P R
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Will diamond be the ultimate semiconductor?

For over four decades I have witnessed transformative shifts in the power electronics landscape. Beginning with bipolar transistors, moving through MOSFETs and into the realm of wide band gap (WBG) semiconductors such as silicon carbide (SiC) and gallium nitride (GaN). Each technological evolution has unlocked higher performance, greater efficiency, and the miniaturization of power systems. But today, we stand at the threshold of what could be the next quantum leap in power device performance towards the mythical 99.99% efficiency: the use of synthetic diamond as a semiconductor material, a really exciting new concept for power electronics engineers.

Is the use of diamonds in semiconductors realistic?
The idea might sound exotic - if not far-fetched - but after all, diamonds are traditionally associated with jewelry, industrial applications such as abrasives, and machinery for cutting, drilling, grinding, and polishing or in laboratories for high-pressure experiments though not with power conversion systems or radio-frequency amplifiers.

However, for many years, the scientific community has acknowledged diamonds as the premier material for heat dissipation, exhibiting thermal conductivity that significantly surpasses conventional materials such as silicon. Nevertheless, the material's inherent hardness and the complexity of its processing had previously rendered it unsuitable for utilization in the field of semiconductor technology.

Before delving into the subsequent discussion on performance and benefits, it is imperative to provide a synopsis of the evolution of diamond utilization in technological applications. The narrative commences in 1954 when General Electric (GE) successfully created the first synthetic diamond using the High Pressure High Temperature (HPHT) method, marking the inaugural

	Silicon (Si)	Silicon Carbide (SiC)	Gallium Nitride (GaN)	Diamond
Band gap (eV)	1.11	3.26	3.39	5.47
Breakdown field Ec (MV/cm)	0.3	3.5	3.4	10.0
Electron mobility μe (cm^2/Vs)	1,500	800	900	2,200
Thermal conductivity (W/cmK)	1.5	4.9	2.0	21.3

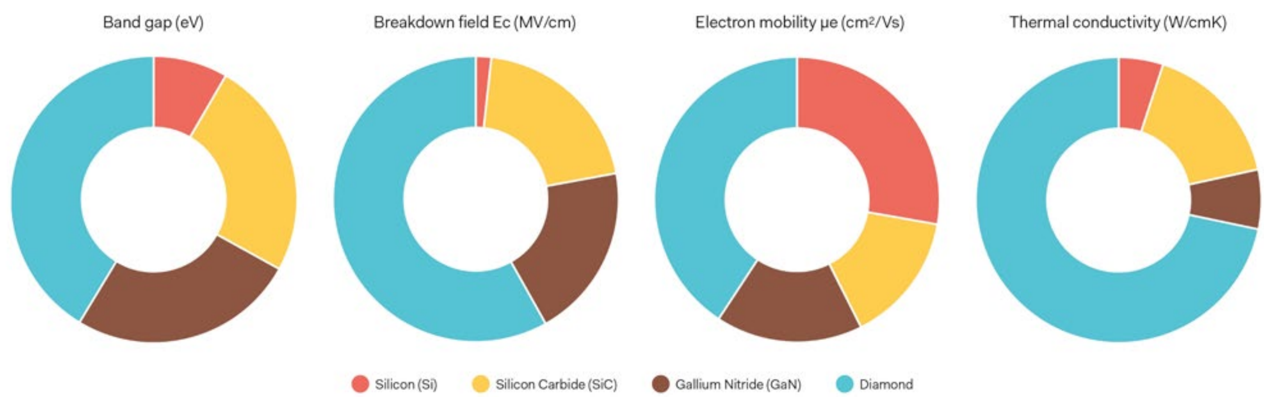


Figure 01 - Material Properties Define Performance (Source PRBX)

instance of human fabrication of diamonds. Subsequent to this landmark, the 1980s bore witness to the inaugural expansion of diamonds by the Chemical Vapor Deposition (CVD) method, which was subsequently followed by the exploration of doping processes in the 1990s. After this, those involved in the development of synthetic diamonds have expanded their knowledge of this material in terms of characterization, manufacturing, and processing.

Yet, advances in materials science and fabrication techniques are rapidly transforming synthetic diamond into a contender for the future of semiconductors. Let's explore why diamond is considered a material of superlatives, how it compares with conventional and established WBG semiconductors (SiC and GaN), and what hurdles remain before it can reach commercial maturity.

The staircase of technical evolution

We used to say that the evolution of power electronics is like a staircase with major leapfrogs bringing in new technology from research to market to improve performance, and diamond semiconductors might be considered as the next step, however some consider it far too big a challenge to become reality.

It's important to note that SiC and GaN weren't overnight successes either. I remember when SiC power diodes first entered the market in the late 1990s, they were expensive, difficult to manufacture, and had reliability issues. GaN's commercial journey began later, finding initial adoption in RF applications and later evolving into high-efficiency power transistors for everything from fast chargers to datacenter power supplies.

There's no doubt that conventional silicon semiconductor technology is well established and is permanently improving with new technologies, though the success of SiC and GaN that was driven by an industry that required higher voltages, higher efficiency and higher switching frequencies to reduce the size of the final equipment. Today SiC and GaN are in everything from EVs to solar inverters. WBG materials offered significant size, weight, and power (SWaP) benefits, and we all enjoy powerful, energy efficient, and compact USB adapters.

GaN brought advantages in high frequency switching due to its high electron mobility and low capacitance. Meanwhile, SiC found its place in medium to high voltage ranges, replacing IGBTs and silicon MOSFETs in applications like electric vehicles and industrial drives.

However, both SiC and GaN have their limits and some applications operating in high temperatures and harsh environments may require higher performance levels and robustness, and this is where diamond's properties appear not just superior - but transformative.

Diamond benefits at glance.
To understand diamond's potential, we must start with material science. In semiconductor technology, the performance of material for high-power, high-frequency, or high-temperature applications is governed by key physical properties. Presenting the fundamental properties of Silicon, Silicon Carbide, Gallium Nitride and Diamond, in the table (Figure 01) we selected four key parameters, making it easy to compare the performance and benefits of the different materials:

Band Gap
The band gap, which is indicative of a material's capacity to conduct electricity, serves as a critical criterion in determining its suitability for environments characterized by high temperatures or high energies. A wider band gap is indicative of superior resistance to current leakage and breakdown, which is critical for applications in extreme conditions. Here, diamond outshines every other material by far. Its wide bandgap of 5.5 eV allows devices to operate at higher voltages and temperatures.

Breakdown Field
The Breakdown field is a measurement of a material's resilience against electrical stress prior to the occurrence of conductivity. It is imperative to note that higher breakdown field values are of essence for devices operating at elevated voltages, particularly in the domain of power electronics. This is due to the fact that ensuring optimal performance under extreme electrical loads is of the utmost importance.

The theoretical critical electric field of diamond is nearly 10 MV/cm which is three times higher than that of GaN or SiC and over 30 times that of silicon. This allows devices to be thinner for the same voltage rating, reducing resistance and improving efficiency. It also opens the door for devices rated for 10 kV, 20 kV or even 50 kV use, potentially revolutionizing high-voltage DC (HVDC) transmission, electric railways, and grid-tied energy systems.

Electron Mobility
Electron mobility is defined as the speed of electron movement under an electric field. It is a critical component of electronic switching and signal propagation, which occurs rapidly. The enhancement of electron mobility in these devices leads to an improvement in the performance of digital circuits and high-frequency analog devices. Although GaN and diamond have similar electron mobilities, diamond devices may benefit from higher saturated velocities, enabling extremely fast switching with low on-resistance and reduced losses. This could push switching frequencies to new heights, further miniaturizing magnetic components like transformers and inductors.

Thermal Conductivity Evaluation
Thermal conductivity is a material property that quantifies its capacity for heat transfer. In the field of electronics, high thermal conductivity is of essence. This property is crucial for the effective dissipation of heat, thereby preventing overheating and enhancing the reliability and longevity of devices. Diamond's thermal conductivity of 20 W/cmK is the highest known of any material, making it exceptionally good at heat dissipation, a constant challenge in power electronics.

As we all know, thermal management is one of the most expensive and limiting factors in high-performance systems. GaN, for instance, often requires exotic substrates like silicon carbide to avoid overheating. Diamond's unparalleled ability to dissipate heat could lead to devices operating at temperatures exceeding 400°C without degradation, enabling more compact and rugged systems, especially in aerospace and high temperatures applications.

Where are we today?
Despite the hype, diamond semiconductors are not yet in mainstream production. But significant progress has been made in the past decade, particularly in synthetic diamond fabrication, led by chemical vapor deposition (CVD). CVD enables the production of large-area, ultra-pure single-crystal diamond wafers - a major prerequisite for reliable semiconductor devices.

Today, diamond Schottky diodes and power FETs transistors have been demonstrated in labs with promising characteristics. However full commercialization is still in early stages, limited by fabrication cost, defect density, doping control, and scalability. However, the latest research is very promising.

Some notable developments:
In hindsight, I feel the same way as I did when SiC and GaN were in the research stages. As a power electronics engineer, I dove into numerous papers on wide-band gap technology and its promises, I wrote articles and presented them at conferences to share my enthusiasm

within the power electronics community. Twenty years later, these promises have become a commercial reality.

After years of fundamental research, the utilization of diamonds in the semiconductor industry is now moving to the next step, which involves pre-industrialization and the development of an ecosystem to support future commercial products.

It is challenging if not impossible to list all the major steps recently occurring within the diamond semiconductor industry. As a French national working for a European company owned by the Japanese company COSEL, I would like to share some notable projects in Japan and France (EU) but for sure many similar steps have taken place in USA.

In Japan

It is known that the first power circuit containing synthetic diamond semiconductors has been developed by a research team from a Japanese university. Following an exploration of the hypothesis that diamond semiconductors have the potential to outperform silicon and other materials currently in use, led by Professor Makoto Kasu, a team at Saga University who initiated an investigation into diamond semiconductors and developed a functional n-channel MOSFET transistor made with a diamond.

Another seminal moment in the Japanese semiconductor industry's evolution was the cessation of operations at the Fukushima Daiichi Nuclear Power Station (NPS), precipitated by the tsunami that followed the Great East Japan Earthquake on March 11, 2011. In the context of the decommissioning process for the reactors, a research initiative was initiated in 2012 with the objective of developing diamond semiconductors that could function in the harsh environment of the damaged NPS, which was contaminated with high radiation.

The initiative was made possible by the convergence of technical expertise from prominent organizations such as the AIST, the Japan Atomic Energy Agency (JAEA), Hokkaido University, and the High Energy Accelerator Research Organization (KEK).

The objective was unambiguous: to engineer a critical approach, monitoring systems utilizing diamond semiconductors capable of withstanding high radiation levels, thereby providing detailed data, including neutron dose on fuel debris. This endeavor was undertaken to ensure the planning for debris removal was both safer and more efficient.

As part of this project, Ookuma Diamond Device Co., Ltd., a startup founded jointly by Hokkaido University and the National Institute of Advanced Industrial Science and Technology (AIST) established a vertically integrated system for manufacturing diamond semiconductors, covering everything from substrate design to assembly of the world's first differential amplifier circuit using diamond semiconductors, which has been confirmed to operate for a long-term period under a high temperature environment (300°C) resulting in the latest prototype shown in Figures 02 and 03.

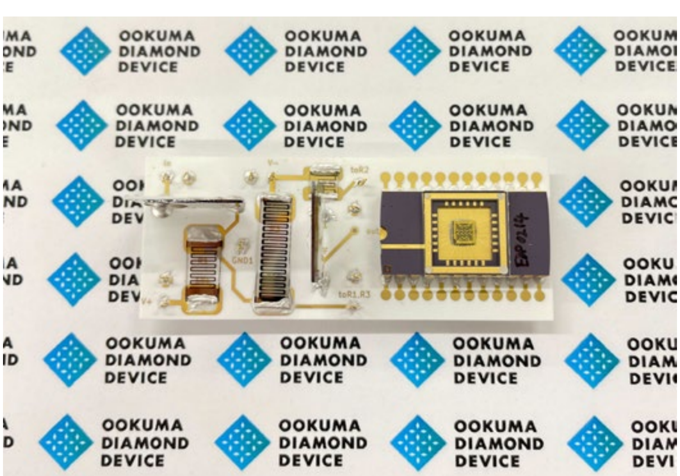


Figure 02 - World's first amplifier circuit of diamond semiconductor operating at 300°C (572°F) patent pending (Photo by courtesy of Ookuma Diamond Device Co., Ltd)

Figure 03 - Diamond MOSFET Differential Amplifier Circuit (Photo by courtesy of Ookuma Diamond Device Co., Ltd)

In early 2025, reports emerged of a significant development in the field of advanced semiconductor technology. The National Institute of Advanced Industrial Science and Technology (AIST), in collaboration with Honda R&D, successfully fabricated a prototype of a H-terminated diamond MOSFET. This breakthrough marked the first demonstration of ampere-level high-speed switching operation, a major advancement in the realm of semiconductor research and development. The Keita Takaesu et al. research team increased the size of the substrate and developed parallel wiring technology to increase the current (doi: 10.35848/1882-0786/adba3a). In the future, they plan to apply this technology to the next generation of mobile power devices. They are currently in the process of verifying and validating the preliminary results, which will pave the way for higher-current diamond MOSFETs.

In Europe:
In Europe several projects took place but it's wise to mention the framework program for research and innovation called Horizon 2020 which took place in January 2014. The objectives of Horizon 2020 were to strengthen the EU's scientific and technological foundations, to create a European Research Area with free circulation of researchers and knowledge and drive the EU towards a knowledge society and competitive economy.

As part of Horizon 2020, a sub project Green Electronics with Diamond Power Devices, coordinated by the French Centre National de la Recherche Scientifique (CNRS) aimed to explore the possibilities and feasibility of the promising technology and so formed a consortium. The consortium gathers experts on power device design, diamond growth and characterization, packaging and testing as well as an innovative end-user. Most of the partners were also involved in SiC or GaN technology, allowing the project to benefit from their ample experience and achievements in wide bandgap semiconductors.

Among the notable reports published under this project, and as part of the next phase, I would like to mention the French company Diamfab, founded in March 2019 by CEO Gauthier Chicot and CTO Khaled Driche, housed at the Institute Néel-CNRS. Since its inception, Diamfab has established a collaborative network contributing to the technological development of synthesizing diamonds and developing cutting-edge components like Schottky diodes and MOSFET transistors (Figure 04).

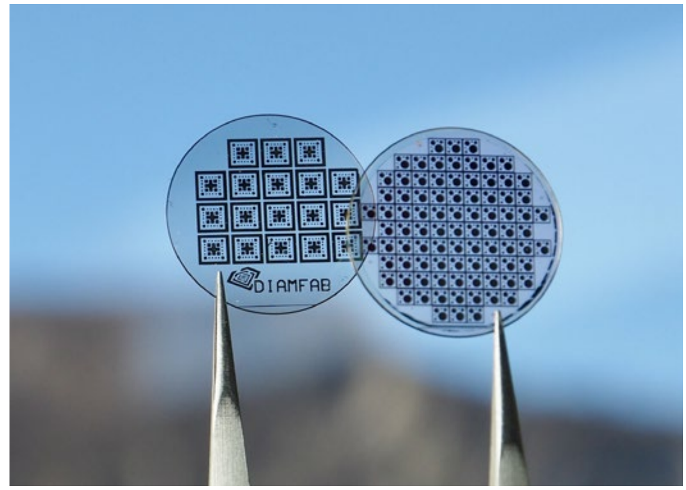


Figure 04 - Schottky diodes and power FET transistors on semiconductor diamond wafers, prior packaging. (Photo by courtesy of Diamfab)

In terms of research, it's worth mentioning the collaboration between the Institute Néel (CNRS), the Plasma and Energy Conversion Laboratory (LAPLACE, CNRS/Toulouse INP/University) and DIAMFAB who have designed a diamond transistor achieving a record volume current conduction of 50 mA. The component is a junction field-effect transistor (JFET) using volume conduction. The team succeeded in obtaining homogeneous layers of diamond doped with boron, without any harmful defects. They were thus able to increase the useful volume of the transistor and its gate, which reaches 14.7 mm with 24 parallel fingers. The transistor is no longer a simple miniature demonstrator, but a real usable component, which prevails a good future for diamond transistor technology (Figure 05).

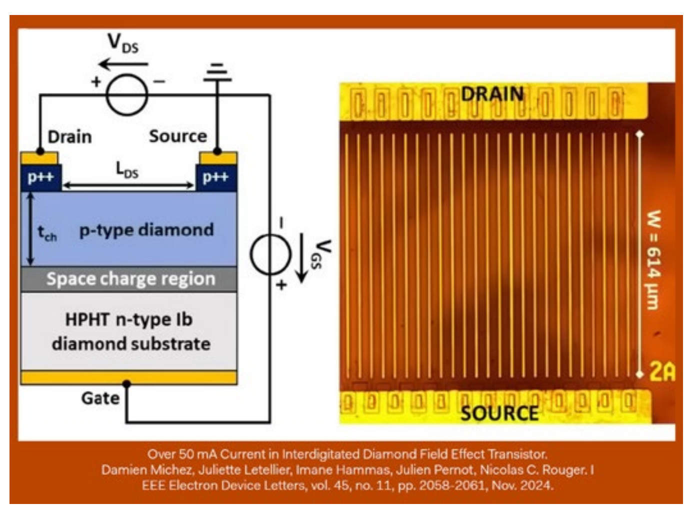
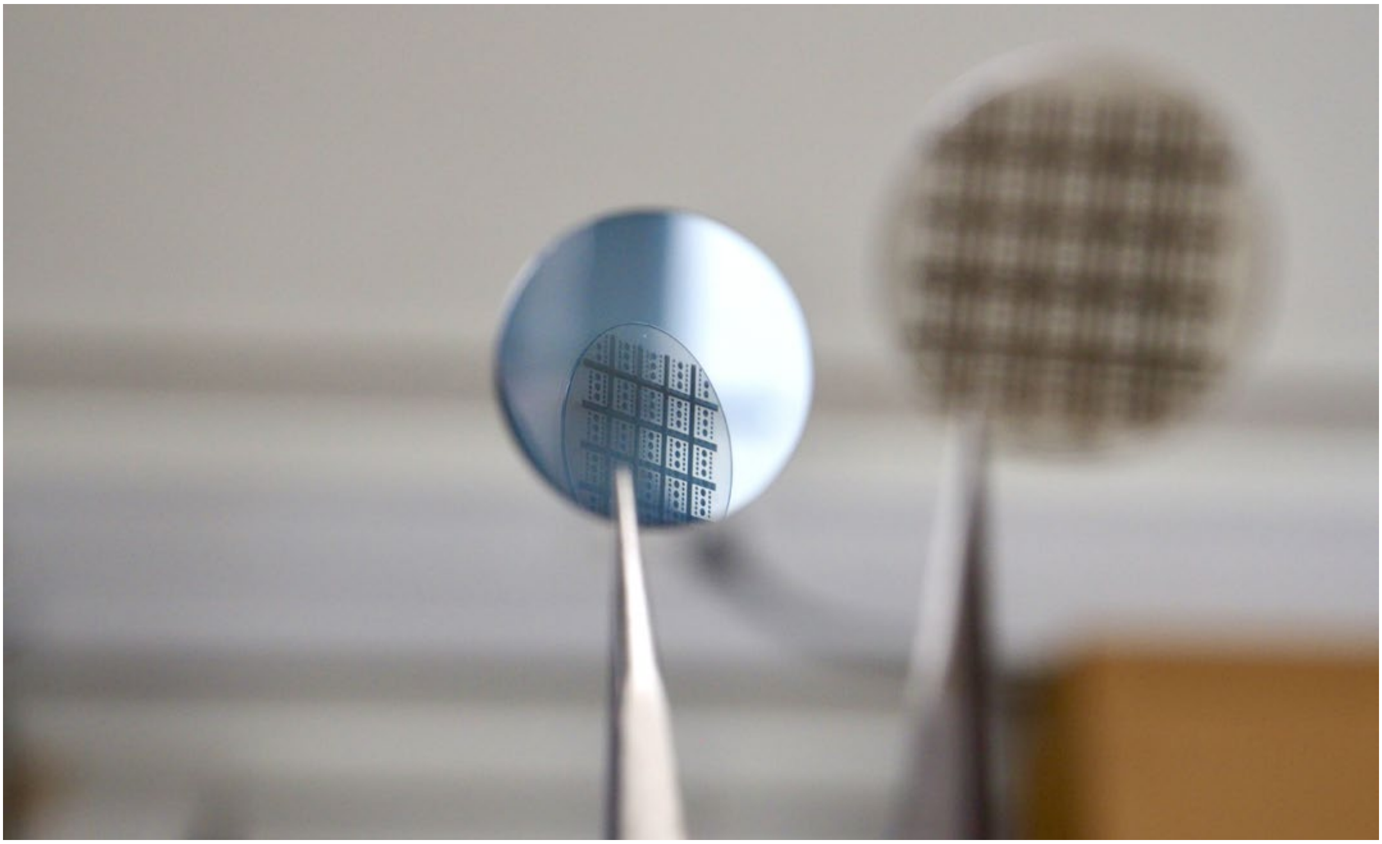


Figure 05 – (Left) Cross-sectional schematic of an elementary diamond JFET with the electrical measurement setup. (Right) Optical microscopy top view of interdigitated diamond JFET at the end of the fabrication process. (Photo by courtesy of Diamfab)



Diamond semiconductor wafer (Photo courtesy of Diamfab).

Vision: Where Could Diamond Lead Us?
Imagine EV inverters with 99.9% efficiency, switching at 1 MHz, requiring no bulky cooling systems. Picture ultra-compact space power modules surviving extreme temperatures and radiation on the Moon or Mars. Or envisage smart grids operating at 100 kV with embedded sensors powered by diamond ICs. Such visions may sound futuristic - but so did SiC/GaN 25 years ago.

If development continues, diamond-based semiconductors could become the platform of choice for ultra-high-power, high-reliability applications within the next two decades. Governments and private sector players are increasingly investing in diamond R&D, viewing it as a strategic technology with both energy and defense implications.

Conclusion: Not Just a Sparkle, But a Beacon
In the world of semiconductors, the material defines the limits - and diamond redefines those limits. While commercial readiness may be years away, the performance ceiling that diamond promises is too significant to ignore. As power electronics continues to demand higher efficiency, higher voltage, and smaller form factors, the industry must keep an open eye on this gem of a material.

Just as we transitioned from silicon to Wide Band Gap SiC and GaN to enable breakthroughs in electric mobility and renewables, the next frontier may well be forged in carbon's hardest form—paving the way to the ultimate power semiconductor platform.

And just like we did with previous waves of innovation, those of us in the field must prepare - not just with technical readiness, but with imagination and curiosity.

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About Powerbox

Founded in 1974, with headquarters in Sweden and operations in 15 countries across four continents, Powerbox serves customers all around the globe. The company focuses on four major markets - industrial, medical, transportation/railway and defense - for which it designs and markets premium quality power conversion systems for demanding applications. Powerbox's mission is to use its expertise to increase customers' competitiveness by meeting all of their power needs. Every aspect of the company's business is focused on that goal, from the design of advanced components that go into products, through to high levels of customer service. Powerbox is recognized for technical innovations that reduce energy consumption and its ability to manage full product lifecycles while minimizing environmental impact. Powerbox a Cosel Group Company.

Patrick Le Fèvre
Powerbox Chief Marketing & Communication Officer

About the author

Chief Marketing and Communications Officer for Powerbox, Patrick Le Fèvre is an experienced, senior marketer and degree-qualified engineer with a 40-year track record of success in power electronics. He has pioneered the marketing of new technologies such as digital power and technical initiatives to reduce energy consumption. Le Fèvre has written and presented numerous white papers and articles at the world's leading international power electronics conferences. These have been published over 450 times in media throughout the world. He is also involved in several environmental forums, sharing his expertise and knowledge of clean energy.

For more information

Visit www.prbx.com
Please contact Patrick Le Fèvre, Chief Marketing and Communications Officer
+46 (0)158 703 00

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