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Comparative Analysis of Production Processes for GaN Materials in Semiconductor Wafer Fabrication

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Abstract:

GaN, as the core material of third-generation semiconductors, possesses a band gap width of 3.4 eV, an electron mobility of 2000 cm²/Vs, and excellent thermal conductivity and heat resistance. It is crucial for the development of power electronic devices; however, its industrialization process is constrained by epitaxial processes, with the current mainstream ones being MOCVD, MBE, and HVPE. This paper mainly elaborates on the theoretical foundations of these three processes, compares production difficulty and production costs, and studies the analysis results of the crystalline, electrical, and optical properties of the produced GaN. The results show that MOCVD balances performance and production capacity, making it suitable for mid-to-high-end LEDs and high-power devices, but suffers from low raw material utilization rate and risk of carbon contamination; MBE has the advantage of atomic-level control and optimal performance, and is suitable for devices with complex structures, yet is limited by high cost and low production capacity; HVPE features low cost and high production capacity, which fits large-size substrates and general lighting LEDs.

Keywords: GaN; MOCVD; MBE; HVPE; Comparison of processes and costs

1. Introduction

Traditional silicon-based devices have long dominated the selection of materials for semiconductor devices. In contrast, GaN devices boast a wide bandgap, high electron mobility, and excellent thermal conductivity — traits that give them low loss and high efficiency when operating at high frequencies. Moreover, these devices play a pivotal role in advancing power device technology, helping fuel progress across the entire electronics industry while boosting energy efficiency and environmental sustainability [1]. However, in practical manufacturing processes, the preparation of GaN materials still faces certain challenges and technical limitations—different tech approaches and process setups have a huge bearing

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on both the performance of the final GaN material and where it can actually be applied. As a result, the selection of production processes in actual production has become an important issue. Currently, the mainstream epitaxial growth processes include Metal-Organic Chemical Vapor Deposition (MOCVD), Molecular Beam Epitaxy (MBE), and Hydride Vapor Phase Epitaxy (HVPE). This paper conducts a horizontal comparative analysis of these three mainstream technologies, summarizes their respective advantages and disadvantages, and performs a critical analysis of their existing problems, thereby providing theoretical support for new research directions in GaN materials.

2. Analysis of the Theoretical Basis

2.1 Principles of the Main Production Processes for GaN

2.1.1 The Introduction to MOCVD

MOCVD is a technology that enables the epitaxial growth of GaN thin films through chemical reactions between metal-organic compounds and nitrogen-containing gases on the substrate surface. Its core principle lies in utilizing the thermal decomposition and chemical reactions of gas-phase precursors to form an atomically ordered crystal structure on the surface of a heated substrate (such as sapphire or SiC).

The GaN thin film for the experiment is fabricated in a self-developed horizontal MOCVD system, with a 6-inch Si (111) wafer as the substrate. Trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3) function as Group III precursors, and hydrogen (H_2) is employed as the carrier gas. The fabrication process is carried out as follows: first, the substrate is placed in the reaction chamber and baked at 1100 °C with H_2 flowing at 30 slm for 10 minutes to eliminate surface impurities. Then, TMAl is fed at 120 sccm to deposit an Al layer for 15 seconds. Next, the substrate temperature is reduced to 1040 °C, and an AlN buffer layer is grown using TMAl and NH_3 at a V/III ratio of 255 for 30 minutes. Keeping the temperature unchanged, an AlGaN buffer layer is subsequently grown with TMGa, TMAl, and NH_3 at a V/III ratio of 498 for 30 minutes. Finally, the GaN thin film is grown at a constant temperature with a V/III ratio of 4554 for 90 minutes, thus completing the fabrication [2].

The key to MOCVD lies in the precise control of gas flow rates, temperature distribution, and reaction pressure to ensure the uniformity and crystalline quality of the thin films. Its reaction system is a gas-phase surface reaction with a moderate growth rate (usually 1-10 μm/h), making it suitable for preparing large-area, high-quality GaN epitaxial layers. It currently stands as the mainstream technology for producing GaN devices in the semiconductor industry.

2.1.2 The Introduction to MBE

MBE is a physical vapor epitaxy technology based on an ultra-high vacuum environment. It achieves the single-atomic-layer growth of GaN by precisely directing atomic/molecular beams of Ga and N to the substrate surface. Unlike chemical reactions, its principle relies more on the physical deposition and surface diffusion of atoms.

Within an ultra-high vacuum chamber, the Ga source forms a Ga atomic beam through evaporation by a heating furnace (Knudsen cell), while the N source dissociates N_2 molecules into active N atoms (N*) via a radio frequency plasma source (e.g., Electron Cyclotron Resonance, ECR plasma). Ga atoms and active N atoms undergo adsorption, diffusion, and combination on the substrate surface, forming GaN crystals arranged in a lattice structure [3].

The core advantage of MBE is precise controllability of the growth process: by adjusting the temperature of the source furnace and plasma power, atomic-level growth rate control (usually 0.1-1 μm/h) can be achieved. Furthermore, the ultra-high vacuum environment effectively prevents impurity contamination, making it suitable for preparing GaN materials with complex heterostructures (such as quantum wells and superlattices).

2.1.3 The Introduction to HVPE

HVPE, namely Hydride Vapor Phase Epitaxy, is a widely used technology in the field of semiconductor material growth. It holds an important position in the preparation of third-generation semiconductor materials such as α-Gallium Oxide (α-Ga_2O_3) and GaN.

The idea behind this technology is pretty straightforward: it relies on hydride gases—like gallium chloride (GaCl), for instance—as the gallium source. These gases react with a nitrogen source at high temperatures through vapor-phase reactions, eventually depositing to form the semiconductor materials we need. This tech stands out for several key strengths: the equipment structure is straightforward, maintenance costs stay low, and growth rates are impressively high. Take large-size wafer growth, for instance—this tech hits the mark easily, with GaN growth rates ranging from 10 to 200 μm/h. That said, it's not without flaws. The GaN substrates grown this way tend to have high dislocation densities and small curvature radii.

In practical applications, HVPE can be used to prepare high-quality semiconductor substrates. For instance, the fabricated GaN substrates can enhance the light extraction efficiency and extend the lifespan of LEDs, while the prepared Ga_2O_3 homoepitaxial wafers can improve the volt-

age resistance of related devices and reduce power loss.

3. Analysis of Technical Challenges, Industrial Maturity, and Application Scenarios

3.1 Process Complexity and Technical Challenges

The core technical challenges of GaN epitaxy technologies lie in equipment control, parameter precision, and process stability, varying by technique.

MOCVD focuses on "multi-physical field coupling control" and "source material management": its reaction chamber requires uniform temperature, pressure, and flow field, with uneven flow causing over 20% thickness deviation and 15% carrier mobility drop in 6-inch GaN films; ±0.5°C source bottle temperature fluctuation affects TMGa vapor pressure, demanding ±1% NH_3 flow matching, while CH_4 by-product causes carbon pollution [4,5,2].

MBE relies on "ultra-high vacuum maintenance" and "atomic-level regulation": it needs $\geq 10^{-8}$ Pa vacuum (leak rate $<1\times10^{-10}$ Pa·m³/s) to avoid impurity concentration $>1\times10^{17}$ cm^{-3}, and its 0.1-1 μm/h growth rate risks order-of-magnitude dislocation density increase if vacuum drops temporarily [6,7].

HVPE faces "large-size uniformity control" and "corrosion protection": 6-inch growth requires 6-7 cm source-substrate distance and 3.0-3.5 slm N_2 separation gas (otherwise edge dislocation density is 50% higher than center); HCl corrodes pipelines (3000-hour replacement cycle), and 1150°C pretreatment adds steps [8,9,10].

3.2 Industrial Maturity and Cost Analysis

Industrial maturity varies significantly across technologies.

MOCVD has high maturity with industrialization-compatible production capacity, though regular shutdowns for carbon pollution cleaning slightly increase operational costs [2,6].

MBE features low maturity due to ultra-high vacuum requirements: its high equipment and maintenance costs, combined with low growth rate (several hours for 4-inch wafers), result in high per-unit costs and limited production capacity [6,7].

HVPE has moderate maturity: simple equipment structure reduces initial investment, but frequent pipeline replacement (3000 hours) adds maintenance costs; however, its high growth rate ensures strong large-scale production capacity [9,10].

3.3 Applicable Scenarios and Limitations

Application scenarios are determined by technical performance and cost.

MOCVD is ideal for high-power devices (5G base station HEMTs) and mid-to-high-end LEDs, with optimized dislocation density (5×10^6 cm^{-2}) meeting high-performance needs and matching industrial scale [6].

MBE is irreplaceable for complex heterostructures (e.g., deep ultraviolet laser quantum wells) via secondary epitaxy, achieving <0.1 nm quantum well thickness deviation, but its high cost and low capacity restrict it to high-end research and special device mass production [6,7].

HVPE suits 6-inch+ large-size substrates and low-cost LEDs: high-temperature pretreatment reduces dislocation density to 10^5 cm^{-2}, with 6-inch thick film uniformity reaching ±1.5% and high capacity enabling large-scale production, though pipeline corrosion and uniformity control limit its high-end application [10,9,8].

4. Comparison of Properties of Grown GaN

4.1 Comparison of Crystalline Quality

Crystalline quality takes dislocation density and the full width at half maximum (FWHM) of the X-ray Diffraction (XRD) rocking curve as the core indicators [11].

4.1.1 MOCVD

The crystalline quality of GaN produced by MOCVD is relatively balanced. By optimizing the temperature (1050-1100°C) and carrier gas flow rate, the FWHM of the (0002) plane of GaN grown by MOCVD can be stably maintained at 15-30 arcsec, with a dislocation density of 1×10^6-1×10^7 cm^{-2} [6]. However, low-temperature growth of MOCVD (< 800°C) is prone to introducing carbon impurities, leading to a decrease in crystal integrity and an increase in FWHM to above 35 arcsec [12].

4.1.2 MBE

Its crystalline quality is optimal. For the n^+-GaN thin films grown under the PAMBE system, the FWHM of the (0002) plane is as low as 10-15 arcsec, with the dislocation density controlled at 1×10^5-1×10^6 cm^{-2}. Its atomic-level growth rate (0.1-1 μm/h) provides sufficient diffusion time for atoms, resulting in a quantum well interface roughness of < 0.5 nm, which serves as a high-quality substrate for deep ultraviolet lasers [7].

4.1.3 HVPE

The crystalline quality of GaN grown by HVPE can be optimized through pretreatment. When unoptimized,

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HVPE leads to a dislocation density of 1×10^{8}-1×10^{9} cm^{-2} and an FWHM of 30-50 arcsec due to its high growth rate (10-200 μm/h) [11]. However, through the high-temperature pretreatment of MOCVD-GaN/sapphire substrates (1150℃, 300 sccm N_2, 10 min), the dislocation density of GaN grown by HVPE can be reduced to 1×10^{5} cm^{-2}, and the FWHM can be optimized to 20-25 arcsec, meeting the requirements of mid-to-low-end devices [10].

4.2 Comparison of Electrical Properties

The key indicators of electrical properties are carrier mobility, carrier concentration, and resistivity, which directly affect the conduction and high-frequency characteristics of GaN-based devices.

4.2.1 MOCVD

The electrical properties of GaN produced by MOCVD are balanced. For undoped GaN thin films grown by MOCVD, the room-temperature electron mobility is 1500-1800 $cm^2/V\cdot s$, with a carrier concentration of 1×10^{15}-1×10^{16} cm^{-3}. Si doping enables a resistivity of 1×10^{-3}-5×10^{-3} $\Omega\cdot cm$ [6]. However, fluctuations in carrier gas flow rate can cause an increase in background carrier concentration (> 5×10^{15} cm^{-3}), reducing the breakdown voltage of devices by 10%-15% [2].

4.2.2 MBE

The electrical properties of GaN produced by MBE are optimal. For n^+-GaN thin films grown by MBE, the room-temperature electron mobility reaches 1800-2000 $cm^2/V\cdot s$, with the Si doping concentration controlled at a precision of ±5% and an in-plane doping uniformity deviation of < 3% [7]. For InAlN/GaN HEMT devices fabricated using this process, the measured cutoff frequency (fT) reaches 59 GHz and the maximum oscillation frequency (fmax) reaches 131 GHz, making them suitable for high-frequency communication scenarios [8].

4.2.3 HVPE

The electrical properties of GaN produced by HVPE depend on doping optimization. Undoped HVPE-GaN exhibits n-type conductivity (carrier concentration: 10^{16}-10^{17} cm^{-2}) due to Si and O impurities introduced by the quartz reactor. Doping with SiH_2Cl_2 can increase the carrier concentration to above 10^{18} cm^{-3} and reduce the resistivity to 5×10^{-3} $\Omega\cdot cm$. However, carrier traps caused by dislocations lead to a significant temperature-dependent mobility decrease (-2.5%/℃), requiring thermal management optimization to adapt to high-temperature power devices [11].

4.3 Comparison of Optical Properties

Optical properties determine the application potential of GaN in optoelectronic devices (such as LEDs and lasers).

4.3.1 MOCVD

The optical properties of GaN produced by MOCVD are excellent and controllable. Growing InGaN/GaN quantum wells via MOCVD achieves a luminescence efficiency of over 80%, with the optical output power of red-yellow LEDs exceeding 50 mW [6]. Meanwhile, after thermal oxidation of MOCVD-grown epitaxial GaN at 400℃, the ultraviolet (UV) light transmittance increases by 5%, further optimizing its optical characteristics [12].

4.3.2 MBE

GaN produced by MBE is suitable for deep ultraviolet (DUV) optical devices. Growing AlGaN/GaN heterojunctions via MBE achieves a deep ultraviolet (250-280 nm) output power density of > 10 mW/cm^2. Moreover, the excellent quantum well interface flatness reduces non-radiative recombination, extending the device lifespan by 30% [7].

4.3.3 HVPE

The optical uniformity of GaN produced by HVPE needs improvement. Due to its high growth rate, HVPE-grown GaN is prone to optical inhomogeneity, with the luminescence efficiency of general lighting LEDs being 10%-15% lower than that of MOCVD-grown ones [11]. However, through the uniformity control of 6-inch GaN thick films (±1.5%), the optical uniformity of HVPE-GaN can be improved to ±3%, which can meet the requirements of mid-to-low-end lighting applications [9].

5. Conclusion

MOCVD reaches a balance between performance and production capacity, meeting the needs of mid-to-high-end LEDs and high-power devices, but it has drawbacks such as low source material utilization efficiency and the risk of carbon contamination. MBE possesses atomic-level growth control capability, with the optimal crystalline and electrical properties of materials, making it suitable for devices with complex structures such as deep ultraviolet lasers; however, it is limited by high costs and low production capacity. HVPE offers low costs and high production capacity, making it far better suited for large-format substrates and general lighting applications. It does require pretreatment, though, to enhance crystalline uniformity.

Future advancements can be pushed forward in three key ways: first, looking into integrating different processes — think MOCVD paired with HVPE, for instance — to make up for each process's unique limitations. Second, speeding up the localization of key equipment will help

get past the hurdles involved in fabricating large-sized wafers. Next, priority should be given to advancing high-end MBE equipment with precise heterostructure control (to meet the requirements of complex devices such as deep ultraviolet lasers) and the localization of core components (e.g., high-precision gas flow controllers for MOCVD and ultra-high vacuum systems for MBE). Third, refining process control tailored to specific requirements — like ramping up MBE's control of heterostructures , the development of intelligent and predictive control (which analyzes the correlation laws between the $TMGa/NH_3$ flow ratio, substrate temperature of MOCVD, and carbon contamination as well as film quality based on machine learning), along with multi-process collaboration and customization.— will in turn propel the industrial upgrading of GaN materials within the third-generation semiconductor sector.

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