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RF Power Performance of 2DHG Diamond MOSFETs with thick ALD-Al_2O_3 Film

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Abstract

Two-dimensional hole gas diamond MOSFETs were fabricated with a 200-nm-thick atomic-layer-deposited Al_2O_3 film for high breakdown voltage. The RF power performance at 1GHz was evaluated when biased at V_{DS} of −70 V for the first time in diamond. As a result, an output power density of 2.5 W/mm and a maximum gain of 8.0 dB were obtained using a device with L_G of 1 µm and L_{SD} of 6 µm.

1. Introduction

Two-dimensional hole gas (2DHG) diamond is expected to be applied as a surface positive-channel field-effect transistor (p-FET) material for high-frequency and high-power transistor due to high electric field and highest thermal conductivity. Especially, diamond p-FETs are promising radio-frequency (RF) transistors to realize complementary S-class high-power RF amplifiers combined with GaN n-FETs.

The sheet resistance of hydrogen terminated (C-H) diamond surface strongly depends on the plane orientation. The reason is that the C-H dipole density and the C-H dipole angle are differ depending on the plane orientation. The sheet resistance of the diamond (110) and (111) film are lower than that of the (001) film by 30-40% [1], [2]. Actually, we have reported on the carrier velocity of 1.0×10^7 cm/s and the output power density (P_{out}) of 3.8 W/mm at high V_{DS} (~50 V) for 2DHG diamond MOSFETs on II-a type polycrystalline diamond with a (110) preferential surface [3]. We have been improving the breakdown voltage in these works by thickening the atomic-layer-deposited (ALD) Al_2O_3 insulator (100-nm-thick) and extending gate-drain length (L_{GD}) up to 3 µm [3].

In this work, we fabricated 2DHG diamond MOSFETs to improve the breakdown voltage by thicker Al_2O_3 insulator (200-nm-thick) and extending L_{GD} up to 4.5 µm. As a result, large-signal performance was evaluated when biased at V_{DS} of −70 V for the first time in diamond RF devices.

2. Device Fabrication

A cross-sectional view of ALD-Al_2O_3 2DHG diamond MOSFETs is shown in Fig. 1. The devices were fabricated on II-a type polycrystalline diamond with (110) preferential orientation. First, Ti/Pt/Au (20/20/90 nm) were evaporated and lifted off to act as the source and drain electrodes; TiC layers [4] were formed at interface between diamond film and Ti by annealing for ohmic contacts. Second, to induce the 2DHG layer, the whole substrate surface was H-terminated using a remote hydrogen plasma [4]. The electrical isolation was performed by O_2 plasma treatment except for active area. Third, Al_2O_3 film (200 nm) was deposited as gate insulator and passivation layer by high temperature ALD method (Oxidant: H_2O, Temperature: 450 °C) [5]. Finally, the gate electrode was defined using electron beam lithography and an Al (100 nm) layer was evaporated and lifted off. In this work, the source-gate length (L_{SG}) and the gate length (L_G) were fixed at 0.5 and 1 µm, respectively, while the L_{GD} ranged from 1.5 to 4.5 µm.

3. Results and Discussion

Fig. 2 (a) and (b) show I_{DS} as a function of V_{DS}, and I_{DS} and transconductance (g_m) as a function of V_{GS} for a device with L_{SG} = 0.5 µm, L_G = 1 µm, L_{GD} = 1.5 µm and gate width (W_G) = 50 µm. From Fig. 2 (a), the maximum drain current density was −740 mA/mm at V_{GS} = −28 V and V_{DS} = −40 V. Extrapolating from V_{DS} = −1 V and V_{GS} = −28 V, the on-resistance (R_{on}) was 25 Ω mm. From Fig. 2 (b), the g_m was as high as 13 mS/mm at V_{DS} = −40 V with 9 V ≤ V_{GS} ≤ 16 V. Under high voltage operation, both extrinsic cutoff frequency (f_T) and maximum oscillating frequency (f_{max}) were over 20 GHz. Therefore, using $f_T = v/2\pi L_G$ and assuming $f_T \geq$ 20 GHz and L_G of 1 µm, the carrier velocity can be estimated and is at least 1.3×10^7 cm/s corresponding the saturation velocity of diamond.

Uncooled continuous-wave RF power performance was evaluated on-wafer using a load pull system at 1 GHz. The source and load impedances were tuned to give maximum gain. Fig. 3 shows the large-signal performance for a device with L_{SG} = 0.5 µm, L_G = 1 µm, L_{GD} = 4.5 µm and W_G = 100 µm. The bias point for A-class operation was fixed. A device with L_{GD} = 4.5 µm was able to be biased at V_{DS} of −70 V and demonstrated an output power density of 2.5 W/mm at 1 µm gate-length device and a maximum gain of 8.0 dB. To investigate the influence of L_{GD} scaling on the P_{out}, large-signal performances of devices with various L_{GD} were evaluated. Fig. 4 shows the P_{out} for devices with the various L_{GD} as a function of V_{DS}. we confirmed an improvement of output power density as increasing V_{DS}. The device with L_{GD} = 4.5 µm was evaluated when biased at V_{DS} of −70 V. The voltage swing reached −140 V in this case. The devices with L_{GD} = 1.5 µm broke down at V_{DS} of −40 V. However, the output power of the devices with large L_{GD} was lower than that of small L_{GD} at low voltage (V_{DS} ~ −20 V). The reason is that high on-resistance due to extending the drift layer. From these results, the higher output power is expected by lowering the on-resistance. The reason for output power density saturation (Fig.4) might be that impedance matching has not been completed between output and load impedances. Output power during RF operation in diamond FETs can be improved by optimization of gate insulating technology.

4. Conclusion

We fabricated 200-nm-thick ALD-Al_2O_3 2DHG polycrystalline diamond MOSFETs and evaluated RF power performance at high voltage ($V_{DS} = -70$ V). The maximum output power density of 2.5 W/mm for 1 µm gate-length device for the first time in diamond and the maximum gain of 8.0 dB were obtained without a field plate structure.

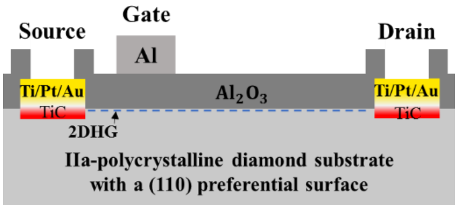

Fig.1 The cross-sectional view of ALD-Al_2O_3 2DHG diamond MOSFETs

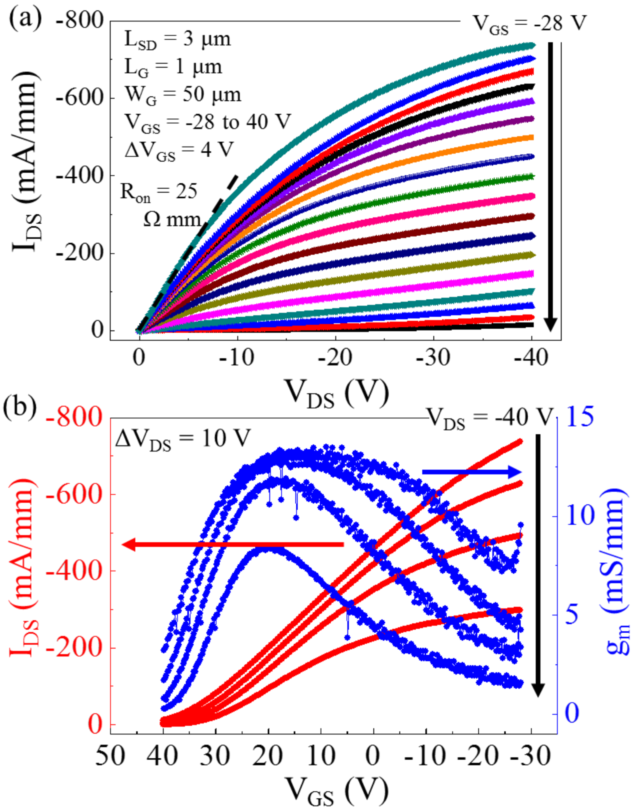

Fig.2 I_{DS} as a function of V_{DS} and I_{DS} and g_m as a function of V_{GS} for a ALD-Al_2O_3 diamond MOSFET with $L_{SG} = 0.5$ µm, $L_G = 1$ µm, $L_{GD} = 1.5$ µm and $W_G = 50$ µm. (a) The maximum I_{DS} was −740 mA/mm at $V_{GS} = -28$ V and $V_{DS} = -40$ V and the R_{on} was 25 Ω mm.(b) The g_m was as high as 13 mS/mm at $V_{DS} = -40$ V with $-9\text{ V} \leq V_{GS} \leq 16\text{ V}$

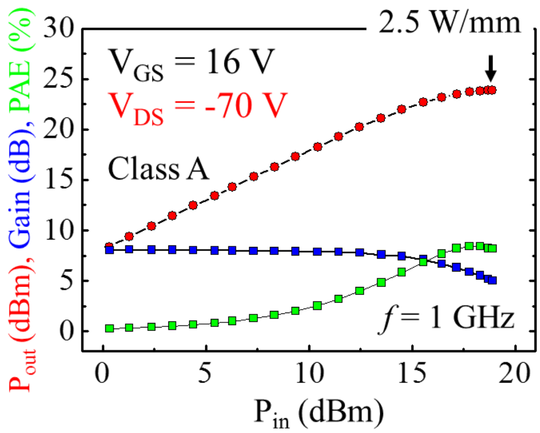

Fig.3 The RF power performance for a device with $L_{SG} = 0.5$ µm, $L_G = 1$ µm, $L_{GD} = 2.5$ µm and $W_G = 100$ µm. The bias point for A-class operation was at $V_{GS} = 16$ V and −70 V. The output power density of 2.5 W/mm was obtained.

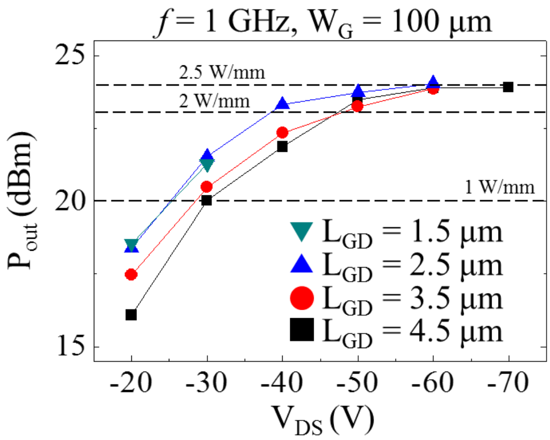

Fig.4 The output power densities during RF operation for the various L_{GD} of 2DHG diamond MOSFETs as a function of V_{DS}.

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