Microwave Operation of Diamond Field-Effect Transistor

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Abstract

Among semiconductors, diamond intrinsically possesses many superior physical properties suitable for high-frequency high-power electronic devices and is thus called the "ultimate semiconductor". NTT Basic Research Laboratories (BRL) has developed a technology for growing high-quality diamond film, and, in collaboration with the University of Ulm, Germany, successfully fabricated diamond field-effect transistors (FETs) using the film. These diamond FETs exhibited the highest cut-off frequency reported for diamond and showed the first amplification operation in the millimeter-wave range. Diamond FETs will replace the vacuum tubes currently used in the high-frequency high-power regime and will enable us to greatly increase the output power of communications satellites and broadcasting stations.

1. Introduction

At present the data transfer rate in communications is increasing very rapidly. Therefore, electronic devices that operate at higher frequencies and produce higher output power are urgently needed for present and future communications systems.

Figure 1 shows the output power and operating frequency currently required for some specific applications and the performance of devices made from various semiconductors. Portable phones require an output power of 0.9 W and frequency of 1.45 GHz. Conventional semiconductor devices can meet these requirements, and indeed, all devices in portable phones are based on semiconductors. On the other hand, broadcasting stations, communications satellites, and radars require higher output powers and frequencies: for example, 120 W and 10 GHz for communications satellites. Such performance is beyond the ability of conventional semiconductor devices, so these applications still rely on vacuum tubes. However, the power efficiency of vacuum tubes is quite low, because almost all of their input power is consumed as heat. Therefore, from the environmental viewpoint, vacuum tubes should be replaced by semiconductor devices. Diamond has many superior physical properties to conventional semiconductors such as silicon (Si), silicon carbide (SiC), gallium arsenide (GaAs), indium phosphide (InP), and gallium nitride (GaN). Therefore, our research points to diamond as the most promising semiconductor for this purpose.

Table 1 summarizes the physical properties of specific semiconductors. Diamond has the highest thermal conductivity among materials, so it has the highest heat-dissipation efficiency during high power operation. It exhibits a very high breakdown electric field strength, so diamond devices can operate at an extremely high voltage. These properties are important for high-output-power devices. In addition, the carriers in diamond have a high mobility and a high saturation velocity, which allows high-frequency and high-speed operation. Furthermore, diamond has a very low dielectric constant, so its power loss during high-frequency operation is low.

Device figures of merit (FOMs) (Table 1), which are calculated on the basis of material's physical properties, indicate its performance capabilities. For diamond, Johnson's FOM, which indicates high-frequency high-power capability, is 1100 times that for Si. Keyes' FOM, which indicates high-speed capability, is 19 times that for Si. Diamond is therefore the most suitable semiconductor for high-frequency high-power electronic devices [1] and called the "ultimate semiconductor". Driven by such expecta-

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tions, groups at Waseda University and the University of Ulm in Germany continued researching diamond transistors for about ten years [2], [3].

As previously reported in this journal [4], NTT has recently developed technology for growing high-quality diamond thin film, which had not been possible until now. In this paper, I describe in more detail this growth technology and diamond FETs fabricated using the film. Then, I present more detailed results that show the excellent microwave characteristics of the diamond FETs.

2. High-quality diamond thin film

NTT Basic Research Laboratories (BRL) has developed technology for growing high-quality diamond thin films [4], [5]. We grew a high-quality diamond homoepitaxial thin film about 1 μm thick on a commercially available HPHT-synthesized diamond substrate (3 mm × 3 mm in size) (HPHT: high pressure and high temperature) by a microwave plasma chemical-vapor-deposition (CVD) method. The source gases were high-purity methane (CH_4) and

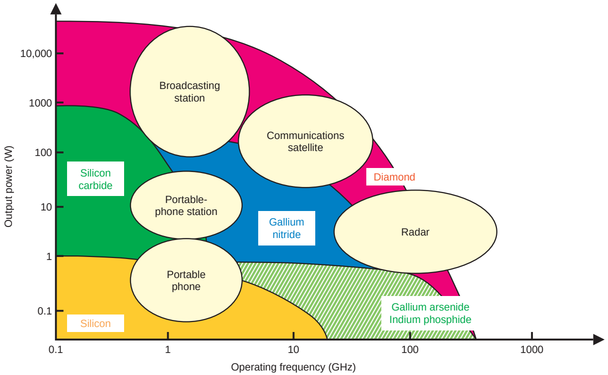


Fig. 1. Demand for high-frequency high-power semiconductors to support the rise in communication capacity.

Table 1. Physical properties and device figures of merit.

Material	Band gap E_G (eV)	Thermal conductivity λ (W/cmK)	Breakdown electric field strength E_B (MV/cm)	Mobility μ (cm^2/Vs)	Saturation velocity v_{sat} (× 10^7 cm/s)	Dielectric constant ε_r	Johnson's figure of merit (vs. silicon)	Keyes' figure of merit (vs. silicon)
Diamond	5.45	20	10	up to 3800 (holes)	up to 1.0 (hole) ?	5.7	1100	19
Silicon carbides	3.27	4.9	3.0	up to 1000 (electrons)	up to 2.0 (electrons)	9.7	400	5.0
Gallium nitrides	3.4	1.5	2.5	up to 2000 (electrons)	2.5	8.9	433	1.8
Silicon	1.12	1.5	0.3	up to 1400 (electrons)	1.0	11.8	1	1

hydrogen (H_2). The growth rate was about 0.15 µm/h. The growth temperature was 650°C.

Figure 2 shows SEM (scanning electron microscope) images of a diamond film grown by conventional processes and one grown with our technology. During conventional growth, numerous crystalline defects appear because of twinning in diamond crystal. Between those defects, grain boundaries frequently form. The grain boundaries and defects contain graphite components. This is because diamond consists of sp^3-hybridized carbon (C) atoms, whereas graphite consists of sp^2-hybridized C atoms. Thus, thermodynamically, graphite forms much more easily than diamond. The conventional film also contains residual impurities, especially nitrogen, which exist in the hydrogen source gas and are incorporated into the diamond crystal during growth. Our experiments revealed that crystalline defects and residual impurities result in current leakage during device operation, which reduces the output power of the device drastically [6]. The graphite components decrease the carrier mobility and thereby the power gain of diamond devices.

In contrast, the thin film grown by NTT BRL has far superior quality. The crystalline-defect density is more than three orders lower and graphite components have been eliminated. The impurity concentration is decreased to 1/20. The growth of this high-quality film opened the way to fabricating a device exhibiting the superior properties of diamond.

The keys to this success are the high purity of the CH_4 and H_2 source gases and a special diamond substrate treatment performed before growth. An HPHT substrate inevitably contains impurities such as N and metals that are incorporated during substrate growth. These impurities remain on the HPHT substrate and trigger the formation of crystalline defects during the growth of the diamond homoepitaxial thin film [7]. Therefore, we developed a technique for removing the impurities on the HPHT substrate.

3. Fabrication of diamond field-effect transistors

Using a high-quality diamond thin film, NTT BRL, in collaboration with the University of Ulm, fabricated diamond field-effect transistors (FETs) as shown in **Fig. 3** [8]. We formed the source and drain contacts of the FETs from gold (Au) because Au has a large work function (5.1 eV) and forms ohmic contacts on the diamond layer. Finally, using electron-beam lithography and self-alignment techniques, we formed short T-shaped aluminum (Al) gate contacts. As shown in the SEM image of the cross section of a T-shaped gate (Fig. 3), the length of the foot of the gate is only 0.2 µm. The T-shaped gate fabrication process is state-of-the-art semiconductor technology developed by the University of Ulm. Because it has a small work function (4.3 eV), Al forms a Schottky contact on the diamond. The Schottky barrier height was about 0.8 eV. The diamond surface after CVD growth is terminated with hydrogen (H) atoms [9] because the surface is exposed to H plasma during the CVD growth. The H surface termination causes a two-dimensional hole channel to form in the diamond layer several nanometers below the surface [10], but the mechanism is still not clear. During FET operation, holes travel through this channel from the source contact to the drain contact near the surface. The gate

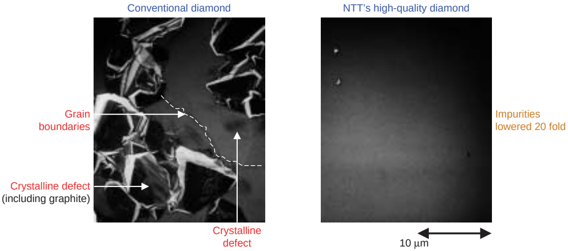


Fig. 2. SEM images of conventional and NTT's diamond surfaces.

voltage changes the hole conduction, making FET operation possible.

4. Microwave performance of diamond FETs

Figure 4 shows DC characteristics of a diamond FET (gate length L_G = 0.2 µm; gate width W_G = 200 µm) [11], [12]. The maximum drain current I_D is about 280 mA/mm. The transconductance g_m is about 100 mS/mm. These values satisfy demands for the practical use.

Figure 5 shows microwave characteristics (frequency dependence of power gains) of the same diamond FET device [11], [12]. A transition frequency f_T of 25 GHz was obtained from the second power of the current gain $|h_{21}|^2$ measured experimentally. The

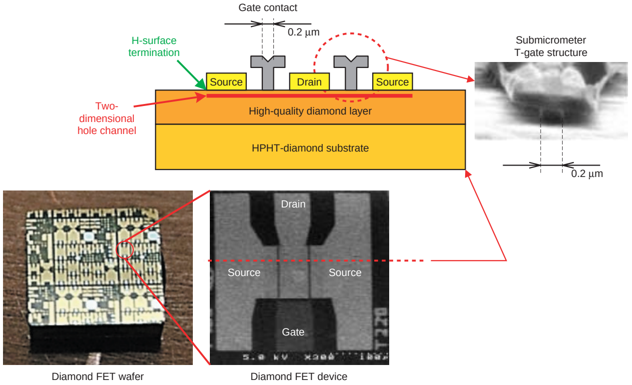


Fig. 3. Diamond field-effect transistors (FETs).

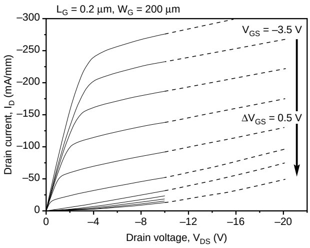


Fig. 4. DC characteristics of the diamond FET.

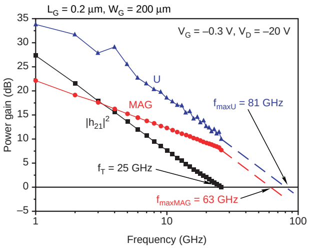


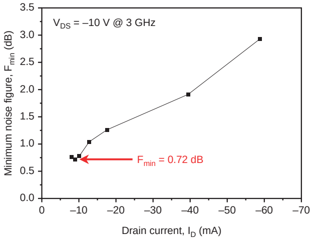
Fig. 5. Microwave characteristics of diamond FET.

measured data and the extrapolation are shown by plots and the broken line, respectively. This f_T is the upper limit of the operating frequency of devices in a digital circuit. The maximum oscillation frequency (f_{max}), the upper limit of the operating frequency in analog amplification, can be obtained by extrapolation in the same way, but for two differently defined power gains: the maximum available gain (MAG) and the unilateral power gain (U). The f_{maxMAG} and f_{maxU} are 63 and 81 GHz, respectively. These cut-off frequencies are about twice those reported previously by the University of Ulm [3], and they are the highest ever for diamond devices. These results were the first amplification operation in the millimeter-wave (30–300 GHz) range.

Figure 6 shows noise characteristics of the same diamond FET. The minimum noise figure F_{min} of 0.72 dB was obtained at 3 GHz [12]. The table in Fig. 6 compares the F_{min} of our device with those of other semiconductor devices with similar gate lengths L_G and frequencies f. The low-noise performance of the diamond FET is better than that of Si MOSFET and approaches those of p-type GaAs and n-type GaN HEMTs. So far, applications of diamond have focused only on output power devices, which will be used in transmitters in communications systems. But this excellent low-noise performance of a diamond FET shows the possibility of a low-noise amplifier in a receiver operating in the microwave range.

Figure 7 shows the microwave class-A power characteristics of the diamond FET at 1 GHz [12]. The linear gain of 14 dB was obtained in a wide input power range from –30 to 0 dBm. This indicates the possibility of power amplification without distortion in a wide input range. The maximum power level P_{MAX} is 0.35 W/mm. This is the highest P_{MAX} among diamond devices, but it is not very high compared with other semiconductor devices. The reason for this is that there was a large impedance mismatch between the output side of the diamond FETs and the input side of the tuner in the power measurement system. This problem can be solved by using a suitable power device structure, such as a multi-finger structure.

Figure 8 shows the maximum operating frequency and maximum output power for diamond and conventional semiconductors. The maximum output power for our diamond FETs is 0.35 W/mm [12]. The highest previously reported value for diamond devices was 0.2 W/mm [3]. If we optimize the device structure for power devices, we estimate that the output power level will increase to about 3 W/mm. This output power is comparable to that of SiC and GaN, but diamond can be operated in a much higher frequency range. Moreover, with further improvement of the diamond crystal, we foresee an output power level of about 27 W/mm [3], which is the goal for the practical use of diamond FETs.



	F_{min} (dB)	L_G (µm)	f (GHz)
Diamond FET	0.72	0.2	3
Si MOSFET	0.88	0.3	2
GaAs p-HEMT	0.5	0.25	2
GaN n-HEMT	0.5	0.15	3-8

Fig. 6. Low noise-performance of the diamond FET in the microwave regime.

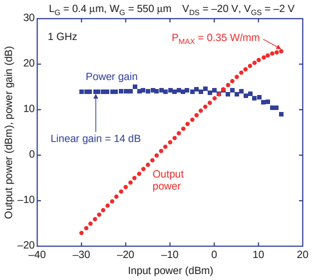


Fig. 7. Microwave power characteristics of the diamond FET.

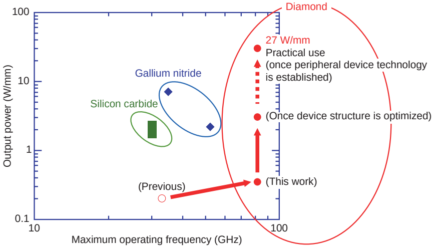


Fig. 8. Diamond devices: a step closer to applications.

5. Conclusion

NTT Basic Research Laboratories has developed technology for growing high-quality diamond thin films, and, in collaboration with the University of Ulm, fabricated diamond FETs. These diamond FETs exhibited the highest reported cut-off frequency and showed the first amplification operation in a millimeter-wave range. Their high-power and low-noise performances make these devices very promising for communications systems in the microwave and millimeter regimes. In the future, we will try to further decrease the impurities in diamond crystal and optimize the power device structure to achieve diamond electronic devices with the output power needed for communications.

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