III-V Material Growth Based on Optimized MOCVD Process in High-Efficiency Photonic Integrated Circuits

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Abstract. Metal-Organic Chemical Vapor Deposition (MOCVD) has become a crucial epitaxial growth method for the fabrication of high-quality integrated photonic circuits (PICs). The present research is aimed at the investigation of the MOCVD growth processes for GaAs, InP, and GaN, as well as substrate preparations and process optimizations in the case of MOCVD for III–V compound semiconductors. MOCVD provides precision control of temperature, pressure, and V/III ratio that allows the deposition of very uniform and accurately composed high-quality layers. These layers act as a base for the construction of quantum wells, heterostructures, and hybrid integration, which are the key parts of modern optoelectronic and photonic systems. The MOCVD's capacity to create complex multilayer structures also renders it a pivotal technique for the production of PICs that are large-scale and high-yield. In this paper, the basic process flow and key process parameters of MOCVD are studied. The influence of temperature, pressure, and V/III ratio on the film quality, surface morphology, and compositional uniformity in the epitaxial growth process is analyzed. More specifically, the authors aim to uncover the relationship between MOCVD growth dynamics and the resulting optical and structural properties of the materials used in PIC fabrication by performing a detailed investigation of the MOCVD process flow and the principal parameters.

Keywords: MOCVD, PIC, III-V compound, V/III ratio.

1. Introduction

Optical communication and information technologies are developing very quickly, and at the same time, photonic integrated circuits (PICs) are becoming the main platform for high-speed, low-power, and miniaturized photonic systems. The performance of PICs depends mainly on the quality, uniformity, and composition of the semiconductor materials used in the optical components like lasers, modulators, and photodetectors [1-3].

Among different epitaxial growth methods, Metal-Organic Chemical Vapor Deposition (MOCVD), by virtue of its ability to make high-purity and stoichiometrically controlled layers of compound semiconductors, is the most favored one. MOCVD allows the III–V materials like GaAs, InP, and GaN to be deposited in a heated reaction chamber where the metal-organic precursors (e.g., trimethylgallium, trimethylindium) and hydride gases (e.g., arsine, phosphine, ammonia) are introduced [4-6]. This process, carried out with careful regulation of temperature, pressure, and precursor flow ratios, achieves superb thickness uniformity and compositional accuracy, which are both important and necessary for the large-area wafer fabrication and mass production of PICs [2].

In this paper, we are going to analyze the MOCVD method, its process, and the mechanisms of growth dynamics as they relate to photonic integrated circuit manufacturing. Section 2 discusses the chemical vapor deposition process in detail, covering substrate choice, main process parameters, and surface reaction dynamics. Section 3 discusses the MOCVD application in PICs, covering material systems, quantum well structures, and the development of hybrid integration methods. Finally, Section 4 talks about the obstacles and prospects for MOCVD in the creation of next-generation photonic devices.

2. Fundamentals of MOCVD for Photonic Integrated Circuits

2.1. Principles of MOCVD growth

In the process of MOCVD film growth, volatile metal-organic precursors (such as trimethylgallium, trimethylindium, or trimethylaluminum) and hydride gases (such as arsine, phosphine, or ammonia) will be placed into the reaction chamber to heat it. After heating the mix of metal-organic precursors and hydride gases to a carefully controlled temperature, the reacted gas would be directly introduced into the reaction chamber and thermal decomposition would happen near the substrate surface [4]. The metal atoms from the metal-organic precursors and the hydrides would then combine to form crystalline layers like GaAs, InP, or GaN [7]. At the same time, the other carrier gas would enter the organic metal source container to bring out the saturated vapor of the organic metal source, then enter the reaction chamber to mix with the reacted gas. The organic metal source and the reaction gas would undergo a chemical reaction on the heated substrate to grow a thin film [2]. A key advantage of MOCVD is its ability to achieve precise stoichiometric control by tuning the flow rates and ratios of the precursors, often expressed as the V/III ratio [8]. This method allows uniform deposition over large-area wafers, which is essential for the scalability of PICs [2]. Some other advantages are a fast growth rate, high film uniformity, high growth accuracy, and being able to grow complex structures and multi-component thin films [1]. The MOCVD is currently the most common process for the large-scale production of semiconductor thin films. Nevertheless, some disadvantages of MOCVD are toxic organic metal sources and high equipment and maintenance costs.

2.2. Substrate selection and surface preparation (Si, GaAs, InP)

The substrate selection is a key factor in determining the structural and optical quality of the thin films grown by MOCVD. Some common substrates used for the PICs include silicon, gallium arsenide, and indium phosphide [8-9]. For silicon, its advantages include low cost, being able to be in large wafer sizes, and being compatible with Complementary metal-oxide-semiconductor technology, which makes it ideal for large-scale photonic integration. The disadvantages of Si are that due to the large lattice and thermal conflict between Si and III-V materials, dislocations and cracks often happen during its growth [1-2]. However, methods like building a buffer layer and patterned substrates to reduce defect density have been developed to overcome the disadvantages [9]. GaAs offers superior lattice matching for many III-V compounds and is commonly employed in optoelectronic devices such as lasers and detectors. InP with its direct bandgap and suitable lattice parameters is extremely compatible with GaAsP and is the material of choice for optical communication devices [9]. The surface cleaning and preparation processes (oxide removal, passivation) are vital for the control of nucleation quality and film uniformity [7].

2.3. Key process parameters (temperature, pressure, V/III ratio, precursor flow)

The growth qualities of the thin film in MOCVD mostly depend on the parameters of temperature, pressure, V/III ratios, and precursor flow. The temperature determines the efficiency of decomposing metal-organic precursors and the adatom mobility on the substrate surface [2-4]. Normally, the III-V materials such as GaAs and InP are grown at temperatures of 600 and 750 °C, respectively, whereas the GaN-based materials are subjected to a temperature of more than 1000 °C for the growth process [7]. A low temperature results in poor crystallinity, a high temperature results in desorption, and the roughness of the surface is also caused by high temperature. The deposition process is mainly controlled by two major parameters [8-10]. First, the reactor pressure (normally 50-100 Torr) has an effect on gas diffusion and kinetics; a lower pressure increases the precursor mean free path, which in turn directly improves the uniformity of the film. Secondly, the V/III ratio, where the amount of Group-V to Group-III precursors supplied is given, determines very accurately the stoichiometric composition and morphological quality of the film produced. A high V/III ratio may lead to parasitic reactions, because droplets of hydrides, which are the main precursors, are hardly formed, while a low ratio may yield a rich surface of hydrides and non-stoichiometric growth [11,12]. The flow of the

precursor must be very precisely controlled in order to achieve a uniform thickness and composition of the film. Uniformity in flow rate will result in consistent transfer of the precursor across the large-area wafers, and this is particularly important for PICs [1].

2.4. Growth dynamics: adsorption, decomposition, diffusion, nucleation

The growth kinetics of MOCVD involve a series of chemical and physical reactions occurring on the surface, which determine the microstructure and uniformity of the film. Adsorption, decomposition, diffusion, and nucleation are the main steps of MOCVD growth [5,9]. The process begins with the transport of metal-organic and hydride precursors to the heated substrate, during which the precursor molecules adsorb onto the surface and decompose. Subsequently, atoms such as gallium and arsenic are released and become the basic building blocks for crystal growth [7]. Finally, these adsorbed atoms diffuse on the substrate surface and migrate to lattice positions with favorable energy to achieve incorporation. The diffusion rate is affected by temperature, which influences surface flatness and film quality [10]. Under suitable conditions, these adsorbed atoms nucleate to form stable clusters, which then grow into continuous epitaxial layers. The balance between adsorption rate, surface diffusion, and desorption determines the overall growth mode [2].

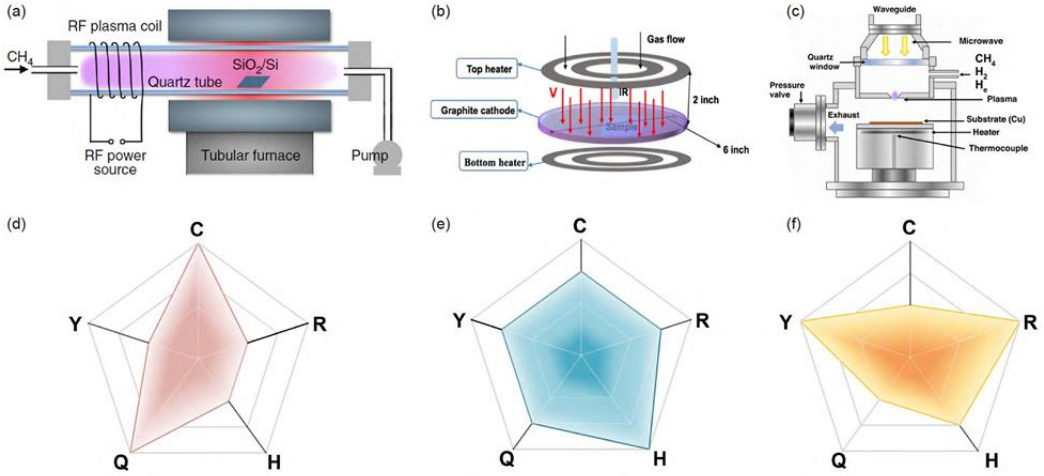


Fig. 1 PECVD experimental setup: (a-c) RF-PECVD; DC-PECVD; MW-PECVD; (d) Preparation of graphene by PECVD: (d-f) five key indicators [11-13].

Generally, Radio Frequency (RF) plasma systems operate at the frequency of 13.56 MHz, which is the standard frequency for the industry. RF generators may be classified into three major types that are based on the mode of energy coupling, namely the evanescent electromagnetic mode, the propagating wave mode, and the electrostatic mode. Among the three types, the evanescent electromagnetic mode is preferred in RF plasma-enhanced chemical vapor deposition (RF-PECVD) systems due to its high energy density, capability to produce large-volume plasma, and high production rate. An example of a typical configuration of this system is given in Figure 1(a) [10].

The RF technique excites the gas by means of a high-frequency alternating electric field, whereas direct current plasma-enhanced chemical vapor deposition (DC-PECVD) utilizes a parallel-plate DC glow discharge mechanism featuring a less complex structural design as illustrated in Figure 1(b) [11]. In this case, a stable plasma needed for deposition is formed when the gas between the parallel plates undergoes a Townsend breakdown process due to the application of a high enough DC voltage across the plates.

3. Applications of MOCVD in Photonic Integrated Circuits

3.1. Material Systems and Epitaxial Layers

MOCVD has become the primary epitaxial growth method for the development of ever more advanced material systems that support today's photonic integrated circuits (PICs). The method's dominance is due to its outstanding potential in synthesizing complex compound semiconductor heterostructures with precise control over composition, doping profile, and layer thickness down to the atomic scale [4]. This unique accuracy is a very important factor to provide the bandgap and optoelectronic properties of active and passive components in PICs with enormous versatility, and subsequently leading to the monolithic integration of different functionalities on a single chip. In addition, MOCVD's scalability and reproducibility make it the preferred method for the large-scale production of modern photonic devices [2].

3.1.1 III–V Compounds Semiconductors (GaAs, InP, GaN)

The III–V compounds, such as gallium arsenide (GaAs), indium phosphide (InP), and GaN, are the key materials for today's modern photonic applications. Materials based on GaAs have found great applications for near-IR lasers, modulators, and photodetectors due to their direct bandgap nature and high mobility of carriers [6]. InP provides a lattice-matching with InGaAsP and InAlAs alloys, which allows for the development of long-wavelength (1.3–1.55 μm) photonic devices suitable for optical communications [14]. Blue and ultraviolet LEDs, as well as laser diodes, are possible in GaN-based III-nitride materials with the ongoing efforts towards PICs in the visible light range [2]. These materials can achieve good uniformity and interface control with MOCVD, which is important for monolithic and hybrid PIC platforms 9. The research team reported innovations in MOCVD epitaxial growth technology based on the Planetary Reactor® system. By employing a novel four-channel injector combined with an in-situ Cl_2 chamber cleaning process, they successfully achieved high-quality epitaxial growth of AlGaInAs and InGaAsP materials on 150 mm indium phosphide (InP) wafers. The results demonstrated that this process maintains sub-nanometer-level photoluminescence uniformity while effectively suppressing compositional drift in InGaAsP, even with increased wafer size. This advancement provides a feasible pathway for large-scale photonic device fabrication operating in the 1.30–1.55 μm wavelength range [13-15].

3.1.2 Quantum Wells, Barrier Layers, and Strain Control

Even quantum wells (QWs) and superlattices can be grown with atomic specificity, allowing for nanometer-precision-controlled layer thicknesses that determine electronic band structures and optical transitions [5]. Such structures are critical to obtaining high-efficiency lasers and modulators in PICs. Buffer layers are important to alleviate lattice mismatch between unlike materials (e.g., GaAs-on-Si or InP on Si) and consequently reduce the number of threading dislocations, relax strain, and obtain film homogeneity [10]. It is possible to optimize carrier confinement and emission wavelength even better, especially in quantum well and quantum dot devices, through strain engineering with composition grading or the insertion of strain-compensating layers [16-17].

3.1.3 Emerging Hybrid/Heterogeneous Integration

The recent advancement of hybrid and heterogeneous integration endeavors to incorporate the advantages of III–V materials into the scalability spectrum of silicon photonics. High-performance lasers, amplifiers, and detectors between III–V layers grown by MOCVD-processed bonded or direct growth on Si platforms have been reported 8. These methods all sidestep silicon's indirect bandgap but are compatible with CMOS technology [2]. MOCVD also offers the ability to create defect-tolerant and thermally stable layers for such hybrid architectures and to realize compact, energy-efficient, and affordable photonic integration [5].

4. Conclusion

MOCVD is essentially the best method in all respects of precision, material versatility, and scalability when it comes to producing photonic integrated circuits. The MOCVD process, combined with optimal growth parameters and suitable substrate conditions, can yield the best quality III–V layers, which in turn will give efficient and reliable performance of the photonic devices. The MOCVD process's capacity to help with heterogeneous and hybrid integrations has opened up new areas for its use and also made it possible to integrate photonics and electronics perfectly on one platform. It can be expected that the development of optical communication and sensing technologies will require advances in MOCVD process control and material engineering for next-generation PICs which will lead to high-speed, miniaturized, and energy-efficient photonic systems being developed.

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