Development of The Third Generation of Semiconductors with SiC and GaN as The Mainstay

Zhanpeng Deng [1, *]

[1]School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan, China

*Corresponding author: u201914222@hust.edu.cn

Abstract: The application and development of semiconductor technology has a very important role in the development of the world's science and technology. The third-generation semiconductors are broadband semiconductors with high thermal conductivity, high breakdown field strength, high saturation electron drift rate and high bonding energy, which are incomparable to the previous two generations of semiconductors. In this paper, we focus on the third-generation semiconductor materials and further study the most mature and widely used SiC and GaN, and introduce the mainstream methods for the preparation of SiC and GaN. The paper also introduces the applications of these two materials in energy, communication, and consumer electronics, taking into account the current development of the industry. Finally, the paper also considers the problems and challenges that still need to be solved in the next stage of the industry's development.

Keywords: SiC, GaN, Third Generation Semiconductor.

1. Introduction

5G technology, new energy vehicles, robotics and other emerging electronics, communications technology is developing rapidly, while the global energy and environmental crisis is prominent, a variety of high temperature, high voltage, low-power needs, the traditional first and second generation semiconductor materials due to their own performance limitations have been unable to meet the needs of science and technology, which calls for the emergence of new materials to replace. Third-generation semiconductors have a wider band width, higher breakdown electric field, higher thermal conductivity, in the field of high temperature, high voltage performance is more excellent, and therefore has been widely studied and applied. From the current research on third-generation semiconductor materials and devices, the more mature third-generation semiconductor materials are SiC and GaN, while the research on third-generation semiconductor materials such as ZnO, diamond, and aluminum nitride is still at a relatively early stage. Therefore, it is necessary to summarize the status and development of SiC and GaN in this paper. Chapter 2 of the article introduces the current mainstream preparation methods of SiC and GaN, and the advantages and disadvantages of different methods. Chapter 3 focuses on the applications of both materials in the fields of communication and energy. Chapter 4 presents some challenges in the development of the two materials. These challenges are in the areas of material production, cost control, and other constraints on the development of third-generation semiconductors, and require effective methods to solve them.

2. Preparation of SiC and GaN

2.1 The Preparation of SiC

The excellent material properties of SiC crystals make it highly valuable and promising, and it has received great attention from the semiconductor industry worldwide. Research institutes and commercial companies around the world have invested a lot of manpower and resources in the growth and application of SiC materials. The vapor phase method is an important technology for the preparation of SiC single crystals. The vapor phase method has gone through three main stages of development: the Acheson method [1], the Lely method [2], and the PVT method. The Acheson

method has a low production efficiency and cannot provide a large number of high quality SiC single crystals for the production of SiC devices on a large scale.

In 1978, Tairov and Tsvetko of the former Soviet Union proposed a high-temperature sublimation method to introduce seed crystals in crystal growth and control the nucleation process by using seed crystals, which laid the foundation of the current SiC crystal preparation [3]. The high-temperature sublimation method using seed crystals, also known as the PVT (Physical vapor transport) method and the modified Lely method, is currently the most ideal method for preparing SiC bulk single crystals. The basic principle is to place the high-purity SiC powder as the growth source at the bottom of the graphite crucible and fix the seed crystal at the top of the graphite crucible, and then heat the graphite crucible and adjust the relative position of the crucible and the coil so that the temperature of the growth source is higher than that of the seed crystal. The growth source is sublimated at high temperature to produce gaseous material, which is transported to the low temperature seed crystal surface and crystallized to form SiC crystals by the pressure gradient driven by the temperature gradient between the growth source and the seed crystal.

2.2 The Preparation of GaN

At present, the growth methods of GaN single crystal materials are mainly divided into two ways: gas phase epitaxy and liquid phase epitaxy. The former is mainly hydride vapor phase epitaxy (HVPE) [4], while the latter mainly adopts the ammonia heat method and flux method (i.e. sodium flow method).

HVPE method is the mainstream growth technique for preparing GaN single crystal substrates due to the advantages of high growth rate and the ability to obtain large size crystals. The Ga source is provided by the reaction of gaseous HCI with liquid metallic gallium to form GaCI gas, and the Ga source reacts with the N source at 1000~1050°C to deposit and crystallize GaN. The flow control of HCI and NH3 gas is achieved by optimizing the reaction equipment and growth conditions to enable the rapid growth of GaN single crystals. The method also uses the epitaxy technique to bend and merge dislocation lines to promote dislocation annihilation, thus reducing dislocation density to improve crystal quality and release growth stress.

The ammonia-thermal method is used for growth in an autoclave [5]. During the growth process, Ga metal or GaN used as feedstock is dissolved in ammonia in one region of the autoclave, and GaN is transferred to the low-solubility growth region by convection, and the solution is supersaturated to recrystallize on the seed crystal to produce GaN single crystals. Usually, the addition of mineralizing agent can be improved to accelerate the dissociation of ammonia and increase the solubility of Ga or GaN.

The flux method is also known as the sodium flow method [6]. This method realizes the reaction of Ga and N by adding Na to the Ga melt and using the strong reducing ability of Na to promote the ionization of N_2 and increase the solubility of N in the Ga melt. This method enables the growth of GaN at relatively low temperatures (~800°C) and pressures (<5 MPa.) Na in the Ga-Na molten liquid breaks the nitrogen triple bond of nitrogen at the gas-liquid interface to form N-3 ions. The N-3 ions gradually tend to supersaturate within the solution accompanied by a temperature gradient or concentration gradient drive, and when the solubility of nitrogen in the Ga-Na molten liquid exceeds the critical value required for GaN crystalline growth, spontaneous nucleation of GaN begins to form, or nucleation growth continues on GaN seed crystals.

3. The application of SiC and GaN

3.1 Application of SiC

3.1.1 Electric vehicles and charging pile field

New energy vehicles and charging pile application field new energy vehicle industry has become the key strategic emerging industry to fight energy conservation and emission reduction and environmental management battle, and countries around the world have elevated it to national

strategy. New energy vehicle system architecture involving power semiconductor applications components include motor drivers, on-board chargers (OBC), on-board power conversion (DC/DC) systems. In addition, power semiconductor devices in the field of non-vehicle charging pile also has a certain application space.

At present, most of the power semiconductor devices equipped with new energy vehicles sold in the market are silicon-based devices, such as silicon-based insulated gate bipolar transistors (IGBTs) and silicon-based metal-oxide semiconductor field-effect transistors (MOSFETs). But as the technology and products mature, silicon carbide semiconductor devices are accelerating their penetration in the electric vehicle market. Research institute Yole Development points out that the whole vehicle with silicon carbide power devices can largely improve system efficiency, effectively reduce body mass and make the structure more compact [7]. In new energy vehicles, the inverter is the device that converts the mainstream voltage (power cell, battery) into AC power, and is a key component in the vehicle motor drive to achieve energy conversion. At present, the vast majority of electric vehicle drive inverters are based on the design of traditional silicon-based IGBT power modules, which have the disadvantages of low switching frequency and high losses, which seriously restrict the improvement of the power density of new energy vehicles drive. The high saturation electron drift rate of silicon carbide material enables it to support faster switching speed, which means more power can be converted in the same time, and the corresponding switching loss is reduced. At the same time, with the reduction of switching losses, it enables silicon carbide devices to operate at switching frequencies above 20 kHz, which in turn significantly reduces the size and cost of passive devices.

With the progress of new energy vehicle technology and product design upgrades, the development of stand-alone vehicle chargers is increasingly challenged by integrated power units, and silicon carbide diodes (SBD) and silicon carbide MOSFET devices can be used for vehicle charger power factor correction (PFC) and DC-DC secondary rectification links to promote vehicle chargers to bi-directional charging and discharging The development of silicon carbide MOSFETs is the first in the world to use silicon carbide MOSFETs for the power factor correction (PFC) and DC-DC secondary rectification of vehicle chargers. As the first car company in the world to adopt silicon carbide inverter, Truss has already launched Model 3, Model Y and Model S Plaid series, all of which adopt silicon carbide technology. 650V SiC MOSFET inverter introduced by STMicroelectronics is adopted in Model 3 [8], and its range is significantly improved compared with the model using silicon-based IGBT. The silicon carbide inverter is shown in the Figure 1.

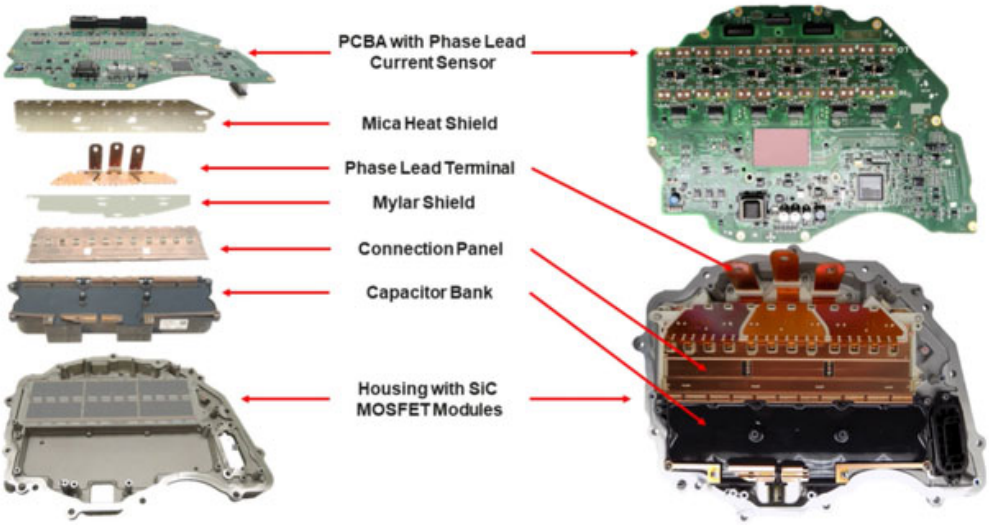


Figure 1. Silicon carbide inverter

3.1.2 Photovoltaic power generation field

Compared with traditional energy sources, solar energy resources are easily accessible and not affected by the environment, and can be called the cleanest and most sustainable type of energy. Among them, PV inverters are an important part of ensuring efficient, economic and stable operation of PV power generation systems. Existing PV inverters generally use silicon-based devices, and their performance is close to the theoretical limit after more than 40 years of development. The future technology trend of solar photovoltaic equipment is to improve efficiency, reduce the size and quality, improve reliability, and fundamentally improve the performance of PV inverters. In order to use new energy more efficiently, the wide application of silicon carbide devices in inverters will become an inevitable development trend. The silicon carbide PV inverter is shown in Figure 2.

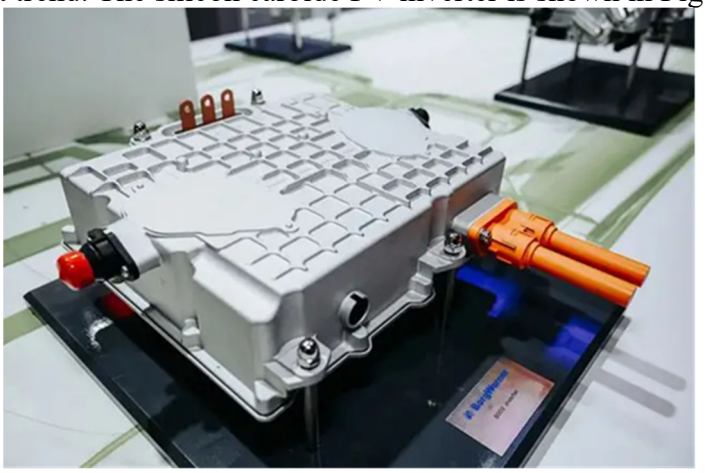


Figure 2. Silicon carbide PV inverter

Silicon carbide has more advantages than silicon in solar power applications. Its breakdown voltage is more than 10 times that of silicon, and silicon carbide also has lower on-state resistance, gate charge and reverse recovery charge characteristics, and higher thermal conductivity than silicon. As a result, silicon carbide devices can switch at higher voltages, frequencies and currents, and manage heat dissipation more effectively. PV inverters using silicon carbide device power modules can increase conversion efficiency from 96% to more than 99%, reduce energy losses by more than 50%, and increase equipment cycle life by 50 times [9], which can reduce system size, increase power density, reduce temperature cycling, and extend device life, thereby reducing production, installation, and maintenance costs. According to the International Energy Agency (IEA), it is expected that by 2024, global renewable energy generation will grow by 50%. About 60% of this will be in the form of solar PV [10]. Silicon carbide devices can increase the efficiency of solar energy conversion, improve the efficiency of electrical energy production and reduce energy losses, so silicon carbide materials have a very broad application prospect in the field of photovoltaic power generation.

3.2 Application of GaN

3.2.1 Fast charging

The new GaN fast charger compared with the traditional fast charger, due to the material characteristics of GaN can provide higher energy conversion efficiency, reduce power consumption, reduce the heating problem when charging; GaN charger has greater power density, can achieve faster charging speed; In addition, the GaN charger power device switching frequency is significantly higher than the traditional fast charger Si power device, so you can achieve a smaller size charger product design.

As Apple personally came down and released 140W GaN fast charging products, cell phone and computer manufacturers who used to hold a wait-and-see attitude also began to follow suit. The main reason for using GaN in cell phone fast charging is that the charging power of cell phones is growing, and the portability of adapters and chargers is getting worse when the power is changed from 5W and 10W to 65W and 125W. And the use of GaN chip charger volume is small, fast charging speed. At

the same time, USB standardization organizations to promote Type-C interface and USB Power Delivery Protocol (USB Power Delivery, USB PD) led to the explosion of the accessories market. A standard adapter, cell phones, laptops, tablets can be used, the user recognition and acceptance of the product will naturally increase. The Apple 140W GaN fast charger is shown in Figure 3.



Figure 1. Apple 140W Charger

In addition to the products launched by cell phone manufacturers such as OPPO, Realme, Xiaomi, Nubia, Samsung, Lenovo, ZTE, etc., third-party manufacturers are also sparing no effort to follow up. As many as 60 manufacturers at home and abroad produce and manufacture GaN fast charging products, and there are hundreds of 20W-120W GaN fast charging products on the market.

3.2.2 5G technology

There are two mainstream technologies that can achieve the high frequency performance required for a complete 5G implementation: gallium arsenide and gallium nitride. Compared with GaAs, GaN-on-Si can achieve excellent high frequency performance, mainly in terms of higher power density. The high-power density allows signals to be transmitted over long distances, extending the coverage of the base station. It also supports a smaller form factor, requiring less space on the PCB. It is clear that GaN will play a leading role in high-frequency solutions in these size-constrained applications as the technology continues to evolve.

In Massive MIMO applications, GaN has the advantage of higher power density and higher cutoff frequency. It enables highly integrated solutions, such as modular RF front-end devices. In millimeter wave applications, in addition to the much larger number of RF devices required in the base station RF transceiver unit display, the base station density and the number of base stations will also be greatly increased. GaN's high power density feature can effectively reduce the number of transceiver channels and the overall solution size under the same coverage conditions and user tracking function. To achieve the most optimal combination of performance and cost.

4. Challenges

At present, although the third generation of broadband semiconductor materials in power, communications, military and other fields have a wide range of application prospects. However, there are still many problems that need to be solved.

1. sic manufacturing process, process difficulties lead to low manufacturing efficiency of silicon carbide substrates. Unlike the traditional monocrystalline silicon using the pull method of preparation, silicon carbide materials because of the general conditions is difficult to liquid-phase growth, the mainstream of the market today using the gas-phase growth method, in the closed high-temperature cavity for the orderly arrangement of atoms and complete crystal growth, but also to enhance the crystal growth efficiency is a complex system engineering. Compared to silicon, which only requires a growth temperature of about 1600°C, the gas phase growth temperature of silicon carbide is above 2300°C and needs to be precisely regulated during production [3]. The high temperature places high

demands on the equipment and process control, and the production process is almost a black box operation that is difficult to observe. The slightest error in temperature and pressure control can lead to product failure. The hardness of silicon carbide is second only to diamond, which makes it significantly more difficult to cut, grind and polish.

2. the same as SiC manufacturing, GaN manufacturing also has the same challenges. One of the main obstacles is still the growth of GaN crystal material on silicon substrate. Among several possible substrate materials for growing GaN, although Si substrate has obvious advantages such as low price, large size, and easy compatibility with industrial CMOS platforms, it is still very difficult to realize heterogeneous epitaxial high quality GaN material on Si substrate. The reason for this is the lattice constant mismatch and thermal expansion coefficient (TEC) mismatch between the Si and GaN epitaxial layers of the heterogeneous substrate, which can create fatal defects in the GaN layer. Therefore, it requires a complex buffer layer and epitaxial layer.

Due to these and some other factors, the price of various consumer products of third-generation semiconductor materials is also on the high side. Further process improvements and cost reductions remain the key to attracting many consumers.

5. Conclusions

The importance and strategic position of third-generation semiconductor materials has been widely emphasized due to their broad application prospects in many fields such as new energy vehicles, 5G communication, photovoltaic power generation, smart grid, consumer electronics, defense industry, aerospace, etc. The European Commission, the U.S. Department of Energy, Japan's new energy industry technology development agencies and other developed countries and institutions have started the third generation of semiconductor substrates and devices of a number of development plans and R & D projects. In addition to the major capital and industry leaders are also laid out in advance, a variety of new materials from the preparation to the application of the problem to tackle, to solve. It is believed that under the joint promotion of all forces, the third-generation semiconductor will definitely be more widely used in the future, for the benefit of the people and society.

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