Beyond Moore's Law: Current Research on New Semiconductor Materials and Future Applications' Trends

Ziheng Qiao *

International Division of high School Attached to Northeast Normal University, Changchun, 130000, China

* Corresponding Author Email: a15844188888@gmail.com

Abstract. With Moore's Law approaching its physical limits, developing, and discovering new semiconductor materials will reshape the entire semiconductor field. Even the ability to create high-performance chips and devices hinges on advances in new materials and related technologies—making this area crucial for determining the future of technology. Today, two-dimensional (2D) materials such as graphene and MoS_2, wide-bandgap semiconductors like silicon carbide (SiC) and Gallium nitride (GaN), oxide semiconductors including Indium Gallium Zinc Oxide (IGZO), and organic semiconductors are attracting growing research interest and finding increasing applications. Owing to their unique physical properties and stable performance, these materials have enormous potential for future applications. This paper discusses the specific structures of these new materials, as well as their advantages—such as stability, adaptability to operating environments, and high carrier mobility. It primarily focuses on their strengths in optoelectronic integration, energy efficiency improvement, and performance in extreme environments. The paper also examines the challenges that have emerged or may arise in current manufacturing and design processes, such as technical issues related to contact resistance and thermal mismatch. Finally, it outlines future trends, including multi-material collaboration, 3D integration, the development of new device architectures, interface engineering, and potential performance breakthroughs. In summary, new semiconductor materials provide a pathway to breaking through and even surpassing Moore's Law. They will profoundly impact the future development of fields such as energy, communications, aerospace, and even wearable devices.

Keywords: 2-D materials, wide bandgap semiconductor, heterojunction integration, future trends.

1. Introduction

Moore's Law states that the number of transistors on an integrated circuit doubles approximately every two years, put forward by Gordon Earle Moore in 1965 [1]. As Moore referred Moore's law at the first time, semiconductor technology has advanced rapidly during few decades. The integration level and performance also made significant progress and keep improving. However, as transistor manufacturing processes approach the nanometer scale, it has become constrained by quantum effects, thermal effects, and manufacturing limitations, thermal effect, and manufacturing process [2]. Moore's law is gradually close to the limit of physics, the exponential growth trend is gradually slowing so the concept of "More than Moore" was proposed and its core lies not only in relying on reducing component size to increase performance, but also adopting new materials, component structures, and integration methods to achieve the breakthrough in function and performance [3].

The new semiconductor material plays a key role in this changing process of "More than Moore". Nowadays, the main material to manufacture transistors is still silicon semiconductor. The silicon semiconductor has few properties. The first is high melting temperature, the function of this feature is aimed to make sure that it has the stability of physical structure and electronic performance, avoid melting during process of manufacture [4]. In secondly, it got four valence electrons on its outer shell, so it has a few conductivities in room temperature, and it also possess the ability of forming a layer with compact oxide film, this feature could avoid the precise component avoid from corrosion and even gain some special functions on surface. Finally, it is easy to dope with other elements, this feature can precisely control the physical performance and chemical, electronic performance of material. But now, the silicon semiconductor material has played the ultimate limit of technology [5].

It faces lots of problems, such as the limit in high frequency application so it has begun to restrict in the development of integration circuit. In comparison of traditional silicon material, the new semiconductor possesses lots of properties to make up for the disadvantages of silicon semiconductor material, for example, the two-dimensional structure's material such as graphene have extremely high carrier mobility of carrier and excellent optoelectronic properties, even though the zero-bandgap characteristic of it limits its direct application in logical component. Disulfide of transition metal such as MoS_2 have tunable bandgaps, making them suitable for use in field effect transistors [6]. The wide bandgap semiconductor material such as silicon carbide (SiC) and Gallium nitride (GaN) has perfect working ability of high temperature, high frequency and high power. Next, the oxide semiconductor like Indium Gallium Zinc Oxide (IGZO) has transparency and low energy consumption at the same time so it is widely used in display driver circuit and organic semiconductor shows specific advantage in flexible electronics and wearable devices. All these new materials can hopefully achieve a breakthrough in performance and extend its application scenes to optoelectronic integration, sensor integration and special environmental adaptability [7].

Nowadays, the research in new semiconductor material has attracted global attention. However, these materials still face numerous challenges in high scale applications, including preparing high-quality materials for mass production, contact resistance, doping control and compatibility in contemporary complementary metal oxide semiconductor (CMOS) manufacturing process. To gain a comprehensive understanding of these materials' potential and limitation widely, this essay aims to systematically analyze typical new semiconductor material's physical properties, their advantages in practical chip applications of chips and the technological challenge that will face, also explore the future developing trend and available solution then prospect the future materials and possible new developing direction of component's structure.

2. New Semiconductor Material and Physical Properties

2.1. Two-Dimensional Layer Structure Material

The first typical material with two-dimensional layer structure is graphene. As shown in figure 1, Graphene is a two-dimensional honeycomb lattice structure, formed by only one layer of carbon atoms, this structure makes it one of the strongest materials, due to its strong interatomic bonds, as it has a giant covalent lattice structure. This highly ordered structure means that electrons move through its lattice with little scattering, so that electrons are hard be disrupted when they are moving in orbit, a characteristic that gives it excellent electrical conductivity and makes it suitable for thermal applications, also suitable in thermal field. Since it was first exfoliated in a laboratory in 2004, it has sparked extensive research due to the excellent electrical and mechanical properties of it [1]. Graphene has extremely high carrier mobility (More than 200,000 cm^2 / vs in low temperature), far higher than silicon material [2]. In the application of radio frequency electronics and high-speed interconnection, graphene shows clear advantages. However, the feature of zero-bandgap in graphene has serious limit in the application of logic devices. In these days, researchers use methods like graphene nanoribbon and two-layer graphene electric field control to try to bring in controllable bandgap, but still has problems such as complicated manufacturing technology and unstable performance [3]. Novoselov and Geim who based at the University of Manchester in the UK in 2004, has got single-layer graphene by mechanical exfoliation method at the first time all around the world, and also measured the extremely high carrier mobility of graphene about 10,000 cm^2/vs demonstrating graphene's potential as a new semiconductor material. This is the foundation of the whole research of high-speed electronic component.

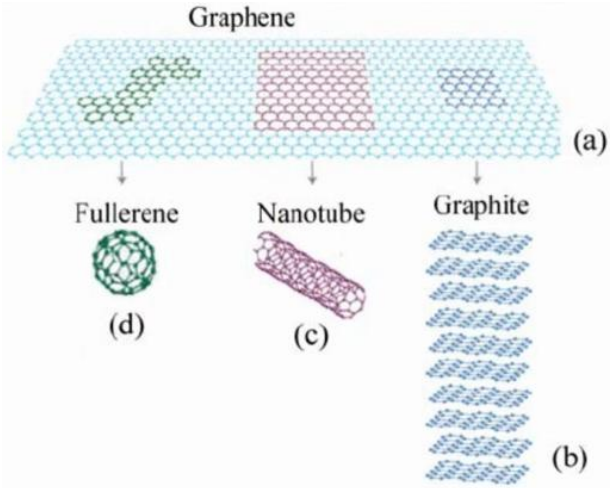


Figure 1. Different molecule structure of carbon [4]

The second material is Molybdenum disulfide (MoS_2), which is one typical representative of transition metal dichalcogenides (TMDs), exhibits a direct bandgap (approximately 1.8 eV). This is also honeycombing lattice structure like graphene in monolayer, and it is typical MX_2 structure, this strong quantum confinement increases the bandgap and enhances Coulomb interactions and show it as a direct bandgap semiconductor. In contrast to the bulk phase's indirect bandgap, it is more suitable for use in logical component and optoelectronic sensors [5]. MoS_2 has high on-off ratio and flexibility, so that it is suitable for application in low power consumption and flexible electronics [6]. Nevertheless, the uniformity of large-area growth, and interface defects are also hinder its manufacturing [7]. In 2011, Radosavljevic produced single-layer MoS_2 field effect transistors (FET) at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. It's on-off ratio exceeded 10^8 and subthreshold swing (SS) near to ideal value, demonstrating that MoS_2 can be used as a logic device. And solved the zero bandgap problems of graphene.

2.2. Wide Bandgap Semiconductor

The first wide-bandgap material is SiC, which has a bandgap of approximately 3.2 eV and exhibits excellent performance in high-temperature, high-frequency, and high-voltage environments [8]. SiC's high thermal conductivity and high breakdown electric field strength make it widely used in power devices such as electric vehicle power modules [9]. However, the defect density of SiC crystals—defined as the number of defects per unit volume or area—remains higher than ideal levels. This directly impacts electrical performance and leads to high manufacturing costs due to low production yields. In 2013, Baliga at North Carolina State University (NCSU) conducted a high-power test on SiC metal-oxide-semiconductor field-effect transistors (MOSFETs). The results showed that the devices could operate normally at 300°C with significantly lower power loss than silicon MOSFETs, confirming SiC's advantage in high-temperature applications.

GaN has a bandgap of 3.4 eV and high electron saturation velocity, making it particularly well-suited for applications in high-frequency, high-voltage, and radio frequency fields [10]. GaN-based high-electron-mobility transistors (HEMTs) are widely used in 5G base stations, fast-charging systems, and radar systems [11]. An HEMT is a field-effect transistor based on a heterostructure—defined as a material composed of two or more semiconductors with different bandgaps. Its core principle involves combining different semiconductors to form a heterojunction, enabling the formation of a high-concentration, high-mobility two-dimensional electron gas (2DEG) that delivers excellent circuit performance. However, the poor compatibility between its epitaxial growth properties and silicon-based substrates poses a significant engineering challenge. In 1994, Nakamura at Nagoya University (NU) in Japan developed gallium nitride-based blue laser diodes that achieved stable room-temperature operation over long periods [12, 13]. This breakthrough laid the foundation for GaN's applications in optoelectronic devices.

2.3. Oxide Semiconductor

IGZO is a type of transparent oxide semiconductor with high carrier mobility (10–50 $cm^2/(V \cdot s)$), low power consumption, and optical transparency [14]. It has been successfully applied in thin-film transistor-liquid crystal display (TFT-LCD) and organic light-emitting diode (OLED) display panels and has been widely studied due to its stability on flexible substrates. However, devices incorporating IGZO still require improved long-term stability under humid and high-temperature conditions. In 2004, Nomura from Tokyo Institute of Technology (Tokyo Tech) fabricated thin-film transistors (TFTs) based on IGZO. This new material exhibited significantly higher carrier mobility (approximately 10 $cm^2/(V \cdot s)$) than traditional amorphous silicon (a-Si) TFTs, addressing the demand for highly sophisticated TFTs in display driver circuits.

2.4. Organic Semiconductor

Organic semiconductors possess flexibility, can be processed via solution-based methods, and offer low-cost advantages, making them widely used in organic light-emitting diodes (OLEDs), organic solar cells, and flexible sensors [14]. The tunability of molecular design endows them with diverse optoelectronic properties. However, their stability and carrier mobility (0.1–10 $cm^2/(V \cdot s)$) remain lower than those of inorganic semiconductors, limiting their long-term applications [15]. In 1987, Tang and VanSlyke at the Eastman Kodak Laboratory in the United States first developed the bilayer OLED. With a minimum driving voltage of less than 10 V, the device efficiency increased significantly [16]. This breakthrough paved the way for the application of organic semiconductors in display and lighting systems.

3. New Semiconductors Applied in Chips

3.1. Optoelectronics Integration and Sensor Integration

Graphene and MoS_2 exhibit excellent performance in high-speed photodetectors and flexible optoelectronic sensors [17]. GaN is widely used in laser diodes and ultraviolet (UV) photodetectors [18]. IGZO is well-suited for transparent electronics and health monitoring systems. GaN-based lasers can emit light ranging from ultraviolet to green wavelengths, making them one of the key research focuses in next-generation optoelectronic devices. UV photodetectors are devices that convert UV light into electrical signals, with their primary function being photoelectric conversion. Owing to their high reliability, they are commonly used in fire detection applications.

3.2. Improvement of Energy Efficient Ratio

GaN and SiC exhibit low energy loss and high breakdown electric field strength. Owing to these properties, they have been widely used in power devices for electric vehicles and renewable energy systems [19]. Additionally, MoS_2 features a low subthreshold voltage, giving it potential for use in low-power logic devices and demonstrating promising prospects [20]. As shown in Figure 2, in actual electric vehicles, the traction inverter is responsible for converting DC to AC to enable motor operation. GaN-based power devices can increase the inverter's power density, improve efficiency, and reduce costs—all thanks to their smaller size and lighter weight.

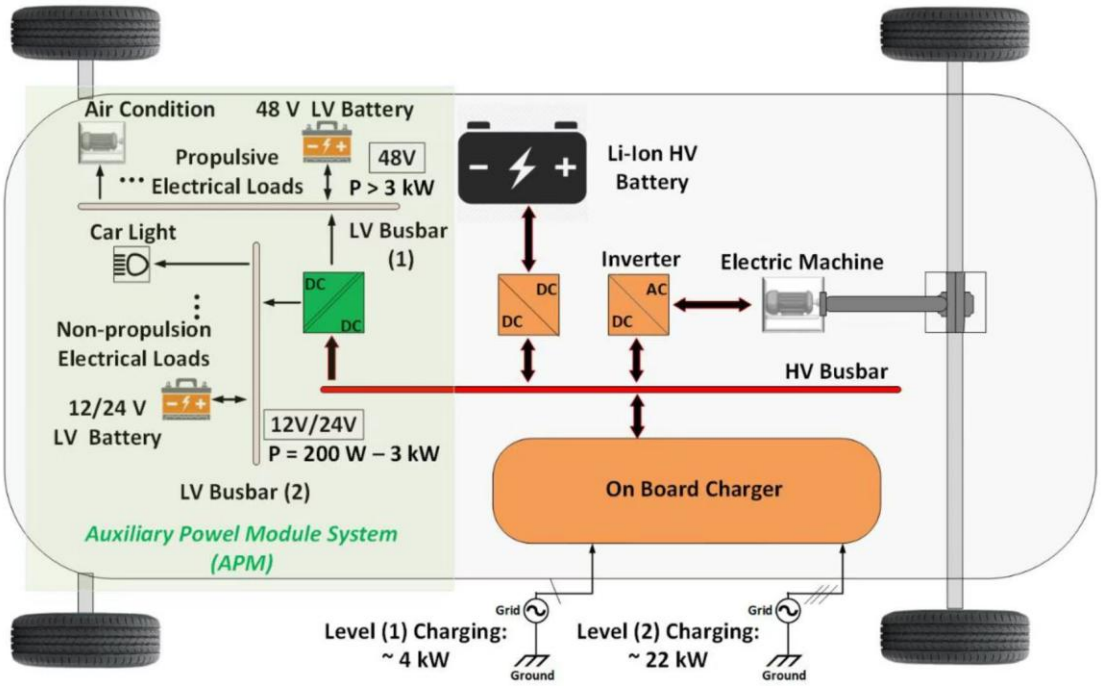


Figure 2. Detail structure of electrical vehicle about DC/AC inverter [21]

3.3. Application in Special Environment

The high-temperature resistance and radiation resistance of SiC and GaN make them suitable for applications in aerospace and nuclear environments [22]. Meanwhile, the flexibility of organic semiconductors makes them ideal for flexible electronics and wearable devices. For instance, due to GaN's radiation resistance, it is also well-suited for use as radio frequency (RF) power amplifiers in communication satellites—particularly in the 26–40 GHz band, where it exhibits excellent performance. A specific example of organic semiconductors applied in wearable devices is an optoelectronic detector (OPD) developed by Du et al. in 2024. This new device is a flexible finger-mounted sensor that simultaneously monitors blood oxygen saturation and heart rate. It exhibits high sensitivity, demonstrating its applicability in healthcare and medical fields [23].

4. Technological Challenges and Future Trends

4.1. Physical Challenges

Two-dimensional materials commonly face problems such as high contact resistance and interfacial defects. Wide-bandgap materials also face challenges in doping and defect control. Thirdly, organic semiconductors suffer from poor stability under unfavorable humidity and temperature conditions.

For two-dimensional materials like graphene, high contact resistance stems from several factors. First, their small contact area leads to low current conduction, with the main reason being the tunneling barrier [24]. Second, they lack vertical chemical bonds and dangling bonds on their surfaces, which may result in low charge transport efficiency. Finally, manufacturing is complex: two-dimensional materials tend to adsorb molecules or polymers, and this interfacial contamination impairs electron transport and increases contact resistance [25].

4.2. Technological Challenges

New semiconductor materials face conflicts between large-scale production, property uniformity, and low compatibility with CMOS manufacturing processes—issues such as thermal mismatch and packaging stress have seriously limited their applications. When different types of semiconductor materials are integrated into a single device and subjected to temperature changes, each material will

deform due to their different coefficients of thermal expansion (CTE). This deformation can lead to surface mechanical strain, known as thermal mismatch stress. Such stress may cause problems like failure of the insulating layer under high-power conditions [26]. For example, SiC and GaN operate under variable temperatures. Ju et al. suggested that using thicker bond lines could mitigate CTE mismatch and improve reliability [27].

4.3. New Component Structure

Examples include NCFETs, three-dimensional integration, and heterogeneous integration. NCFETs (negative capacitance field-effect transistors) are a new transistor technology based on ferroelectric materials, which enhances storage performance and overcomes the fundamental limitations of traditional transistors [28]. A key feature of NCFETs is the use of ferroelectric materials, which exhibit negative capacitance under specific conditions. To enhance gate voltage response, ferroelectric materials can be integrated with traditional field-effect transistors to reduce the subthreshold swing. Thus, NCFETs can operate at low voltages while offering better storage capabilities.

Three-dimensional integration is an emerging direction in the semiconductor field, focusing more on vertical stacking by integrating multiple chips to form a system [29]. Unlike traditional 2D integration, chip scaling is no longer limited by area. This new 3D integration reduces connection distances and improves performance.

4.4. Multiple Material Collaboration

Composite heterojunctions and multi-material integration platforms enable dynamic integration and systematic optimization. A composite heterojunction consists of two or more types of materials, which can be semiconductors or other material types. It contains multiple interfacial regions. A typical example of a composite heterojunction is the p-n junction, which exhibits unidirectional electrical conduction [30]. Most of the time, p-n junctions are used in diodes, and their specific structure is shown in Figure 3. This is also an application of the multi-material integration platform.

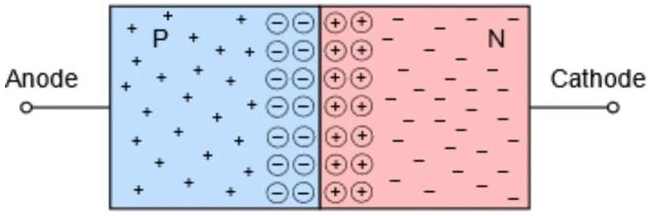


Figure 3. P-N junction model [31]

4.5. Surface Treatment and Interface Engineering

Passivation layer design and interface engineering can address issues related to thermal mismatch and defect states, improving material stability and ensuring consistent performance. The functions of the passivation layer include reducing surface dangling bonds, decreasing surface recombination current, and enhancing interfacial stability—thus preventing thermal failure. SiO_2 is a traditional passivation layer but is not suitable for use in high-temperature environments. Si_3N_4 offers high thermal stability and is often used in GaN/SiC power devices, with SiC MOSFETs being a typical application. A future trend is using high-k materials such as ZrO_2 to enhance electric field control [32].

5. Conclusion

As new semiconductor materials are being discovered and researched for suitable applications, their development has gradually addressed issues such as the limitations of traditional silicon semiconductors and constraints in extreme operating environments. These new materials offer potential advantages for future advancements in chip technology, which is crucial. Two-dimensional

materials are well-suited for high-speed and flexible electronics, while wide-bandgap semiconductors are now widely used in power and high-frequency devices. Oxide and organic semiconductors show potential in transparent and flexible electronics. Although these new applications are limited by physical and technological challenges, these issues will be resolved with advancements in new device architectures, multi-material collaboration, and interface engineering. Ultimately, these materials will propel the entire semiconductor field into a new era, replacing traditional silicon materials and even exceeding the limitations of Moore's Law.

References

[1] Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V., Grigorieva, I. V., & Firsov, A. Electric field effect in atomically thin carbon films. Science, 2004, 306 (5696): 666 – 669.

[2] Bolotin, K. I., Sikes, K. J., Jiang, Z., Klima, M., Fudenberg, G., Hone, J., Kim, P., & Stormer, H. L. Ultrahigh electron mobility in suspended graphene. Solid State Communications, 2008, 146 (9 – 10): 351 – 355.

[3] Schwierz, F. Graphene transistors. Nature Nanotechnology, 2010, 5 (7): 487 – 496.

[4] Fiore, F. G., Sonde, S., & Raineri, V. Electronic Properties of Graphene Probed at the Nanoscale. ResearchGate, 2011.

[5] Radisavljevic, B., Radenovic, A., Brivio, J., Giacometti, V., & Kis, A. Single-layer MoS_2 transistors. Nature Nanotechnology, 2011 6 (3): 147 – 150.

[6] Chhowalla, M., Shin, H. S., Eda, G., Li, L. J., Loh, K. P., & Zhang, H. The chemistry of two-dimensional layered transition metal dichalcogenide nanosheets. Nature Chemistry, 2013, 5 (4): 263 – 275.

[7] Wang, Q. H., Kalantar-Zadeh, K., Kis, A., Coleman, J. N., & Strano, M. S. Electronics and optoelectronics of two-dimensional transition metal dichalcogenides. Nature Nanotechnology, 2012, 7 (11): 699 – 712.

[8] Kimoto, T. Material science and device physics in SiC technology for high-voltage power devices. Materials Science Forum, 2016, 858, 1 – 10.

[9] Baliga, B. J. Gallium nitride devices for power electronic applications. Journal of Power Electronics, 2013, 13 (3): 429 – 436.

[10] Mishra, U. K., Parikh, P., & Wu, Y. F. AlGaN/GaN HEMTs—An overview of device operation and applications. Proceedings of the IEEE, 2002, 90 (6): 1022 – 1031.

[11] Ambacher, O. Growth and applications of Group III-nitrides. Journal of Applied Physics, 1998, 85 (6): 3222 – 3233.

[12] Nakamura, S., Mukai, T., & Senoh, M. (1994). Candela-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting diodes. *Applied Physics Letters, 1994, 64 (13): 1687 – 1689.

[13] Nomura, K., Ohta, H., Takagi, A., Kamiya, T., Hirano, M., & Hosono, H. Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors. Nature, 2004, 432 (7016): 488 – 492.

[14] Forrest, S. R. The path to ubiquitous and low-cost organic electronic appliances on plastic. Nature, 2004, 428 (6986): 911 – 918.

[15] Facchetti, A. Semiconductors for organic transistors. Materials Today, 2007, 10 (3): 28 – 37.

[16] Tang, C. W., & VanSlyke, S. A. Organic electroluminescent diodes. Applied Physics Letters, 1987, 51 (12): 913 – 915.

[17] Koppens, F. H. L., Mueller, T., Avouris, P., Ferrari, A. C., Vitiello, M. S., & Polini, M. Photodetectors based on graphene, other two-dimensional materials and hybrid systems. Nature Nanotechnology, 2014, 9 (10): 780 – 793.

[18] Nakamura, S., Pearton, S., & Fasol, G. The blue laser diode: The complete story (2nd ed.). Reviews of Modern Physics, 2015, 87 (4): 1139 – 1210.

[19] Millán, J., Godignon, P., Perpiñà, X., Pérez-Tomás, A., & Rebollo, J. A survey of wide bandgap power semiconductor devices. IEEE Transactions on Power Electronics, 2014, 29 (5): 2155 – 2163.

[20] Das, S., Chen, H. Y., Penumatcha, A. V., & Appenzeller, J. High performance multilayer MoS_2 transistors with scandium contacts. Nano Letters, 2013, 13 (1): 100 – 105.

[21] G. Pistoia, S. Brand, & L. Bozzutto. Power Electronics Converters for Electric Vehicle Auxiliaries: State-of-the-Art and Future Trends. Energies, 2021, 16 (4): 1753.

[22] Pearton, S. J., Ren, F., Wang, Y. L., Chen, K. H., Chang, C. Y., Lim, W., & Chu, B. H. A review of GaN-based radiation detectors and their applications. Journal of Applied Physics, 2018, 123 (16): 160901.

[23] Du, Z., Luong, H. M., Sabury, S., Jones, A. L., Zhu, Z., Panoy, P., Chae, S., Yi, A., Kim, H. J., Xiao, S., Brus, V. V., Reddy, G. N. M., Reynolds, J. R., & Nguyen, T.-Q. High-performance wearable organic photodetectors by molecular design and green solvent processing for pulse oximetry and photoplethysmography. Advanced Materials, 2024, 36 (2): 2310478.

[24] •Liu, W., Xu, Z., & Bao, Q. A study on graphene–metal contact. Crystals, 2013, 3 (2): 257 – 274.

[25] Khosravi, N., Mohammadi, M., Darbari, S., & Farmani, A. Graphene–metal contact resistance reduction by optimized photolithography sequence. Scientific Reports, 2024, 14, 58360.

[26] Ren, Y., Wu, X., & Zhou, W. Thermo-mechanical reliability of power electronic packaging: A review. Microelectronics Reliability, 2021, 118, 114028.

[27] Ju, H., Lee, D., & Kim, J. Enhancement of thermal reliability in power module packaging by optimized solder joint design. Nano Convergence, 2025, 12 (1): 33.

[28] Rahi, S. B., Ahmad, S., & Alam, M. A review on emerging negative capacitance field-effect transistors: Device physics and applications. Microelectronics Reliability, 2021, 124, 114282.

[29] Zhang, S., He, Y., Wu, Z., & Guo, Y. Challenges and recent perspectives of 3D heterogeneous integration in advanced semiconductor technology. Microelectronics Journal, 2022, 121, 105360.

[30] Balapure, A., Patel, K. D., & Chaki, S. H. Recent advances in semiconductor heterojunctions: Fundamentals to applications. Materials Advances, 2024, 5 (3): 1234 – 1250.

[31] Fiore, J. M. Electronics (Final). LibreTexts, 2023.

[32] Cai, Y., Zhou, H., & Chen, K. J. Effect of high-k passivation layers on the high-voltage characteristics of GaN MIS devices. Applied Surface Science, 2020, 528, 146957.