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FUTURE TRENDS IN POWER ELECTRONIC DEVICES

Titu-Marius I. Băjenescu, ORCID ID: 0000-0002-9371-6766

Swiss Technology Association, Electronics Group Switzerland
tmbajenesco@gmail.com

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Abstract. The recent technological progress of semiconductors and increasing demand for power electronic devices in the different domains of electric energy particularly for applications in aeronautics and networks of transport and distribution impose new specifications such as high frequencies, high voltages, high temperatures and high current densities. All of this contributes in the strong development of power devices. To this end, separation techniques for low-resistivity films should be developed, as well as thick-film growth technologies, including hot filament CVD on insulating wafers. The article outlines the evolution of semiconductor manufacturing, current applications and perspective.

Keywords: *GaN, SiC, Si vs SiC, IGBT, MOSFET, HEMT, HFET, FET, diamond power devices.*

Introduction

The history of semiconductors is long and complicated. Table 1 shows a timeline for the development of power semiconductor devices. In the 1950s the thyristor or silicon controlled rectifier (SCR) was the only option for solid-state power electronics in the hundreds of volts.

As the technology further developed, newer devices such as the JFET, power MOSFET, and IGBT were introduced with greatly improved performance and higher voltage and current ratings. Now, in the 21st century, wide bandgap (WBG) semiconductors are the latest in the trend toward higher-performance power electronics.

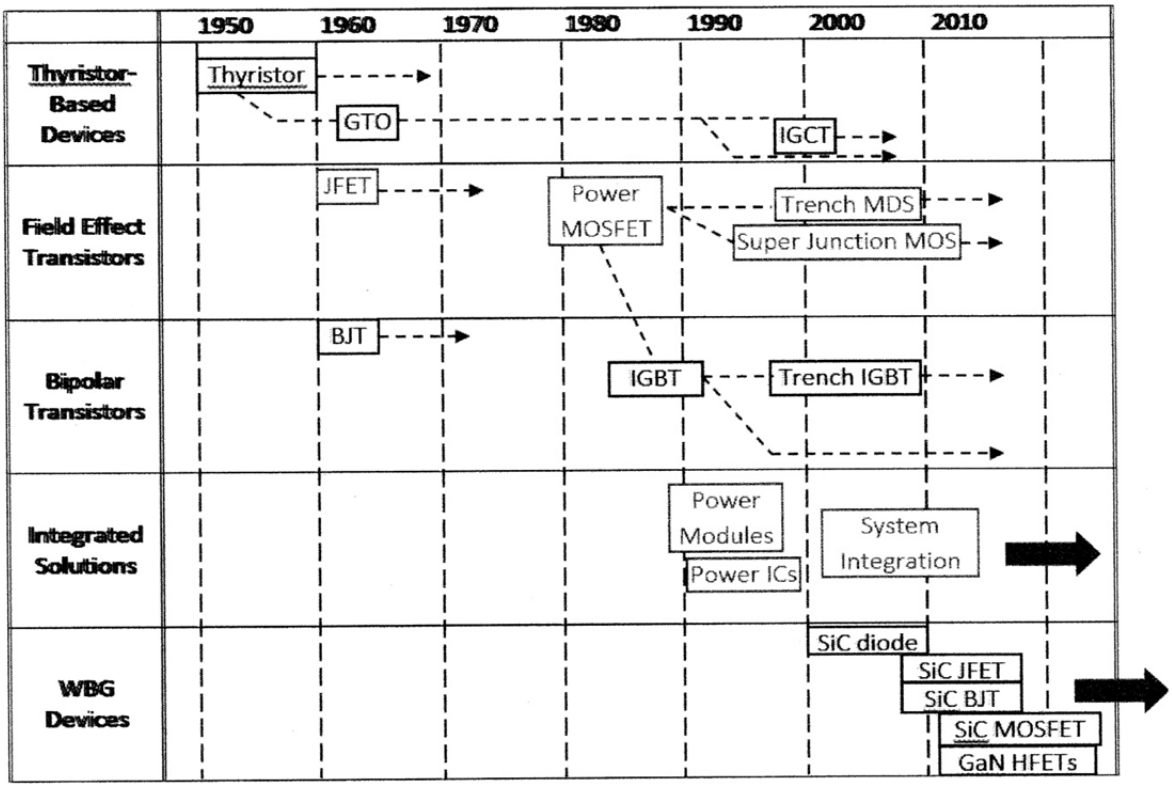
Power electronics is a complex and interdisciplinary technology, and doing research in this area requires a comprehensive background in electrical engineering and beyond. The research on devices is extremely important because evolution in this area has essentially brought on the modern power electronics revolution. The present trend of R&D on silicon and wide bandgap (WBG) power semiconductors (Figures 1, 2, 3, 4) will continue until the power device characteristics and ratings are significantly improved, approaching an ideal switch.

Since the advent of wide bandgap power electronics, device reviews have seen a second wave of popularity, covering materials such as SiC, GaN, and perhaps to a lesser extent diamond. It became clear that, SiC, not GaN, would be the principal WBG power device material for the chosen markets in the near future.

Wide bandgap semiconductors are a sub-class of semiconductor materials, defined by their larger-than-Si bandgap, typically between two and four electron volts (eV).

Table 1

Timeline of the development of power semiconductor devices (after [7])



There are several wide bandgap materials currently being explored for power conversion: silicon carbide (SiC), Gallium Nitride (GaN), Gallium oxide (Ga_2O_3) Aluminium Nitride (AlN), and diamond. Of these, diamond-based devices are considered by many to hold the most promise but are hindered by small wafer size, scalability issues, and cost. Major changes in packaging solutions will be realized on the electrical interconnections level, do to the growing adoption of copper clips as a substitute for more conventional wire and ribbon bonding. The adoption of WBG semiconductor dies technologies (high-temperature epoxy, low-inductance electrical interconnections, silver sintering die attach, etc.). Although the adoption of wide gap devices calls for innovative packaging schemes and solutions, their impact on the packaging materials market will be rather limited due to the still small share of SiC and GaN technologies compared to Silicon, and the smaller die size compared to Silicon devices.

The WBG PE market is currently small: \$160M out of the \$16B power electronics market (*Eden 2016; Fodale and Eden 2015*). The size of the market can largely be attributed to the relative age of WBG technology compared to conventional Silicon. As a less mature field, WBG devices are more expensive, have a low manufacturing level and demand, and have not yet been proven reliable to the level demanded by the application areas. These constraints lead final product manufacturers to be hesitant to begin integration and WBG device manufacturers hesitant to increase production levels to reduce the cost.

Major opportunities for WBG-integration lie in the expected increases in demand for the application areas or expected increases in the demand for more energy accountability (either by increasing system efficiency or by adding renewable energy generation). The relative immaturity of WBG that affects cost and perceived reliability, the necessity of system redesigns to adopt WBG and shortage of knowledgeable engineers to do so, the risk aversion of manufacturers and changing demands for energy accountability continue to remain as major challenges being faced by the industry.

Historically, the U.S. has been a leader in semiconductor manufacturing, and currently U.S. headquartered companies hold half (50%) of the worldwide market (Figure 1). Over half of U.S. companies' wafer manufacturing capacity is located in the United States, and about 86% of U.S. wafer manufacturing capacity is accounted for by U.S. headquartered companies, suggesting that a significant portion of wafer fabrication occurs in the U.S.

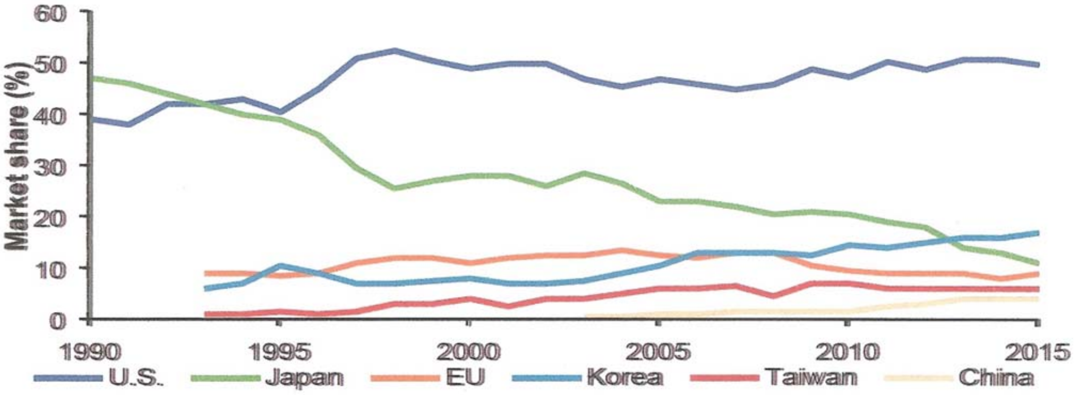


Figure 1. Relative semiconductor device market share based on company HQ (Source: Semiconductor Industry Association SIA, 2016).

Figure 2 shows the ratings of some commercially available and research phase WBG semiconductor devices. Lateral GaN devices have reached ratings up to 650 V and 90 A, while SiC MOSFETs occupy more of the high voltage and high power market segment. GaN and SiC together occupy a large area for both current and voltage, and WBG semiconductors can thereby enable efficient power electronics at power levels infeasible for conventional Si.

The needs in terms of voltage, power density, frequency of use, reliability, or working temperature are becoming more stringent; energy losses must be reduced and performance enhanced. Today progress is hindered by the inherent limitations of silicon; the vast majority of power electronics components commercially available are silicon components. A change of base material for the design of power electronics components must be considered. WBG semiconductors have properties particularly suited to managing high voltages, high frequencies, in hot environment. Silicon carbide (SiC), gallium nitride (GaN) and diamond are the most prominent materials expected to supersede silicon. Among them, diamond has the physical and electronic properties most suitable to power electronics components.

Compared to traditional silicon semiconductor material, WBG materials like SiC and GaN have lots of interesting physical properties such as bigger bandgap energy, larger breakdown field and higher saturation velocity.

Therefore, they are gradually applied to fabricate power semiconductor devices, which are used in power converters to achieve high power efficiency, high operation temperature and high switching frequency.

Increasingly severe operating constraints (high voltage, high temperature, high frequency) in power electronics, have led the community to focus on the exploitation of new materials, such as SiC, GaN and more recently diamond (Table 1).

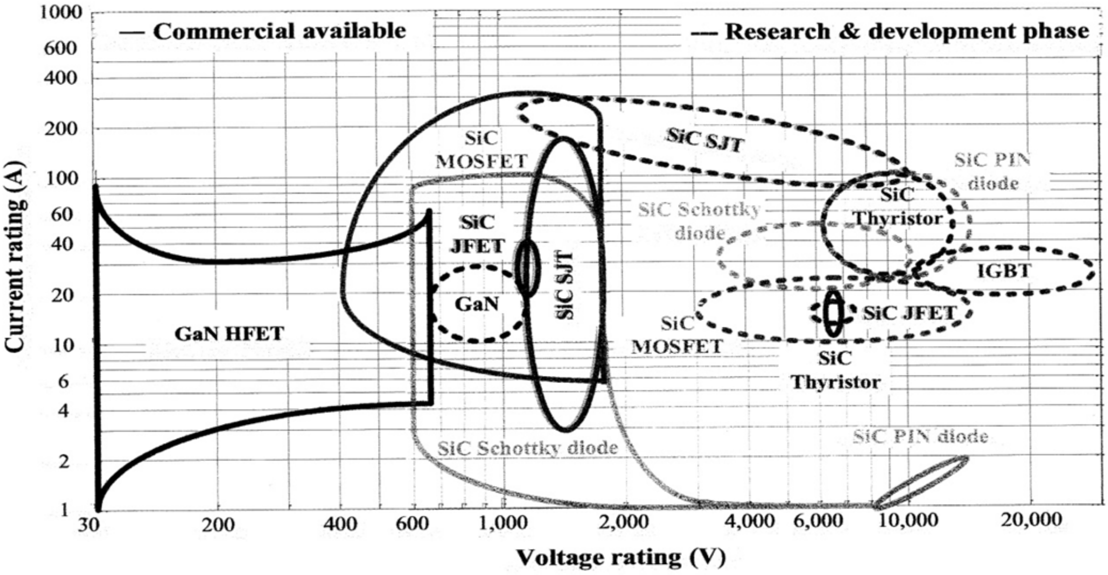


Figure 2. Ratings of selected wide bandgap (WBG) power devices (after[7]).

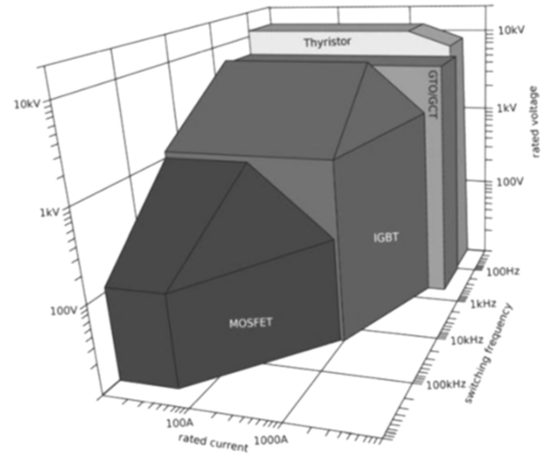


Figure 3. Operating range of silicon power semiconductor devices (after [1]).

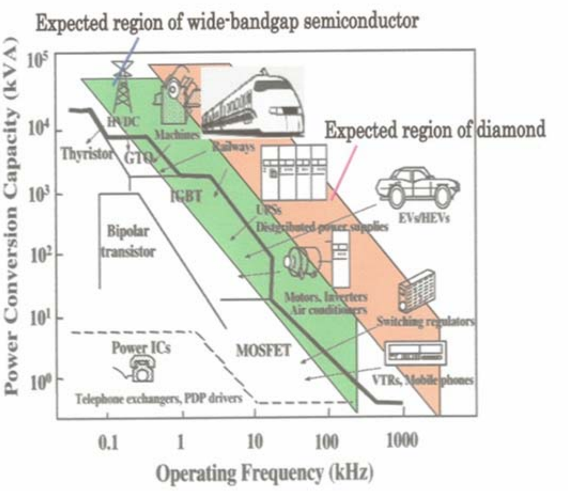


Figure 4. Expected region of wide bandgap semiconductor (after [5]).

These large gaps materials would allow pushing the current limits of silicon components. The increase of current density of power components requires the ability of the environment to evacuate the component losses to limit its warm-up. The concern of the power system designer is, therefore, to reduce the resistance to a minimum between the component and the outside. The diamond properties - better thermal conductivity and better electrical insulation - make this material a valuable ideal candidate for the thermal management problems. This has already been used successfully in different applications of microelectronics.

Silicon Carbide (SiC)

Silicon Carbide is a WBG semiconductor material which has several advantages such as higher maximum electric field, lower ON-state resistance, higher switching speeds, and higher maximum allowable junction operation temperature compared to Silicon (Si).

In the 1.2 kV — 1.7 kV voltage range, power devices in SiC are foreseen to replace Si insulated gate bipolar transistors (IGBTs) for applications targeting high efficiency, high operation temperatures and/or volume reductions.

Table 2

Semiconductor material properties

Material	**Si**	**SiC(4H)**	**GaN**	**Diamond**
Dielectric constant	11.8	9.7	9.0	5.5
Hole Mobility (cm^2/Vs	600	115	150	1600
Band Gap (eV)	1.1	3	3.4	5.47
Electron Mobility (cm^2/Vs)	1400	1000	900	2200
Break-down Field (MV/cm)	0.3	2.5	3.3	10
Thermal Conductivity (W/cm·°C)	1.5	4.9	2.0	20.9

In particular, the SiC metal-oxide semiconductor field-effect transistor (MOSFET) – which is voltage controlled and normally-OFF – is the device of choice due to the ease of its implementation in designs using Si IGBTs.

SiC has underwent a dramatic development during the last two decades. It has a larger bandgap compared with Si, ranging from 2.3 to 3.3 eV. As a consequence, the maximum operation temperature can be higher than for Si. The current status of the metallization, contacts, and packaging limit the temperature of operation. However, the high critical electric field strength allows thinner drift layers required for a given voltage, and higher doping concentrations [1]. As a result, the ON-resistance of unipolar devices can be reduced by almost three order of magnitude as compared to Si. This allows to produce unipolar devices like Schottky diodes and *Metal-Oxide-Semiconductor Field-Effect Transistor* (MOSFET) up to much higher voltages compared to Si devices. As a consequence unipolar SiC devices are today replacing bipolar rectifiers and IGBTs up to voltages above 3.3 kV. The unipolar SiC devices are characterized by extremely fast switching due to the lack of stored charges. Thus, fast-switching and highly efficient devices can be fabricated such as Schottky diodes, high-voltage PiN diodes, bipolar and unipolar active devices.

Physical and electrical properties of SiC

- The saturation rate of SiC is higher and its permittivity lower than that of Si, so SiC components are more efficient than Si components in high frequency applications.
- The breakdown voltage is higher in SiC components because their critical electric field is greater.
- SiC unipolar components have a lower specific resistance because the voltage holding zone is thinner and more doped.
- For bipolar components, switching losses are reduced because their recovery current is lower, due to the shorter life of the carriers compared to Silicon. As a result, these components can operate at higher frequencies.
- The thermal conductivity of SiC is higher, which guarantees a better evacuation of the heat generated by the losses.
- The very small intrinsic concentration of the SiC component gives it a low leakage current even at high temperatures.
- SiC electronic devices can operate at extremely high temperatures, without suffering intrinsic conduction effects due to the bandwidth gap. SiC components are good candidates for high temperature applications (>500°C).
- SiC has a high chemical and physical stability because its binding energy is very high (5 eV).

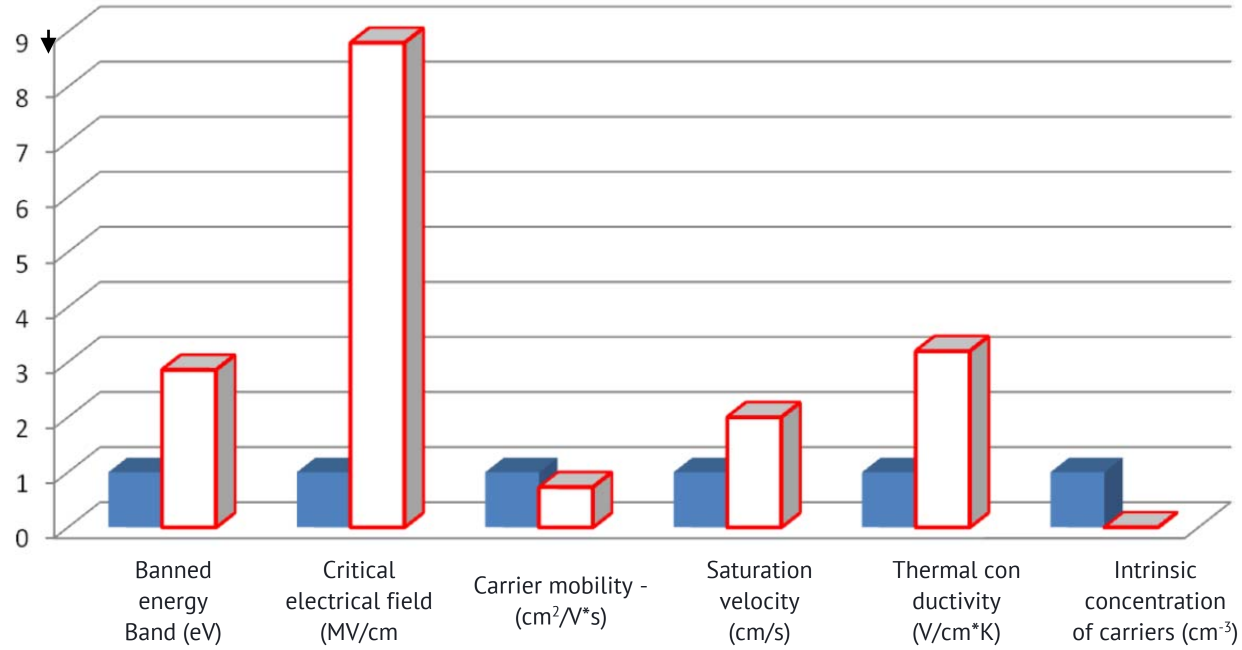


Figure 5. Si vs SiC - Comparison of electrical properties
Values with respect to silicon ■ Si ☐ SiC.

SiC devices

Silicon carbide (SiC)-diodes have been commercially available since 2001 and various SiC-switches have been launched recently. In parallel, Gallium Nitride (GaN) is moving into power electronics and the first low-voltage devices are already on the market. Currently, it seems that GaN-transistors are ideal for high frequency ICs up to 1 kV (maybe 2 kV) and maximum a few 10 A. SiC transistors are better suited for discrete devices or modules blocking 1 kV and above and virtually no limit in the current but in that range they will face strong competition from the silicon insulated gate bipolar transistors (IGBTs). SiC and GaN Schottky-diodes would offer a similar performance, hence here it becomes apparent that material cost and quality will finally decide the commercial success of wide bandgap devices. Bulk GaN is still prohibitively expensive, whereas GaN on silicon would offer an unrivalled cost advantage. Devices made from the latter could be even cheaper than silicon devices. However, packaging is already a limiting factor for silicon devices even more so in exploiting the advantage of wide bandgap materials with respect to switching speed and high temperature operation. After all, reliability is a must for any device no matter which material it is made of. The technical panorama of SiC devices is still varying, and every manufacturer has its own solutions to design and packaging integration. This leads to strong competition, which will accelerate technical innovation and lower prices. In the future, we will see a restructuring of the supply chain driven by the main cost factors.

SiC switches

SiC-switches are currently in an important phase as several manufacturers commercialised 1.2 kV (few 10A) switches by utilising completely different device concepts. None of the concepts shows per se a clear superiority but there are strong indications that the MOSFET will prevail just the way it did in silicon, implying that the IGBT will be the concept for high voltages. In fact, most of the (major) power semiconductor manufacturers work on SiCMOSFETs or have plans to do so. However, some of the recent turnarounds are rather business driven than based on technical facts [2].

GaN devices

Gallium Nitride (GaN) power devices are an emerging technology that have only recently become available commercially. This new technology enables the design of converters at higher frequencies and efficiencies than those achievable with conventional Si devices. Power system design is reaching the theoretical limits of Silicon-based power devices. With its smaller, more energy efficient and cost-effective capabilities, GaN plays a leading role.

Table 3

Bandgap Energy of some semiconductor materials [3]

Material Symbol	Bandgap	Energy (eV
Germanium	Ge	0.7
Silicon	Si	1.1
Gallium Arsenide	GaAs	1.4
Silicon Carbide	SiC	3.3
Zink Oxide	ZnO	3.4
Gallum Nitride	GaN	3.4
Diamond	C	5.5

Challenges encountered in GaN-based converter design: the consequences of faster switching on gate driver design and board layout; the unique reverse conduction behaviour, dynamic on-resistance, breakdown mechanisms, thermal design, device availability, and reliability qualification. SiC and GaN materials among WBG materials exhibit the better trade-off between theoretical characteristics (high-voltage blocking capability, high temperature operation and high switching frequencies), and real commercial availability of the initial materials and the advancement of their fabrication procedures. Economic viability of wide bandgap materials-based devices is limited because their price is about 3 to 5 times higher than silicon semiconductor devices. However, the materials contribute about 40% of the total device cost depending on availability, quality, and performance. Other factors that drive the WBG devices' price so high are, design, fabrication, and packaging procedures and techniques [3].

The key question for GaN devices is the substrate. Of course, the ideal solution would be homo-epitaxy, that is, GaN grown on bulk GaN, as it allows for homo-epitaxy without any mismatches between substrate and epitaxial layer. This would offer the lowest density of dislocations (10^6 cm^{-2}) and, thus, the highest epitaxial quality. However, bulk GaN is only available in small wafer diameters and still prohibitively expensive. At about 100 €/cm² it is expensive even when compared with SiC.

When it comes to GaN-devices the high-electron mobility transistor (HEMT), or hetero-junction FET (HFET) seems to be the natural choice because an AlGaN/GaN interface forms easily a high-electron mobility two-dimensional electron gas (2DEG) and offers very low sheet resistances. The key question for GaN devices is the substrate. Of course, the ideal solution would be homo-epitaxy, that is, GaN grown on bulk GaN, as it allows for homo-epitaxy without any mismatches between substrate and epitaxial layer.

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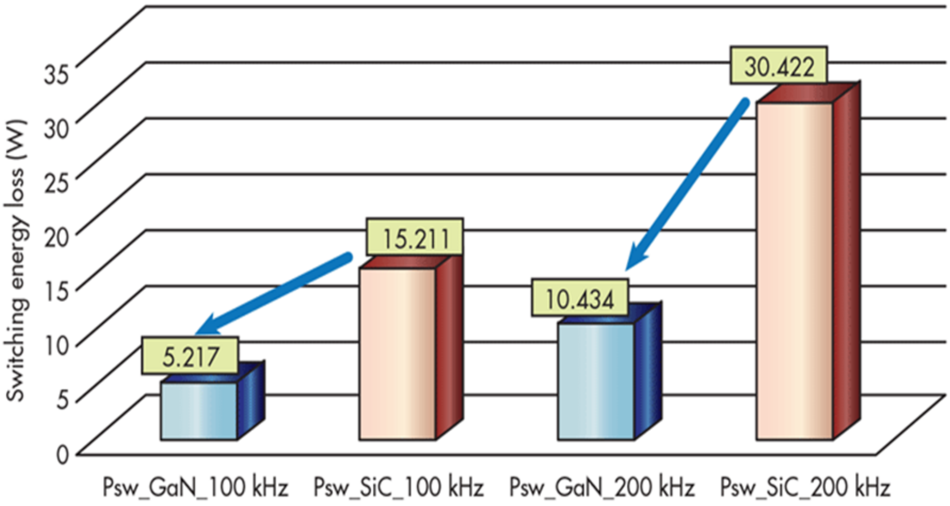


Figure 6. Switching loss comparison between GaN Systems' GS66508T E-HEMT and Cree's (Wolfspeed's) C3M0065090J SiC MOSFET (after [4]).

IGBT

More than three decades ago, the IGBT being a seemingly simple variant of the silicon power MOSFET was set on to change the power electronic landscape. IGBTs are required for applications that operate over a broad spectrum of current and voltage levels (Figure 7). Their characteristics are ideal for applications with operating voltages above 200 V. Typical examples are ballasts, consumer appliances that utilize motors, and electric vehicle drives. The on-resistance of conventional silicon power MOSFET structures is too large to serve certain applications; consequently, today these applications utilize silicon IGBTs. Silicon carbide (SiC) IGBTs offer very promising characteristics for applications that require blocking voltages of above 10-15 kV for use in smart grid applications.

The current ratings for the IGBTs increase with increasing voltage rating for these applications - with the exception of the smart grid (which is requiring very high voltage with low current ratings); this issue is tackled by resorting to multichip press-pack modules. These applications are served by SiC-based IGBTs that can operate at higher frequencies that their Si counterparts.

The high on-state current density for the IGBT structure has allowed for rapid scaling-up of its current handling capability (Figure 9). Future developments will maintain similar past trends for the growing system demands in terms of increased power levels, improved efficiency, greater control and reliability.

Diamond

Diamonds can actually be made using methane and hydrogen. Diamonds are really just carbon, a light and simple element. Their simple yet unique characteristics create significant potential for use in a wide range of purposes, including generation of environmental energy and biological applications, Diamonds, although nonconductive, can be altered to function as semiconductors with the addition of phosphorus and boron.

Diamond is expected to play a key role as a next-generation power semiconducting material owing to its superior properties, including high electric breakdown field strength and thermal conductivity. However, a major issue for the use of diamond is the lack of inch-sized wafers compared with the availability of such wafers for other materials, including Si, SiC, GaN, and Ga_2O_3.

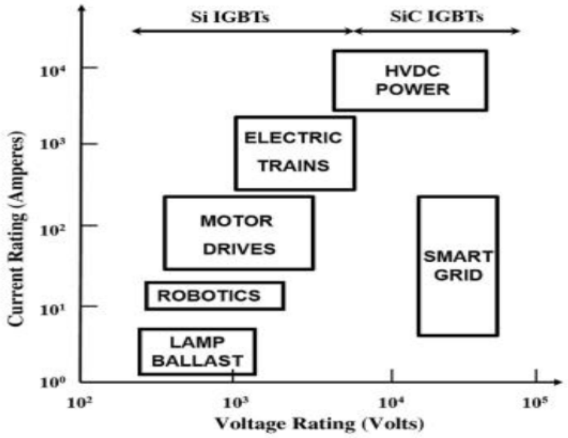


Figure 7. Application spectrum for IGBTs (after [9]).

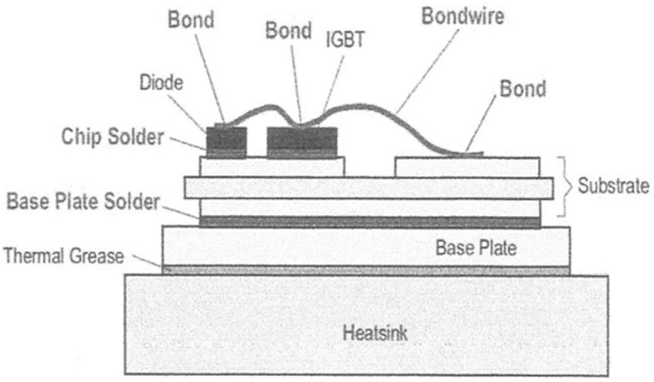


Figure 8. A detailed structure of an IGBT module.

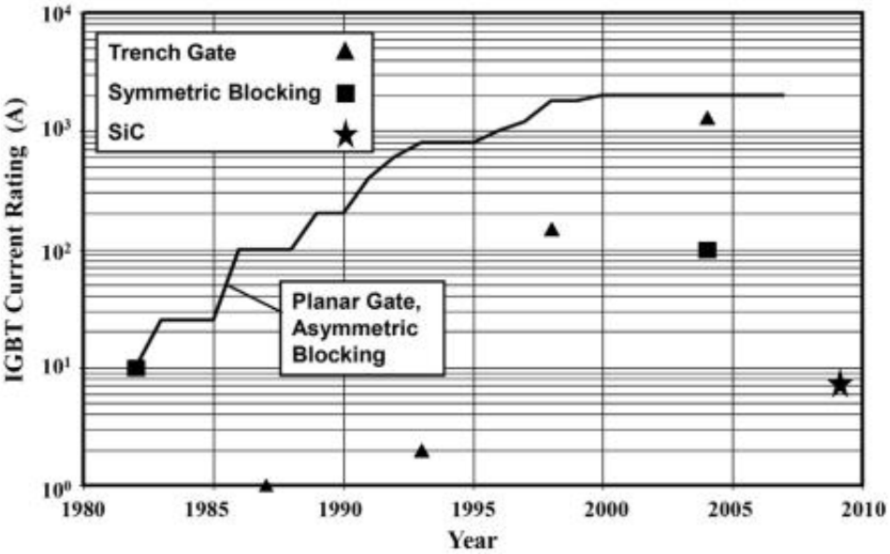


Figure 9. Growth in current handling capability for IGBTs (after [9]).

The thermal conductivity of diamonds is 14 times greater than that of silicon, and electrical field resistance is 30 times greater. High thermal conductivity allows the release of heat, which can reduce the size of cooling systems normally required during the generation of increased levels of electric power. High electrical field resistance suppresses power conversion losses. With these characteristics, diamonds are the ultimate semiconductors for electronic devices that require several kilovolts (kV) of power, such as those used in electric vehicles, railways, and power transmission.

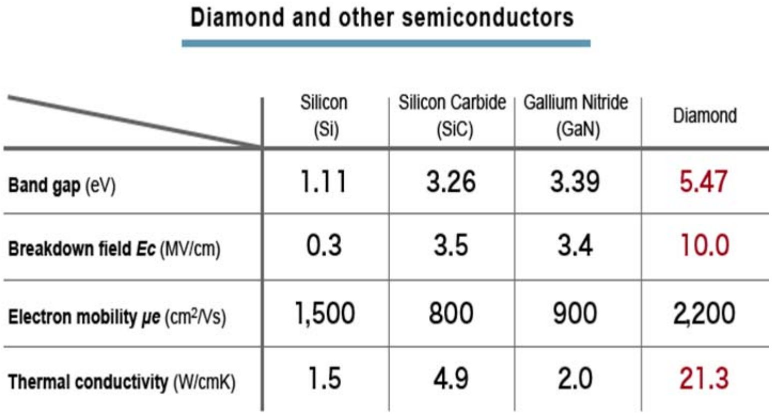
In a diamond crystal, carbon atoms can be replaced by nitrogen atoms to create nitrogen-vacancy complexes (NV centers). Negatively charged NV centers exhibit a magnetic property called electron spin. Green light radiation causes the emission of red fluorescence. Depending on the magnetic field, fluorescence processes change, and magnetic field strength and direction can be detected.

Diamond sensors apply these characteristics, and the imaging of a magnetic field is enabled. Diamond would be the ultimate semiconductor with an almost 20 times smaller specific ON-resistance than SiC and a five times higher thermal conductivity. However, the material quality of diamond is still rather poor and general issues of the wide bandgap semiconductors are aggravated. In particular, the incomplete ionisation is crucial for diamond because the energy level of the p-type dopant boron is 0.37 eV off the valence band edge and the n-type dopant phosphorous is even 0.57 eV off the conduction band edge [10].

Consequently, only a small fraction of the dopants is activated at room temperature and the ON-resistance is factors higher than it should be for a given doping concentration. Only at higher temperatures, the dopants get activated and the ON-resistance is reduced accordingly for 500 K [11]. At room temperature, there would be no advantage over SiC. Furthermore, the incomplete ionisation can lead to dynamic problems (similar but less severe effects in SiC [12]) and the ohmic contacts are difficult, especially on n-type diamond.

Diamond is one of the allotrope of carbon and the hardest natural substance; it is used as gems and abrasives. Diamond is an excellent candidate for power semiconductor devices; however, due to the complexity in the fabrication process, diamond power devices are not yet commercially available.

The use of diamond for active semiconductor devices has been restricted up to now by several limiting factors. One limitation has been the small size of single crystal substrates (below 5 mm). Another limit is associated with the deep boron acceptor and the absence (up to now) of any reliable n-doping technology with shallow donors. This restricts active diamond devices to p-type unipolar carrier transport. Therefore, only two concepts of power devices on diamond could be considered as realistic: p-type channel FETs and large area vertical Schottky diodes. Recently a significant step forward in the synthesis of high-quality single crystal diamond has been demonstrated. Free standing CVD diamond samples with residual doping concentration below 10^{13} l/cm^3 show high values of the low-field mobility of holes of about 3800 cm^2/Vs at room temperature [13].



Diamond and other semiconductors

	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

This high mobility is almost 2 times higher than any previous measurements on single crystal diamond. The CVD diamond growth on Iridium surface provides now quasi-single crystalline diamond films of 1 cm^2 area [14]. The crystal quality of the grown layers on Iridium surface was sufficient to demonstrate FETs with hydrogen-induced surface conductivity showing a cut-off frequency f_T of about 10 GHz [15].

Only recently, there have been encouraging results concerning diamond growth on Iridium, obtaining a single crystalline quasi-substrate for electronic devices. Another serious hurdle is doping, the most important pre-requisite for electronic devices. Bipolar junction transistors are out of the question, even though the principal mode of operation has been demonstrated [16, 17].

Conclusions

The most promising candidate for single-crystal diamond wafer fabrication is the lift-off process based on ion implantation. To achieve this goal, a single large (inch size) seed wafer is required, and further research and development of bulk diamond crystal growth techniques is ongoing. Outstanding problems in microwave plasma CVD used for bulk crystal growth are being addressed with pulse microwave approaches; however, further technical breakthroughs are necessary. As wafer diameter increases, the development of flattening and smoothing technologies for large wafers will become more important. It will become necessary to fabricate low-resistivity wafers required for vertical power devices based on insulating substrates without growing heavily doped bulk crystal. To this end, separation techniques for low-resistivity films should be developed, as well as thick-film growth technologies, including hot filament CVD on insulating wafers [19].

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