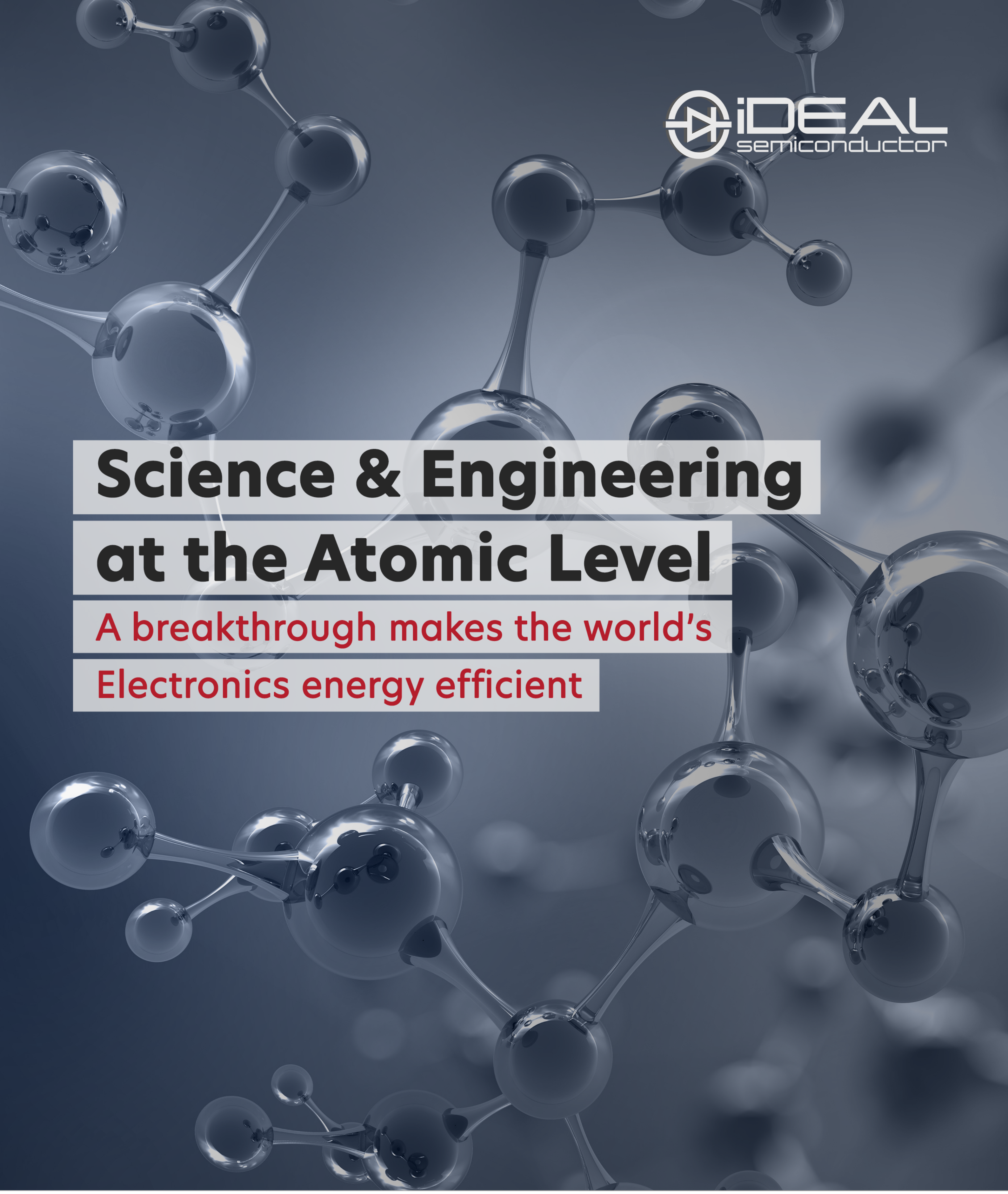

# Science & Engineering at the Atomic Level

## A breakthrough makes the world's Electronics energy efficient

**WHITEPAPER**

May 2023

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# Background

The power electronics industry has assumed that silicon-based power devices have reached their limits. Attempts to further increase the performance of power devices have focused solely on the materials used to build the device. But what if silicon hasn't reached its limits? And what if a power device architecture has unlocked several more decades of performance leadership in silicon? iDEAL Semiconductor's SuperQ™ is this technology.

# Power Semiconductor Evolution

Even before the bipolar junction transistor (BJT) was first invented in the late 1950s, a never-ending pursuit of higher performance, higher efficiency, smaller size, and lower cost products existed in the electronics industry. New power semiconductors spawned like power diodes and thyristors in the 1960s and insulated gate bipolar transistors (IGBTs) and power metal-oxide-semiconductor field-effect transistors (MOSFETs) in the 1970s and 1980s. These devices have enabled new applications to be born including the electrification of vehicles, renewable energy systems and more.

The trend has continued in recent years, with power semiconductors playing a key role in the development of efficient and reliable power electronic systems for these applications. However, the industry didn't just invent new devices - they found ways to improve performance through design and process optimization. Game-changing technologies were created like reduced surface field (RESURF) concepts which is at the core of Superjunction technology. In the late 1990s, Superjunction MOSFETs allowed for the replacement of planar MOSFETs, which at the time were a cornerstone of the power electronics industry. Superjunction technology unlocked performance heights previously unimaginable in silicon.

However, In the last two decades the performance of silicon power devices has plateaued. Instead of improving the power device itself, the industry has turned to alternative materials as the next frontier for performance gains. With the perceived lack of improvement left in the power device architecture, some have proclaimed that the industry has reached "the end of the road for silicon."[1]

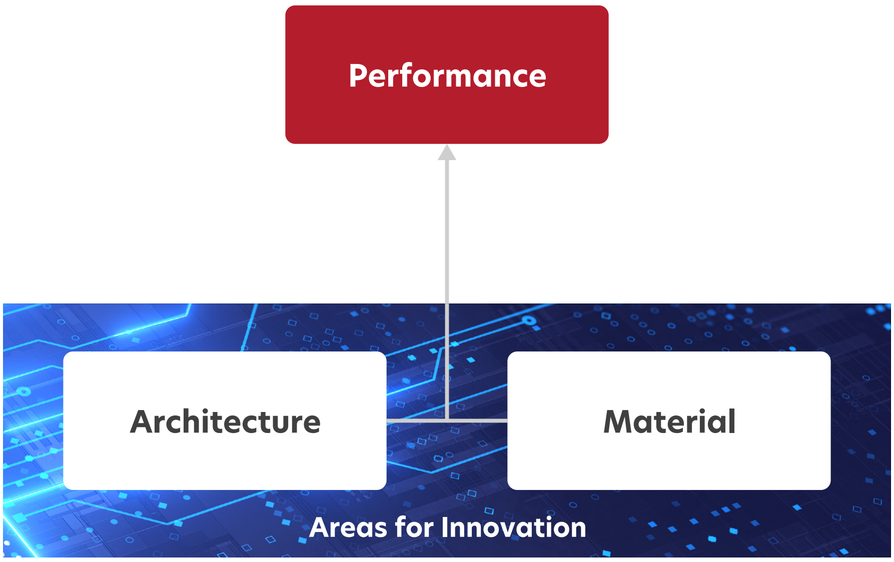



*Figure 1: Power device performance as a function of architecture and material*

# “The End of the Road for Silicon” Explained

The principal jobs of the power device are two-fold - block voltage in the off-state and pass current with low conduction losses in the on-state. When International Rectifier first released their HexFET technology in the late 1970s, the structure presented significant conduction loss benefits versus traditional BJTs. This one-dimensional architecture offers 100% silicon utilization dedicated towards conduction. However, a drawback occurs as this architecture tries to block higher voltage - its resistance goes up with the square of the blocking voltage. At high voltage the conduction losses become less acceptable.

To alleviate the voltage blocking challenges associated with the HexFET, RESURF “Superjunction” devices were introduced in the 1990s. These two-dimensional devices reshaped the electric field and allowed the resistance to rise linearly with increases in blocking voltage. The doping of the N-region can be increased, lowering the resistance and conduction loss. They are symmetrical structures with practical limitations in that the P-region area equals the N-region area for charge balance. However, the p-region does not contribute to conduction, so the structure is limited in practice to 50% silicon utilization.

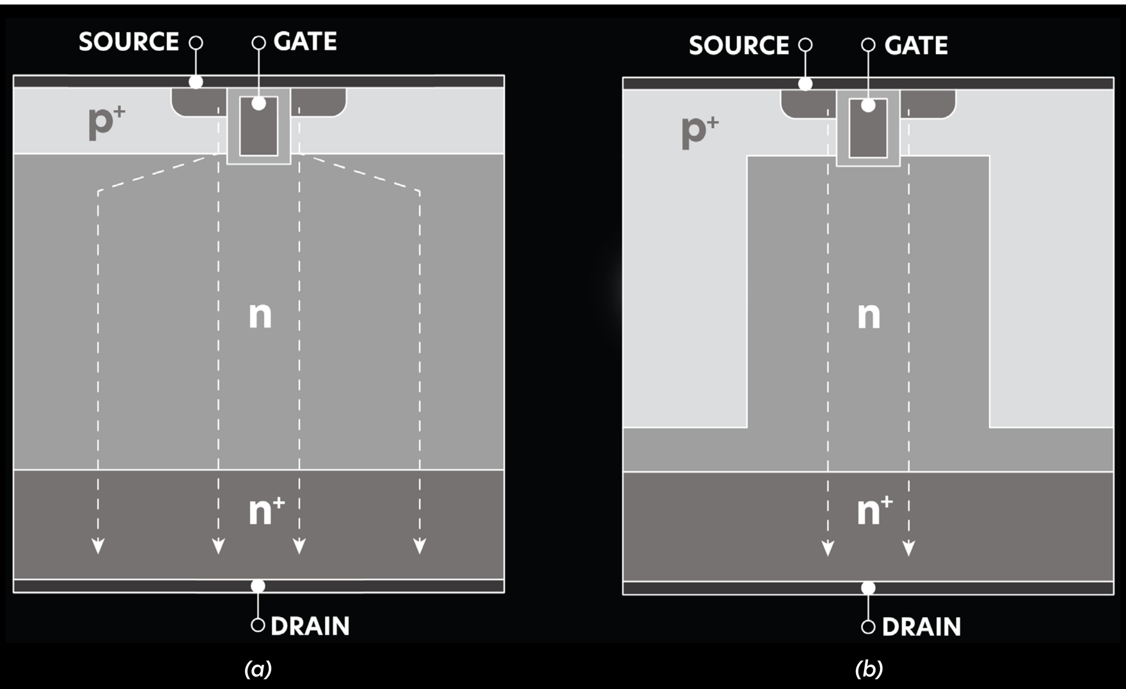



*Figure 2: Schematic cross-sectional structures of (a) conventional 1D power MOSFET, (b) Superjunction MOSFET*

After twenty successful years of performance leadership, plateauing performance of Superjunction has forced the industry’s hand. A better power device is clearly needed to keep the industry moving forward. However, no new technology has surfaced to improve the power device architecture - hence, the “end of the road for silicon” perception by the Power Industry. A new semiconductor material was assumed to be required. For the last several years the industry has shifted its focus towards wide bandgap semiconductor materials - Silicon Carbide (SiC) and Gallium Nitride (GaN).



# The Industry's Move to Wide Band Gap Semiconductor Material

To regain generation-to-generation improvement in power device performance, the power electronics industry has experimented with materials like Silicon Carbide and Gallium Nitride. Raw materials like Silicon Carbide and Gallium Nitride have a wider bandgap as compared to raw silicon, which in theory makes them lower resistance alternatives to silicon.

Silicon Carbide devices have been available for years and have gained popularity in high voltage and high temperature applications. SiC is a vertical device, and it is typically found in applications with voltages >650V. GaN is a newer technology with less penetration in the market. It is a lateral device, and its voltage options are typically <650V. The GaN device is best known for its ability to switch at ultra-high frequencies and leverages unique packaging to do so.

The global manufacturing footprint for semiconductors is well established for silicon. Of the $595 Billion USD semiconductor market in 2021[2], only $1.2 Billion is GaN and SiC[3,4]. A new ecosystem of manufacturing facilities, equipment and manufacturing techniques will all need to be developed to support a transition from silicon. Meanwhile the massive investment in silicon technologies continues with >120 silicon fabs producing 300mm wafers currently in use around the world[5] and with plans to build more in the future[6]. Additionally there are >170 200mm fabs with their respective investments in silicon-based tools[7].

Wide band gap devices are built on 100mm and 150mm wafers with 200mm wafer fabs under construction now. They are more expensive than their silicon counterparts. Justification to use the more expensive devices typically centers around an argument that their usage drives system costs lower. However, unless an application requires higher voltage, higher temperature or higher density, the system cost justification rarely holds water.

The industry clearly needs a higher performing power device than is available today in silicon. However, any new technology should take advantage of the existing infrastructure of silicon manufacturing and provide the same robustness and reliability that designers have come to expect over the last several decades. A new technology should not only improve the performance of silicon, but it should be forward compatible with SiC, GaN and other semiconductor materials if, or when, they reach maturity. This technology has arrived.

# Introducing SuperQ™

To enter the next frontier of performance iDEAL Semiconductor has researched and developed a new silicon-based architecture, SuperQ™ technology. SuperQ is an innovation at the atomic level of the power device, and it is agnostic to semiconductor material. This patented technology unlocks the full potential of the power device, delivering industry leading resistance per unit area (Rsp) and blocking voltage.

SuperQ technology breaks through the practical limitations of Superjunction structures that restrict the N-conduction region to 50% of the structure. Its asymmetrical structure has almost no limit on the conduction area, while providing the additional benefits of higher doping and a thinner epitaxial region due to its highly effective RESURF technology. Combined, these qualities make SuperQ the industry's most efficient process technology reaching up to 95% area utilization. Figure 3 is the SuperQ structure.

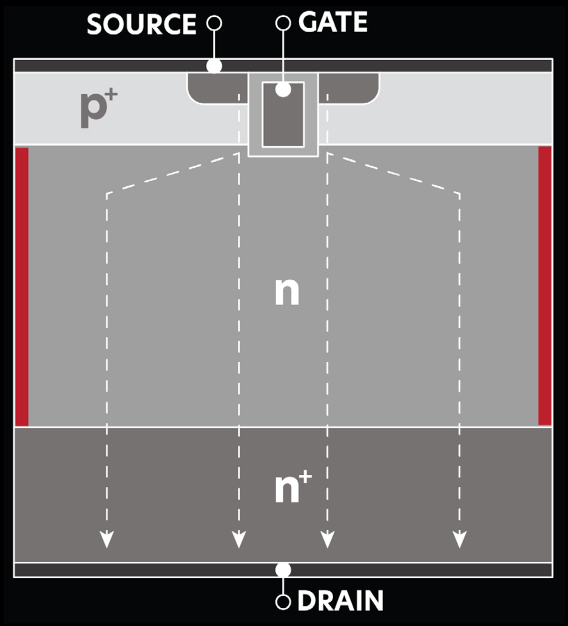
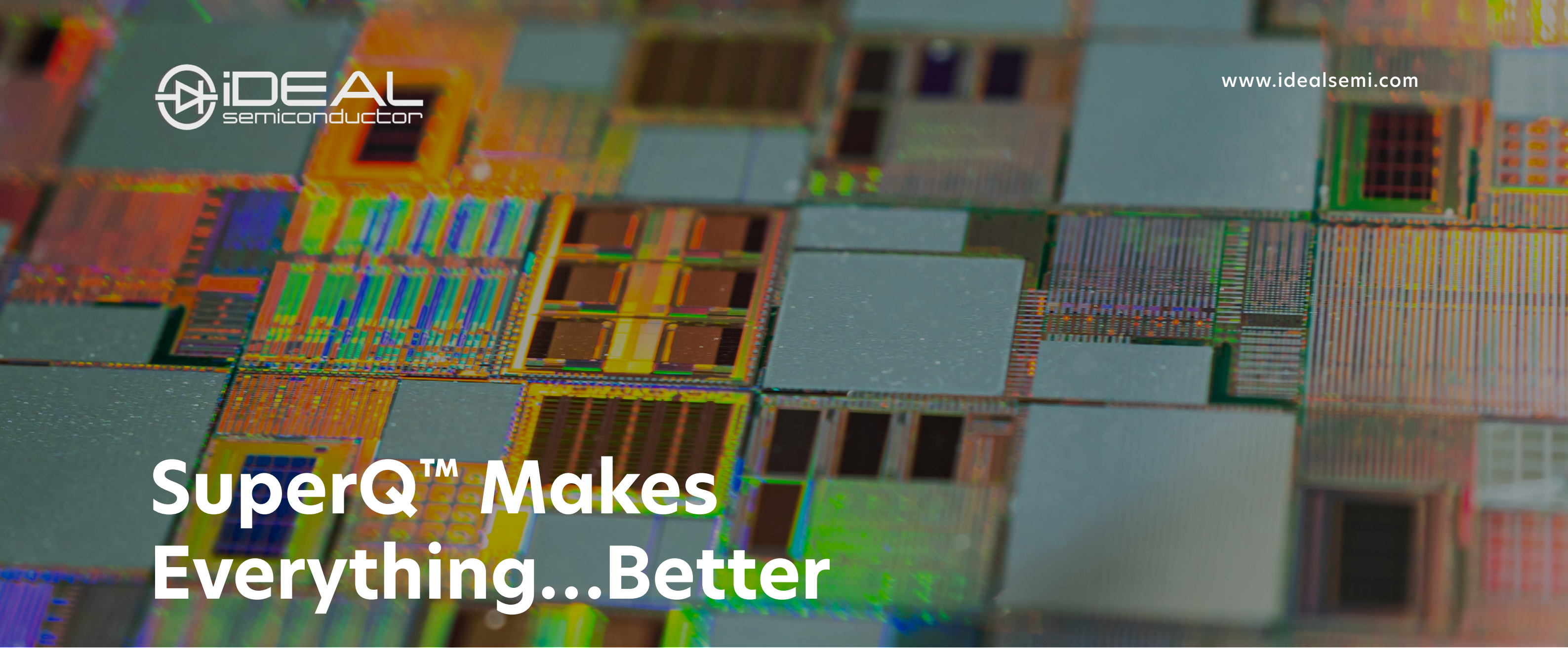



*Figure 3: SuperQ™ Asymmetrical, Charge-Balanced Structure*

SuperQ is manufactured using a traditional CMOS-like flow suitable for 200mm and 300mm wafers. It builds on the innovations in CMOS over the last decades and leverages tools and processes that are commonly found in state-of-the-art 300mm CMOS Fabs.  Though elegant, the SuperQ flow is greatly simplified versus Superjunction's epi+implant or trench+refill flow.





# SuperQ™ Makes Everything...Better

SuperQ's benefits are reaped across all power devices including diodes, MOSFETs, IGBTs and power ICs. When applied to silicon-based semiconductors, SuperQ delivers lower Rsp than commercially available products in the 60V - 850V voltage range.

Figure 4a shows the specific resistance of SuperQ versus the leading competitors mid-voltage silicon and enhancement mode GaN. In the same area, SuperQ delivers a 200V silicon MOSFET that is 6x lower resistance than leading competition and 1.5x lower resistance than competing GaN solutions. At high voltages shown in Figure 4b, SuperQ continues to shine with half that RSP at 650V versus silicon. SuperQ even offers lower RSP than industry leading GaN at 600V.

However, SuperQ is not just optimized for low conduction loss. Products designed with SuperQ technology have ultra-low leakage current, store less energy, and exhibit lower reverse recovery. These products are optimized for hard commutation, outperforming even fast recovery devices from competition.

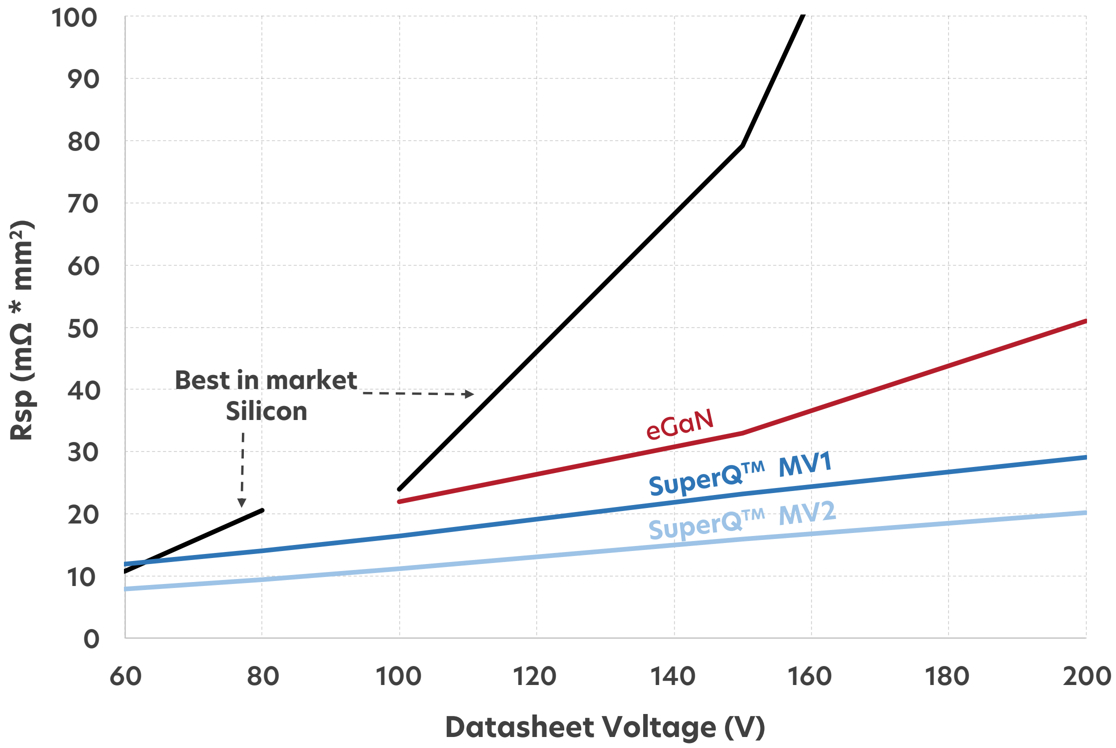



*Figure 4a: Specific resistance for silicon, GaN, SiC and SuperQ (SuperQ mid-voltage)*

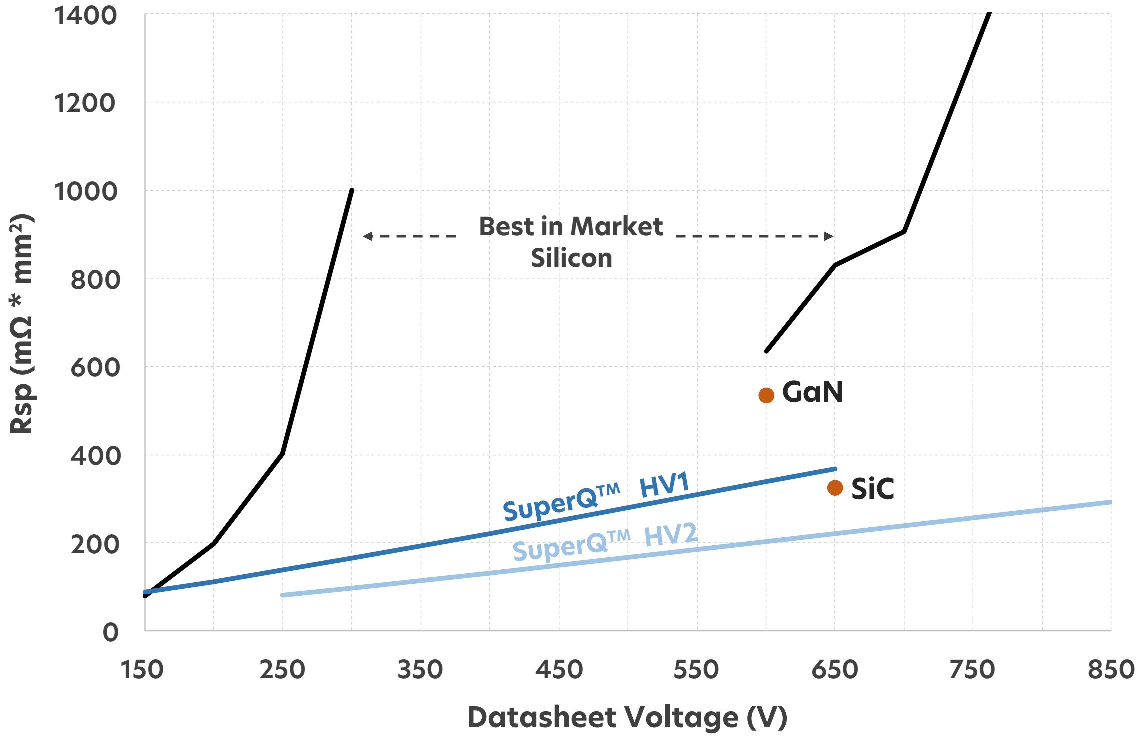



*Figure 4b: Specific resistance for silicon, GaN, SiC and SuperQ, (SuperQ high-voltage)*

The process capabilities of SuperQ far exceed those of its predecessors. The asymmetrical structure, higher doping and thinner epitaxial of SuperQ offer over a magnitude improvement over Superjunction. This capability enables new devices with industry's lowest resistances for a selected package.

# SuperQ™ and Wide Band Gap

The lore of wide band gap semiconductors is enticing. There is no argument that the theoretical limits of these advanced materials are impressive. Yet what's available in the market is a good distance away from theoretical limits.

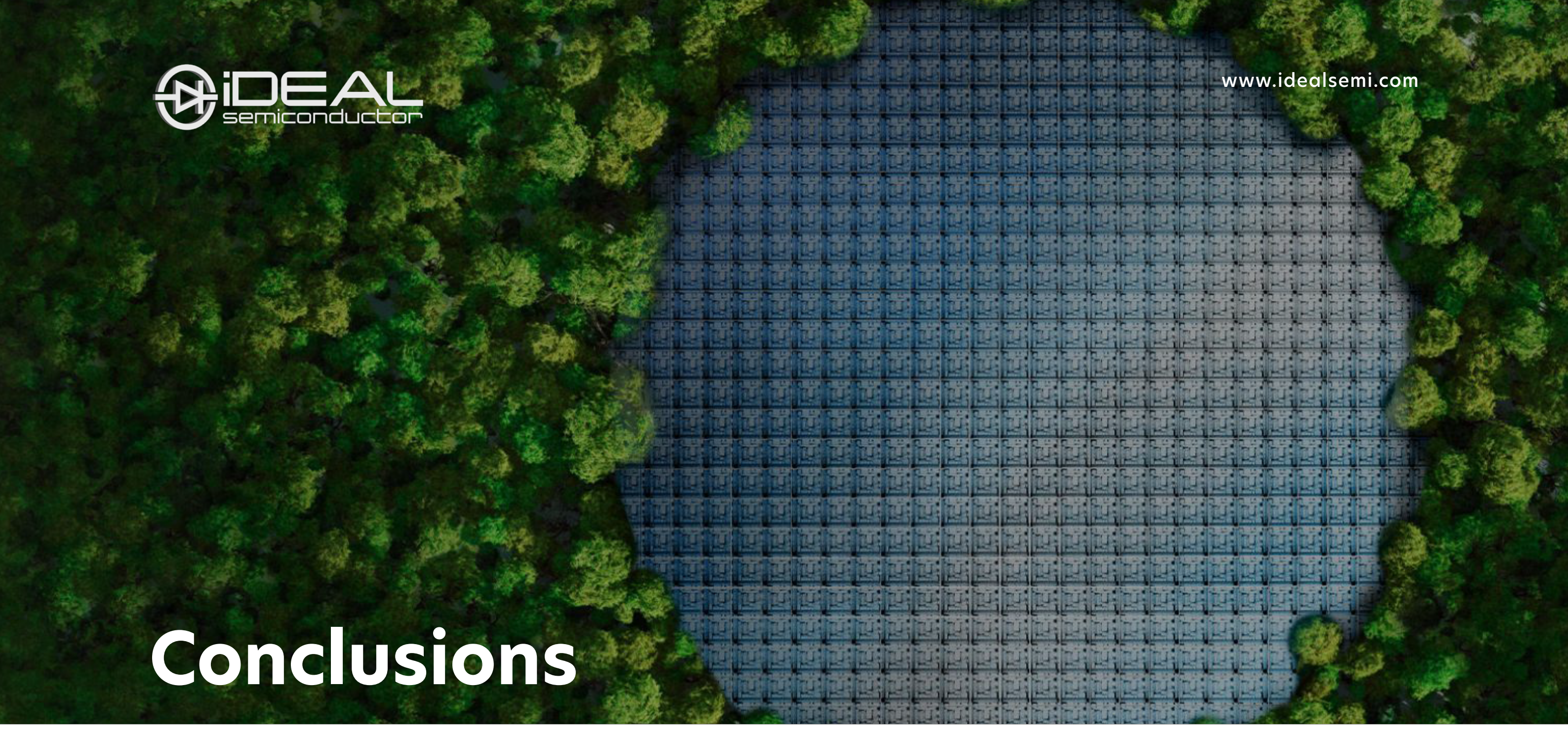
Table 1 illustrates the theoretical limits for several semiconductor materials based on their material properties. When compared to the best in market devices available, there is a gap between what is available and what the theoretical limit says - even for SuperQ.

| Semiconductor Material | Theoretical Limits | Actual Measured Results | |
|---|---|---|---|
| | Rsp @ 650V | Rsp @ 650V | Device |
| | mΩ*mm$^2$ | mΩ*mm$^2$ | |
| Si-1D[8] | 8,909 | 22,834* | IRFRC20 |
| Si-SJ[9] | 278 | 1000 | IPP65R045C7 |
| 4H-SiC-1D[8] | 15 | 325 | IMW65R072M1H |
| GaN-1D[8] | 5.5 | 535* | IGT60R070D1 |
| Si-SuperQ | 22.7 | 380 | iS65M020S1P |

*Table 1: Calculated performance limits of power devices based on materials properties and actual results based on market data.*
** 600V RSPs*

SuperQ is here today, and it offers competitive resistance to what is available in wide band gap at 650V. Combine this with silicon's decades of proven reliability, manufacturability, and cost entitlement, it becomes clear that SuperQ places silicon back into the pole position.

SuperQ on silicon is an important first breakthrough in delivering the next generation of performance gains, and there is a long runway for continued improvement. Yet, it is interesting to also know that SuperQ - as a power device architecture - is applicable to other semiconductor materials. It will further improve their performance for whatever the future holds. In fact, when SuperQ is applied to Silicon Carbide and Gallium Nitride, it reduces their theoretical specific resistance limits by over two orders of magnitude.[9,10]



# Conclusions

SuperQ is a device architecture that delivers on multiple fronts. It is a technology ready today to unlock previously unimaginable performance gains on silicon, including record setting Rsp and low switching loss. It allows system engineers access to power devices built on an existing infrastructure of silicon manufacturing using a state-of-the-art CMOS equipment with established silicon reliability.

SuperQ also delivers a path to what comes after silicon; if, or when, that happens. By implementing it on other semiconductor materials, it can reshape the cost*performance curves of Silicon Carbide, Gallium Nitride, and other future wide bandgap materials. When the wide band gap market matures, SuperQ technology can accelerate its adoption.

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