Diamond High Power and Voltage MOSFETs: Inch-Sized Wafer Growth, Doping, Static and Dynamic Characteristics

Makoto Kasu[1] **and Niloy Chandra Saha**[1]

[1]*Depart. of Electrical and Electronic Engineering, Saga University, 840-8502 Saga, Japan*

Diamond possesses an ultrawide bandgap energy of 5.47 eV, a breakdown field of >10 MV/cm), higher thermal conductivity (22 W/cmK), and higher electron and hole mobilities (4500 and 3800 cm^2/Vs, respectively) than GaN and SiC. Therefore, diamond is considered to be the most capable candidate for the power semiconductor device application. Diamond single-crystal substrates have been limited to sizes of 4 mm. Diamond heteroepitaxial growth has not been achieved because of a large difference in coefficients of thermal expansion between diamond and foreign substrate materials. Recently, we have demonstrated a two-inch-diameter diamond wafer grown on Ir/sapphire (α-Al_2O_3) (11-20) substrate [1]. Diamond heteroepitaxial layer exhibited the highest crystal quality, such as TDD of 1.4×10^7 cm^{-2}, and XRC FWHM of 98 arcsec [2]. We clarified diamond's nucleation process on Ir/sapphire surface by AFM, TEM, and EDS [3]. For diamond p-channel MOSFETs, so far impurity doping into diamond has not been successful because of extremely high activation energy. But we have established p-type doping on the H-terminated diamond using NO_2 gas [4], and thermal stabilization and gate insulation with ALD Al_2O_3 layer [4]. We have fabricated diamond MOSFET (Fig. 1) demonstrating high drain current density (I_D) of 0.68 A/mm, a low ON-state resistance of 50 Ω·mm, and extremely high OFF-state breakdown voltage (V_{BR}) of −2568 V. The specific on-state resistance, ($R_{ON,spec}$) was determined to be 7.54 mΩ·cm^2, and the maximum available power, i.e., BFOM (= $V_{BR}{}^2/R_{ON,spec}$) has been obtained to be 874.6 MW/cm^2 (Fig. 2), the highest ever in diamond, ~40% of GaN's top value [5]. Further, we demonstrated fast turn-on (t_{on}) and turn-off (t_{off}) switching times of 9.97 ns and 9.63 ns, respectively [6]. The first stress measurement was performed, showing 190 h of stable operation under a DC gate bias and drain bias stress [7]. No evident degradation in I_D was observed throughout the stress period; the gate current (I_G) increased after 83 h of stress due to the charge injection into the Al_2O_3 layer, although it did not influence the I_D.

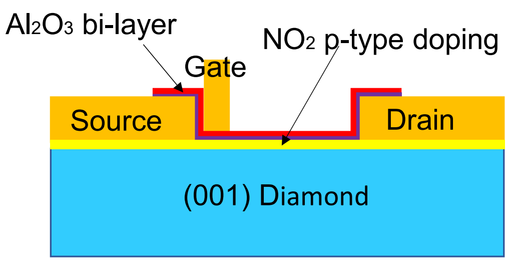

Figure 1. Schematic cross-section of NO_2-p-type-doped diamond MOSFET.

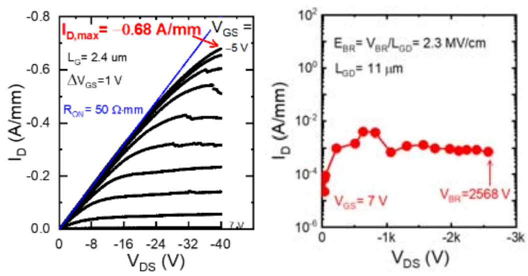

Figure 2. DC output drain current characteristics of the diamond MOSFET, which shows 875 MW/cm^2.

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+ Author for correspondence: kasu@cc.saga-u.ac.jp

Supplementary information

Table 1: Physical properties of diamond and other semiconductors.

Material	E_G (eV)	E_{BR} (MV/cm)	v_{sat} ($\times 10^7$ cm/s)	μ (cm^2/Vs)	ε_r	λ (W/cmK)
Diamond	5.47	>10	1.5 (e) 1.05 (h)	~ 4500 (e) ~ 3800 (h)	5.7	22
Ga_2O_3	4.8	8	---	~ 300 (e)	10	0.23
SiC	3.26	2.8	2.2 (e) 1.3 (h)	~ 1200 (e) ~ 120 (h)	9.8	4.9
GaN	3.4	5	2 (e)	~ 2000 (e)	8.9	1.5
GaAs	1.4	0.4	1–2 (e)	~ 8500 (e) ~ 400 (h)	12.9	0.55
Si	1.1	0.3	1 (e)	~ 1400 (e) ~ 450 (h)	11.7	1.3

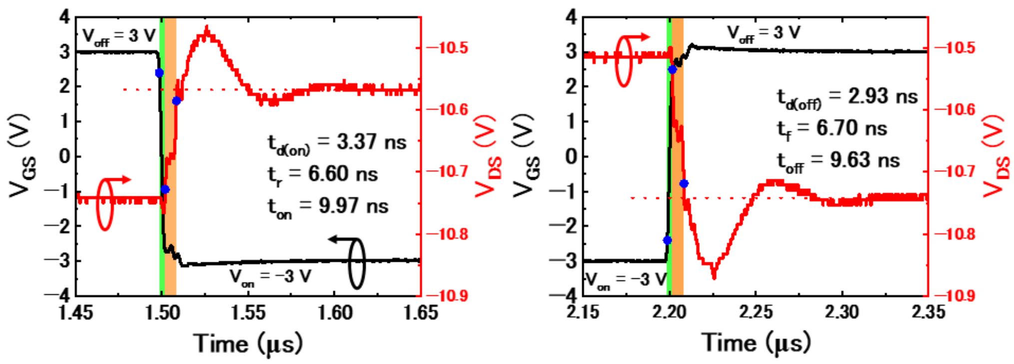

Figure 3. (a)Turn-On and (b) Turn-Off dynamic switching characteristics of the diamond MOSFET.

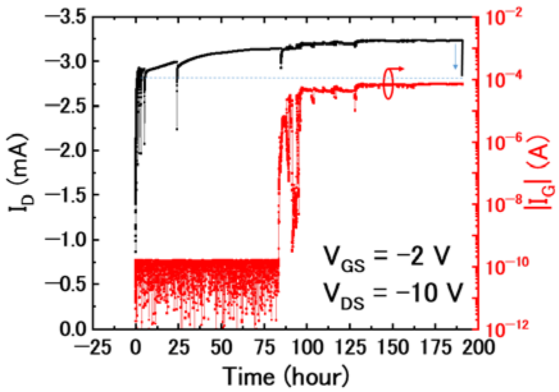

Figure 4. Negative gate bias stress time dependent drain current (I_D) and gate current (I_G).