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Semiconductor Materials in Integrated Circuit Chip Manufacturing

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Abstract. The continuous advancement of integrated circuit (IC) technology and the constant miniaturization of device feature sizes have placed higher demands on the electrical, thermal, and reliability performance of semiconductor materials. This paper traces the development history of core semiconductor materials in IC manufacturing, following the technological trajectory from the first to the fourth generation. It analyzes their current applications and research progress in material preparation methods such as epitaxial growth and thin-film processing. The research shows that silicon-based semiconductors remain the core foundational material for IC manufacturing; second-generation compound semiconductors, represented by gallium arsenide and indium phosphide, have irreplaceable advantages in radio frequency and optoelectronic fields; third-generation wide-bandgap semiconductors, centered on silicon carbide and gallium nitride, are in the accelerated industrialization phase; and fourth-generation ultra-wide-bandgap semiconductors demonstrate enormous application potential in ultra-high voltage and ultra-high frequency applications. This paper points out that different generations of semiconductor materials will coexist and complement each other for a considerable period of time, jointly meeting the diverse performance requirements of ICs for high-frequency, high-voltage, and low-power consumption.

Keywords: Semiconductor materials, integrated circuits, chip manufacturing, wide bandgap semiconductors, crystal growth

1. Introduction

Integrated circuits (ICs) are miniature circuit systems that integrate transistors, inductors, and other components onto a single semiconductor chip using specific interconnection methods [1]. The miniaturization of transistors has driven the evolution of semiconductor materials to the fourth generation, which offers broad application prospects. At the same time, the miniaturization has also spurred the development of technologies such as extreme ultraviolet (EUV) lithography and atomic layer etching (ALE), laying a crucial processing foundation for the application of each generation of materials.

As demands on chips for low power consumption, high frequency, and high voltage become increasingly diverse, a single material cannot meet all requirements. Current research faces the

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following gaps: first, heterogeneous integration between materials of different generations is not yet mature; second, the large-size single-crystal fabrication and defect control of ultra-wide-bandgap materials remain bottlenecks; and third, further research on compound semiconductors for radio-frequency and power applications is still required.

This paper focuses on core semiconductor materials in IC manufacturing, covering the principles and key processes of chip manufacturing, presenting the performance characteristics and application scenarios of key semiconductor materials, and summarizing the research progress of major preparation methods such as bulk single crystal growth and epitaxial layer fabrication. Research methods include literature review, comparative analysis, and inductive summarization. This paper aims to provide a forward-looking reference for the research direction of new material systems in the post-Moore's Law era and to support China's technological strategy in the field of next-generation semiconductor materials.

2. Manufacturing principles of IC chips

IC manufacturing uses microfabrication technology to build a three-dimensional structure on a semiconductor substrate. The modern IC manufacturing process is mainly divided into front-end wafer fabrication and back-end packaging and testing. The front-end process includes processes such as coating, exposure, development, etching, thin film deposition, doping, oxidation diffusion, cleaning and measurement [2]. Among these, etching, photolithography and thin film deposition are the three key technologies of wafer fabrication.

Semiconductor materials are the foundation for manufacturing ICs and devices, and the development of IC chips has spurred advancements in semiconductor materials. First-generation silicon-based semiconductors, with their mature processes and cost advantages, still dominate the logic and memory chip fields. Second-generation semiconductor materials such as GaAs and InP, due to their high electron mobility and excellent optoelectronic properties, are used in radio frequency and communications fields. Third-generation wide-bandgap semiconductors such as SiC and GaN are expanding into fields such as communications, lasers, and power electronics. Fourth-generation ultra-wide-bandgap semiconductor materials (such as diamond and Ga_2O_3) have broad prospects in electronic communications, new energy, smart wearables, and flexible electronics.

Based on ICs, various chips, components and antennas can be packaged and integrated to build more complete electronic systems. Depending on the carrier, packaging methods can be divided into system-in-box (SiB), system-on-board (SoB), system-on-chip (SoC), and system-in-package (SiP) [1]. IC testing runs through the entire process of design, production and application to verify the design effect and meet the system-level application requirements.

3. Key process technologies

3.1. Photolithography

Photolithography is a micro-nano fabrication technique that transfers a mask pattern onto a substrate by using photosensitive materials in response to light sources such as ultraviolet and visible light. Such advancements have increased chip integration, enhancing performance while reducing power consumption.

The field of lithography has developed technologies such as projection lithography, phase shifting mask (PSM), and chemical amplification photoresist (CAR), and is evolving toward high precision, high efficiency and intelligence: EUV technology has high resolution and has become the core

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technology of advanced processes at 7 nm and below; nanoimprint lithography (NIL) challenges the status of EUV with lower cost and energy consumption in specific scenarios; computational lithography is becoming a bridge connecting chip design and manufacturing [3].

3.2. Etching technology

Etching transfers the mask pattern to the wafer surface to form a three-dimensional microstructure, which is a key process for transistor miniaturization.

With the upgrading of IC manufacturing processes and the emergence of three-dimensional structures such as Fin Field-Effect Transistor (FinFET) and 3D NAND flash memory (3D NAND), the requirements for high aspect ratio etching have gradually increased. When the feature size drops below 10 nm, wet etching is insufficient for linewidth and precision control and is gradually being replaced by dry etching [4]. However, reactive ion etching (RIE) and Bosch processes have insufficient etching precision and selectivity. ALE is divided into two steps: self-limiting thin film surface modification and modified layer removal. It has high precision, low damage, and good selectivity, and is currently a research focus [5].

3.3. Thin film deposition

Thin film deposition modulates the surface properties of materials by forming nano- to micron-scale coatings. Thin film deposition has developed rapidly over the past few decades. Commonly used techniques include thermal evaporation, sputtering, chemical vapor deposition (CVD), molecular beam epitaxy (MBE), and atomic layer deposition (ALD). Each mainstream technique has its advantages and limitations: thermal evaporation is simple to operate and suitable for mass production, but uniformity is difficult to control and energy consumption is high; LPCVD and PECVD are suitable for high-quality thin film preparation; MBE and ALD achieve atomic-level precision but have complex processes and high costs [6]. Currently, hybrid deposition processes (such as combining CVD with other methods) have become an important direction for improving thin film performance [6].

4. Core semiconductor materials

Semiconductor materials are the core materials for transistors, ICs, power electronic devices and optoelectronic devices. The first generation of Si and Ge is mainly used for logic chips and memory chips; the second generation of materials such as GaAs and InP focuses on optoelectronics and communication; the third generation of wide bandgap semiconductors expands into communication, laser, power electronics and other fields [7], and the fourth generation of ultra-wide-bandgap semiconductors and ultra-narrow-bandgap semiconductors has broad prospects in electronic communication, new energy, smart wearables and flexible electronics and other fields [8].

4.1. First-generation semiconductors and second-generation compound semiconductors

First-generation semiconductor materials are represented by Si and Ge. Silicon gradually replaced germanium from the late 1960s. Currently, more than 90% of chips are manufactured using silicon. However, silicon has a narrow bandgap and low electron mobility, making it difficult to meet high-frequency and high-power requirements. Therefore, it must be used in combination with compound semiconductors [9].

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Second-generation semiconductors mainly belong to the III-V group, represented by GaAs and InP. However, due to the complexity of material preparation and high costs, it is necessary to optimize the epitaxial growth process to reduce defect density and to combine this optimization with packaging optimization to enhance device performance. The scarcity, high cost, and toxicity of GaAs and InP materials have limited their large-scale application in high-power circuits, driving the development of third-generation semiconductors.

4.2. Third-generation wide-bandgap semiconductors

Third-generation semiconductors, represented by SiC and GaN, are wide-bandgap semiconductor materials suitable for high-temperature, high-power, high-voltage, high-frequency, and radiation-resistant applications. SiC has high thermal conductivity, high electron saturation velocity, strong critical breakdown field, and strong radiation resistance [10], making it suitable for aerospace, information and communication, new energy vehicles, radar, and other fields. High-temperature chemical vapor deposition (HTCVD), liquid-phase growth, and doping are still under development [10]. Therefore, overcoming substrate size and quality limitations is the primary challenge in reducing the manufacturing cost of SiC devices.

GaN has a high breakdown electric field, high temperature resistance, and corrosion resistance. GaN material devices cover power devices, radio frequency devices, and optoelectronic devices, such as laser diodes (LDs), light-emitting diodes (LEDs), and high electron mobility transistors (HEMTs). However, GaN has too high polarity, making it difficult to obtain good ohmic contacts through high doping, which affects further research on devices [11]. At present, basic research on GaN band structure, film growth dynamics, surface morphology and surface reconstruction, electronic transport properties, impurity doping control and impurity defect mechanism has progressed considerably, but further research is still needed [11].

4.3. Fourth-generation ultra-wide bandgap semiconductors

Fourth-generation semiconductors mainly include two categories: ultra-wide bandgap semiconductors (such as diamond and Ga_2O_3) and ultra-narrow bandgap semiconductors (such as GaSb and InSb) [12]. The former has an extremely wide bandgap and good thermal stability; the latter has a lower electron transition energy and higher mobility, making it suitable for photoelectric conversion [8]. Emerging materials such as two-dimensional materials (such as graphene, h-BN, MoS_2, etc.) and topological insulators (TIs) are also classified into the fourth-generation semiconductor category.

Fourth-generation semiconductors have significant potential in fields such as electronic communication, quantum computing, smart wearables and flexible electronics: diamond and Ga_2O_3 can greatly improve the transmission speed and signal processing capabilities of electronic devices and are suitable for high-frequency communication [13]; TI can be used for quantum computing; flexible electronic devices based on two-dimensional materials offer enhanced user experiences for products such as smart bracelets and implantable medical devices.

Currently, the main challenges of fourth-generation semiconductors lie in the high cost of preparing high-quality single-crystal materials and the complexity of device manufacturing processes, which necessitate the development of new device structures and manufacturing processes.

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5. Semiconductor material preparation

The performance of key semiconductor materials such as Si, GaAs, and SiC is determined by single-crystal quality, defect density, and doping uniformity. High-quality, low-cost material preparation is the first step in integrated circuit manufacturing.

5.1. Bulk single crystal growth

The single crystal silicon wafers used for logic and memory chips are mostly grown by the Czochralski (CZ) method, with a diameter of 12 inches. The liquid-solid interface is condensed to form a single crystal. The silicon wafers used for power devices are mostly grown by the Floating Zone (FZ) method, with a size of 8 inches and below: a molten zone is created by locally heating a polysilicon rod, so that the molten zone moves up and the seed crystal moves down, gradually forming a single crystal silicon rod [14].

Second-generation semiconductor (GaAs, InP) single crystals are mainly grown by liquid-encapsulated Czochralski (LEC) and vertical gradient freeze (VGF). The LEC method uses B2O3 liquid encapsulant to suppress the volatilization of group V elements and is used to prepare semi-insulating GaAs and InP single crystals, but the large temperature gradient leads to high dislocation density; the VGF method offers a simple process and controllable temperature field, and can grow large single crystals with low dislocation. While in the third generation of semiconductors, SiC single crystals are mainly grown by liquid-phase growth method and physical vapor transport method (PVT), with growth achieved by establishing a temperature field through induction heating [15]. Due to the high melting point of GaN, it is difficult to use molten liquid GaN to prepare bulk single crystal materials, so heteroepitaxy method is often used.

In fourth-generation semiconductor materials, Ga_2O_3 can be prepared by various melt methods. The edge-defined film-fed growth method (EFG), vertical Bridgman method (VBM) and casting method have achieved 6-inch single crystal substrates; the CZ method and cold crucible method have prepared 2-inch single crystals. The preparation of diamond single crystal materials is mainly carried out by CVD, which is superior to the high temperature and high pressure method (HTHP) with high cost and high defect density. The growth of AlN is carried out by PVT and hydride vapor phase epitaxy (HVPE). The PVT method has a fast growth rate and low dislocation density, but it has problems such as polycrystalline, high impurity concentration and high temperature requirements, and has not yet been mass-produced [16].

5.2. Epitaxial layer growth

Epitaxial growth involves depositing single-crystal thin layers with specific compositions and doping onto a single-crystal substrate to construct the active region of a device.

CVD is a general-purpose epitaxial technology that generates solid products through gas-phase reactions. It is versatile, has a fast growth rate, and can prepare a variety of materials. In recent years, it has been used to synthesize SiC powder [16]. Microwave plasma chemical vapor deposition (MPCVD) has been used to prepare high-quality diamond thin films [17]; metal-organic vapor phase epitaxy (MOCVD) and MBE are the main epitaxial technologies for GaN and its alloys [15].

MBE involves jetting atomic or molecular beams onto the substrate surface layer by layer in an ultra-high vacuum environment. The low temperature allows for precise control of layer thickness, composition, and doping, and it is used to prepare III-V compounds such as GaAs and InP.

Alternating Alternating Layer Deposition (ALD) involves alternating introduction of two or more reaction precursors, depositing only one atomic layer at a time. The thickness control precision reaches the atomic level, and it is used to prepare high- κ gate dielectrics such as HfO_2 and Al_2O_3, as well as thin films such as ZnO. HVPE deposits atomic or molecular beams onto the substrate surface in a vacuum, offering a high growth rate and strong controllability, and is used to prepare GaN substrates and single-crystal AlN thick films [17].

6. Conclusion

This article systematically reviews research progress on core semiconductor materials in IC chip manufacturing, covering fabrication principles, key process technologies, and corresponding growth methods. At the process level, modern IC manufacturing relies on photolithography, etching, and thin-film deposition as three technological pillars, enabling transistor scaling from micrometer to nanometer nodes. At the material system level, from first-generation elemental semiconductors to fourth-generation ultra-wide-bandgap materials, each generation complements the others in logic, optoelectronics, and RF applications: silicon substrates, with mature planar processes and cost advantages, remain mainstream for digital ICs; GaAs and InP hold irreplaceable roles in optical communication and RF; SiC and GaN wide-bandgap semiconductors are rapidly penetrating EVs and 5G base stations; ultra-wide-bandgap materials like diamond and Ga_2O_3 show promise to surpass existing power and frequency limits. At the fabrication technology level, joint development of large-diameter bulk single-crystal growth and epitaxial methods provide solid process foundation.

The limitation of this paper is its relatively brief discussion of emerging 2D materials and organic semiconductors, and a lack of in-depth analysis of integration and compatibility issues between different material systems. Future work will more comprehensively explore cutting-edge material systems, with deeper analyses of emerging fields such as 6G communication and quantum computing.

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