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Planer diamond p-channel MOSFETs with breakdown voltage V_B > 1.8kV and high drain current density by 2DHG

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Abstract: Using homoepitaxial and poly-crystalline diamond, p-channel diamond MOSFETs with 2 dimensional hole gas (2DHG) exhibit more than 1.8 kV breakdown voltage V_B at off-state with drift layer length (gate to drain length, L_{GD}) of 18-24 μm. Compared with those of n-channel AlGaN/GaN FETs and planar SiC MOSFETs in a similar device size, the V_B of diamond become competitive with them. On-state drain current densities of high voltage MOSFETs varies from 2-200 mA/mm depending on crystallinity and channel flatness. Gate insulator and passivation layer were made of ALD Al_2O_3, which originates the 2DHG on C-H diamond surface.

1. Low on-resistance at 1kV expected in diamond

Power electronics has been motivated by electric vehicles such as hybrid or electric automobiles operated at 500-600 V. In this case, an allowable voltage for power device is around 1kV. From an on-resistance R_{onS} of drift layer and allowable (breakdown) voltage V_B relationship of lateral FET, $R_{onS} = 2\sqrt{2}V_B^2 / \varepsilon_0\varepsilon_s\mu_{drift}E_{crit}^3$ (Ωcm^2), a drift layer resistance limit of diamond locates on the right below (blue thick line) of Fig.1 [1] indicating the lowest R_{onS} because of its highest critical (breakdown) electric field $E_{crit.}$(>5.5 MV/cm) and the highest hole mobility ($3800 cm^2V^{-1}s^{-1}$) in wide bandgap semiconductors. However, another limiting factor, so called channel resistance limit, controls R_{onS} in FET operation around 1 kV (Fig.1, dotted red line). With the minimum diamond channel on-resistance R_{ch} of 4 Ωmm [2], however, the channel limiting R_{onS} for hydrogen terminated (C-H) diamond planar FET with 2DHG becomes $10^{-4}\ \Omega cm^2$ at 1 kV (an arrow in Fig.1) based on $R_{onS} \approx R_{ch}L_{drift} = R_{ch}\sqrt{2}V_B / E_{crit} = 10^{-7}V_B$ (Ωcm^2) [1]. Since V_B of diamond exceeds 1.7 kV [3] in the MOSFETs with 2DHG channel and drift layer, "$10^{-4}\ \Omega cm^2$ at 1 kV" is a reachable value. It is an 1/10 of SiC limit (Fig.1).

2. Off-state: Breakdown voltage V_B >1800V

Thermal stabilization of 2DHG on C-H diamond surface is necessary for high power and high frequency device application of diamond. Up to 500℃, the 2DHG is stable under the Al_2O_3 passivation formed by high temperature (450℃) atomic layer deposition (ALD) [4,5]. The ALD Al_2O_3 was used for both gate insulator on channel and passivation on drift layer as shown in Fig.2 (inset). The C-H diamond lateral MOSFETs exhibit very wide temperature (10K-673K) and high voltage operation (~1500V) [3].

At off-state, V_B as a function of gate-drain length L_{GD} shows high-voltage durability in planar FET. In wide bandgap semiconductor FETs with lateral structure, their blocking properties are often evaluated by V_B/L_{GD}, where a critical value for lateral power devices is 1 MV/cm. The V_B-L_{GD} relationship of C-H diamond MOSFETs is shown in Fig.2. At L_{GD} of 2-10 μm of MOSFETs with 200nm thick Al_2O_3 on C-H diamond, the V_B/L_{GD} is on the line of 1 MV/cm

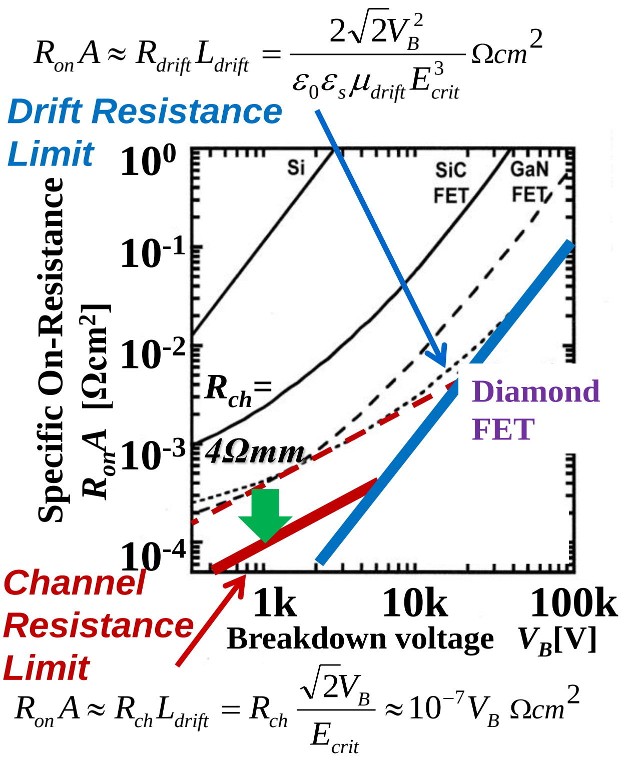

Fig.1 On resistance R_{onS} and breakdown voltages V_B. for Si, SiC, GaN, and diamond FETs. R_{onS} around 1kV is governed by channel resistance limit in wide bandgap materials. AlGaN/GaN and diamond can reach $10^{-4}\ \Omega cm^2$ at 1 kV. The graph is modified from reference [1].

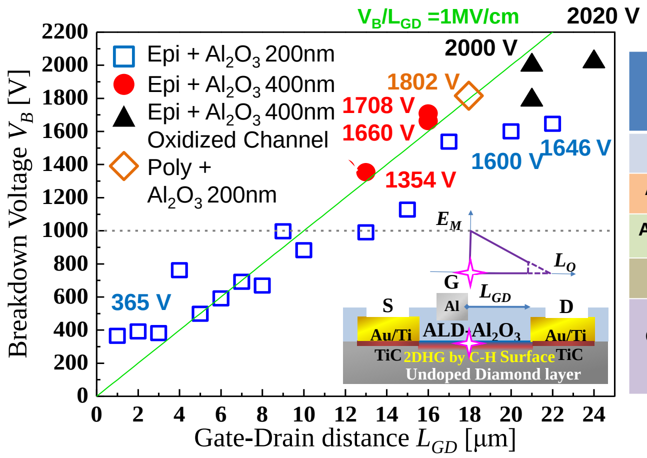

Fig. 2 Maximum breakdown voltages V_B of C-H diamond MOSFETs as a function of gate-drain length L_{GD}. Epitaxial C-H diamond FETs covered by ALD Al_2O_3 films in 200nm thick on channel as gate oxide and in 200 nm (open square) and 400 nm (closed circle) on drift layer. Partially oxidized channel under 200 nm Al_2O_3 gate oxide with 400 nm Al_2O_3 passivation on drift layer (closed triangle) showing normally-off mode. Polycrystalline diamond FET with 200 nm Al_2O_3 gate oxide and passivation on drift layer (open rhomboid).

up to V_B ~1000 V. At L_{GD} >10 µm, V_B exceeds 1000 V and reaches 1646 V at L_{GD} of 22 µm (Fig.2 open squares), though the V_B/L_{GD} is less than 1. With 400nm Al_2O_3 on drift layer, V_B/L_{GD} keeps 1 above 1000 V and V_B reaches 1700 V at L_{GD} of 16 µm (Fig.2 closed circles). In a polycrystalline substrate with 200nm Al_2O_3, V_B of 1800V has been obtained at L_{GD} of 18 µm (Fig.2 open rhomboids). Normally-off MOSFETs have been fabricated by partially oxidized channel under Al_2O_3 gate oxide with a threshold voltage V_{th} of -3~-5V. Its V_B reaches 2000 V at L_{GD} of 21 µm (Fig.2 closed triangles). Electric field distribution at diamond surface is schematically shown in Fig.2, where the maximum electric field E_M of diamond surface is located near the gate edge (cross in Fig.2). The electric field distributes in an oblique line. Its slope is governed by negative or positive surface charge density of diamond in the range of 10^{10}-10^{13} cm^{-2}. L_{GD} dependence of V_B in Fig.2 might originate from a relatively small surface charge density (<10^{12} cm^{-2}) where L_O (length to the extrapolated “zero field point”) is larger than L_{GD}.

The V_B of C-H diamond lateral MOSFETs without field plate structure become comparable to those of other wide bandgap semiconductor planar FETs with field plate such as SiC (V_B/L_{GD}=0.8 MV/cm), AlGaN/GaN (1.0 MV/cm) and AlGaN/ AlGaN (1.7 MV/cm) (Table 1). Diamond can achieve V_B/L_{GD} >3 MV/cm from V_B of 365 V at L_{GD} of 1µm (Fig.2).

Table 1: Comparison with the lateral FETs of SiC, GaN, Ga_2O_3 and Diamond

Types	Maximum drain current density	V_B Breakdown voltage	L_{GD} Gate-Drain length	V_B / L_{GD} Average electric field strength
SiC [1]	90mA/mm	1600 V	20 µm	0.8 MV/cm
AlGaN/GaN [2]	300mA/mm	200 - 1400 V	4 - 20 µm	1 MV/cm
AlGaN/AlGaN[3]	200mA/mm	500 -1700 V	3 - 15 µm	1.7 MV/cm
Ga_2O_3 [4]	80mA/mm	750 V	15 µm	0.5 MV/cm
C-H Diamond p-FET (This work)	190mA/mm	365- 1000V ~1000-1800V	1 - 9 µm 10-18 µm	Max 3.7 MV/cm 1 MV/cm

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3. On-state: High drain current density by 2DHG

At on-state, drain current density is an important parameter. Drain current density normalized by gate width reaches 100mA/mm in the C-H MOSFET with V_B of ~1700V. This value is higher than those of a diamond MESFET of boron-doped channel and drift layer (1mA/mm) with V_B of 1500 V [6] and is comparable of those of SiC planar MOSFETs (90mA/mm), AlGaN/GaN (~300mA/mm) and AlGaN/ AlGaN (~200mA/mm) shown in Table 1. Between 100-600K, C-H diamond MOSFETs can preserve almost the same FET performance indicating a wide temperature power device application.

In the case of polycrystalline diamond, the drain current density varies from 1mA/mm to 100mA/mm depending on surface hole mobility of C-H diamond (10-100 cm^2/Vs). The V_B/L_{GD} is comparable to those of homoepitaxial diamond FETs indicating that large diamond films on non-diamond substrate can be applied in a power electronics market.

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