Diamond Semiconductors Operate at Highest Frequency Ever—A Step Closer to Diamond Devices for Communication Satellites, Broadcasting Stations, and Radars

NTT has developed diamond semiconductor devices whose operating frequency and power are the highest in the world. These diamond devices will one day replace the vacuum tubes now used in the very-high-frequency, very-high-power region, leading to increased output power in communication satellites, television broadcasting stations, and radars.

NTT Basic Research Laboratories, in collaboration with the University of Ulm, Germany, succeeded in fabricating a diamond semiconductor device using high-purity diamond crystals. The device's highest operating frequency is 81 GHz. It therefore operates as an amplifier in the millimeter region (corresponding to a frequency of 30 to 300 GHz), which is the first time this has been achieved for any kind of diamond device. Owing to the properties of diamond, the device dissipates heat very rapidly and can withstand operation at very high voltages, and will operate very stably even in space.

The major problem in fabricating devices from diamond semiconductor had been that the diamond films contained many more defects and impurities than silicon and other semiconductors. In April 2002, NTT developed technology for fabricating high-quality diamond semiconductor, which solved this problem. The semiconductor device technology developed by University of Ulm accelerated the fabrication of diamond semiconductor devices.

Summary of features

1) Successful application of diamond semiconductor devices
2) Amplification at 81 GHz, the millimeter frequency band
3) Reliable long-term operation even in the space
4) Operation in the high power region will boost the output power of communication satellites and broadcasting stations.
5) High-power devices (output power density: 30 W/mm) will be feasible with the development of peripheral technologies.

Background

Recently, communication capacity has drastically increased. There is therefore a demand for high-frequency high-power electronic devices that can operate at high frequencies. A portable telephone needs only about 1 W at 1.5 GHz, but communication satellites and television broadcasting stations require 1 kW at 10 GHz. In the 10-GHz frequency region, vacuum tubes are still used. However, vacuum tubes exhibit low energy efficiency, and thus a high energy loss. From the environmental viewpoint, these vacuum tubes should be replaced by semiconductors.

From the material standpoint, silicon, silicon carbide, gallium arsenide, and gallium nitride are all used in practical applications. Theoretical predictions, however, have shown that ideal diamond semiconductor devices would operate at five times the temperature, 30 times the voltage, and 3 times the frequency of silicon devices. This is because diamond has very high thermal conductivity, high breakdown voltage[*1], and high maximum carrier velocity[*2],

*1 Breakdown voltage: When a voltage higher than a certain value is applied to a semiconductor, the semiconductor is destroyed. This phenomenon is called breakdown. The high-voltage limit at which breakdown does not occur is called breakdown voltage. This voltage depends on the type of material. A material with a high breakdown voltage can be used in high-voltage operation, and has an advantage as a high-power device. Diamond has a very high breakdown voltage.

*2 Maximum carrier velocity, carrier velocity: The carriers of electric current are electrons or holes, and their velocity governs how a device performs. Generally, a crystal with high crystalline quality has a high carrier velocity, and this results in high operating speed in a device. The upper limit of carrier velocity is called the maximum carrier velocity. Ideal diamond has a higher maximum carrier velocity than other semiconductors.

which respectively result in rapid heat dissipation, long lifetime, and high-frequency operation. Therefore, diamond has been touted as the ultimate semiconductor; the one most suitable for high-frequency high-power electronic devices.

Technology

(1) Technology for fabricating high-purity diamond with low defect density

NTT developed a technology for fabricating high-purity diamond with low defect density in April 2002 (Fig. 1). There were three difficult problems in diamond crystals that had prevented us obtaining the superior properties of diamond semiconductors: graphite components, crystalline defects, and impurities*3. Graphite components lower the carrier velocity and consequently the operating speed. Crystalline defects and impurities result in current leakage and low output power.

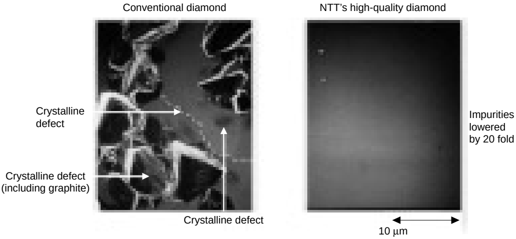
By optimizing the growth conditions, we were able to eliminate graphite components, greatly reduce crystalline defects, and reduce impurities 20 fold. This technology opened the way to diamond semiconductor devices having the superior properties of ideal diamond.

(2) Fabrication technology for diamond semiconductor devices

In collaboration of the University of Ulm, NTT fabricated diamond semiconductor devices using high-quality diamond semiconductor (Fig. 2). On the high-quality diamond layer and substrate, we formed a submicrometer-wide metal contact, the so-called T-shaped gate. The gate width, which determines the performance of devices, is 0.2 μm, making this technology highly advanced of its kind in the world.

With these technologies, we obtained the maximum operating frequency of 81 GHz, the highest among diamond devices and about twice the pre-

*3 Graphite component, crystalline defects, impurities: Both Graphite and diamond consist of carbon atoms. However, while the carbon atoms in diamond have four chemical bonds, those in graphite have only three. Crystalline defects are regions of disorder caused by vacancies and dislocations in the regular crystal structure. Impurities are atoms other than carbon, such as oxygen and hydrogen.



	NTT's high-quarity diamond	Effect on device properties
Graphite	Removed completely	Higher carrier velocity
Crystalline defects	Reduced greatly	Lower current leakage
Impurities	Lowered to 1/20	Lower current leakage

Fig. 1. Fabrication technology for high-quality diamond.

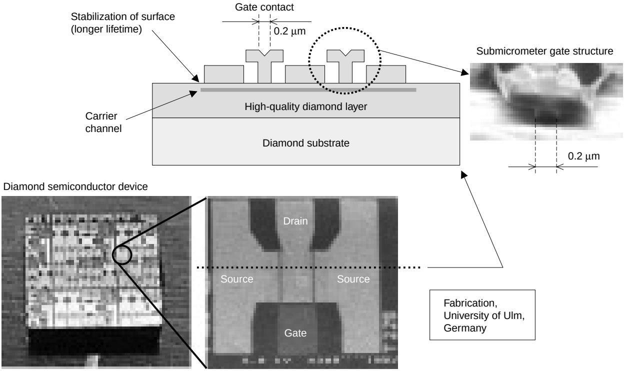


Fig. 2. Fabrication technology of diamond semiconductor devices.

vious record for diamond. We confirmed amplification in the millimeter frequency band for the first time. The 81 GHz was obtained reproducibly because the device operated stably for a long time, which proves the high reliability of our diamond devices. Once we establish device peripheral technologies, we will reach the power density of 30 W/mm, the level needed for practical use.

Future plans

NTT Basic Research Laboratories is now working to further improve the quality of diamond crystal by decreasing the impurities. The target is a frequency of 200 GHz with output power density of 30 W/mm.

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