NEWS RELEASE

NTT
NIPPON TELEGRAPH AND TELEPHONE CORPORATION

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Nippon Telegraph and Telephone Corporation

Diamond Semiconductors Operate at Highest Frequency Ever

A Step Closer to Diamond Devices for Communication Satellites, Broadcasting Stations, Radars

Nippon Telegraph and Telephone Corporation (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 radar.
NTT Basic Research Laboratory (BRL), in collaboration with the University of Ulm, Germany, succeeded in fabricating a diamond semiconductor device using high-purity diamond crystals. The device's highest operation frequency is 81 G ($G=10^9$) Hz. It therefore operates as an amplifier in the millimeter region (frequency: from 30 to 300 GHz), which is the first time this has been achieved for any kind of diamond device. Owing to the properties of the diamond semiconductor, 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.

<Features>
1) Realization of diamond semiconductor devices.
2) Amplification of 81 GHz; the millimeter frequency band.
3) Reliability of long-term operation even in the space.
4) Operation in the high power region boosts output power of communication satellites and broadcasting stations.
5) High power devices (output power: 30 W/mm) feasible, with 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 (Fig. 1). 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 environment 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 (Fig. 2). This is because diamond has very high thermal conductivity, high breakdown voltage (*1), and high maximum carrier velocity (*2), 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. 3). 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 (*2) and consequently the semiconductor operation 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 and 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 the high-quality diamond semiconductor (Fig. 4). On the high-quality diamond layer and substrate, we formed a submicrometer-wide metal contact, the so-called T-shaped gate. The width, which determines the performance of devices, is 0.2 micrometers (1 micron=1/1000 mm). This technology is the most advanced of its kind in the world.
With these technologies, we obtained the maximum operation frequency of 81 GHz, the highest among diamond devices and about two times higher than the previous record for diamond (Fig. 5). 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 of 30 W/mm (Fig. 6), the level needed for practical use.

<Future>

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

<Definitions of Terms>

*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 is a

hard material and has a very high breakdown voltage.

*2 Maximum carrier velocity, Carrier velocity
Carriers are electrons or positive 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 operation speed in a device.
The high limit of carrier velocity is called the maximum carrier velocity. Ideal diamond has a higher maximum carrier velocity than other semiconductors.

*3 Graphite component, Crystalline defects, Impurity
Graphite, like diamond, consists of carbon atoms. However, carbon atoms in diamond have four arms (chemical bonds). On the other hand, carbon atoms in graphite have only three arms. Crystalline defects are disordered carbon atoms surrounded by ordered carbon atoms. Impurities are atoms other than carbon, like oxygen and hydrogen.

For further information, contact:
Minako Sawaki, Hirofumi Motai
Planning Division
NTT Science and Core Technology Laboratory Group
Tel: 046-240-5152
E-mail: st-josen@tamail.rdc.ntt.co.jp