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Chemical Engineering in the Processing of Electronic and Optical Materials: A Discussion

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I. Introduction

The processing of electronic and optical materials involves scientific and engineering concepts from a multitude of disciplines, including chemistry, solid-state physics, materials science, electronics, thermodynamics, chemical kinetics, and transport phenomena. Chemical engineers have a long history of solving multidisciplinary problems in other specialized fields, such as food processing and polymer processing, and there is a growing recognition of the useful contributions that chemical engineers can make to electronic materials processing. Within the last decade, between 15 and 30% of chemical engineering graduates have taken positions in electronic materials processing companies, and chemical engineering research on the topic has grown to the point where it has become recognized in the electronic materials community.

The emergence of electronic materials processing, along with other specialized topics within the chemical engineering discipline, raises questions about research, teaching, and the profession in general, questions similar to those asked in other areas, such as biotechnology. The aim of this discussion is to address some of these questions and not to present an exhaustive review of the field. A more complete overview is given in the contribution to this volume by Thompson [1] and in other recent reviews [2, 3]. In particular, the issues to be addressed are research opportunities as well as undergraduate and graduate teaching. The views expressed in the following are those of the author and cannot do justice to the many different viewpoints possible in this highly interdisciplinary research area.

II. Characteristics of Electronic Materials Processing

Electronic materials processing is a chemical manufacturing process aimed at modifying materials to form microstructures with specific electronic and optical properties. For example, in the manufacturing of silicon-based integrated circuits, silicon is refined into high-purity crystals. These are sliced into wafers that serve as the foundation for the electronic devices. The subsequent process sequences involve oxidation of the wafer surface and deposition of semiconductors, dielectrics, and conductors interspersed by patterning through lithography and etching. The final microstructure is then cut from the wafer and enclosed in a ceramic or polymer-based package that provides connections to other electronic components and protects the microstructure from contamination and corrosion. Similar process steps are used in other applications of electronic materials processing, including production of optical coatings, solar cells, sensors, optical devices, magnetic disks, and optical storage media. While microelectronic applications have typically received the most attention, many other related processes present equally challenging chemical engineering problems.

Regardless of the final device, electronic materials processing involves a large variety of chemical procedures applied to a multitude of material systems. In addition to conventional chemistry, electron- and photon-driven reactions play a major role through plasma- and laser-assisted processes. Multiple length scales are involved in the fabrication. Typical sizes of reactors used for depositing and removing layers are of the order of 1 μm and the substrate wafers are 15–20 cm across. On the other hand, in electronic devices the typical feature size is of the order of 1 μm and shrinking with each new generation of devices. The active region in quantum well lasers is less than 5 nm. By way of comparison, the ability to resolve a 1-μm feature on a 20-cm wafer corresponds to being able to observe individual houses on a map of the United States. The microstructures have to be reproduced uniformly across each wafer as well as from wafer to wafer.

Electronic materials processing demands high-purity starting materials. Even minute quantities of impurities have the potential to alter or destroy the electronic and optical properties of a device. Unlike many other chemical processes, the costs of starting materials are usually insignificant in comparison to the value added during the process. Furthermore, the field changes rapidly, is highly competitive, and is based on innovation, unlike commodity chemicals, where small improvements in large-volume processes are typical.

The manufacture of even simple devices may entail more than 100 individual steps. However, many of the same concepts and procedures are invoked several times. Therefore, it is advantageous to group the process steps broadly in terms of unit operations analogous to those used successfully to conceptualize, analyze, design, and operate complex chemical plants involving a similarly large number of chemical processes and materials. Examples of these unit operations are listed in Table 1.

The use of chemical engineering concepts has already contributed significantly to crystal growth [4], thin-film formation [5–7], and plasma

Table 1. Examples of Unit Operations in Electronic Materials Processing

Unit Operation	Examples of Processes
Bulk Crystal Growth	Czochralski Bridgman Float zone
Chemical Modifications of Surfaces	Oxidation Cleaning Etching
Thin Film Formation	Liquid Phase Coating Physical Vapor Deposition Chemical Vapor Deposition
Plasma Processing	Etching Deposition
Lithography	Spin Coating Exposure Development
Semiconductor Doping	Solid-State Diffusion Ion Implantation
Packaging	Polymer Processing Ceramics Processing Metallization

processing [8, 9]. These unit operations involve the complex blend of transport phenomena and chemical reactions that chemical engineers have a unique background for understanding and controlling. The polymer processing aspects of lithography [10, 11] and packaging of devices [12] as well as the ceramics processing problems related to packaging provide additional opportunities for chemical engineering research.

III. Research Opportunities

Research in electronic materials processing must necessarily revolve around one general question: *How do structural, electronic, and optical properties of a material or a device depend on the processing and how can they be controlled?*

The many ways in which chemical engineers can contribute to addressing this question have been described in the Amundson report [13] in broad terms. Therefore, the present discussion will focus on three examples: (1) organometallic vapor-phase epitaxy of compound semiconductors, (2) plasma processing, and (3) process control. These examples are chosen on the basis of the author's experience to illustrate particular research issues rather than to promote specific research topics. The first example explores research questions with clear analogies to similar problems already solved by chemical engineers in the areas of heterogeneous catalysis and combustion. The second example introduces research issues related to the presence of charged species and the control of microscopic features. The third case is intended to show how chemical engineers could use their analysis and modeling skills in process control of electronic materials manufacture. In addition, a discussion of general research trends appears at the end of this section.

A. *Example 1: Organometallic Vapor-Phase Epitaxy*

Organometallic (also called metalorganic) vapor-phase epitaxy (MOVPE) is an organometallic chemical vapor deposition (MOCVD) technique used to grow thin, high-purity, single-crystalline films of compound semiconductors such as GaAs, InGaAsP, ZnSe, and HgCdTe [14]. These films form the basis for a wide range of optoelectronic devices, including solid-state lasers and detectors. The technique, which is illustrated schematically in Fig. 1, derives its name from the fact that the film constituents are transported as organometallic species in the gas phase to the heated growth surface, where the individual metal atoms are cleaved from their organic ligands and incorporated into the compound semiconductor lattice. For example, GaAs can be grown by combining trimethylgallium and arsine according to the overall reaction

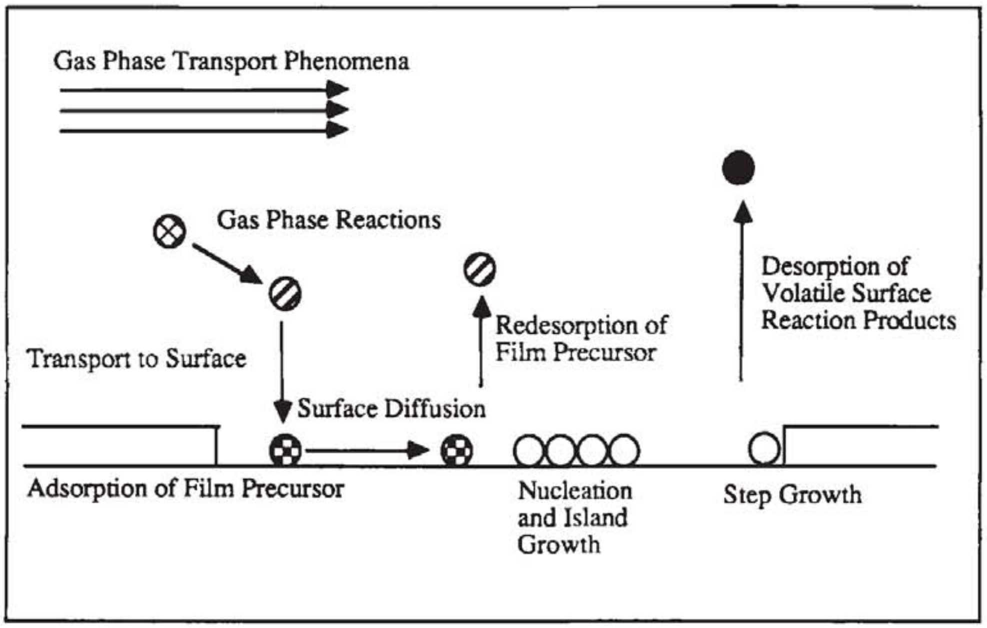

Figure 1. Schematic diagram of transport phenomena and chemical reactions underlying organometallic vapor-phase epitaxy.

$$Ga(CH_3)_3(gas) + AsH_3(gas) = GaAs(solid) + 3CH_4(gas) \qquad (1)$$

The technique has the flexibility to grow a multitude of compound semiconductor alloys by varying the composition of the source gas.

Transport processes govern the extent of gas-phase reactions and the access of the resulting film precursors to the growth interface. As the organometallic compounds approach the hot substrate, they react to form growth precursors as well as undesirable species causing unintentional doping of the growing film. Similarly, surface reactions participate in the film growth. However, parasitic reaction paths may incorporate impurities into the solid film, in particular carbon which is derived from the organometallic precursors. In the worst case, the incorporation of unintentionally added optically and electronically active impurities will render the grown semiconductor useless for device applications. This complex mixture of chemical reactions and transport phenomena is well known to chemical engineers in the context of heterogeneous catalysis, combustion, and in particular catalytic combustion. The same modeling and experimental approaches can in principle be utilized to investigate MOVPE processes. In fact, the presence of well-defined, high-purity source compounds and single-crystalline substrates used in MOVPE means that the actual process can be studied without the need for model systems, which have had to be invoked to gain insight into the more complex heterogeneous catalytic processes.

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