

Retraction

Retracted: A Comprehensive Examination of Bandgap Semiconductor Switches

Advances in Materials Science and Engineering

Received 26 December 2023; Accepted 26 December 2023; Published 29 December 2023

Copyright © 2023 Advances in Materials Science and Engineering. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This article has been retracted by Hindawi, as publisher, following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of systematic manipulation of the publication and peer-review process. We cannot, therefore, vouch for the reliability or integrity of this article.

Please note that this notice is intended solely to alert readers that the peer-review process of this article has been compromised.

Wiley and Hindawi regret that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

References

- [1] S. Siva Subramanian, R. Saravanakumar, B. P. Ganthia et al., "A Comprehensive Examination of Bandgap Semiconductor Switches," *Advances in Materials Science and Engineering*, vol. 2021, Article ID 3188506, 8 pages, 2021.

Review Article

A Comprehensive Examination of Bandgap Semiconductor Switches

S. Siva Subramanian ¹, **R. Saravanakumar**,² **Bibhu Prasad Ganthia**,³ **S. Kaliappan** ⁴,
Surafel Mustefa Beyan ⁵, **Maitri Mallick**,⁶ **Monalisa Mohanty**,⁷ and **G. Pavithra**⁸

¹Department of EEE, Karpagam College of Engineering, Coimbatore, India

²Department of Wireless Communication, Institute of Electronics and Communication Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamilnadu, India

³Electrical Engineering, IGIT Sarang, Dhenkanal, Odisha, India

⁴Department of EEE, Kumaraguru College of Technology, Coimbatore, Tamilnadu, India

⁵School of Chemical Engineering, Jimma Institute of Technology, Jimma University, Jimma, Oromia, Ethiopia

⁶Department of Civil Engineering, KMBB College of Engineering and Technology, Khordha, Odisha, India

⁷Electrical & Electronics Engineering, ITER, Siksha "O" Anusandhan Deemed to be University, Bhubaneswar, Odisha, India

⁸Department of Electronics and Communication Engineering, Dayananda Sagar College of Engineering (DSCE), Bangalore, Karnataka, India

Correspondence should be addressed to S. Siva Subramanian; siva.ace@gmail.com and Surafel Mustefa Beyan; surafel.beyan@ju.edu.et

Received 5 July 2021; Accepted 29 July 2021; Published 25 September 2021

Academic Editor: Samson Jerold Samuel Chelladurai

Copyright © 2021 S. Siva Subramanian et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Improvements in the material characteristics of bandgap semiconductors allow the use of high-temperature, high-voltage, and fast switch rates in power devices. Another good reason for creating new Si power converter devices is that previous models perform poorly. The implementation of novel power electronic converters means high energy efficiency but a more logical use of electricity. At this moment, titanium dioxide and gallium nitride are the most prospective semiconductor materials because of their great features, established technology, and enough supply of raw components. This study is focused on providing an in-depth look at recent developments in manufacturing Si-C- and high-powered electronic components and showcasing the whole scope of the newly developing product generation.

1. Introduction

Using electronic switching devices is the most efficient way to handle electrical energy. As of today, over 40% of global energy is used to generate, store, and distribute electricity, making power electronics a critical part of the process. On power electronic converters, the power semiconductor devices' losses account for a substantial percentage of the energy loss. Si's blocking voltage capabilities as well as the operating temperature and switching frequency have been proven to be limited [1–5]. So far, the maximum commercial breakdown voltage for

Si IGBTs is 6.5 kV, and the device must operate at a restricted switching temperature of 200°C.

Currently used power converters must contend with certain inevitable physical limitations, including costly cooling systems and costly passive components. As a result, we may anticipate a young generation of power converters that use wide bandgap semiconductors. Enhancing the performance of the power transformations will enable better overall utilisation of energy and improved size and durability of power converters [6–10].

According to researchers, silicon carbide (Si-C) or gallium nitride (Ga-N) are considered the most promising

semiconductor material candidates because they have excellent theoretical qualities, lucrative business availability of the starting ingredients, and mature technological processes. WBG semiconductors' prospects as a replacement for Si (Figure 1) emphasise several important material characteristics [11–14].

Therefore, the process technology for WBG semiconductor materials is of higher interest to device manufacturers, which makes these materials attractive for high-power electronics. Ga-N's potential performance advantage is reduced high-frequency and high-voltage requirements [15–18], along with limited high-quality bulk substrates for vertical devices, which means that Si-C has a higher chance of securing high-voltage device sales.

This is a new development in power electronics; while many improvements are still required, this represents a breakthrough. Material benefits, such as reduced manufacturing costs, low maintenance costs, and so on, are only partly realised owing to varying material qualities, technological constraints, unoptimized device designs, and device reliability problems [19–23]. In addition, there will be a significant research effort for the development of modelling and electro thermal characterization techniques for these power devices, as well as for optimal package at elevated performance, controllers, and processors.

This article provides an overview of current and anticipated future advancements in new Si-C- or Ga-N-based electrochemical capacitors as well as current improvements [24–29].

2. Power Devices

Compared to Si-C equivalents, an increase of 10 in blocking voltage is achievable, because of the higher dielectric critical field of Si-C. The major benefit of Si-C's greater thermal conductivity is that it enables operation at higher power density ratings and uses less space for the cooling system, as illustrated in Figures 2 and 3 [30, 31].

In Figure 4, in order to reduce DMOSFET inversion channel resistance, the development of 4H-Si-C DMOSFETs was postponed. A brilliant MOSFET integration and MOS interface research effort have been made in the last few years. One of the most impressive breakthroughs in the field of Si-C MOS consumer electronics was realised by lowering the charge carrier density (D_{it}) and enhancing the surface morphology, resulting in an increase in the MOS channel's performance [32].

IGBTs have gained popularity recently, and blocking voltage capacities exceeding 10 kV have been recorded [33]. An expectation is that Si-C power switches will boost their voltage capabilities to about 20–30 kV in the near future [34–36]. As in development of power MOSFETs, important breakthroughs were made in the quality and large circuit mobility of the MOSFETs. Best-outcome n-channel IGBT structures also require advances in the epilayer growing process. Cree has published details on ultra-high-voltage 4H-Si-C thyristors [37–39]. A 4 h silicon-controlled switch with IGBT chip size of 6.7 mm

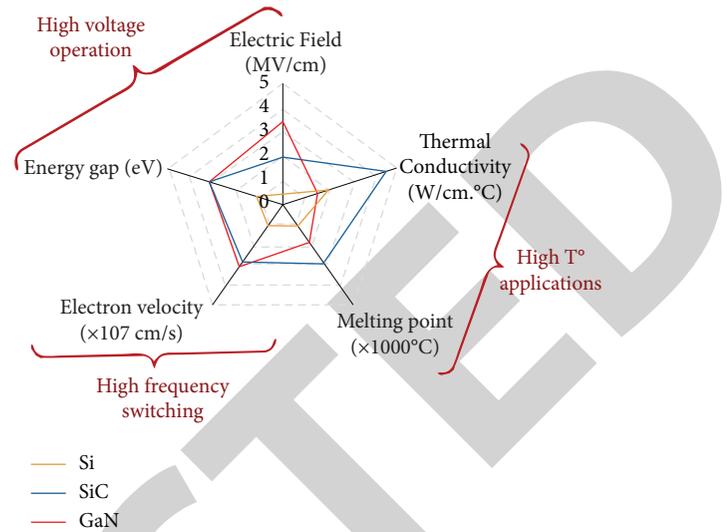


FIGURE 1: An overview showcasing silicon, silicon carbide, and gallium nitride properties.

and an environment influences of 0.16 cm^2 had a 0°C differential specified on to one of $24 \text{ m}\Omega \text{ cm}^2$ with just a gate bias of 20 V.

It is a need of filtering 4.7 kV with just a capacitance of $50 \mu\text{A}$, and turn-on \pm turn-off periods of 168 but rather 106 ns at room temperature. BJTs made from silicon carbide nevertheless exhibit deterioration in both load current and forward voltage drop under forward stress, caused by layering failures in the base-emitter region [40–44].

Conductivity manipulation and the inverse thermal resistance with the forward voltage drop are beneficial for Si-C-GTO structures as well. The Si-CGT (silicon-based gate turn-off thyristor) [45–48] has the cross section illustrated in Figure 5.

3. Ga-N Power Devices

WBG, huge critical magnetic current, high electron mobility, and somewhat good thermal conductivity make Ga-N excellent for high-voltage, high-frequency, and high-temperature applications. Ga-N-based devices are currently marketed in the photonics sector, whereas silicon is in the early stages of power applications. As a result, Ga-N epilayers have mostly been produced on substrates other than commercial high-quality free-standing Ga-N substrates. Gaining top-notch, single-crystalline Ga-N films is critical for power conversion, and thus good worldwide epitaxial relationships are necessary. Compared with the other substrates, Ga-N epilayers produced on Si substrates provide a low cost technique, as well as provide growth on high-strength resins up to 200 mm [49, 50].

Due to the absence of phase change Ga-N substrates, most reported Ga-N semiconducting power diodes are lateral or quasi-vertical devices. A breakdown voltage of 9.7 kV was observed on sapphire substrates [51–53] even if the forward voltage loss is still significant. Sapphire substrate-mounted Ga-N rectifiers are gaining a lot of interest

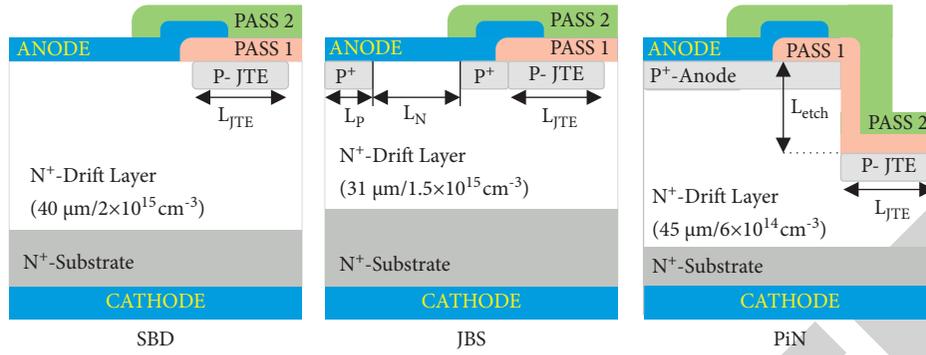


FIGURE 2: Schottky diode.

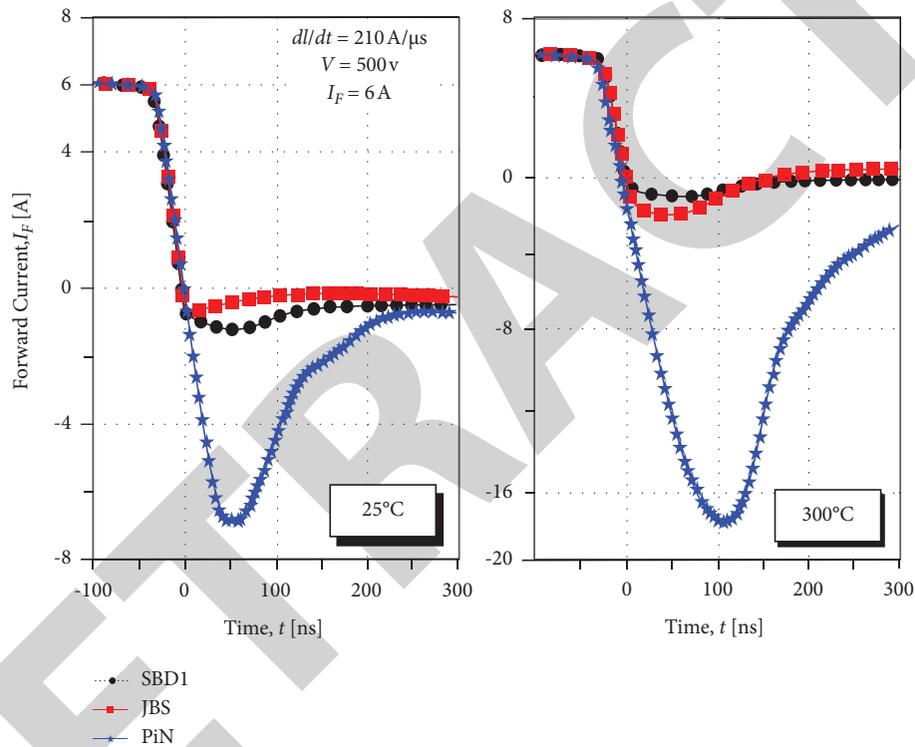


FIGURE 3: Inductive load turn off.

because of their low cost. Recently, 600 V Ga-N ZnO diodes are expected to be introduced in market with Si-C Schottky rectifiers. Additionally, professional Ga-N eukaryotic initiation will now be readily accessible in the market in the 600 V–1.2 kV output voltage. However, on the other hand, Ga-N-based voltage dc-dc converters in the range of 600 V–3.3 kV are also being studied, but improvements in material strength of inserted p-type Ga-N are still required.

AlGa-N/Ga-N heterostructures include a 2-D electron gas (2DEG) because of the significant band edge discontinuity of Ga-N and AlGa-N and also because of the presence of polarisation forces that provide a substantial 2DEG concentration with transistors values (1200–2000 cm²/Vs). Ga-N HMT-S (Figure 6) are inherently normally on semi-conductors since a negative gate bias is required to remove the 2DEG. A significant trade-off has recently been achieved

between breakdown voltage and on-resistance with these devices [54–58].

Significant advancements have been achieved since the Ga-N-based HEMT switch appeared [45]. For instance, HEMT microwave output power output both on diamond and Si-C has increased from 1.1 degree in 1996 to 40 W/mm lately. Additionally, Ga-N HMT-S is approaching 10 kV, and Ga-N-based pv panels have already been demonstrated. The initial HEMT structures' electrical performance may be improved by reducing the dielectric constant collapse and increasing the gate-to-drain breakdown voltage by adjusting the surface morphological trap densities [47]. Three approaches are shown here: surface pay n-Ga-N-cap fabrication, submerged gating with professional plate arrangement, and ferric oxide of surface states through silicon nitride and perhaps other insulating layers [59].

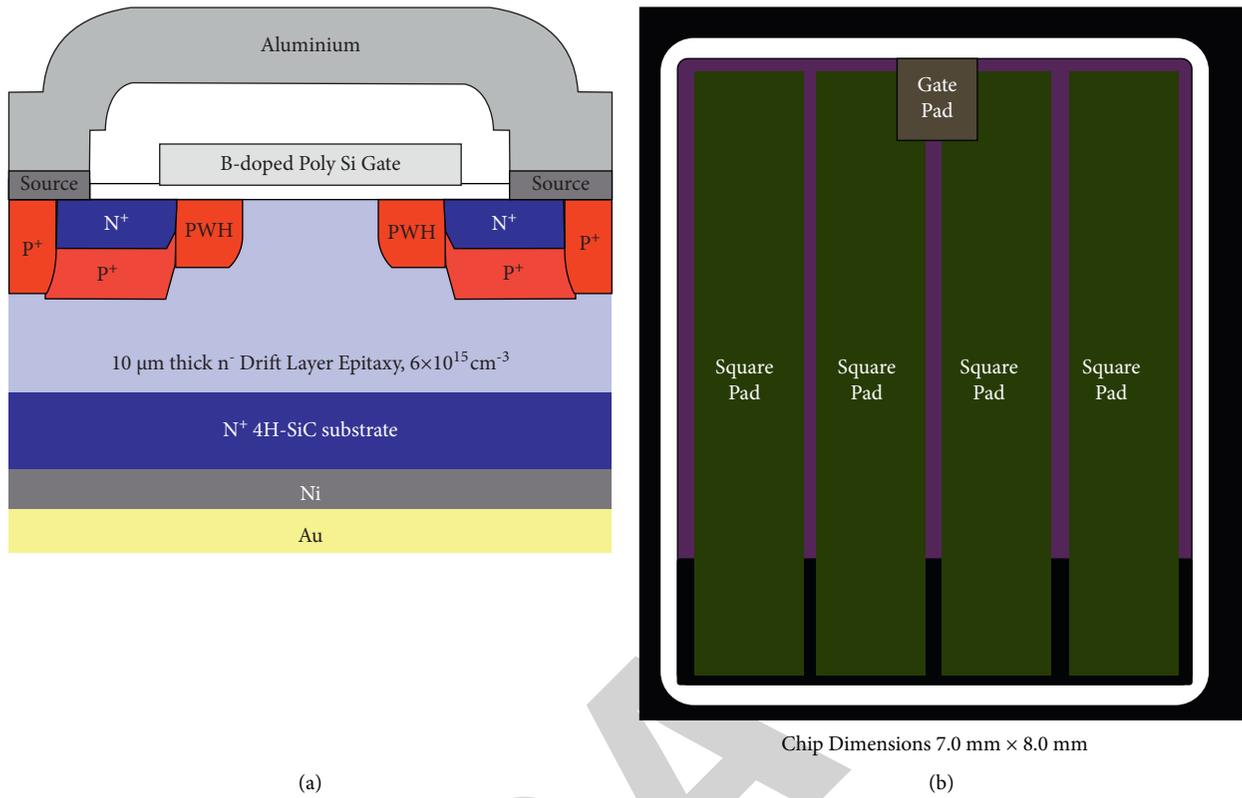


FIGURE 4: Diagram of DMOSFET.

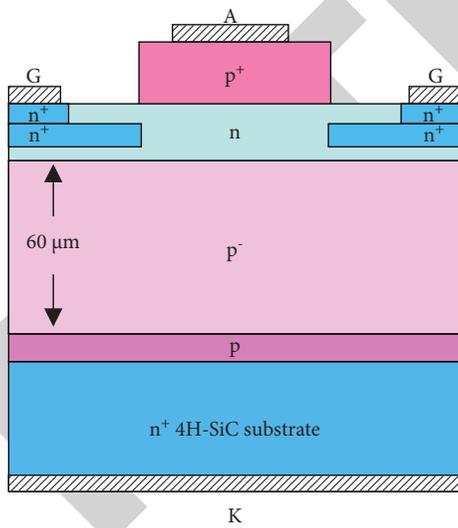


FIGURE 5: Structure of Si-C.

Specifically, 2.2kV HEMT structures produced on silicon utilising a novel Si substrate removal technique have recently been described [60]. In contrast, structures produced on bulk silicon have a blocking voltage capacity of 700 V. Also, Ga-N-based HEMT power switches for kilowatt-level power conversion are manufactured on semi-insulating Si-C substrates, which include field-plated gates [61].

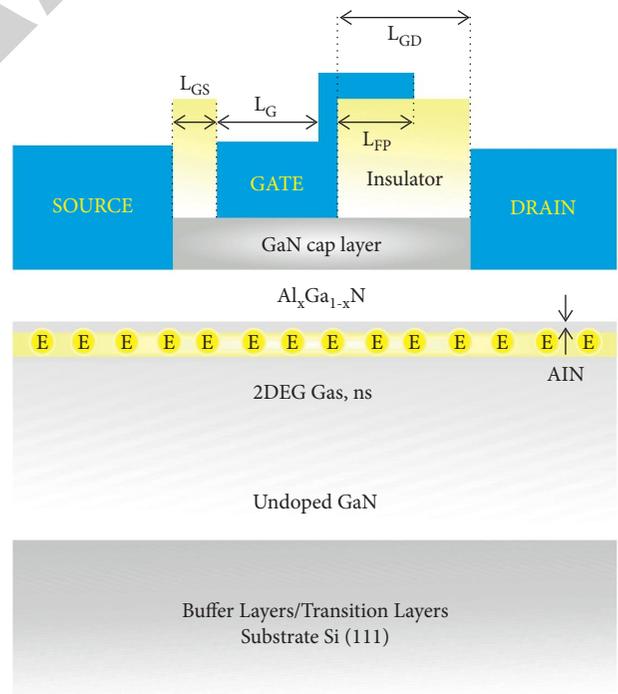


FIGURE 6: Cross section of a normally on Ga-N HEMT.

Ga-N HMT-S are essentially normally off devices, making them challenging to employ in power systems where apparently controls are desired. In light of this, considerable

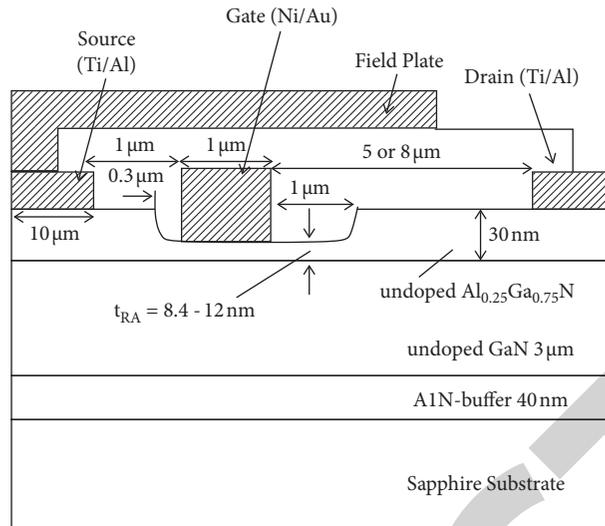


FIGURE 7: Recessed-gate Ga-N HEMT structure.

research has been done in developing Ga-N HEMT devices via many different approaches. A recessed-gate structure (Figure 7) was shown in [62] such that the AlGa-N layer beneath the gate area is too thin to create a 2DEG, which gives rise to a good threshold voltage. One solution for creating a routinely Ga-N HEMT is to use a diethyl ether plasma treatment in the gate area [63] instead of decreasing the AlGa-N thickness. Incorporation of fluoro ions in the AlGa-N barrier results in an increase in threshold voltage shift, which may be eliminated by postgate annealing at a low temperature. AlGa-N/Ga-N HMT-S acquire their high performance when they are combined with a gate recess and a fluorine-based surface treatment. The selective development of a p-n connection gate [58, 64] allows the thinning of the 2DEG barrier below (see Figure 8).

Ga-N-HMT-S are usually available with breakdown voltages in the range of 20–600 V. Breakdown voltages for Ga-N-HMT-S are typically in the 20-600 V range. EPC, for example, offers 600V-170mΩ nitride HMT-S with output impedances ranging from 40 V/33 A to 200 V/12 A, whereas MicroGa-N has 600 V-170 mΩ Ga-N HMT-S with an applied voltage and a 200 kΩ output impedance.

Devices, also called fabricated HMT-S, are layered on a sapphire substrate, and their measured on-resistances and insulating voltages are both higher than 2 kV with estimated on-resistances reaching 24–22 Ω-mm in both directions. Since the introduction of improved Ga-N HEMT process technology, it is also proper to say that the introduction of Ga-N diodes, which can shield the HEMT gate from voltage peaks, allows the combination of Ga-N diodes. Additionally, high-voltage power devices are also being developed for monolithic integration and for use in peripheral structures that include sensing/protection/control capabilities.

Because of the normally off operation and wide conduction band offset of Ga-N lateral MOSFETs, they are less vulnerable to hot electrostatic interaction and other reliability issues, especially issues related to the surface states and present collapse. To enable the incorporation of lateral

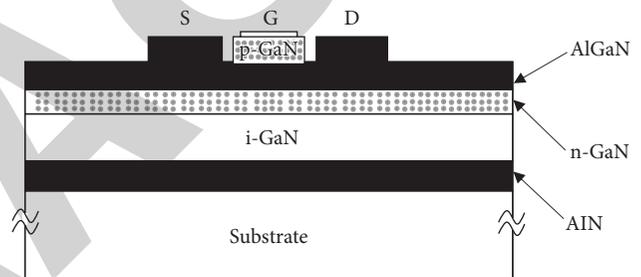


FIGURE 8: Schematic cross section of a p-n gate Ga-N HEMT [57].

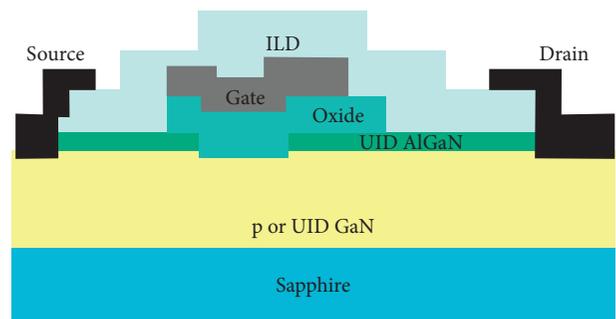


FIGURE 9: Schematic cross-sectional view of a lateral Ga-N hybrid MOS-HFET.

nitride MOSFETs with channel mobility numbers of 170 cm²/Vs and a blocking voltage capacity of 2.5 kV, the high-quality SiO₂/Ga-N interface [63] was used. However, the existence of rare metal and its layer thickness and scattering issues causes an impact on silicon. A heterostructure including AlGa-N/Ga-N may be introduced into the RESURF area of something like the Ga-N MOSFETs in order to overcome this (see Figure 9). This hybrid MOS-HEMT [64] combines the advantages of either the MOS barrier height or the 2DEG Ga-N power switching.

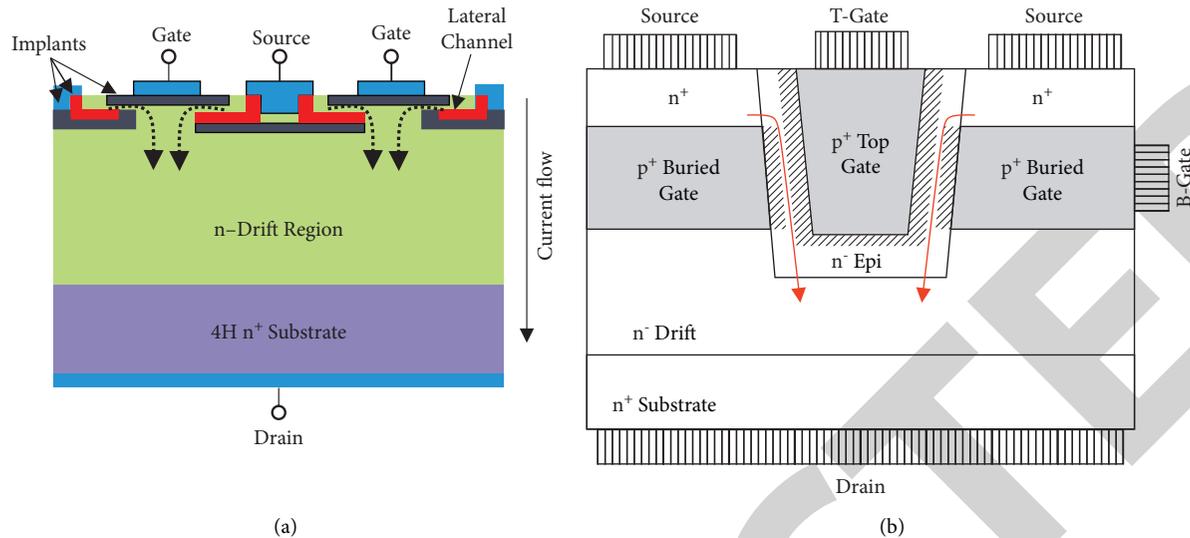


FIGURE 10: Diagram of JFET.

4. Conclusion

This article provides an overview of current advances in power devices, especially WBG semiconductor materials, that are powered by miniature RF motors. It is possible that future generations of more efficient power converters may be realised using WBG characteristics, even in applications that are limited by Si-based systems, including such increased and greater operation. Wafer-based bipolar (WB) semiconductors, such as Si-C and Ga-N, are currently the most appropriate WBG nanomaterials for next-generation power devices because of the excellent quality of wafers and the ready-to-use technical procedure.

Also, commercially available Si-C SBDs and JBS diodes are strong rivals to Si diodes. In Figure 10, Si-C JFETs or MOSFETs would contend alongside Si IGBTs through to collapse values in the area of 5 kV, while Si IGBTs will thereafter compete with Si-C JFETs and MOSFETs beyond breakdown voltages of 5 kV. JFETs will be the first industrial Si-C switches since Si-C MOSFETs cannot be made to work with better gate-contact interfaces. Si-C JFETs and low-voltage Si MOSFETs in series with a normally on JFET are well established for hybrid cascade topologies. Conversely, JFETs with the gate turned off still have large resistive channels that need further enhancement. Over the last few years, 1.2 kV Si-C MOSFETs have already been commercially available. Improving the Si-C MOSFET should lead to improvements in the Si-C IGBT, which may pave the way for IGBTs with breakup voltages exceeding 10 kV.

Most of the Ga-N power devices produced use epitaxial layers of Ga-N on substrates like silicon, sapphire, or silicon carbide. A Ga-N diode of this magnitude has been successfully demonstrated and is expected to be put into general commercial use soon. One last alternative that is being explored for limited, increased Ga-N power switches is hybrid MOS-HEMT architectures.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

- [1] M. Berzelius, "XLII. On the mode of obtaining silicium, and on the characters and properties of that substance," *Philosophical Magazine*, vol. 65, no. 324, pp. 254–267, 1825.
- [2] T. Thomson, *A System of Chemistry in Four Volumes*, Baldwin, Cradock, and Joy, vol. 1, p. 252, London, UK, 5th edition, 1817.
- [3] M. Faraday, *Experimental Researches in Electricity*, vol. 1, pp. 122–124, Richard and John Edward Taylor, London, UK, 1839.
- [4] F. Braun, "Über die Stromleitung durch Schwefelmetallic," in *Semiconductor Devices: Pioneering Papers*, S. M. Sze, Ed., vol. 153, no. 4, pp. 556–563, World Scientific Publishing Co., Singapore, 1874.
- [5] J. C. Bose, "Detector for electrical disturbances," 1904, U. S. Patent 755,840, <https://ieeexplore.ieee.org/document/658774>.
- [6] J. E. Lilienfeld, "Method and apparatus for controlling electric currents," 1930, U. S. Patent No. 1,745,175, <https://patentimages.storage.googleapis.com/fa/5d/33/ed2769d48fac4d/US1745175.pdf>.
- [7] A. H. Wilson, "The theory of electronic semi-conductors," *Proceedings of the Royal Society of London - Series A: Containing Papers of a Mathematical and Physical Character*, vol. 133, no. 822, pp. 458–491, 1931.
- [8] A. H. Wilson, "A note on the theory of rectification," *Proceedings of the Royal Society of London - Series A: Containing Papers of a Mathematical and Physical Character*, vol. 136, no. 830, pp. 487–498, 1932.
- [9] B. Davydov, "On the rectification of current at the boundary between two semiconductors," *Compt. Rend. Doklady Acad. Sci., URSS*, vol. 20, p. 279, 1938.

- [10] N. F. Mott, "Note on the contact between a metal and an insulator or semi-conductor," *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 34, no. 4, pp. 568–572, 1938.
- [11] W. Schottky, "Halbleitertheorie der Sperrschicht," *Naturwissenschaften*, S. M. Sze, Ed., vol. 26, no. 52, p. 843, 1938.
- [12] R. S. Ohl, *Light-Sensitive Electric Device*, 1946, U. S. Patent 2402662, <https://patents.google.com/patent/US2443542A/en>.
- [13] J. H. Scaff and R. S. Ohl, "Development of silicon crystal rectifiers for microwave radar receivers," *Bell System Technical Journal*, vol. 26, no. 1, pp. 1–30, 1947.
- [14] W. Shockley, "The theory of p-n junctions in semiconductors and p-n junction transistors," *Bell System Technical Journal*, vol. 28, no. 3, pp. 435–489, 1949.
- [15] H. C. Theurer, "Method of processing semiconductive materials," U. S. Patent 3,060,123, 1962, <https://patents.google.com/patent/US3060123A/en>.
- [16] J. R. Harris, "WILLIAMSON v THE INSPECTOR--GENERAL OF PENAL ESTABLISHMENTS," Victorian Reports, [1958] VR, pp. 330–334, Bell Laboratories Record, New York, NY, USA, 1958.
- [17] M. Tanenbaum, *Bell Labs Notebook No. 25505*, p. 30, Texas Instruments, Dallas, TX, USA, 1954.
- [18] J. Andrus and W. L. Bond, "Photoengraving in transistor fabrication," in *Transistor Technology*, F. J. Biondi, Ed., vol. III, pp. 151–162, D. Van Nostrand, Princeton, NJ, USA, 1958.
- [19] W. Shockley, "Memorandums, golden west theme book, and record," in *Shockley Papers, Accession Listing 95-153, Box 2B* Department of Special Collections, Stanford University Libraries, Stanford, CA, USA, 1955.
- [20] G. E. Moore, "The role of Fairchild in silicon technology in the early days of Silicon Valley," *Proceedings of the IEEE*, vol. 86, no. 1, pp. 53–62, 1998.
- [21] J. A. Hoerni, "Method of manufacturing semiconductor devices," U. S. Patent 3,025,589, 1962, <https://patents.google.com/patent/US3333324>.
- [22] R. N. Noyce, "Semiconductor Device-And-lead Structure," U. S. Patent 2981877, 1961, <https://ieeexplore.ieee.org/document/4785577>.
- [23] D. Kahng, "Electric field controlled semiconductor device," U. S. Patent No. 3,102,230, 1963, <https://patents.google.com/patent/US3102230A/en>.
- [24] R. Norman, J. Last, and I. Haas, "Solid-state micrologic elements," in *Proceedings of the Solid-State Circuits Conference. Digest of Technical Papers*, vol. 3, pp. 82–83, IEEE International, Philadelphia, PA, USA, February 1960.
- [25] R. L. Fogelsohn, "The Design of High Speed All Transistor Logic Circuits," *Fairchild Silicon Transistors, Application Data APP-49*, vol. 49, 1962.
- [26] H. W. Ruegg and R. H. Beeson, "New Forms of "All Transistor" Logic," in *Proceedings of the 1962 IEEE International Solid-State Circuits Conference. Digest of Technical Papers*, Philadelphia, PA, USA, February 1961.
- [27] R. H. Norman and H. E. Stephenson, "Shift Register Employing Insulated Gate Field Effect Transistors," U. S. Patent 3454785, <https://patents.google.com/patent/US3454785A/en>.
- [28] G. Moore, *The Future of Integrated Electronics*, Fairchild Semiconductor internal publication, Sunnyvale, CA, USA, 1964.
- [29] F. Faggin and T. Klein, "Silicon gate technology," *Solid-State Electronics*, vol. 13, no. 8, pp. 1125–1144, 1970.
- [30] M. P. Forrer, "Survey of circuitry for wristwatches," *Proceedings of the IEEE*, vol. 60, no. 9, pp. 1047–1054, 1972.
- [31] el-cat.com, "Properties of silicon and silicon wafers," <http://www.el-cat.com/silicon-properties.htm>.
- [32] D. K. Schroder, R. N. Thomas, and J. C. Swartz, "Free carrier absorption in silicon," *IEEE Transactions on Electron Devices*, vol. 25, no. 2, pp. 254–261, 1978.
- [33] et-cat.com, "Properties of silicon and silicon wafers," <http://www.el-cat.com/silicon-properties.htm>.
- [34] C. B. Collins, R. O. Carlson, and C. J. Gallagher, "Properties of gold-doped silicon," *Physical Review*, vol. 105, no. 4, pp. 1168–1173, 1957.
- [35] C. B. Collins and R. O. Carlson, "Properties of silicon doped with iron or copper," *Physical Review*, vol. 108, no. 6, pp. 1409–1414, 1957.
- [36] Y. Tokumaru, *Properties of silicon doped with nickel*, Japan Society of Applied Physics, Tokyo, Japan, 1963.
- [37] W. B. Chua and K. Rose, "Electrical properties of high-resistivity nickel-doped silicon," *Journal of Applied Physics*, vol. 41, no. 6, pp. 2644–2647, 1970.
- [38] B. E. Deal and M. Sklar, "Thermal oxidation of heavily doped silicon," *Journal of the Electrochemical Society*, vol. 112, no. 4, pp. 430–435, 1965.
- [39] M. J. Mleczko, C. Zhang, H. R. Lee et al., "HfSe₂ and ZrSe₂: two-dimensional semiconductors with native high- κ oxides," *Science Advances*, vol. 3, no. 8, Article ID e1700481, 2017.
- [40] D. M. Zajac, A. J. Sigillito, M. Russ et al., "Resonantly driven CNOT gate for electron spins," *Science*, vol. 359, no. 6374, pp. 439–442, 2018.
- [41] B. G. Yacobi, *Semiconductor Materials: An Introduction to Basic Principles*, pp. 1–3, Springer, Berlin, Germany, 2003.
- [42] L. Łukasiak and A. Jakubowski, "History of semiconductors," *Journal of Telecommunication and Information Technology*, vol. 3, 2010.
- [43] P. Robin Morris, *A History of the World Semiconductor Industry*, pp. 11–25, IET, London, UK, 1990.
- [44] Y. P. Varshni, "Temperature dependence of the energy gap in semiconductors," *Physica*, vol. 34, no. 1, pp. 149–154, 1967.
- [45] S. M. Sze, *Physics of Semiconductor Devices*, John Wiley & Sons, New York, NY, USA, 2nd edition, 1981.
- [46] K. Chain, J.-h. Huang, J. Duster, P. K. Ko, and C. Hu, "A MOSFET electron mobility model of wide temperature range (77 - 400 K) for IC simulation," *Semiconductor Science and Technology*, vol. 12, no. 4, pp. 355–358, 1997.
- [47] A. G. Sabnis and J. T. Clemens, "Characterization of the electron mobility in the inverter Si surface. Int Electron Devices Mtg 18–21. 69," *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, vol. 7, no. 1, pp. 50–70, 1979.
- [48] K. Chen, H. Clement Wann, J. Dunster, P. K. Ko, C. Hu, and M. Yoshida, "MOSFET carrier mobility model based on gate oxide thickness, threshold and gate voltages," *Solid-State Electronics*, vol. 39, no. 10, pp. 1515–1518, 1996.
- [49] D. S. Jeon and D. E. Burk, "MOSFET electron inversion layer mobilities—a physically based semi-empirical model for a wide temperature range," *IEEE Transactions on Electron Devices*, vol. 36, no. 8, pp. 1456–1463, 1989.
- [50] W. Grabinski, M. Bucher, J. M. Sallese, and F. Krummenacher, "Compact modeling of ultra-deep sub-micron CMOS devices," in *Proceedings of the International Conference on Signals and Electronic Systems, ICSES*, pp. 13–27, Ustron, Poland, October 2000.
- [51] F. F. Fang and A. B. Fowler, "Hot electron effects and saturation velocities in Silicon inversion layers," *Journal of Applied Physics*, vol. 41, no. 4, pp. 1825–1831, 1970.

- [52] Y. Cheng, K. Imai, M.-c. Jeng, Z. Liu, K. Chen, and C. Hu, "Modelling temperature effects of quarter micrometre MOSFETs in BSIM3v3 for circuit simulation," *Semiconductor Science and Technology*, vol. 12, no. 11, pp. 1349–1354, 1997.
- [53] R. F. Pierret, *Semiconductor Fundamentals*, Addison-Wesley, Boston, MA, USA, 2nd edition, 1988.
- [54] I. M. Filanovsky and A. Allam, "Mutual compensation of mobility and threshold voltage temperature effects with applications in CMOS circuits," *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, vol. 48, no. 7, pp. 876–884, 2001.
- [55] A. Agarwal, S. Mukhopadhyay, A. Raychowdhury, K. Roy, and C. H. Kim, "Leakage power analysis and reduction for nanoscale circuits," *IEEE Micro*, vol. 26, no. 2, pp. 68–80, 2006.
- [56] F. Fallah and M. Pedram, "Standby and active leakage current control and minimization in CMOS VLSI circuits," *IEICE - Transactions on Electronics*, vol. E88-C, no. 4, pp. 509–519, 2005.
- [57] J. R. Black, "Electromigration-A brief survey and some recent results," *IEEE Transactions on Electron Devices*, vol. 16, no. 4, pp. 338–347, 1969.
- [58] A. Yariv, *Optical Electronics*, p. 565, Saunders College Publishing, Philadelphia, PA, USA, 4th edition, 1991.
- [59] P. G. Snyder, J. A. Woollam, S. A. Alterovitz, and B. Johs, "Modeling Al_xGa_{1-x}As optical constants as functions of composition," *Journal of Applied Physics*, vol. 68, no. 11, pp. 5925–5926, 1990.
- [60] B. Johs, J. Hale, and J. Hilfiker, "Real-time process control with in situ spectroscopic ellipsometry," *III-vs Review*, vol. 10, no. 5, pp. 40–42, 1997.
- [61] Basel, "Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal - Document," 2010, <http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx>.
- [62] S. Sinha, "E-waste time to act now –toxic alert," 2006, <http://enews.toxicslink.org/feature-view.php?id=1>.
- [63] R. Gopalan, "A study on the Indian IT sector from nautilus.org," 2002, <http://oldsite.nautilus.org/archives/cap/reports/IndiaExecSummary.PDF>.
- [64] A. Bandhopadhyay, "Electronic waste management: indian practices and guidelines," *International Journal of Energy and Environment*, vol. 1, no. 5, pp. 193–807, 2010.