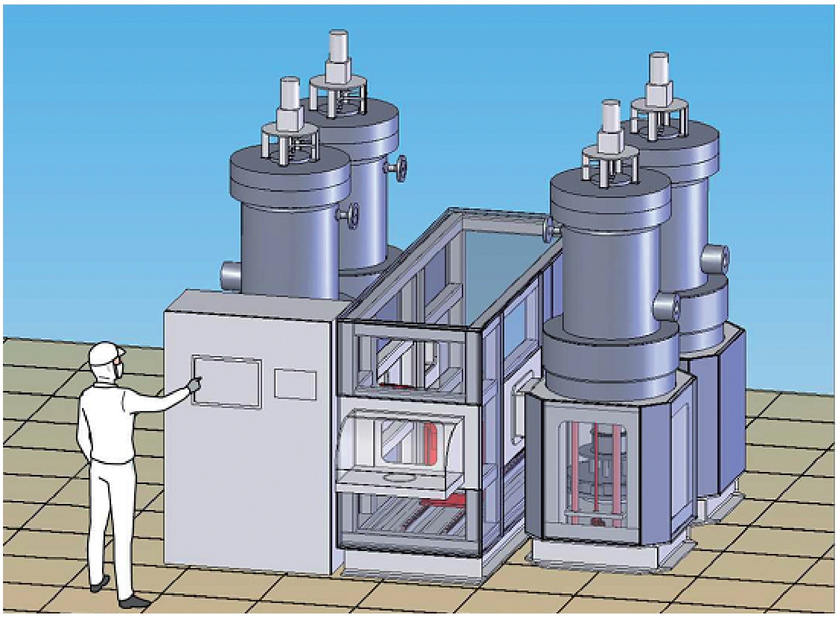
The Next Generation Semiconductor World - Expanded via High-Temperature, High-Pressure Technology

IHI Group has challenged the established manufacturing methods of the difficult mass-produce technology of “gallium nitride (GaN).”

“Gallium nitride (GaN)” is a next-generation semiconductor, crucial for the performance improvement and spread of optical and power devices. IHI Group is developing a high-temperature, high-pressure furnace aimed at the mass production of GaN. What is the GaN semiconductor? What is the furnace’s technology for GaN production?



Next-generation semiconductor producing prototype furnace

Contribution of semiconductors

When talking about semiconductors, we often see the names of devices such as LSIs, DRAMs, and CPUs in the newspapers. These devices are mainly used for information and signal processing and silently operate in various types of equipment such as mobile phones, PCs, white goods, cars, and control systems for huge plants. This is why semiconductors are called the "rice of industry" in Japan.

Apart from this, there are also semiconductor devices used for energy processing, and such semiconductor devices are called power devices. These power devices play a major role in hybrid vehicles and inverters. Furthermore, devices transmitting or receiving energy via light, the so-called optical devices, are located in many everyday items such as semiconductor lasers used in CD/DVD/BD players, laser pointers, and LEDs (Light Emitting Diodes); these are rapidly spreading as a means of energy-saving illumination that convert electrical energy into light. Conversely, well-known solar cells are ones that convert light into electrical energy in an opposite manner.

Based on such trends, it is obvious that power and optical devices will become increasingly important in the future, and the improvement in performance, sufficient supply, and cost reduction, will be necessary. For these reasons, the next-generation semiconductors called wide-gap semiconductors are attracting attention, and one of them is GaN.

Characteristics of GaN

GaN is, as its name suggests, a compound derived from of a metal called gallium, and nitrogen. To give it semiconductor properties, orderly crystallization is required. The expected applications of GaN include light emitting devices, and in this section, characteristics of GaN when used as a substrate for an LED among the light emitting devices are described.

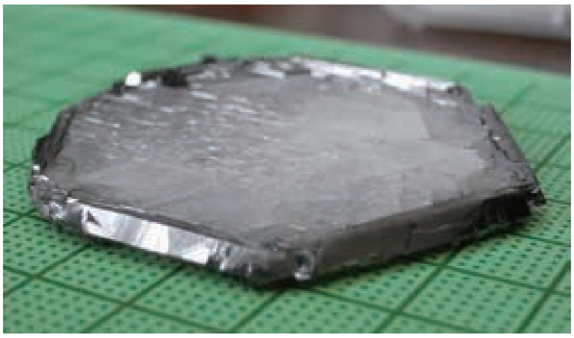
For a conventional substrate, sapphire is mainly used. When compared with the sapphire substrate, the GaN substrate is characterized by the following points.

(1) Less defects in the LED light emitting layer on the substrate
  → Improvement in reliability and lifetime
(2) Higher thermal conductivity (five times higher than sapphire)
  → Usable at large current (large heat generation)
  Efficiency reduction due to high temperature is small.
(3) Higher electrical conductivity (sapphire is almost an insulator)
  → Uniform light emission within a surface
  Able to simplify device structure
(4) Transparent substrate
  → High use efficiency of light emitted from LED
(5) Higher processability
  → Easy chipping (cutting out of a wafer is easy)

As described, GaN is full of advantages as a substance. However, the reason why GaN cannot easily replace sapphire is because it is a material that is difficult to produce.

How to produce semiconductor

Talking about the production of semiconductor devices, you may hold an image of a robot moving at a tremendous speed above circular, shining thin plates. This image represents semiconductor wafers on which various processing steps are performed to make the wafers into LSIs or solar cells. These steps are close to the last steps in the whole process. Now, the question is how to produce the substrates.



GaN substrate
(Courtesy of Prof. Mori of Osaka University)

Most semiconductor devices used for applications such as information processing described above are made of silicon (Si). A way to produce silicon substrates has already been established, which includes the following steps:

(1) High purity silicon is melted in a crucible.
(2) A rod is moved down to the molten silicon to bring the tip of the rod into contact with the surface of the molten silicon, and then slowly pulled up and rotated simultaneously. Silicon is attached to the rod while being solidified.
(3) A thick silicon ingot is formed. The ingot itself is a single large silicon crystal (bulk crystal). Currently, a silicon ingot is grown up to a diameter of 30 cm and a length of 1.8 m, which is a surprisingly large-size considering that a grain of salt corresponds to one crystal.
(4) By slicing the silicon ingot with a thin sharp blade, a large number of circular silicon substrates (wafers) are obtained.

A production method as described above is called a bulk crystal production method. This method of producing a large number of ingots at low cost has widely spread, and therefore the silicon semiconductor has been able to serve as the "rice of industry."

On the other hand, for GaN, there has been no method of producing a large bulk crystal with enough speed, and the only available method has been to grow a GaN bulk crystal during the gas phase. This of course increases cost; which has prevented high-performance devices using GaN from spreading.

A bulk crystal production method finally appeared and is called the Na flux method.

Na flux method

In the Na flux method, molten (liquid) gallium and nitrogen react with each other to produce a bulk crystal, in a similar manner as with silicon. When doing so, nitrogen cannot be sufficiently dissolved in gallium unless considerable high pressure or temperature is applied. Therefore, by adding sodium (Na) as an additive, nitrogen is made easily dissolvable.

However, only raising the temperature to dissolve nitrogen in molten gallium is not sufficient to make the GaN ingot process work, unlike the silicon ingot process.

(1) Temperature must be raised to a value where nitrogen can be sufficiently dissolved in molten gallium (approximately 1 000°C). In addition, the nonuniformity of temperature must be within 5°C throughout a crucible.

(2) High pressure is applied in order to dissolve nitrogen in the molten gallium (approximately in the pressure of 100 atm).

(3) It is necessary to keep the melt (molten gallium) in the crucible slowly moving to ensure the nitrogen and gallium mix sufficiently, and the fresh melt is uniformly distributed over the surface of a growing crystal. Note that the movement or flow of the melt must be gentle and uniform everywhere.

(4) Even a tiny amount of impurities make the crystal defective.

(5) The growth speed of the GaN crystal is low, and therefore to obtain the bulk crystal, the above conditions should be kept stable for several days.

To develop a furnace to be used in such severe and delicate conditions, high-temperature, high-pressure technology of IHI Group was utilized.

Swing, propeller and rotation methods

To keep the temperature and pressure constant while avoiding contamination by impurities, a crucible in a completely closed state is desired. The swing method is a method of slowly swinging the whole of the crucible in such a way as to form the flow of the melt. However, with this method, it is difficult to control the flow of the melt, limiting the speeding up of the melt flow corresponding to a crystal growth speed, and the uniformity of flow for quality improvement.

On the other hand, a propeller or rotation method is a method that directly stirs the melt with a propeller inserted into the crucible to form the flow, or rotates only an internal container. The propeller or rotation method is expected to be able to freely control the flow of the melt and quickly grow a high-quality crystal through the preliminarily preparation of several types of propeller shapes and positions suitable for the properties of a crystal to be grown, and also changing a rotational speed during operation.

Now, the question is whether or not the propeller or rotation method can go well as expected.

IHI Group's high-temperature high-pressure technology and new designs

The "severe conditions of 1 000°C and 100 atm" were described above; however, in practice, these values are "not challenging enough" for IHI Group's furnace technology. Blast furnaces playing a major role in ironworks have been operating for years at approximately 2 000°C, and IHI Group is also familiar with ceramic sintering furnaces utilizing 100 atm. However, inserting a propeller into a furnace under the conditions of 1 000°C and 100 atm for stirring was the first challenge.

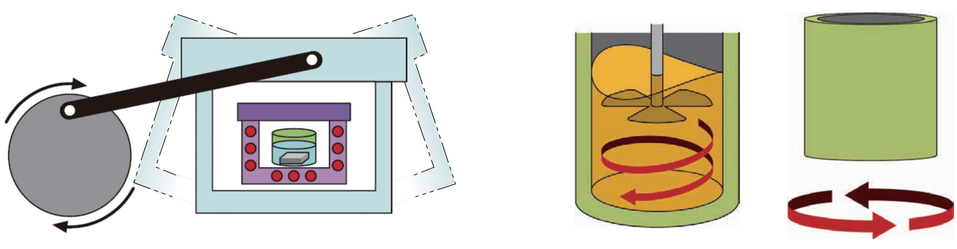
The first problem was that the heat inside the furnace escaped outside through the gaps between the propeller shaft and bearings. With a conventional high-pressure propeller unit, the heat directly goes outside. For this reason, we focused on reducing the loss of the heat by attaching a bellows cover around the shaft to stop the flow of high-pressure gas.

The next problem lied in the bearings supporting the propeller shaft. This furnace has a triple container structure, and bearings are required in three positions. Since even a tiny amount of impurities are unacceptable, lubricant such as grease cannot be used. In addition, the bearings should be resistant to high temperatures of close to 1 000°C. For these reasons, we employed plain bearings made of special composite material (the shaft and the bearings slide on each other). Furthermore, since it was necessary to introduce nitrogen gas from outside while preventing the mixture of impurities, both high sealing performance and ease of gas introduction were achieved by appropriately designing the gaps between the shaft and the bearings. The whirling of the shaft was also modified.

In order to confirm whether or not such high-temperature, high-pressure technology actually functions, a prototype was fabricated, and under the supervision of Professor Yusuke Mori of Osaka University, continuous operation was performed for days to evaluate performance. In addition, the prototype was improved accordingly. For example, due to the thermal deformation of the triple container while in high temperature continuous operation, the displacement of bearings occurred, and therefore we designed a structure which accepts the

(a) Swing method

(b) Propeller and rotation methods



Swing, propeller and rotation methods

displacement and keeping the shaft stable while in rotation.

Simulation of melt flow

How does the propeller form the melt flow in the crucible? To form the flow suitable for crystal growth, how should we set the shape, arrangement, and rotation speed of the propeller? Setting up a sensor in the crucible to make measurements is impossible, and making an observation model using water also has limitations.

For these reasons, flow simulation technology that had been developed, and utilized for years in IHI, came to play an important role. The crucible, propeller, and substrate for growing the crystal were represented by "calculation meshes," and the propeller was rotated to calculate the flow of the gallium melt. Since the meshes and the rotation speed of the propeller were freely changeable, we ran many simulations to predict what flow will be formed and under what conditions. From the simulation results, we determined the optimum shape and arrangement of the propeller.

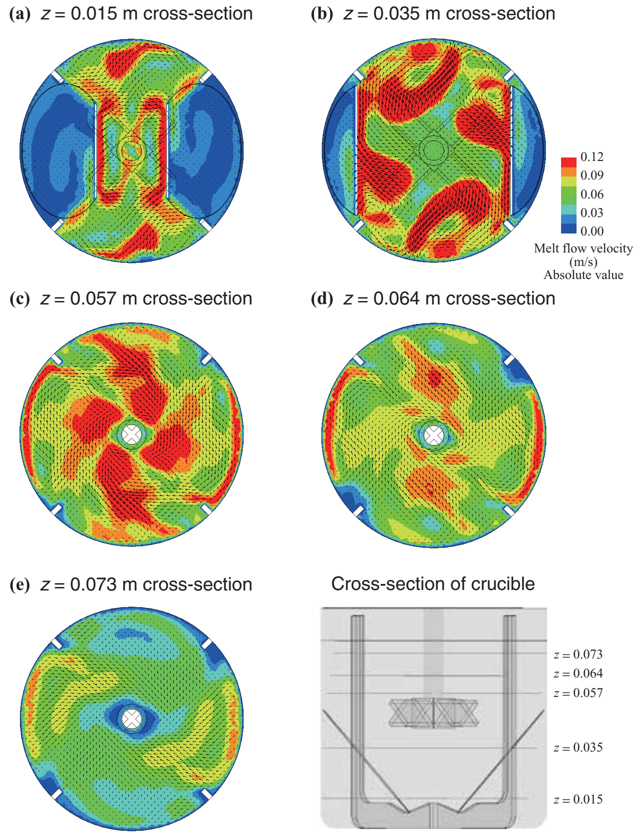
Completion of furnace and further testing

IHI Group has developed the Na flux method-based GaN substrate production furnace employing the propeller/rotation method incorporating the design described above. The basic potential of the substrate producing furnace of this type has already been confirmed. However, to actually produce a high-quality crystal at high speed, we have to design better methods in regards to substrate setting, stirring, speed control, and so on. This is because keeping the methods fixed is not necessarily the best policy. Such settings and operation methods are collectively called a "recipe" by professionals. The furnace developed by IHI Group is a prototype for research and can easily be utilized to follow various recipes. Therefore we believe this furnace will be widely used in the future.

Social infrastructure envisioned with GaN semiconductor

As first described, the GaN semiconductor is expected to play an increasingly important role. When the Na flux method is industrially established in place of the vapor phase method, a massive number of lower-cost substrates will be achievable. This will lead to ordinary people experiences of the benefits such LED illumination which is not only brighter, but also lower-cost and longer-lasting.

The furnace for producing the substrates works behind the scenes. Sophisticated technologies acquired through many experiences and accomplishments are, while hidden, nonetheless responsible for this.



Simulation of Ga melt flow

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