Three Generations of Semiconductors Research and Bottleneck of Development

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Abstract. The new technological revolution triggered by semiconductors is affecting all aspects of production and life. However, the semiconductor industry is difficult to develop and has yet to meet the high demand in many fields. This thesis explores the semiconductor industry in depth from the perspective from material performance to industry chain, exploring the development process of the three generations of semiconductors, applications, and their bottleneck. The research also explores the development of semiconductors from the nature of their materials, technology, market industry and other dimensions. The energy gap of the three generations of semiconductors is increasing, the breakdown voltage increases with it, and the semiconductor operating voltage increases as a result. Third-generation semiconductors have the highest heat conduction, so they can be adapted to more extreme working environments, and have great application prospects. Semiconductors are used in a wide range of applications, which are the cornerstone of smart healthcare, the core technology of smart manufacturing products, and the heart of information and communication. Semiconductor industry is facing difficulties in wafer manufacturing technology and the market structure of the existence of monopoly. It's the national strategic security of high-tech, but building a complete industry chain construction is difficult. Semiconductor development requires multidisciplinary innovation, multi-participation, and multidisciplinary integration. This paper provides a reference for the understanding of semiconductor evolution and new ideas for the macro development of the semiconductor industry.

Keywords: Semiconductor; development; application; bottleneck.

1. Introduction

At present, the scientific and technological revolution is developing rapidly. The development of semiconductor science and technology plays an important role in promoting the development of information science and technology. More and more semiconductors are applied to industrial or military applications, in recent years its industry has been a high degree of heat. From a strategic point of view, semiconductor materials are related to a large number of domains, affecting a large number of industries and even the national economy. The development of semiconductor materials is highly valued by countries around the world. The U.S. government will invest huge amounts of money to support semiconductor manufacturing and research. The U.S. also set up a number of chip-related bills to encourage local semiconductor companies and inhibit China's manufacturing and development of chips. In the next ten years, the company which has the production capacities to increase in advanced process chips will be restricted from investing in production capacity in a number of countries and will not be able to invest in factories in countries such as Iran, Russia, and China. China's semiconductor industry development is limited by the United States, and the reason is that the core of the semiconductor bottleneck of the technology has not been completely broken. In recent years, some Chinese enterprises strive for self-reliance and self-improvement, and constantly break through the technology blockade, more and more products achieved localization alternative.

Therefore, the investigation of the development history of semiconductor materials and their key technical difficulties has become an important topic. First, this paper clarifies the nature of the three generations of semiconductor materials and their development history, then explores and compares their advantages and disadvantages in terms of material performance parameters such as bandwidth. This thesis then explores the applications of semiconductor materials, categorizing and delving deeper into them from the perspectives of biomedical, smart manufacturing and communication fields. Then, this thesis explores the bottlenecks of semiconductor materials from four aspects: manufacturing technology, strategic security, market structure and industry chain association. Finally, it looks into the future development of semiconductor industry based on the research and development progress of semiconductors and industry demand.

2. Semiconductor Materials and Their Properties

2.1. First-Generation Semiconductor

The first generation of semiconductor materials refers to the elemental semiconductors silicon and germanium the main semiconductor material in about 1940 to early 1950 was germanium, but it was expensive and less stable, and was mainly used in some light-emitting diodes and solar cells [1]. Silicon has richer stores and a higher melting point than germanium. These excellent mechanical and thermal properties make silicon easy to process and have surfaces that can easily form natural oxides. Silicon materials are not only relatively inexpensive and easy to grow large sizes, but also easy to get high purity crystals, which makes silicon quickly replace germanium materials, entering a relatively mature stage of development. Nowadays, 85% of the material in the chip is silicon, and in the long term future, silicon will still be in the dominant and core ground [1].

Table 1 shows Material Performance Parameters for three semiconductor materials. The electron mobility rate determines the high-frequency performance of semiconductors under low-voltage conditions, and the electron mobility rate of silicon is 1350 $cm^2/V{\cdot}s$. The energy gap determines the wavelength of the emitted light, the energy gap of silicon is 1.1 eV. Under blue light emission conditions, the larger the forbidden bandwidth, the shorter the emission wavelength; the smaller the forbidden bandwidth, the longer the emission wavelength. The breakdown voltage determines the operating voltage and thus the output power. Silicon has a low breakdown voltage of 0.3 MV/cm. Because of the photovoltaic effect, silicon semiconductor materials can be used to make solar cells. First-generation semiconductors are mainly used for low-voltage, low-frequency, medium-power transistors and photodetectors.

Table 1. Material Performance Parameters.

	Si	GaAs	GaN
Energy gap (eV)	1.1	1.4	3.4
Heat conduction (W/cm·K)	1.3	0.6	2.0
Breakdown voltage (MV/cm)	0.3	0.4	5.0
Electron migration rate ($cm^2/V{\cdot}s$)	1350	8500	900

2.2. Second-Generation Semiconductor

The second-generation semiconductor materials include gallium phosphide (GaP), indium phosphide (InP), indium arsenide (InAs), gallium arsenide (GaAs), aluminum arsenide (AlAs), etc. and their alloys. The second generation of semiconductors are mainly used in the manufacture of high-performance microwave, millimeter-wave devices and light-emitting devices for satellite communications, mobile communications, optical communications, and GPS navigation and so on. However, GaAs and InP materials are scarce and expensive, and they are toxic and pollute the environment during use, and InP is even considered a suspected carcinogen. These shortcomings make the application of second-generation semiconductor materials have certain limitations.

GaAs, the dominant second-generation semiconductor material, currently accounts for 79% of the compound semiconductor market [2]. The electron mobility of GaAs materials is 8500 $cm^2/V{\cdot}s$, which is six times higher than that of silicon material. GaAs materials show better high-frequency, high-speed and optoelectronic properties. Its application has been extended to the field where silicon, germanium devices cannot reach. GaAs materials are used to produce integrated circuit substrates, infrared detectors, γ photon detectors, etc., having important applications in the production of wave devices and high-speed digital circuits [3]. GaAs devices can simultaneously process different optoelectronic signals on the same chip, making it an ideal material for communications. However, the natural stock of GaAs is scarce, and it is mainly produced through industrial chemicals. Since the 1950s, scientists have developed a variety of GaAs single crystal growth methods. The mainstream industrialized processes include: liquid-sealed straight pull (LEC), horizontal Bridgman (HB), vertical Bridgman (VB), and vertical gradient solidification [4].

2.3. Third-Generation Semiconductor

Third-generation semiconductor materials include silicon carbide (SiC), gallium nitride (GaN), diamond (C), zinc oxide (ZnO), etc., with energy gap wider than 2.3ev. Driven by new market demands such as 5G and new energy vehicles, the third-generation wide energy gap power semiconductor materials are expected to usher in accelerated development. The performance of Si-based semiconductors can no longer fully meet the demands of electrified transportation such as 5G communications and efficient new energy vehicles, as well as aerospace and military industries, etc., and the advantages of third-generation wide energy gap power semiconductors, such as SiC and GaN, have been magnified [2]. The energy gap of GaN material is 3.4ev, which is more than three times that of silicon material. Larger energy gap brings high breakdown voltage, making the third generation of semiconductor materials can work at higher voltages, and have greater output power. It can be made of blue-green light, ultraviolet light-emitting and detector devices. It is compared to silicon devices and gallium arsenide devices, in high-power, high-temperature, high-frequency, high-speed and optoelectronics applications performance is better [5]. In the field of radio-frequency(RF) microwave, GaN melting point is at 1700 °C, the frequency can now reach 25 GHz, the power reaches 1800 W. GaN has a very big advantage in aerospace, microwave radar, satellite communications, 5G communication [2]. SiC power devices in the application of high conversion efficiency, high power density, high-frequency reduction of the size of the peripheral components, high temperature resistance, long service life and other advantages. Therefore, it has a unique advantage in the frequent demand for power conversion, power conversion components have volume or quality requirements, relatively high-temperature use of the environment. Currently, the main application areas of SiC power devices are various types of power supplies and servers, photovoltaic inverters, wind power inverters, new energy vehicles, on-board chargers, motor drive systems, DC charging piles, inverter air-conditioning, rail transportation, the military and so on [2].

3. Applications of Semiconductors

3.1. Biological and Medical Applications

Semiconductor technology is the cornerstone of the development of intelligent medical care, security. Due to market-driven, diversified intelligent medical iterative update. The future of intelligent medical present more intelligent into the life, prompting the future development of semiconductor to be able to have a strategic technological evolution in time, space, efficiency, environmental protection, intelligence and other dimensions. Intelligent healthcare covers a wide range of areas such as medical products, medical processes, diagnosis, treatment, and platforms. The main problem that smart healthcare face is the risk of platform paralysis due to database loss. Data encryption utilizing semiconductor technology, state-hosted data platforms, and stringent national data management regulations can to some extent alleviate data security concerns [6].

Semiconductor-microbe composite systems play an important role in the fields of deep pollutant degradation, synthesis of valuable chemicals, and elemental biogeochemical cycling. Semiconductor-mineral-microbe composite systems combine the high efficiency of light capture by semiconductors with the selectivity of microbial metabolism [7]. The composite system enables heterotrophic microorganisms, which are unable to utilize light energy, to obtain the ability to utilize photoelectrons, thus enhancing the ability to utilize photoelectrons, and it is expected to realize efficient fuel production.

3.2. Intelligent Manufacturing

Smart fiber refers to a one-dimensional material system with a certain aspect ratio and unique optical, electrical, force, thermal and magnetic properties. The advantages of semiconductor fiber structure itself, such as intrinsic flexibility, directional conductivity, weavability, etc., and semiconductor materials with unique electrical, optical, magnetic, thermal properties of the organic fusion of the semiconductor fiber materials with intelligent interaction function. Semiconductor fiber materials are intelligent and have applications in logic response, brain-computer interface, neural repair, electromagnetic modulation, smart clothing, space exploration and other fields [8].

Semiconductor scintillation materials have been popularized in medical X-ray tomography (XCT) and positron tomography (PET) technology, and have become prominent in the fields of anti-terrorism, security inspection and industrial inspection (such as non-destructive flaw detection of important components of rockets, missiles and aircraft), geologic exploration, outer space exploration, environmental protection, etc. It has been used in a large number of international large-scale scientific engineering projects, such as high-energy physics and astronomy [9].

3.3. Information and Communication Engineering Field

The key challenge for the semiconductor industry is to develop and deliver technologies that can empower 5G and 6G information transmission networks, increasing the amount of information transmitted, the coverage space and the transmission distance. These needs will translate into requirements for semiconductor device performance metrics such as radio frequency, operating frequency, power consumption, gain, noise figure, linearity and transmit power. Some key technologies that have been used for years in military applications have become ideal for 5G telecommunications [10].

Theoretically, more data can be transmitted faster using another, more long-lasting method of increasing system throughput, i.e., expanding the modulating signal to a wider frequency range to increase its bandwidth, innovating semiconductor technology, and developing semiconductor devices and materials for millimeter-wave and terahertz band operation [10]. Achieving higher operating bandwidth by compressing data in higher modulation formats to operate in millimeter-wave mode.

4. Bottlenecks in the Semiconductor Industry

4.1. Manufacturing Technology

From the perspective of manufacturing technology, the technology of bottleneck products consists of key core technology, system integrative technology and key application technology, etc. together. Solving the core technology bottleneck requires strong and continuous basic research and development investment, efficient scientific research organization and management system, and large-scale and repetitive market applications.

Wafer fabrication technology is the most basic part of semiconductor materials, and crystal defects must be controlled for crystal fabrication. The complexity of the wafer preparation process, with more than a dozen procedures, makes it easy to produce crystal defects and contamination by impurities. The larger the crystal diameter, the more difficult it is to produce [11]. In the space-limited hot field, to make larger diameter crystals, involving many technical difficulties, such as the unevenness of the hot field temperature, the diameter control of large crystals and so on. Manufacturing links need to consume more huge sums of money, the current investment required to build a new 12-inch advanced wafer fab more than $6 billion [12]. Advanced lithography is not only long and difficult technology, such as the Netherlands ASML spent decades to build the world's most advanced lithography EDV. by the United States restrictions, high-end lithography can not be exported to China, China's lithography technology lags behind the international advanced level.

SiC substrate materials are the cornerstone of GaN devices in the future new energy and 5G communication fields, and SiC single crystal materials mainly have two kinds of conductive substrates and semi-insulating substrates [2]. High-quality, large-size SiC single-crystal materials is the key development direction of SiC technology. Continuously increase wafer size, reduce defect density, solve problems such as microtubes, dislocations, layer faults, etc. International SiC epitaxial wafer has now achieved 6-inch high-volume commercialized products, 8-inch products have also appeared.

4.2. Strategic Security

From the perspective of strategic security, bottleneck products are often the basic parts or intermediate products of strategic industries, or they are widely used in many links of the industrial chain, and a cut-off in supply will cause extremely serious economic and security consequences [13]. The third-generation of semiconductor materials is the core of power electronics, radio frequency power devices, semiconductor lighting and other technologies, belonging to the strategic high-tech must contend. Its superior performance and in the national economy, national defense and security, social livelihood and other areas of wide application, become one of the focus of the international community's scientific and technological competition.

The United States launched the Chip and Science Act of 2022, its government will invest about $52.7 billion in financial support in the field of semiconductor manufacturing and research and development, the semiconductor head of the enterprise to provide about $24 billion of post-investment tax credits, to encourage its research and development and manufacture of chips in the United States. The United States to carry out the chip competition, clearly put forward, Semiconductor companies receiving grant funding, in the next ten years are restricted in some specific countries to increase the capacity of advanced process chips, can not invest in Iran, Russia, China and other countries to build factories.

4.3. Market Structure

From the perspective of market structure, the global market where the bottleneck products are located is usually monopolized by a few companies. At present, about 90% of the international market SiC power device industrialization companies are Cree's U.S. company Wolfspeed, Germany Infineon, Japan Rohm, Europe's ST Microelectron - ics , Japan Mitsubishi [2]. SiC chip main process equipment is almost completely monopolized by Western companies, especially high-temperature ion implantation equipment, ultra-high-temperature annealing equipment and high-quality oxide layer growth equipment, etc., China's large-scale establishment of SiC process line used in the key equipment is mainly dependent on imports.

GaN power amplifiers have made significant progress in the 4G field and are thriving in the 5G field. Currently there are more than 30 companies worldwide engaged in research and development of GaN semiconductors, however, only about 10 have achieved commercial mass production. This means that the number of companies that can engage in Research and Development is extremely small, and the number of companies that can achieve mass production is miniscule. The GaN substrate market is dominated by Japanese companies, with Sumitomo Electric's market share reaching over 90%.

Third-generation semiconductor application materials, the United States has been ranked first for many years, China's high-end photoresist is almost dependent on imports. The world's top five suppliers of silicon wafers occupy as much as 92.8% of the production capacity, in which the U.S., Japanese, and South Korean companies have a monopoly. In terms of production foundry, in 2019, TSMC's market share is as high as 52%, South Korea's Samsung accounts for about 18%, China's best chip manufacturing company Semiconductor Manufacturing International accounts for only 5%, and there is a gap of 8~10 years between the process and the previous 2 head companies [2].

Chip target material is a high value-added special electronic materials. Previously, this magnesium target has been monopolized by Japan, in recent years, East Microelectronics production of self-developed magnesium target material, Chinese enterprises to break this monopoly. In the traditional Moore's law, size shrinkage approaching physical and economic limits, new devices, advanced packaging, 3rd generation semiconductors and other new technologies and new materials will lead the semiconductor industry to a new industrial pattern [14].

4.4. Industry Chain Connection

From the perspective of industry chain connection, the bottleneck product has a long industry chain, and is usually in a key node position in the industry system that affects the whole situation. The semiconductor industry chain is long, with high capital investment and strong demand for globalization. Semiconductor industry chain construction capital investment is huge, TSMC in the United States to build factories in the United States is one times the cost of the Taiwan region in China, the operating cost is 5 to 6 times in Taiwan." TSMC founder Zhang Zhongmou pointed out. Second, the semiconductor industry is a high-tech field with a high degree of internationalization, an industry with global division of labor and trade. Global semiconductor trade involves 120 countries and regions, and more than two-thirds of the semiconductor industry in international trade is intermediate goods trade, which has formed a highly interrelated and nested global industrial chain supply chain. This is a complex and indivisible industrial chain supply chain formed by semiconductor enterprises seeking to match supply and demand through the market [15].

In 2017, starting with Zhongxing Telecom Equipment (ZTE) being sanctioned by the United States, China's lack of chips was exposed. In the following years, the lack of chip problem then spread to cell phones, automobiles, home appliances and other fields. Nikkei Asia reported that a number of chip manufacturing giants in the United States, Japan and the European Union believe that it is difficult to replicate the industrial chain supply chain to other countries or regions in the short term. Samsung is ready to build factories in the United States, only one of its planned investment of up to 17 billion U.S. dollars. Chip manufacturing into 16 nm or 14 nm or more, the design cost will climb to hundreds of millions of dollars, the cost of building factories will reach 15 billion dollars [15].

5. Conclusion

Information technology products made of semiconductors have covered various industries, and the development of semiconductors is leading to a new round of technological and industrial revolution. This study illustrates the evolution of three generations of semiconductor materials. The third-generation of semiconductors, represented by SiC and GaN, has obvious advantages in energy gap, and is expected to see rapid development in many fields. Semiconductor materials are the cornerstone for the development of smart healthcare, advancing medical technology in multiple dimensions, including space-time, efficiency and safety. It offers unlimited possibilities for realizing more conceptual products in the field of smart manufacturing. In the field of communication, it is expected to solve the problem of the huge gap between the low data transmission rate and the high information generation rate of the existing wireless communication system. The manufacturing of advanced wafers is a difficult point in semiconductor technology.

Semiconductors are significantly linked to national economy and national defense security, which makes them of strategic security significance. Internationally, the main SiC power device industry and GaN power amplifiers are monopolized by a few companies, and the United States is still the giant of semiconductor. The semiconductor industry chain is difficult to build, requires large investment, and is a high-tech field with a high degree of internationalization. In the future, semiconductors, which are deeply integrated with many fields, will still drive the development of information technology revolution. The evolution of the three generations of semiconductors explored in this paper provides a reference for the preliminary understanding of semiconductors; the difficulties in the development of semiconductors studied in this paper provide new ideas for the macro development of the semiconductor industry.

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