Customer Service Experience
Application Diversity	Brand Equity

Industry Challenges and Match to Needs

Modern-day applications, such as electric vehicles (EVs), and 5G mmWave communications, require power and radio frequency (RF) semiconductor components that perform well at higher voltages, temperatures, and frequencies — needs that conventional silicon-based semiconductor devices cannot meet. Designing power electronics and RF systems from silicon-based components leads to a trade-off between system performance, efficiency, and form factor. For instance, switching a semiconductor at higher frequencies requires high power density and reduced device size, but designing with silicon will cause increased power loss and heat dissipation while reducing system efficiency. Conversely, designing a device for high efficiency and reduced power loss is achieved by lowering the switching frequency – yet with larger component size and lower power density.

> *"Frost & Sullivan commends Qromis for its innovative QST, which effectively addresses cost and reliability challenges in the GaN semiconductors market. QST will play a crucial role in expediting the commercialization of highly reliable GaN devices while showcasing versatility in applications and demonstrating scalability for future advancements."*
>
> ***- Prabhu Karunakaran***
> ***Industry Principal, Semiconductors Program***

Recognizing these limitations, the semiconductor industry explored alternatives, leading to the discovery of wide-bandgap semiconductor materials, such as silicon carbide (SiC), gallium nitride (GaN), and diamond. While diamond remains niche and in the early development stage, commercial opportunities currently revolve around SiC and GaN. Each material excels in specific applications; while SiC finds widespread use in EV inverter applications, GaN plays a crucial role in power (EV charging, consumer electronics) and RF applications.

With a bandgap of 3.4 electronvolts (eV), GaN surpasses silicon and SiC in intrinsic properties, boasting a wider bandgap, higher critical electric field and electron mobility, lower on-resistance, and 3-to-5 times higher Baliga's figure-of-merit (BFOM) compared to SiC, making it quite ideal for high-frequency operations, high-power systems, elevated temperature environments, and stable performance requirements. However, due to challenges in scaling to higher voltages beyond 650V, current applications are limited to fast chargers, on-board chargers (650V) for EVs, solar inverters, and 5G RF devices.

Established in 2015 and headquartered in California, Qromis has successfully addressed critical technical challenges associated with cost-effective and reliable GaN devices for higher-voltage and frequency applications, as well as for light emitting diodes (LEDs) / microLEDs, through its innovative Qromis Substrate Technology (QST) which is very similar to the mainstream Silicon-on-Insulator (SOI) substrates with respect to manufacturing processing and cost. As a rapidly growing Silicon Valley-based fabless company, Qromis is driving the commercialization of its patented QST substrate innovation, protected by close to 300 worldwide patents, by leveraging the manufacturing platforms of its worldwide industrial partners through close collaborations, up and down the supply chain.

At QST's core is a high mechanical strength aluminum nitride (AlN) polycrystalline material with a coefficient of thermal expansion (CTE) very closely matched to GaN/AlGaN epitaxial layers over a wide temperature and prevents excessive stress or GaN cracking or wafer breakage during the cooling stage of GaN epitaxy growth process. High thermal conductivity (170-230 W/mK) AlN ceramic core material is encapsulated into a series of thin films, on top of which a SiO_2 bonding layer is deposited, and a single crystalline Si (111) layer is formed, which serves as the nucleation layer for the epitaxial GaN growth. Si (111) GaN growth-ready surface can be changed to single crystal GaN, SiC, or other GaN growth-ready surfaces. This strategic design ensures compatibility with standard SEMI specifications for complementary metal-oxide-semiconductor (CMOS) fabrication, eliminates the thermal mismatch associated with GaN-on-Si structures and enables superior thermal conductivity.

QST enables GaN power devices to exceed the 650V threshold by utilizing scalable substrates up to an impressive 300mm. Frost & Sullivan notes that this helps to overcome the limitations of the prevailing GaN-on-Si technology (mainly processed on 150 mm wafers), which struggles with scalability to higher voltages due to wafer breakages, warping, and unreliable performance, among other issues including non-SEMI specifications.

While QST platform enables higher performance and application scale for GaN devices, it also brings a critical economies of scale advantage for device manufacturers and foundries since all GaN devices (power, RF, microLED and others) can be manufactured on the same CMOS-fab friendly, SEMI-spec platform for efficiency and further cost reduction.

Price/Performance Value, Commercialization Success, Customer Ownership Experience

Thermal conductivity plays a crucial role in determining thermal stress-handling capability and serves as the foundation for producing high-voltage products with exceptional reliability. Gan-on-QST boasts a thermal conductivity of 170-230 W/mK, surpassing GaN-on-Si's 130 W/mK thermal conductivity. QST facilitates thickness scaling of epi layers without encountering wafer breakage, warpage, or reliability issues by very closely matched CTE of GaN/AlGaN epitaxial (epi) layers and QST. Qromis has showcased its capability with a 16-micron-thick GaN-on-QST-based GaN diode, a 17-micron-thick GaN-on-QST vertical GaN transistor, and a 30-micron-thick GaN in collaboration with its partners such as Imec, Aixtron, Shin-Etsu Chemical and Toshiba.

> *"Qromis is building on its early commercialization success by consistently demonstrating efforts to innovate, create, and focus on diverse applications, accelerating GaN penetration in the power, RF and microLED markets. Consequently, the company is well-positioned to experience continued growth above that of the GaN devices market."*
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Epi layers' cost reduction and scalability along with very high quality (low dislocation density epi - approaching to costly and small diameter GaN-on-GaN) enabled by QST empowers GaN device manufacturers to create highly reliable lateral GaN structures and cost-effective vertical GaN structures for critical market segments such as EV inverters. This is a significant advancement, especially in areas dominated by silicon IGBTs and high-cost SiC FETs and diodes.

With the CTE matched structure, GaN epitaxy layers on QST do not require complex and costly strain management layers which are essential for GaN-on-Si and other heteroepitaxy platforms. As such, GaN-on-QST platform enables very significant GaN epitaxy cost reduction, process simplification and increased reactor uptime via reduced process times, while yielding thicker GaN layers. A drastic cost and performance improvement from a comparative, side-by-side study led by Shin-Etsu Chemical, which was presented at 2023 SEMICON Taiwan, show that GaN epitaxy growth time is cut in HALF for GaN-on-QST® compared to GaN-on-Si. This opportunity of simplified and low cost GaN epitaxy process will further propel GaN-on-QST® adoption.

Also, with its highly electrically insulating polycrystalline AlN core material, QST enables wafer-level monolithic power integrated circuits (ICs) without any cross-talk issue, which is another major challenge in GaN-on-Si platform. Imec has demonstrated high performance 650V GaN ICs with trench isolation design, integrated with drivers, current sensors and logic all on the same 200mm QST wafer. This opens the path for system-on-chip (SoC) GaN ICs, enabling very high performance GaN power devices with further reduction in packaging and system costs.

In summary, Qromis' QST technology enables low cost 100V-to-1800V and beyond GaN power devices in lateral, vertical and SoC IC forms in mainstream 200mm and 300mm CMOS fabs which will propel GaN adoption significantly.

GaN-on-QST's excellent price-performance value has translated into early commercialization success with 2 companies: Vanguard International Semiconductors (VIS) and Shin-Etsu Chemical Co Ltd (Shin-Etsu Chemica).

Qromis' partnership with VIS, a Taiwanese pure-play foundry service company, has helped the latter produce QST substrates exclusively for Qromis since 2016 under license from Qromis. In 2018, Qromis collaborated with VIS to develop a 650V GaN power device using 0.35 um process technology on a 200mm GaN-on-QST substrate as a device foundry service for all industry players. The process technology achieved full qualification and mass production in Q4 2022, a noteworthy achievement given typically lengthy commercialization timelines.

Remarkably, with no prior experience in fabricating GaN devices before collaborating with Qromis, VIS successfully entered the market as the world's first 200mm GaN power device foundry service provider within ~3 years, aided by the ease of working with QST. Customers collaborating with VIS have acknowledged QST's superior thermal properties, leading to enhanced heat dissipation performance and world-leading capabilities via Gen1 650V devices, starting in fast-charging applications for 65W, 100W and higher power specifications.

Manufacturing volume of Gen1 GaN-on-QST E-mode HEMT devices at VIS is currently ramping for initial 650V applications which will be followed by Gen2 devices in second half of 2024, designed for industrial and automotive applications with additional cost reduction by using three-level metal layer architecture. Gen2 devices, which are currently in design/pilot shuttle/reliability test stage, will be qualified at full rating 650 V hard switching. The success of this initial commercialization step has prompted VIS to collaborate with new customers to extend the application of its product to higher voltages, such as 900V and 1,200V, enabling GaN penetration in EV inverters and industrial applications. 1200 V GaN-on-QST® development at VIS is underway and scheduled to be released by end of 2025. One of the target applications will be 800 V EV charging.

Qromis also witnessed commercial success with Shin-Etsu Chemical with the market launch of QST, which was licensed to the latter in 2019. Shin-Etsu Chemical is currently selling 200mm QST substrates and GaN-on-QST epi wafers based on customers' application-specific requirements. Shin-Etsu Chemical is evaluating various applications with its customers, including power, RF and light-emitting diodes (LEDs) / microLEDs, with noteworthy efforts in enabling GaN power devices for 650 V to 1,800 V specifications in both lateral and vertical device architectures via its QST-based materials products offerings.

Another important feature that QST solution brings is that the QST substrates are assembled and manufactured in traditional CMOS fabs (similar to mainstream SOI substrates with respect to manufacturing processing and cost) by utilizing energy efficient mainstream semiconductor process tools with >98% yield and less than 7 days of process cycle time while e.g. SiC substrates are manufactured in isolated, non-CMOS compatible fabs with low yielding crystal growth processes at extreme temperatures >2200ºC for several days which result in excessive amount of power consumption, water cooling and consumables such as graphite and felt. This is a critical component of the QST process design innovation / IP which is developed per the projected sustainability / net zero activities coming up or already happening in the semiconductor industry. More importantly, the power GaN devices manufactured on QST is showcasing a high device and back-end yield of over 90%.

In summary, Frost & Sullivan commends Qromis for its innovative and groundbreaking QST, which effectively addresses cost and reliability challenges in the GaN semiconductors market. QST will play a crucial role in expediting the commercialization of highly reliable GaN devices while showcasing versatility in applications, demonstrating scalability, for future advancements, and enabling companies to accelerate the innovation to zero in sustainability.

Commitment to Innovation and Creativity and Application Diversity

With the successful development of a highly reliable 650V GaN device on a 200mm wafer, Qromis and its licensee Shin-Etsu Chemical are actively pursuing the transition of their process technology platform to 300mm QST wafers. This strategic move aims to further enhance cost reduction, addressing power, RF and microLED markets cost challenges. Qromis and Shin-Etsu Chemical target the release of 300mm QST substrate and GaN-on-QST epi wafer products by 2024-2025, positioning themselves well ahead of competing technologies, whose roadmaps indicate a launch of 300mm wafer-based GaN only by 2030. With this current roadmap, Qromis is poised to disrupt the GaN market and drive accelerated growth in the emerging space for GaN power.

In terms of application diversity, a significant application area for GaN devices is currently RF applications, contributing 92.7% of the GaN market revenue. At present, RF applications for high frequencies predominantly use GaN-on-SiC technology due to its superior thermal conductivity and semi-insulating properties compared to conventional GaN-on-Si. This technology ensures stable and reliable performance, which is crucial for applications in telecom and aerospace and defense. However, GaN-on-SiC devices are costlier, being fabricated on 6-inch (150mm) wafers and utilizing higher-priced SiC substrates. Notably, GaN-on-SiC for RF applications is more expensive than its power application counterpart, as RF applications require semi-insulating material, and the 4H n-type GaN-on-SiC used for power cannot be applied.

Qromis' QST effectively addresses cost and reliability challenges through innovative material engineering. QST's AlN-based substrate core boasts superior thermal conductivity comparable to GaN on SiC and GaN, making it suitable for RF applications. Moreover, QST employs a thin semi-insulating Si(111) top layer on its substrate, as one of the application-specific QST products, making it ideal for developing GaN devices for higher-frequency applications. Therefore, QST enables RF components, such as power amplifiers and low-noise amplifiers, with specifications similar to GaN on SiC, with the scalability benefits of GaN on Si, resulting in a significantly lower cost. QST's ability to facilitate low-cost RF applications stems from the much lower cost of GaN-on-QST compared to GaN-on-SiC. In addition, QST enables RF fabrication on large substrates, such as 200mm, allowing the production of more RF devices within 1 wafer and reducing the overall cost. Looking ahead, with QST's future scalability to 300mm wafers, GaN component manufacturers can scale their product platform to meet high-frequency requirements and access to much higher resolution lithography tools for much better yield and performance without facing cost and reliability issues, swiftly building a robust product portfolio.

With initial commercial success, Qromis generates revenue through its QST and GaN-on-QST epi wafer sales and also royalties from VIS and Shin-Etsu Chemical through their sales of QST-based products. The company is witnessing above-market growth due to technology demonstrations in partnership with Imec, Shin-Etsu Chemical and VIS, producing GaN for various applications across voltage and frequency ranges.

Qromis is also fostering the growth of fabless GaN, enabling the development of new devices and creating additional demand for its QST.

From a market standpoint, Qromis and its partners select the right voltage segment to develop new products. Frost & Sullivan's Global Wide-bandgap Semiconductor Growth Opportunities study indicates that 650 V to 1,800 V will be the fastest-growing segment in the next 10 years, with a compound annual growth rate CAGR (2022-2032) of 40.1%. The 650 V to 1,800 V segment will also generate the largest revenue for wide-bandgap semiconductors, with a cumulative revenue opportunity of $70.13 billion from 2022 to 2032. The study also indicates that the overall GaN semiconductors market, which currently generates majority revenue from the RF segment, will grow at a 22.7% CAGR (2022-2032).

In summary, Qromis is building on its early commercialization success by consistently demonstrating efforts to innovate, create, and focus on diverse applications, accelerating GaN penetration in both the power and RF markets. Consequently, the company is well-positioned to experience continued growth above that of the GaN devices market.

Conclusion

GaN holds significant potential to deliver high performance in the power and RF semiconductors markets, addressing the needs of new-age and futuristic applications. However, existing limitations in substrate technology raise concerns regarding the technology's cost and scalability for high-voltage and frequency applications, posing challenges to market growth. Frost & Sullivan analysts conclude that Qromis' QST substrate technology emerges as the solution to unlock GaN's full potential with the following crucial features in summary.

QST substrates are similar to mainstream SOI substrates with respect to substrate assembly processing and cost. As such, the pricing is very similar to SOI in volume shipments, e.g. significantly cheaper than SiC. At such volume pricing levels, QS® brings a highly competitive and sustainable device cost advantage and business economics against the alternative platforms such as GaN-on-Si, GaN-on-Sapphire, GaN-on-SiC and GaN-on-GaN by the following key features.

Firstly, QST substrates support wafer sizes from 200 mm to 300 mm and beyond, facilitating large-scale production, which is critical for accelerating the growth of power GaN market. These substrates are SEMI-spec compliant and compatible with mainstream CMOS fabs, eliminating the need for dedicated manufacturing lines. Further, due to high mechanical strength, QST substrates prevent epitaxy cracking and wafer breakage, achieving over 90% device and backend yield. They enable cooler devices with a high thermal conductivity AlN ceramic core and support a broad spectrum of GaN products, including power switches and monolithic ICs. Additionally, QST substrates promote sustainability, as the substrates are manufactured through energy-efficient processes that delivers over 98% yield, and short process cycle times. Finally, the interchangeable GaN growth-ready surface allows for easy business expansion and adaptation to different GaN material qualities. These features collectively position Qromis as a leader in the semiconductor market, providing a cost-effective, scalable, and versatile solution that meets modern electronics demands while promoting sustainability and efficiency.

QST has demonstrated success in early commercialization efforts in the GaN power market, specifically with 650V e-mode GaN devices. Currently, Qromis collaborates with leading research institutes and foundries to facilitate the scaling of GaN applications to high voltage (both lateral and vertical structures) beyond 1,200V, as well as in high-frequency applications, ensuring both low cost and high reliability. Frost & Sullivan anticipates that these collaborative efforts will accelerate GaN market growth, enabling technology penetration in a wide range of applications and bolstering long-term market prospects.

In conclusion, QST stands as a key enabling technology poised to propel the GaN market to new heights in the coming years. With its strong overall performance, Qromis, Inc. earns the 2024 Frost & Sullivan Global Enabling Technology Leadership Award.

What You Need to Know about the Enabling Technology Leadership Recognition

Frost & Sullivan's Enabling Technology Leadership Award recognizes the company that applies its technology in new ways to improve existing products and services and elevate the customer experience.

Best Practices Award Analysis

For the Enabling Technology Leadership Award, Frost & Sullivan analysts independently evaluated the criteria listed below.

Technology Leverage

Commitment to Innovation: Continuous emerging technology adoption and creation enables new product development and enhances product performance

Commitment to Creativity: Company leverages technology advancements to push the limits of form and function in the pursuit of white space innovation

Stage Gate Efficiency: Technology adoption enhances the stage gate process for launching new products and solutions

Commercialization Success: Company displays a proven track record of taking new technologies to market with a high success rate

Application Diversity: Company develops and/or integrates technology that serves multiple applications and multiple environments

Customer Impact

Price/Performance Value: Products or services provide the best value for the price compared to similar market offerings

Customer Purchase Experience: Quality of the purchase experience assures customers that they are buying the optimal solution for addressing their unique needs and constraints

Customer Ownership Experience: Customers proudly own the company's product or service and have a positive experience throughout the life of the product or service

Customer Service Experience: Customer service is accessible, fast, stress-free, and high quality

Brand Equity: Customers perceive the brand positively and exhibit high brand loyalty

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The Growth Pipeline Engine™

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- **Growth Pipeline:** *Continuous Flow of Growth Opportunities*
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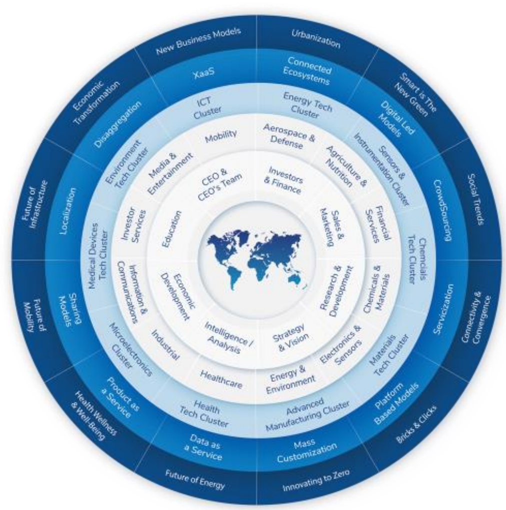
- **Innovation Culture:** *Optimized Customer Experience*
- **ROI & Margin:** *Implementation Excellence*
- **Transformational Growth:** *Industry Leadership*

The Innovation Generator™

Our 6 analytical perspectives are crucial in capturing the broadest range of innovative growth opportunities, most of which occur at the points of these perspectives.



Analytical Perspectives:

- **Mega Trend (MT)**
- **Business Model (BM)**
- **Technology (TE)**
- **Industries (IN)**
- **Customer (CU)**
- **Geographies (GE)**