Advancing Beyond Silicon: Future Directions in Semiconductor Technology

Hongjun Hu
Teensen Genesis School, Nanchang, China
hjj200808@txyzedu.com

Abstract. This essay delves into the semiconductor industry, emphasizing the developmental trajectory and challenges of silicon-based technologies. The introduction provides a foundational overview of semiconductors, with a specific focus on silicon and its limitations in high power and temperature scenarios. Methodologically, the analysis is rooted in a comprehensive literature review and data examination, ensuring a robust discourse. The core of the essay explores alternative materials and technologies that could potentially revolutionize the industry. New materials such as SiC and GaN are analyzed for their superior properties compared to silicon, including higher band gaps and thermal conductivities, which make them better suited for high power and temperature environments. Furthermore, the discussion extends to innovative 3D structure chips and the utilization of 2D materials like MoS2, highlighting their potential to enhance chip performance and reduce feature size. The conclusion synthesizes these insights, noting the current shortcomings of the alternatives and the ongoing need for research to fully realize their potential in practical applications.

Keywords: Semiconductors, Silicon, GaN, SiC, 2D materials, MoS2.

1. Introduction

Semiconductors, occupying a pivotal position between insulators and conductors in terms of electrical conductivity, present a unique class of materials that are integral to the fabric of modern electronics [1]. Their variable conductivity under different environmental conditions and the ability to modify their conductive properties by doping with impurities make semiconductors versatile for various applications including diodes and transistors. The initial discovery of the basic principles of electricity and conductivity by Michael Faraday and contemporaries in the early 19th century set the stage for the semiconductor revolution [2]. Yet, it was the advent of quantum mechanics in the early 20th century that provided the crucial theoretical framework necessary for developing semiconductor technology. This era ushered in groundbreaking innovations such as the invention of the first transistor at Bell Labs in 1947 by John Bardeen, Walter Brattain, and William Shockley, followed by Jack Kilby’s development of the first integrated circuit in 1958. These foundational advances have significantly shaped the technological landscape, enabling the proliferation of electronic devices that permeate every aspect of daily life.

Despite the monumental strides in semiconductor technology, the journey has been fraught with challenges, particularly with silicon—the industry standard since the 1960s. Silicon, prized for its abundance and robustness in high-power and high-temperature environments, replaced germanium to become the cornerstone of semiconductor materials. However, as the requirements of modern electronics have escalated, the limitations of silicon have become increasingly apparent. Specifically, power semiconductors, crucial for energy conversion and distribution in systems as varied as wind turbines and trains, struggle under extreme conditions where silicon’s performance falters. Additionally, in the realm of chip semiconductors, the push towards ultra-miniaturization has reached a bottleneck. The prevailing industry trend towards reducing the feature size of chips to enhance computational capacity and efficiency now grapples with physical limitations like the short channel effect, which introduces issues such as leakage and overheating at scales as small as 3 nanometers [3].

This research aims to address the critical challenges facing contemporary semiconductor technologies by exploring alternative materials and advanced technological solutions. The focus will be twofold: firstly, identifying and characterizing new semiconductor materials that can surpass the performance thresholds of silicon, particularly in high-power and high-temperature applications. This involves a detailed examination of materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN), which are posited to offer superior properties in terms of efficiency, durability, and operational stability under harsh conditions. Secondly, the study will delve into innovative design paradigms such as 3D chip architectures and the utilization of two-dimensional materials like MoS2, which promise to revolutionize chip semiconductor technology by overcoming the physical limitations currently impeding silicon-based devices. Through comprehensive analysis and experimentation, this research seeks to pave the way for next-generation semiconductor devices that not only enhance performance but also drive the sustainable evolution of electronic systems worldwide.

2. Methods

The main methods in this essay are literature review and data analysis. The literatures related to this topic have been found using the research engines and database such as Google Scholar and Web of Science by key words. The influence impact of each literature was also considered to see its academic value and impact [4]. After that, the papers that are needed to be read in more detail were chosen. The data and results from these literatures, including tables, line charts and bar charts will be analyzed, compared and discussed to make a conclusion.

3. Results and discussion

3.1. Wide Band gap materials

In the introduction part of this essay, the problems of silicon in environment with high power and temperature have been introduced [5]. To solve these problems, the most appropriate method is to find other new materials suitable to work in that environment.

In order to find new materials, the properties which can affect the suitability need to be analyzed first. They are mainly band gap, breakdown voltage, thermal conductivity, electron mobility and saturated electron velocity. In the following section, these properties of semiconductors will be introduced in detail and their effects will be investigated.

Band gap is a property of materials, it is basically the difference of energy of an electron between the top of valance band (where the electrons are bonded to an atom) and the bottom of the conduction band (where electrons are free to move). The value of band gap affects the suitability of a material in certain applications. In power semiconductors, however, the materials with higher band gap are more suitable to work in this environment with high power and temperature. This is because for materials with high band gap, they need higher energy to move their electrons from valance band to conduction band, which make them more stable in environment with high volts and temperature.

The breakdown voltage is a property of a semiconductor, it is the maximum reverse voltage applied on a semiconductor without damage it. This property is affected by its band gap. The higher band gap, the higher breakdown voltage. It is apparent that materials with higher breakdown voltage and band gap are more suitable to work in environment with high power since they are more likely to suffer high voltage.

Thermal conductivity is the property of conducting heat of a semiconductor, the higher thermal conductivity, the better it can work in high temperature environment. Since it is more likely to conduct heat and keep relatively low temperature and high efficiency without cooling system.

Electron velocity and electron mobility of a semiconductor are related to its responding speed. The higher electron velocity and mobility, the faster responding times means these materials are able to work in high frequency environment.

Among all of these properties, the band gap of a material has the greatest impact on its suitability in high voltage and temperature environment, therefore, to find new materials, the wide band gap materials need to be focused first, and then other properties need to be compared and analyzed to find the most suitable material in certain environments.

The most popular wide band gap materials nowadays are SiC and GaN, they have relatively higher band gap compared to silicon, the values of band gap of these three materials are shown in table 1.

Table. 1 Band gaps of the three materials

Materials	Si	SiC	GaN
Bandgap / eV	1.1	3.26	3.4

As presented in Table 1, the data drawn from various literatures clearly demonstrate the substantial differences in band gap values between traditional silicon and the newer semiconductor materials, specifically Silicon Carbide (SiC) and Gallium Nitride (GaN) [6]. This information is critical as the band gap is a key property that determines a material's ability to function in high voltage environments. A larger band gap enables semiconductors to withstand higher voltages and temperatures without breaking down, making SiC and GaN far superior for applications involving significant power loads, such as in power electronics and electric vehicles.

Furthermore, these materials exhibit properties that are vastly improved over silicon in several other aspects crucial to semiconductor functionality. For example, the thermal conductivity of SiC is significantly higher than that of silicon, which allows devices made from SiC to dissipate heat more efficiently, thereby operating at higher temperatures without the risk of thermal damage. This makes SiC an excellent material for use in harsh environments where cooling options are limited. GaN, on the other hand, excels in terms of electron mobility, which translates to faster electronic switching times and higher efficiency in applications like RF amplifiers, LEDs, and laser diodes. The enhanced performance characteristics of these materials are further illustrated in Figure 1, which provides a comparative analysis of SiC, GaN, and silicon across several parameters including breakdown voltage, electron mobility, and thermal conductivity [6]. This visual representation helps to underscore the practical implications of their superior properties. For instance, the breakdown voltage of GaN and SiC is significantly higher than that of silicon, suggesting that devices utilizing these materials can operate safely at much higher voltages, a crucial factor in power transmission and conversion systems. Additionally, the broader implications of adopting these materials extend beyond just improved performance. The increased efficiency and durability provided by SiC and GaN could lead to reduced maintenance costs, longer device lifespans, and potentially lower energy consumption overall. As industries continue to push the boundaries of what is technically feasible, the adoption of materials with higher performance thresholds is not just beneficial but necessary. In conclusion, the data from Table 1 and the subsequent analysis in Figure 1 [6] provide compelling evidence that SiC and GaN are not merely alternatives to silicon but represent significant advancements in semiconductor technology. Their adoption is poised to drive transformative changes across a range of high-voltage and high-power applications, marking a significant shift in the landscape of materials science in semiconductors. This transition supports the development of more robust, efficient, and compact devices that can handle the increasing demands of modern technology.

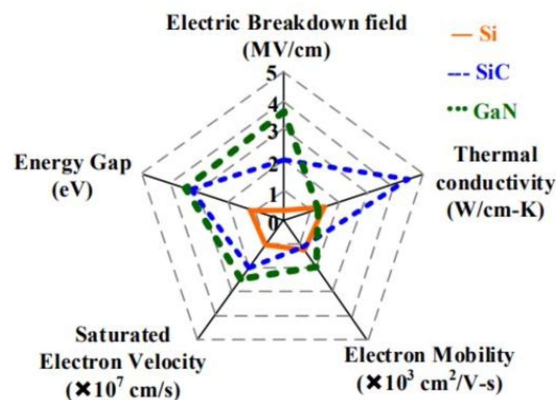

Fig. 1 Comparison of the three materials (Photo credit: Original).

The data in Fig 1 are also from literatures and evident [7]. All the data of the three materials then can be compared. The band gaps and breakdown fields of the two new materials are much higher than silicon, means they are the better choice in high voltage environment. It is clear that the breakdown voltage of GaN is even much higher than SiC, which makes it perform better at high voltage devices. For thermal conductivity, SiC has the most outstanding value, which is almost four times greater than the rest two materials. This makes SiC to be the optimum semiconductor materials in devices with extremely high temperatures. For GaN, however, its thermal conductivity is even a little bit lower than Si, means it is not suitable in high temperature environment. The electron velocity and mobility of GaN are both the highest among the three materials, which shows that GaN is the best material for devices with high frequencies. For SiC, the electron mobility is close to the value of GaN, but the electron mobility is a little bit lower than Si.

To conclude, both SiC and GaN are more suitable in power semiconductors than silicon. More specifically, SiC excels in high power and temperature devices, such as electric vehicles and train systems, while GaN preferred in high frequency applications such as communication systems and wireless networking.

Although SiC and GaN have better performance than Si in power semiconductors, it is still unlikely for them to replace the position of Si, since their manufacturing processes are not mature and their manufacturing costs are still high compared to silicon. These are the main challenges of the two materials. However, the problems might be solved over time by technological innovations and improvement of their manufacturing process.

3.2. 3D structure chips

For chip semiconductors, the main problem is about how to improve their performance in the future since silicon chips' feature size cannot be reduced further. One solution would be using 3D structure chips.

Currently, most silicon chips are 2D structures, means all their components are in one layer. The 3D structure chips, also known as 3D integrated circuits, which is another type of chip structures with multiple layers of electronic circuits and components. There are several advantages of 3D structures over 2D. Firstly, 3D chips have higher volumetric density than 2D chips. This is because 3D chips have multiple layers, means more transistors and components can be put in the same volume. Moreover, the components can be put more closely to each other, this improves the connection speed and power efficiency. At the same time, because of the increase of components in both lateral and vertical dimensions, the interconnectivity in the 3D chips will also increase [8].

These advantages of 3D chips could improve the performance of chips further, which is an excellent solution of the problems in chip semiconductors. However, 3D structures also have some disadvantages. Firstly, because more components are put in the same volume, more heat will be produced during usage, at the same time, 3D structures have less space for heat dissipation. The heating problem is serious and fatal since it means more devices and energy for cooling systems.

Moreover, although 3D structure increase the flexibility of designing chips, it also increases the complexity to design and package chips [9].

Nevertheless, 3D chips still have great advantages over 2D chips and deserve further research to improve chip performance.

3.3. 2D materials

Another method to solve the problems in chip semiconductors is to use 2D materials. 2D materials are a type of materials that have thickness about few atoms, their structure is a layer or several layers of atoms, this property makes it suitable to make smaller and more flexible electronics.

MoS2 is one of the most popular 2D materials, the research and published papers on this material have an increasing trend in the last decade. The data have shown that half research on 2D material transistors is about MoS2.

Compare to silicon, MoS2 has several advantages on chip semiconductors. Firstly, because of the characteristics of 2D materials, it is able to exist as a single atomic layer, which makes it suitable for extremely thin and flexible devices. Moreover, MoS2 has good channel immunity, means that it would perform better at small feature size than silicon. In addition, MoS2 has high on/off ratio, means its chip has lower power consumption and has more accurate digital signal processing ability, as well as better logic circuit performance. Also, the large effective mass of MoS2 can reduce the leakage currents in extremely short channel devices by reducing direct tunneling between source and drain electrodes [10].

These advantages make MoS2 the next generation of chip semiconductors, its unique properties enable chips to have smaller sizes, more flexible applications and better performance.

4. Conclusion

In this essay, the history of development of semiconductors have been introduced as well as the difficulties faced by current silicon semiconductors. The problems are mainly in two topics: power semiconductors and chip semiconductors. Some power devices have high power and temperatures, it is difficult for silicon to work at that environment. For silicon chips, its feature size cannot be smaller further, therefore it is tough to improve chip performance.

The methodology used in this essay has also been introduced, which is mainly literature review and data analysis. The detail of finding literatures and gather data have also been described in the method part.

In the results and discussion part, several solutions have been investigated. To solve the problem in power semiconductors, two new materials have been suggested, they are SiC and GaN. Their properties and data have been shown in a table and a figure, and compared with silicon to get a conclusion. Finally, the results shows that both SiC and GaN has higher band gap, means that they are better materials for high volts devices. Moreover, SiC has the highest thermal conductivity, means it is suitable for high temperature devices, while GaN has high electron velocity and mobility, make it is the best materials for high frequency materials.

For chip semiconductors, the solution of using 3D structure chip has been investigated. The results show that 3D chips have several advantages over traditional technologies, which can increase the performance of chips. However, the heating problem and complexity of 3D chips are also a difficulty for this new technology. 2D materials are another method for chip semiconductors. The most popular material is MoS2, it has a great number of advantages over silicon, its chip is able to have smaller size, more flexible applications and better performance.

Although this essay has already listed some new materials and technologies, it is unlikely that they will replace silicon and current technology recently. At the same time, they also have their own problems and limitations, such as relatively high cost and not mature enough manufacturing processes. Therefore, these materials are still not feasible nowadays.

This paper also has limitations. Firstly, there are more methods and materials to solve the problems of silicon nowadays and are not in this paper, some of them might be better than the methods listed in this paper. Moreover, the comparison of SiC and GaN in the results and discussion part also have limitations, since their data are actually dependent on the environmental temperature, it would be better to draw a graph of their data against temperature and then compare them in actual situation. In the part of 3D technology and 2D material parts, more details and data can be given, such as technological details and some graphs to make the results more convincible and evident.

Overall, this research concludes problems faced nowadays about semiconductors, and gives some methods, but more research needs to be done in the future to find a better and more feasible method to solve these problems.

References

[1] Song, J.: 'The history and trends of semiconductor materials’ development', J. Phys.: Conf. Ser., 2023, 2608, (1), p. 012019.

[2] Wang, R., Zhu, J., Wang, S., Wang, T., Huang, J., Zhu, X.: 'Multi-modal emotion recognition using tensor decomposition fusion and self-supervised multi-tasking', International Journal of Multimedia Information Retrieval, 2024, 13(4), pp. 39.

[3] Xu, H., Zhu, X., Zhao, Z., Wei, X., Wang, X., Zuo, J.: 'Research of Pipeline Leak Detection Technology and Application Prospect of Petrochemical Wharf', IEEE ITAIC, 2020, pp. 263–271.

[4] Wei, X., Zhu, X., Wang, X., Zhao, Z., Zuo, J.: 'Fuzzy Fault Tree Analysis Method and Its Application in Fault Diagnosis of Denitration System in Thermal Power Plant', Proceedings of the 2020 8th International Conference on Information Technology: IoT and Smart City, 2020, pp. 227-232.

[5] Zhao, Z., Peng, Y., Zhu, X., Wei, X., Wang, X., Zuo, J.: 'Research on Prediction of Electricity Consumption in Smart Parks Based on Multiple Linear Regression', IEEE ITAIC, 2020, pp. 812–816.

[6] Zhu, X., Zhao, Z., Wei, X., Wang, X., Zuo, J.: 'Action recognition method based on wavelet transform and neural network in wireless network', Proc. 5th Int. Conf. Dig. Signal Process., 2021, pp. 60–65.

[7] Zhang, Y., Zhao, H., Zhu, X., Zhao, Z., Zuo, J.: 'Strain Measurement Quantization Technology based on DAS System', 2019 IEEE 3rd Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), 2019, pp. 214-218.

[8] Sadulla, S.: 'Next-Generation Semiconductor Devices: Breakthroughs in Materials and Applications', Prog. Electron. Commun. Eng., 2024, 1, (1), pp. 13–18.

[9] Zhu, X., Zhang, Y., Zhao, Z., Zuo, J.: 'Radio frequency sensing based environmental monitoring technology', Fourth International Workshop on Pattern Recognition, 2019, Vol. 11198, pp. 187-191.

[10] Liang, D., Bowers, J. E.: 'Recent progress in heterogeneous III-V-on-silicon photonic integration', Light: Adv. Manuf., 2021, 2, (1), pp. 59–83.