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 polycrystalline 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 $\mu$m. 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$_2$O$_3$, 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, $R_{onS} = \frac{2\sqrt{2}V_B^2}{\mu_e E_{crit}} E_{drift}^2$ ($\Omega \text{cm}^2$), 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$^2$/V$\cdot$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 channel on-resistance $R_{ch}$ of 4 $\Omega$mm [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 $R_{onS} \approx R_{ch} L_{drift}^{crit} = \frac{\sqrt{2}V_B}{E_{crit}} = 10^{-7} V_B$ ($\Omega$cm$^2$) [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°C, the 2DHG is stable under the Al$_2$O$_3$ passivation formed by high temperature (450°C) atomic layer deposition (ALD) [4,5]. The ALD Al$_2$O$_3$ 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 $\mu$m of MOSFETs with 200nm thick Al$_2$O$_3$ on C-H diamond, the $V_B/ L_{GD}$ is on the line of 1 MV/cm
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$_2$O$_3$ 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$_2$O$_3$ gate oxide with 400 nm Al$_2$O$_3$ passivation on drift layer (closed triangle) showing normally-off mode. Polycrystalline diamond FET with 200 nm Al$_2$O$_3$ gate oxide and passivation on drift layer (open rhomboid).

up to $V_B \approx$1000 V. At $L_{GD} > 10 \mu$m, $V_B$ exceeds 1000 V and reaches 1646 V at $L_{GD}$ of 22 $\mu$m (Fig.2 open squares), though the $V_B/L_{GD}$ is less than 1. With 400nm Al$_2$O$_3$ on drift layer, $V_B/L_{GD}$ keeps 1 above 1000 V and $V_B$ reaches 1700 V at $L_{GD}$ of 16 $\mu$m (Fig.2 closed circles). In a polycrystalline substrate with 200nm Al$_2$O$_3$, $V_B$ of 1800V has been obtained at $L_{GD}$ of 18 $\mu$m (Fig.2 open rhomboids). Normally-off MOSFETs have been fabricated by partially oxidized channel under Al$_2$O$_3$ gate oxide with a threshold voltage $V_T$ of -3~5V. Its $V_B$ reaches 2000 V at $L_{GD}$ of 21 $\mu$m (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 $10^{10}$ to $10^{13}$ $\text{cm}^{-2}$. $L_{GD}$ dependence of $V_B$ in Fig.2 might originate from a relatively small surface charge density ($<$10$^{12}$ $\text{cm}^{-2}$) 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 1 $\mu$m (Fig.2).

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 100 mA/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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References