Fields of Materials Science and Production

Achievement

Development of metal-organic chemical vapor deposition technology for compound semiconductor electronic and optoelectronic devices, and pioneering contribution to its large-scale commercialization

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Compound semiconductor devices as the backbone of information society

Silicon devices that perform computations are not the only devices that play a significant role in today's information society; there is also a need for electronic and optical devices made from compound semiconductors, which can handle light and radio waves.

Compound semiconductors are semiconductors made from two or more different elements. When building a compound semiconductor device, single-crystal films to a thickness of between a few nanometers and a few hundred nanometers are used (1 nanometer is equal to one-billionth of a meter) (Fig.1). Metal-organic chemical vapor deposition (MOCVD) is widely used in the large-scale commercial production of such films. For example, to fabricate a thin film of gallium nitride (GaN) or gallium arsenide (GaAs), trimethylgallium ($Ga(CH_3)_3$) and other organometallic compounds are turned into gas and fed into a reactor. It is from this that the process gets its name.

MOCVD and other methods such as liquid-phase epitaxy and molecular-beam epitaxy – all of which produce thin, single-crystal films by layering atoms as described above – are known as "epitaxial crystal growth" techniques. The 1970s saw a great amount of research being conducted into which of these techniques was most suitable for commercial production of compound semiconductors, and Dupuis focused his research on MOCVD.

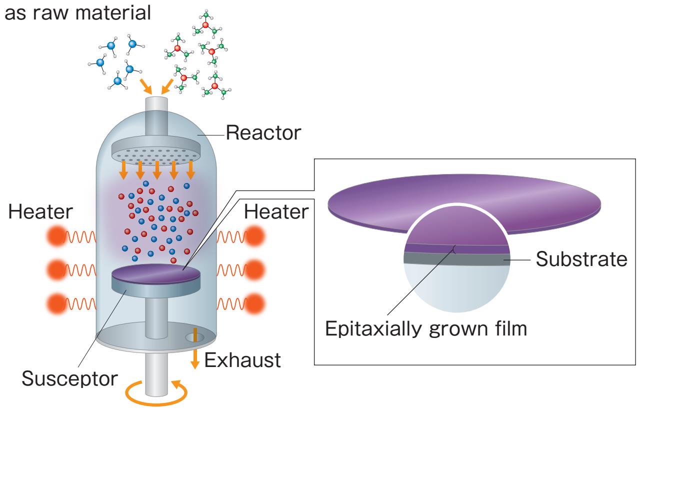


Figure 1: Schematic diagram of reactor used in MOCVD, and an image of a film formed using this technique.

What is metal-organic chemical vapor deposition (MOCVD)?

Figure 2 shows the MOCVD reaction for gallium arsenide, a typical compound semiconductor. Gallium arsenide allows for higher electron mobility than silicon, making it well-suited for use in high-speed communications, and it is also widely-used in infrared optical sensors used in television and air conditioner remote control devices.

During the production process, a mixture of organometallic trimethylgallium ($Ga(CH_3)_3$) gas and arsine (AsH_3) gas is supplied to a reactor and subjected to thermal decomposition. The pyrolysis of the vapor-phase mixture allows for deposition of a single-crystal film of gallium arsenide on the substrate. The formation of this film is precisely-controlled at the atomic level, and it can now perform the desired function, such as being used in optical sensors.

Harnessing raw materials in gaseous form, MOCVD is capable of producing large, flat films in a comparatively shorter time than other epitaxial crystal growth techniques. Moreover, MOCVD does not require an ultra-high vacuum to work, and has a number of other features that make it advantageous for use in mass production. However, a number of reports in the earliest days of MOCVD research claimed that it was difficult to use the technique to grow high quality films, so research into it lagged for a period of time.

Improvements in MOCVD equipment make large-scale commercial production possible

Dupuis conducted a detailed analysis of the crystal growth process in the early 1970s, and used what he

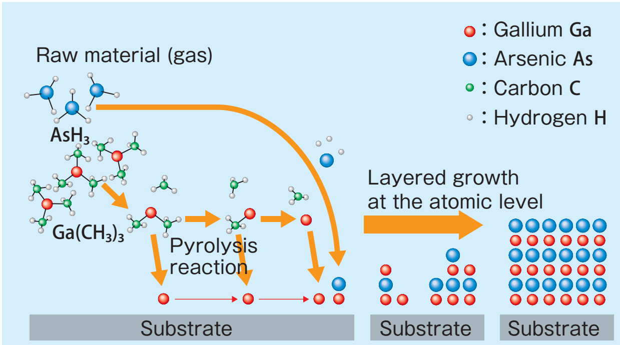
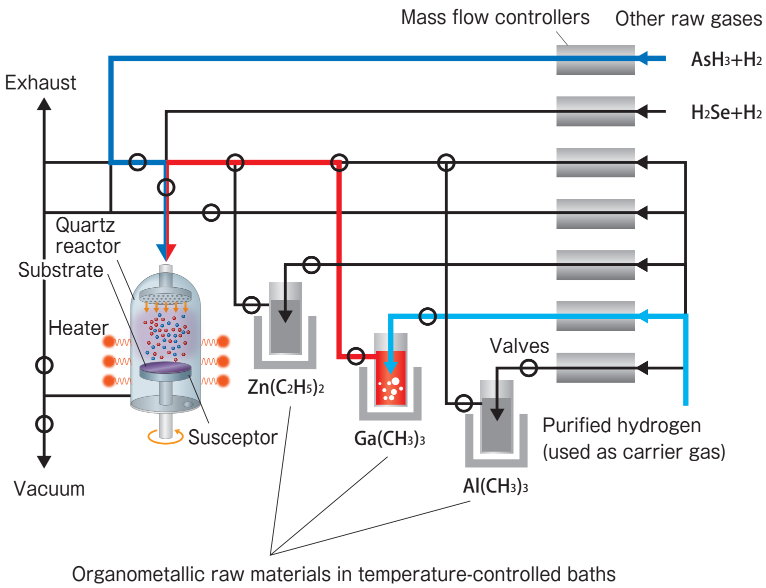


Figure 2: The MOCVD epitaxial growth process.
The gaseous raw material is subjected to thermal decomposition and leaving only the elements of interest to be grown as a crystalline film on the substrate.



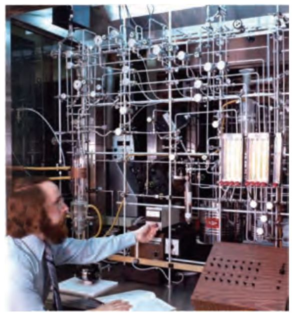


Figure 3: Dupuis' first MOCVD reactor at Rockwell International (photograph from October 1975) and diagram showing how the device was operated.

Hydrogen and nitrogen are used as carrier gases to transport the vaporized organometals, and the gaseous raw materials are supplied to the quartz reactor at a precise mixture rate by adjusting the flow rate with valves. Within the reactor, the raw material is subjected to thermal decomposition, leaving the elements of interest to form an epitaxial single-crystal thin film on a substrate.

Photograph source : R.D. Dupuis, *IEEE J. Sel. Top. Quantum Electron* 2000, 6 (6), 1040-1050.

discovered to improve his MOCVD system in various ways (Fig. 3). First, he made the piping used to transport the gas more efficient, and built a system that allowed him to quickly adjust the flow of gas. He also introduced all-welded gas supply bubblers of his own design to store the raw material, which ensured that the system was as clean and as leak-tight as possible. In addition, he used a computer to control the opening and closing of valves, allowing him to precisely control the composition of the raw gases and fabricate heterojunctions with two different compound semiconductors.

Through innovations like these, Dupuis was able to demonstrate that MOCVD could produce a high quality, uniform, defect-free film over a large area at high speeds. In 1977, he used a newly-constructed MOCVD system to build a double heterostructure with two semiconductors, gallium arsenide and aluminium gallium arsenide, in three layers, and thereby successfully demonstrated the world's first continuous operation of a laser at room temperature. Dupuis was also able to use the process to fabricate high efficiency solar cells and quantum well lasers, for which emission wavelength could be adjusted by changing the thickness of the film. His research demonstrated that MOCVD could be used in manufacturing semiconductor heterojunctions that could handle practical use, which then became the catalyst for its later use in commercial mass production.

Supporting the commercialization of new functionality demanded by society

Today, semiconductor lasers are widely-used in a variety of applications, from optical communications and DVD laser diodes to laser pointers and bar code scanners (Fig. 4). Some types of solar cells are also manufactured using the MOCVD technique developed by Dupuis.

These techniques are in particularly wide use in the manufacture of blue LEDs and other LEDs, which are used as lights around the world due to their ability to provide bright illumination with lower power consumption than conventional lighting options, and the market for MOCVD-produced LED lighting will surely continue to grow. Moreover, as compound semiconductors can be made by combining multiple elements to provide various different functions, it is expected that they will continue to contribute to the future development of new electronic and optical devices.

Professor Russell Dean Dupuis' breakthrough led to the commercialization of compound semiconductor production. It has become the foundation upon which our modern information society is built, and will continue to play an essential role in societal development into the future.

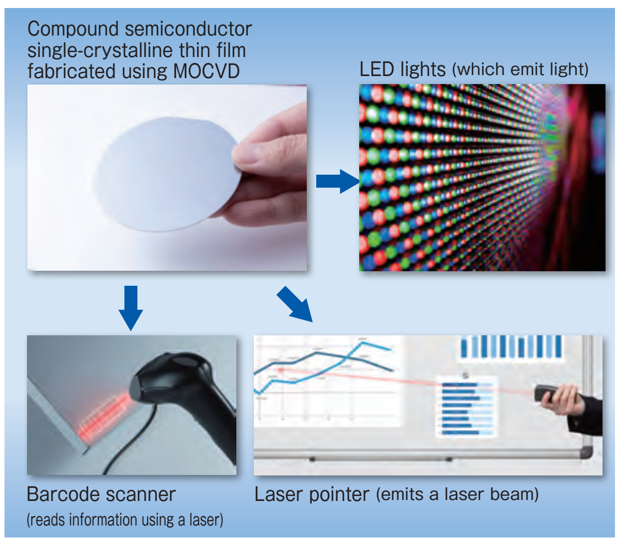


Figure 4: Some applications for compound semiconductors produced using MOCVD.

These are just a few of the many applications in which compound semiconductors can be used, with examples here including optical devices such as LEDs and semiconductor lasers.