Recent Progress of Diamond Devices for Power Applications

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Abstract

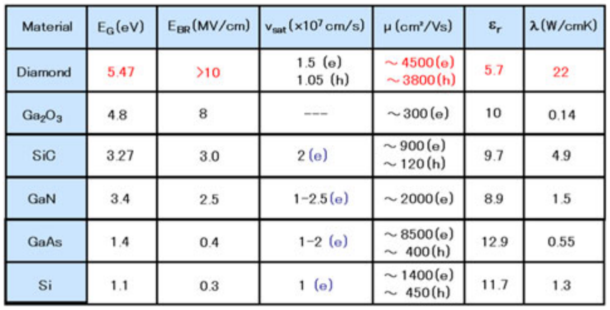
Diamond semiconductor possesses exceptional physical properties, such as a high breakdown field, carrier mobility, and thermal conductivity. Therefore, it is expected to be highly efficient for high-power RF devices. We have found hole carrier doping in diamond using nitrogen dioxide (NO_2). Furthermore, we have found that an aluminum oxide (Al_2O_3) passivation layer improves the thermal stability of the hole channel greatly. These technologies enable us to create thermally stable high-performance diamond field-effect transistors (FETs). The diamond FET shows a maximum I_{DS} value of -1.35 A/mm, cut-off frequencies f_T and f_{MAX} of 35 GHz and 70 GHz, respectively, and an RF output power density of 2 W/mm at 1 GHz.

INTRODUCTION

Diamond has remarkable semiconductor properties, such as the highest thermal conductivity (22 W/cm/K), a relatively high breakdown field ($>10^7$ V/cm), and a relatively high carrier velocity ($>10^7$ cm/sec) (Table I) [1]. Therefore, diamond appears promising for use in high-power and high-frequency devices. Previously, we reported relatively high cut-off frequencies f_T and f_{MAX} of 45 GHz and 120 GHz, respectively, as well as an RF output power (P_{OUT}) of 2.1 W/mm at 1 GHz in hydrogen surface-terminated (H-) diamond field-effect transistors (FETs) with a hole channel [2]-[4]. To date, various models for the hole accumulation layer have been proved controversial [5]-[7] and the FET lifetime was very short. However, recently, we identified a hole doping mechanism by which hole carriers are mainly generated by nitrogen dioxide (NO_2) adsorption on the H-diamond surface (NO_2 hole doping). Using this method, we then increased the hole carrier density by an order of magnitude to $\sim 10^{14}$ cm^{-2} [8]. Further, we have found that an atomic layer-deposited (ALD) Al_2O_3 passivation layer is extremely effective at improving the thermal stability of H-diamond.

In this study, we report a NO_2 hole doping method and an Al_2O_3 passivation technique for H-diamond FETs that facilitate a highly stable high-performance diamond FET [9].

TABLE I
COMPARISON OF PHYSICAL PROPERTIES OF 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	0.14
SiC	3.27	3.0	2 (e)	~900(e) ~120(h)	9.7	4.9
GaN	3.4	2.5	1-2.5(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

EXPERIMENTAL

Fig. 1 shows a schematic of the diamond FET fabrication process. (1) We utilized single-crystal diamond (001) substrates. The residual boron acceptor concentration in the diamond is less than 10^{16} cm^{-3}, and the thermal activation energy of the boron acceptors is as high as 0.37 eV. We used Hall effect measurements to confirm that the bulk conduction in the diamond substrates is negligible at least up to 300 °C. H-termination was performed by exposing the diamond surface to microwave-generated hydrogen plasma. Au was deposited on the H- surface after which Au patterning and isolation were performed. (2) After the electron-beam (EB) resist patterning of the gate electrode area, (3) Au was etched through the EB resist mask. In this process, Au was separated from the source and drain electrodes. Here we exposed the H-diamond surface between the source and drain contacts to highly concentrated NO_2 gas (2% in N_2). (4) We then deposited Al_2O_3 layer by using the ALD technique [10] on the NO_2-adsorped H-diamond surface. To avoid NO_2 desorption from the H- surface, Al_2O_3 was deposited at a temperature less than 150 °C. (5) Finally, the gate electrode was formed by Al deposition and the lift-off technique. (6) Al_2O_3 acts as a passivation layer and gate insulator.

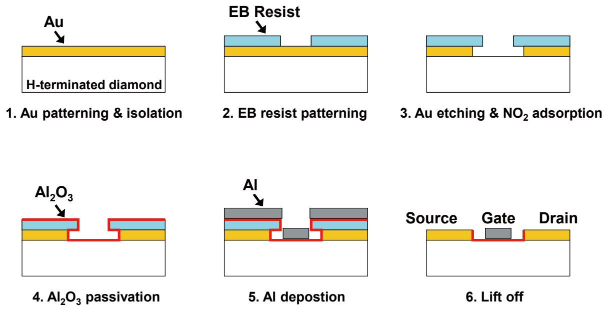


Fig. 1. Schematic of diamond field-effect transistor (FET) fabrication process.

DIAMOND FET

Fig. 2 shows the drain current–voltage (I_{DS}–V_{DS}) characteristics of a 0.4-μm gate-length diamond FET. The gate voltage (V_{GS}) was varied from +11 V to −5 V in steps of −2 V. No drain leakage current was observed, and the threshold voltage (V_{th}) was +11 V. The value of I_{DS}max at V_{GS} = −5 V was −1.35 A/mm, which is the highest ever value reported for diamond FETs [11]. Previous FETs without NO_2 hole doping showed values of ~0.35 A/mm. Therefore, NO_2 hole doping results in an increase of hole concentration, and consequently, the drain current (I_{DS}max).

Fig. 3 shows the I_{DS}–V_{DS} characteristics at 200 °C and at room temperature (RT) before and after heating at the 200 °C in a vacuum [12]. At 200 °C, the I_{DS}–V_{DS} characteristics were measured after 1 h of temperature stabilization. The V_{GS} value was varied from +2 V to −4 V in steps of −1 V. Prior to heating at 200 °C, I_{DS}max at RT was −200 mA/mm. At 200 °C, I_{DS}max decreased to −180 mA/mm. After the 200 °C heating, I_{DS}max increased to the initial value of −200 mA/mm at RT. Before and after heating, the I_{DS} values for each value of V_{GS} clearly agree well with each other. This result proves that ALD Al_2O_3 passivation improves the thermal stability of the hole channel, and consequently, the FET operation.

Fig. 4 shows the frequency dependence of the current gain $|h_{21}|^2$ and the unilateral power gain U. The cut-off frequencies f_T and f_{MAX} are extrapolated as 35 GHz and 70 GHz, respectively [12]. These results show the potential of diamond FETs for RF applications in the microwave and millimeter wavelength ranges.

Fig. 5 shows a power sweep at 1 GHz (continuous wave). The values of L_G and W_G were 0.2 μm and 390 μm, respectively. The maximum output power density (P_{OUT}), maximum power gain, and power added efficiency (PAE) at a V_{GS} of −1.0 V and a V_{DS} of −25 V are 2.1 W/mm, 18 dB, and 33%, respectively. The load impedance (Z_{load}) is 226 − j453, whereas the reflection coefficient (Γ) for Z_{load} is 0.9. Although the P_{OUT} and maximum power gain values are comparable to the highest values ever reported for diamond FETs [3, 4], the P_{OUT} value was limited by the impedance mismatch between the output and load impedances. The relatively high P_{OUT} value shows the potential of using diamond FETs in microwave power applications.

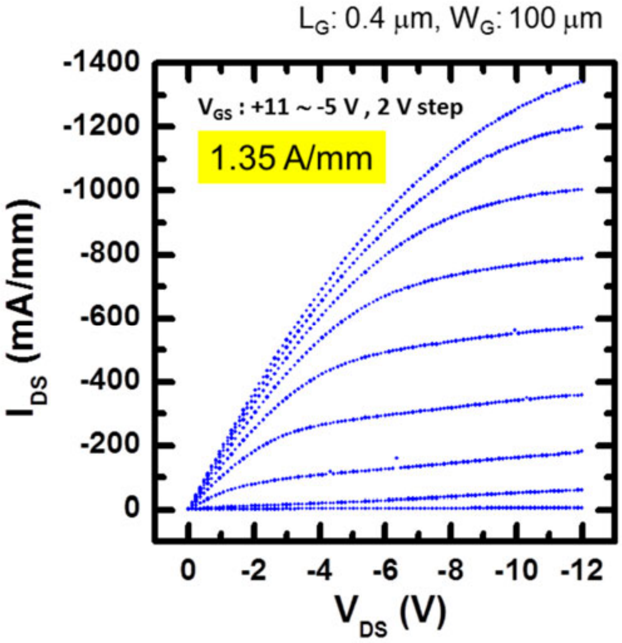


Fig. 2. I_{DS}–V_{DS} characteristics of a passivated diamond FET with L_G = 0.4 μm (V_{GS} = +11 – −5 V; ΔV_{GS} = −2 V).

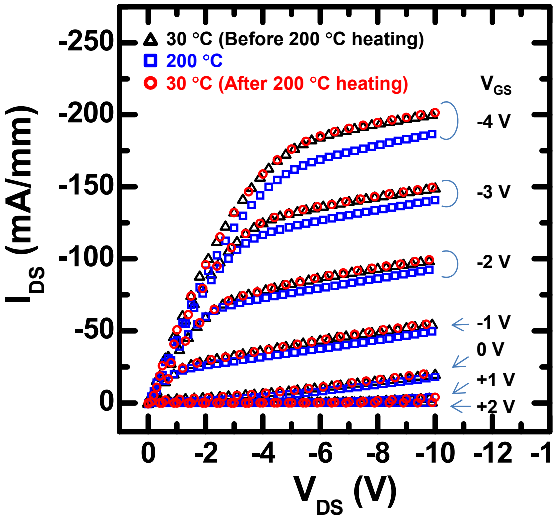


Fig. 3. I_{DS}–V_{DS} characteristics of a 0.4-μm gate-length diamond FET with a passivation layer before, during, and after 200 °C heating.

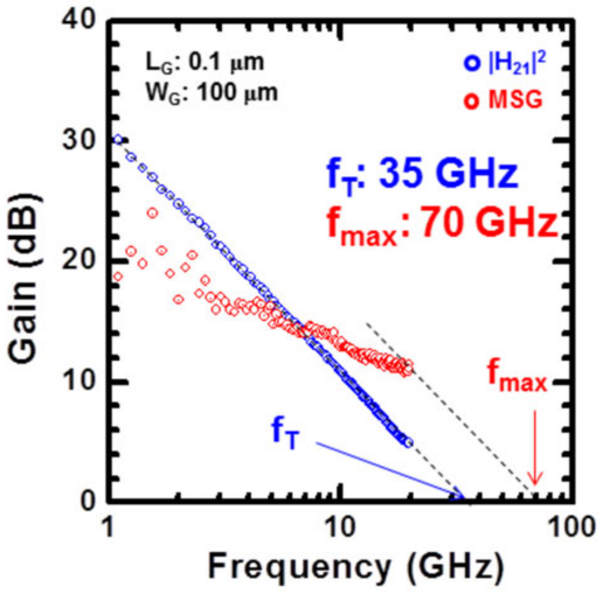


Fig. 4. RF small-signal characteristics of a passivated diamond FET. The cut-off frequencies of f_T (35 GHz) and f_{MAX} (70 GHz) are extrapolated.

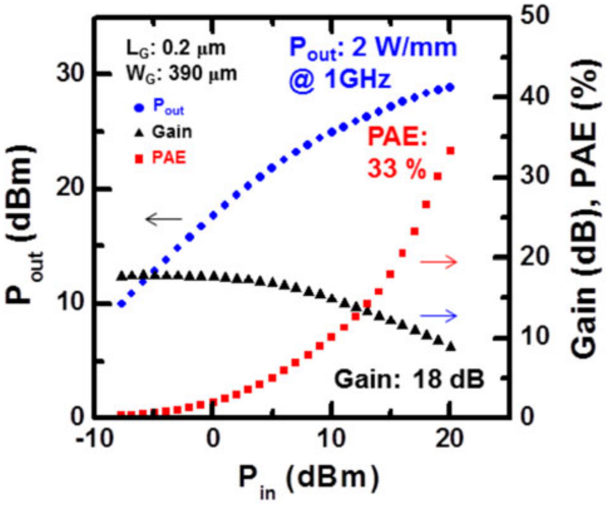


Fig. 5. RF power sweep of diamond FET. The RF output power density was 2.1 W/mm at 1 GHz.

CONCLUSIONS

Thermally stable high RF-performance diamond FETs were reviewed. During fabrication, we used NO_2 hole doping and Al_2O_3 passivation techniques. The I_{DSmax} and g_{m_max} values of the diamond FETs were −1.35 A/mm and 200 mS/mm, respectively The I_{DSmax} value is the highest ever value reported for diamond. The cut-off frequencies f_T and f_{MAX} were extrapolated as 35 GHz and 70 GHz, respectively. The RF output power density at 1 GHz was 2 W/mm. The potential of using diamond FETs in microwave power applications was discussed.

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