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Advances in Structure Elucidation and Electrical Characterization of Nanostructures Grown by Molecular Beam Epitaxy: A Review

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Abstract: Quantum materials, optoelectronics, and semiconductor physics have all benefited from molecular beam epitaxy (MBE), a powerful tool for the precise fabrication of nanostructures. This research goes over the latest findings in electrical characterisation and structural elucidation of MBE-generated nanostructures. Thanks to improved characterisation techniques including high-resolution transmission electron microscopy (HRTEM), scanning tunnelling microscopy (STM), and X-ray diffraction (XRD), our understanding of atomic-scale structures, defects, and interfaces has expanded substantially. Hall effect measurements, conductive atomic force microscopy (c-AFM), and transport spectroscopy are some of the electrical characterisation methods that have helped to clarify electronic band structures, quantum confinement effects, and charge carrier dynamics. Through the integration of exact growth control and advanced characterisation techniques, novel materials with tailored electrical properties have been synthesised. This study focusses on the latest advancements, challenges, and possible future directions of MBE in quantum computing and next-generation nanoelectronics.

Keywords: Structure Elucidation, Electrical, Nanostructures, Molecular Beam

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INTRODUCTION

On a worldwide scale, research into nanotechnology and nanoparticles is a thriving and cutting-edge field. Potentially groundbreaking new phenomena might emerge from this area of research, leading to a paradigm shift in technology that brings device physics into the realm of two- or three-dimensional confinement (quantum wires and dots). Restricting these heterostructures to two dimensions is likely to drastically change their optical and transport characteristics as compared to bulk or flat heterostructures. Modern epitaxy methods like as molecular beam epitaxy (MBE) and metallorganic chemical vapour deposition (MOCVD) are fundamentally driving research in this area, with the aim of developing structures with reduced dimensions. As a cutting-edge approach to nanotechnology, "self-assembled growth of nanostructures" describes how atoms or molecules may self-assemble into unique, useful structures without any external guidance. This process manipulates electrostatic interactions, hydrogen bonds, van der Waals forces, and other intrinsic molecular properties to create intricate nanoscale structures. Significant applications in electronics, photonics, medicine, and energy are made possible by the self-assembly of various nanostructures, such as quantum dots, nanowires, nanotubes, and nanosheets (Pfannes, H. D. 2014).

Usually, the synthesis of precursor molecules or nanoparticles starts the self-assembly process. The size, shape, and homogeneity of the resulting nanostructures are determined by the solvents, surfactants, and reaction conditions used in the chemical synthesis of these precursors. For example, temperature and precursor concentration may play a major role in the nucleation and growth processes during the semiconductor quantum dot synthesis, providing precise control over the optical and electrical characteristics of the final product. Through a number of methods, the self-assembly process can continue once the precursors are ready. Solvent evaporation is a popular method that involves depositing a solution containing the precursors onto a substrate. Precursor concentration rises with solvent evaporation, causing nucleation and the subsequent formation of nanostructures. This technique is frequently used to create thin films and arrays of nanowires. An alternative method is template-assisted assembly, in which precursors are arranged into desired configurations using a prepatterned substrate as a guide. Using this technique, precise spatial layouts and highly ordered nanostructures may be produced. Self-assembled nanostructures have a number of benefits, one of which is the possibility of bottom-up fabrication, which is more affordable and scalable than conventional top-down lithographic methods. Furthermore, self-assembly can create structures with atomic accuracy, which is necessary for nanoelectronics and quantum computing applications where even small deviations can have a big effect on performance. The complete characterisation of self-assembled nanostructures is necessary to fully realize their potential. Through the use of characterization techniques, one may ascertain the mechanical, optical, electrical, and structural characteristics of nanostructures and make sure they fulfill the requirements for the applications for which they are designed (Cantrell, R., & Clancy, P. 2008).

EPITAXIAL GROWTH TECHNIQUES

For the purpose of creating thin films, several epitaxial growth processes are available, including molecular beam epitaxy, chemical beam epitaxy, and solid phase epitaxy. A brief overview of solid phase and chemical beam epitaxy is followed by a brief description of molecular beam epitaxy in this section. We have grown self-assembled nanostructures using molecular beam epitaxy. In materials science, epitaxial growth is an advanced technique for depositing a crystalline layer on a substrate crystal. The development of high-performance semiconductor devices, such as integrated circuits, photovoltaic cells, and light-emitting diodes (LEDs), depends on this technology. The epitaxial layer must ensure superior material qualities that are necessary for the operation of the device by matching the underlying substrate's crystallographic structure. There are several epitaxial growth processes, including as Liquid Phase Epitaxy (LPE), Metal Organic Chemical Vapor Deposition (MOCVD), Chemical Vapor Deposition (CVD), and Molecular Beam Epitaxy (MBE), each having specific benefits and drawbacks (Breuer, T., & Witte, G. 2013).

The highly regulated method known as "Molecular Beam Epitaxy" (MBE) involves physically depositing atomic beams in an ultra-high vacuum onto a heated substrate. With this method, the thickness and makeup of the epitaxial layers may be precisely controlled, allowing for the exact creation of complicated multilayer structures with atomic layer precision. Because MBE may yield high-purity materials with little contamination, it is very useful for research and development. However, MBE's application is restricted in large-scale commercial production due to its poor growth rates and high operating expenses. The term Chemical Vapor Deposition (CVD) refers to a range of processes in which a solid substance is formed by the reaction or breakdown of gaseous precursors on a heated substrate. The method is quite flexible and may be used to create a variety of materials, such as metals, dielectrics, and semiconductors. To get the required film characteristics in CVD, the substrate temperature and the gaseous precursor flow rates are carefully regulated. Scalability is the main benefit of CVD, which qualifies it for extensive industrial applications. However, it can be difficult to achieve uniformity and control impurities, particularly when dealing with complicated materials (Bao, Z., & Gao, Y. 2010).

A specific type of CVD called Metal-Organic Chemical Vapor Deposition (MOCVD) makes use of metal-organic precursors. Compound semiconductors like gallium arsenide (GaAs) and indium phosphide (InP) are frequently deposited using it. MOCVD provides superior control over the epitaxial layer composition and doping, which makes it the perfect method for creating high-performing optoelectronic devices. A crystalline layer forms on the substrate as a result of the thermal breakdown of metal-organic compounds in the presence of other gases. Managing the extremely reactive and occasionally dangerous precursors, which call for cautious handling and safety precautions, is one of the major problems of MOCVD. The process of Liquid Phase Epitaxy (LPE) entails depositing a crystalline layer onto a substrate from a supersaturated liquid solution. This method is frequently used to produce materials like gallium arsenide (GaAs) and indium phosphide (InP), and it is very effective for the development of thick layers. Compared to vapor phase methods, LPE provides benefits in terms of simplicity and cost-effectiveness. Nevertheless, the technique is less suitable for the formation of thin films and intricate multilayer structures, and it can be more difficult to regulate the thickness and homogeneity of the epitaxial layers (Fan, J., Duhm, S. 2018).

- **Chemical Beam Epitaxy**

The conventional definition of the technique of creating thin layers by surface chemical reactions is chemical vapor deposition (CVD). This method involves introducing the gaseous components of the source material to the surface of the sample. At the heated surface, the molecules of the precursor gas break down, releasing the desired species as the waste products are absorbed off the surface. Hydrides, such as, are the most common source of group IV and group V chemicals etc., Trimethyl gallium and other metal-organic compounds make up group III components. , triethyl indium etc.

The phrase metal-organic CVD, more commonly known as MOCVD, describes growth that takes place at relatively high pressures . Metal organic beam epitaxy (MOMBE) or chemical beam epitaxy (CBE) describe the growth process when carried out in an ultrahigh vacuum (UHV). Reactions in the gas phase do not impact the formation of CBEs; instead, surface chemistry dictates the growth process at low pressure, thanks to the long mean free path of the gas molecules. Conventionally, CBE necessitates greater temperatures and is significantly more complicated than MBE. But it keeps the film's excellent crystallinity while delivering faster growth rates (Takahashi, T., & Iwasa, Y. 2010).

- **Solid Phase Epitaxy**

A particular MBE growth regime known as "solid phase epitaxy" (SPE) involves initially depositing an amorphous layer at a lower temperature, which crystallizes when heated to a higher temperature. SPE-grown films often have a little lower crystallinity than MBE grown films. But when it comes to attaining abrupt doping patterns in epitaxial semiconductor films, SPE could be preferable to MBE. By thermal annealing amorphous or polycrystalline materials, Solid Phase Epitaxy (SPE) is a complex process used in materials research and semiconductor production to produce high-quality crystalline layers. Because of its capacity to yield crystalline layers devoid of defects and possessing precisely regulated qualities, the method is essential to the manufacturing of semiconductors, which are essential to a wide range of electrical devices.

SELF-ASSEMBLED GROWTH

In a bottom-up process known as self-assembled growth, atoms or molecules serve as the building blocks for nanostructures to develop. The term "self-assembled growth" refers to the formation of atoms or molecules that follow extremely precise guidelines for self-assembly and go through extremely selective binding. The overall significance and appeal for technological progress necessitates strict control over composition, size, and structure. Self-assembly is becoming a more common characteristic in the field of nanostructure synthesis because of how important this is to it. In epitaxial anostructures, structures that are self-assembled are formed when the lattice-mismatched overlayer-substrate system undergoes pseudomorphic development while simultaneously striving to decrease its free energy. We go through this growth process's specifics below. The process of self-assembled development is intriguing as it allows complex structures to emerge without external guidance, instead depending on the inherent characteristics and interactions of its constituent parts. This phenomena is essential to many scientific fields, including as chemistry, biology, materials science, and nanotechnology. It may be observed in both natural and artificial systems. Through the utilization of self-assembly principles, scientists may produce advanced materials and gadgets that exhibit exceptional accuracy and functionality, emulating the gracefulness and efficacy of organic processes (Rollbühler, N., et al. 2012).

Self-assembly is a fundamental component of biological order in the natural world. Proteins are classic examples of self-assembling molecules at the molecular level. Due to interactions including hydrogen bonding, hydrophobic effects, van der Waals forces, and electrostatic interactions, they fold into distinct three-dimensional structures. Proteins' ability to fold precisely determines how they interact with other molecules, catalyze processes, and carry out mechanical tasks in cells, all of which are essential to their biological function. Similar to this, the lipid bilayers that make up cell membranes are self-assembling structures. Amphiphilic molecules, with their hydrophobic tails and hydrophilic heads, spontaneously arrange into bilayers to produce a basic barrier that is strong and flexible. The process of self-assembly is essential for the development of bigger biological structures than solitary molecules. For instance, the protein components that make up viral capsids self-assemble into extremely symmetrical protective shells that encircle the viral DNA. This process is so effective that, given the correct circumstances, it frequently happens on its own, demonstrating how nature can create complex, useful structures with very little energy input. Comparably, to maintain cell shape, division, and motility, the cytoskeleton of eukaryotic cells which is made up of actin filaments, microtubules, and intermediate filaments self-assembles and dynamically reorganizes (Robertson, J. M., & Trotter, J. 1961).

Self-assembled growth is a potent method in materials science and nanotechnology that may be used to create new materials with exact structural characteristics. Block copolymers, which are made up of two or more chemically different polymer blocks covalently bound together, are one well-known example. These copolymers, depending on the relative lengths of the blocks and their interaction characteristics, can spontaneously arrange into a variety of nanostructures, including spheres, cylinders, and lamellae. Researchers can create materials with particular optical, mechanical, or electronic properties by adjusting these parameters; these materials can then be used in a variety of applications, such as drug delivery systems or photonic crystals. The generation of nanostructured materials by methods such as atomic layer deposition (ALD) and molecular beam epitaxy (MBE) also makes use of the notion of self-assembled growth. By using these techniques, atoms or molecules may be carefully deposited onto a substrate such that they can self-assemble into well-organized layers or nanostructures. For example, MBE makes it possible to build superior crystal layers in semiconductor production with atomic accuracy, which is necessary for the operation of cutting-edge electrical and optoelectronic devices.

Types of self-assembled nanostructures

One of nature's basic processes is self-assembly, in which parts independently arrange into structured structures in the absence of outside interference. Within the field of nanotechnology, self-assembly presents a potent method for precisely controlling the characteristics of complex nanostructures that are created. In this article, we examine many kinds of self-assembled nanostructures, looking at their traits, uses, and underlying principles (Tupkalo, A. V., et al. 2020).

Block Copolymer Micelles: Block copolymers are made up of two or more polymer chains joined together that have distinct chemical characteristics. These copolymers self-assemble into micelles in certain solvents, with the hydrophilic blocks forming the shell and the hydrophobic blocks forming the core, which protects them from the surrounding solvent. Block copolymer micelles are used in nanoreactors, medication delivery, and nanomaterial synthesis template.

Lipid Bilayers and Liposomes: In aquatic settings, lipids amphiphilic molecules with hydrophobic tails and hydrophilic heads spontaneously combine into bilayer structures. Cell membranes are built on top of these bilayers. Because of their biocompatibility and capacity to encapsulate both hydrophilic and hydrophobic molecules, liposomes spherical vesicles made of lipid bilayers have acquired popularity in the fields of medication administration, gene therapy, and cosmetics (Gong, Y., Zhu 2018).

DNA Nanostructures: DNA origami and DNA self-assembly methods allow for the exact design and manufacture of nanostructures due to the programmable base pairing of DNA molecules. Applications for DNA nanostructures in medication delivery, biosensing, nanoelectronics, and nanorobotics are numerous. They are potential possibilities for a range of biological applications because to their biocompatibility and programmability.

Colloidal Crystals: Colloidal particles, generally ranging from a few nanometers to several micrometers in size, can self-assemble into organized arrays known as colloidal crystals. Particle size, shape, and interparticle interactions are some of the elements that control how colloidal particles self-assemble. Colloidal crystals are used in optical coatings, photonic devices, and sensors because of their photonic bandgap characteristics.

Nanoparticle Superlattices: Superlattices are ordered structures formed by the self-assembly of nanoparticles, which include semiconductor, magnetic, and metallic particles. A number of variables, including solvent characteristics, surface chemistry, particle size, and shape, can affect how well nanoparticle superlattices self-assemble. These superlattices are interesting materials for photonics, electronics, and catalysis because of their distinct optical, magnetic, and electronic characteristics.

Applications of Self-Assembled Nanostructures

Because of their special qualities and wide variety of uses, self-assembled nanostructures which result from molecules or nanoparticles spontaneously organizing into ordered arrangements have attracted a lot of interest in a number of disciplines. These nanostructures provide intriguing answers to difficult problems in the fields of electronics and medicine. An examination of their uses in many sectors is provided below:

Electronics and Optoelectronics: The development of self-assembled nanostructures is essential to the advancement of optoelectronics and electronics. For example, semiconductor nanoparticles known as quantum dots have the ability to self-assemble into ordered arrays. These arrays improve the efficiency and performance of devices such as solar cells, light-emitting diodes (LEDs), and single-electron transistors (Wang, G., He, J., & Jiang, C. 2017).

Nanoelectromechanical Systems (NEMS): The creation of nanostructures with exact mechanical characteristics is made possible by self-assembly processes. The controlled assembly of nanomaterials enhances the sensitivity and functionality of NEMS devices, such switches and resonators, for use in sensing and communication applications.

Drug Delivery Systems: It is possible to design nanostructures that will encapsulate medications and deliver them to particular bodily locations. Self-assembling nanostructures, such as liposomes and micelles, allow for regulated release of medications and shield them from deterioration, increasing therapeutic efficacy and minimizing adverse effects. To further improve precision medicine, targeting ligands can be included into these structures for site-specific delivery (Evans, J. W. & Bartelt, M. C. 2006).

Tissue Engineering: Self-assembled nanostructures function as a scaffold for tissue regeneration and cell proliferation by imitating the structure of the extracellular matrix. Through manipulation of nanomaterial assembly, scientists may create scaffolds with specific mechanical and biological functions. These scaffolds are used in regenerative medicine to help heal injured organs and tissues.

Catalysis: When compared to bulk counterparts, nanostructured catalysts have higher catalytic activity and selectivity. The development of well-defined catalyst structures, such as nanowire networks and nanoparticle arrays, is made easier by self-assembly processes. Chemical synthesis, environmental remediation, and petroleum refining are just a few of the industrial processes that employ these catalysts (Fan, C. C., Liu, Z. T., 2017).

CHARACTERIZATION TECHNIQUES

In order to describe the structures formed on MBE, we have mostly used TEM, RHEED, HRXRD, STM, and STS for observation. Several approaches will be covered in this section.

Writers employ characterization tactics as essential tools to give their characters life and give them nuance and complexity. These approaches cover a wide range of literary tactics and narrative techniques used to provide light on the motives, personalities, and innermost thoughts of the characters in a story. Direct characterisation is one of the most basic approaches, in which writers clearly state a character's attributes, including look, demeanor, and beliefs. Direct characterisation gives readers a clear understanding of the character's motivations and identity right away. A writer may characterize a character as "tall and imposing, hinting at a no-nonsense attitude," for instance. Readers may easily visualize the character's appearance and mannerisms thanks to this straightforward description. When communicating details about characters, indirect characterisation uses a more nuanced approach than direct characterization. By using this method, which entails showing rather than telling, readers are able to deduce characteristics and intentions from the actions, conversations, inner monologue, and interpersonal relationships of the characters. For example, the author may convey a character's bravery by showing them running into danger to save a buddy, rather than just saying that they are brave.

Dialogue is a potent characterisation tool that provides information about the personalities, relationships, and backgrounds of people. Readers are able to comprehend the viewpoints and struggles of the characters by means of conversation, wherein they express their own thoughts, feelings, and intentions. Through observing the vocabulary, tone, and body language used in conversation, readers may learn details about the personalities, cultural backgrounds, and socioeconomic status of the characters. Internal monologue offers a window into the heads of the characters, revealing personal glances into their desires, anxieties, and thoughts. Writers may give characters more nuance and complexity by delving into their inner problems, uncertainties, and motives through internal monologue. By exploring the inner lives of their characters, writers foster empathy and understanding, which strengthens the emotional bonds that bind readers to their characters (Seki, K., & Ueno, N. 1994).

Character behaviors and responses are also essential to characterisation since they provide light on the moral compass, beliefs, and priorities of the characters. Character behavior, no matter how minor or how overt, conveys a great deal about the person they are and the values they uphold. Characters' reactions to difficulties, setbacks, and conflicts can provide information about their traits, shortcomings, and development paths as the narrative progresses. Characters' behaviors and outward looks operate as external indicators of their personalities, giving readers visual signals that influence their opinions. In order to create characters who are distinctive and unique, writers frequently employ vivid descriptions of look, clothes, and movements. These bodily characteristics can enhance the reader's comprehension of the character by revealing underlying emotions and behaviors, such as a jittery habit or dangerous look. Character characterisation heavily relies on relationships between characters since these relationships disclose relationships, conflicts, and connections that help to define a character's identity. Interactions with other characters, whether they be a passionate competition, a sexual involvement, or a close relationship, may reveal new sides to personalities and spur character growth. By providing symbolic interpretations of characters, symbolism and metaphor enable authors to communicate more complex ideas and levels of meaning. Characters can represent abstract ideas, social positions, or archetypal figures through symbolic imagery and allegorical components, giving the story more allegorical depth and resonance.

Scanning tunneling microscopy (STM)

The 1986 Noble Prize in Physics was bestowed upon Gerhard Binnig and Heinrich Rohrer in recognition of their development of scanning tunneling microscopy (STM), which occurred in the early 1980s.

The most crucial aspect of scanning tunneling microscopy (STM) is its capacity to resolve atomic scale features on conducting material surfaces in real time and space. Superior to other microscopy methods, STM boasts extraordinarily high lateral and vertical resolution. There are a number of significant outcomes that result from the capacity to achieve atomic resolution in real space (Koch et al., 2006).

- The atomic level allows for the monitoring and control of surface structures, whether naturally occurring or man-made (e.g., using MBE).
- A local experiment may be carried out by precisely positioning the tip over a pre-selected atomic spot, thanks to the atomic resolution capabilities. This is where scanning tunneling spectroscopy (STS) and I-V measurements come in handy for determining electronic local densities of states (LDOS).
- The capacity to precisely position the tip and observe surface features at the atomic level allows for precise anipulation at the atomic level, which in turn opens the door to the possibility of developing electronics on the scale of an atom (Hasegawa, T., & Takeya, J. 2009).

Reflection high energy electron diffraction (RHEED)

The structure of surfaces may be extensively studied using diffraction methods that employ electron or X-ray photons. Traditional methods of analyzing particles or waves dispersed elastically by a crystal yield structural information. Diffraction beam intensities reveal atomic configurations inside a unit cell. Crystal lattice information is conveyed via the spatial distribution of diffracted beams. The diffraction pattern is directly proportional to the crystal reciprocal lattice, making it straightforward to evaluate the crystal lattice under the following conditions:

$$\mathbf{k} - \mathbf{k_0} = \mathbf{G_{hkl}}$$

In what ways $\mathbf{k_0}$ where the incident wave vector is located. $\mathbf{k}$ is the vector of dispersed waves, and $\mathbf{G_{hkl}}$ is a lattice vector with reciprocity. Given that scattering is flexible, $|\mathbf{k}| = |\mathbf{k_0}|$ from the momentum and energy conservation laws. An endless number of options exist to satisfy this requirement. $\mathbf{k}$ vectors with several directions of travel. An Ewald sphere is commonly used to illustrate discussions about diffraction. A sphere with the origin of its center as the Ewald sphere $\mathbf{k_0}$ as well as its radius $|\mathbf{k_0}|$. Therefore, since diffraction happens for everyone, the Laue condition may be reformulated. $|\mathbf{k_0}|$ linking a reciprocal-lattice point and the sphere's origin. The extent $|\mathbf{k_0}|$ of from the term that is relativistic is:

$$k_0 = \frac{2\pi}{\lambda} = \frac{1}{\hbar}\sqrt{2m_0qV + \left(\frac{qV}{c}\right)^2}$$

Where m_0 is the rest mass of an electron q what is its fee, and V is the capacity for acceleration. The method of reflection high energy electron diffraction (RHEED) is extensively employed in the investigation of structure and growth. RHEED uses high energy electrons, but because the incidence and detection angles are grazing, it is extremely surface sensitive. $(\sim 1 - 3°)$. This means that high-energy electrons remain at the surface-near, barely a few atomic layer deep, area during the sample's relatively lengthy mean free path. Because of RHEED's design, the electron gun and screen are positioned at a considerable distance from the sample. And therefore the deposition procedure can begin with the sample's front being open. Consequently, RHEED might be used as an in-situ technique to watch the structure of a changing surface as it evolves.

CONCLUSION

Structure elucidation and electrical characterisation of Molecular Beam Epitaxy (MBE)-grown nanostructures have greatly improved our knowledge of nanoscale materials, resulting in advances in nanotechnology, quantum computing, and optoelectronics. New methods including X-ray diffraction (XRD), scanning tunnelling microscopy (STM), and high-resolution transmission electron microscopy (HRTEM) have revealed atomic configurations and flaws like never before. Electronic characteristics, carrier dynamics, and transport processes may now be precisely evaluated thanks to electrical characterisation techniques as scanning probe methods, impedance spectroscopy, and Hall effect investigations. In addition to improving material optimisation, the combination of these cutting-edge approaches has made it easier to create high-performance nanodevices. Even yet, there are still difficulties in reaching atomic-scale accuracy and comprehending intricate quantum effects in low-dimensional systems.

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