Black polycrystalline diamond transistors with high breakdown

Despite material imperfections such as cracks and grain boundaries, devices also achieve high maximum drain currents.

Waseda University and Yokogawa Electric Corp in Japan have used black polycrystalline diamond (BPD) to fabricate field-effect transistors (FETs) with breakdown voltages up to 1.8kV, comparable with the performance of silicon carbide (SiC) and gallium nitride (GaN) devices [M. Syamsul et al, Appl. Phys. Lett., vol109, 203504, 2016]. Despite imperfections of the polycrystalline material such as cracks and grain boundaries, the resulting devices also achieved high maximum drain currents.

The researchers comment: "We showed that BPD-FETs may be worthy candidates for high-power FET devices, and demonstrated comparable electrical characteristics to single-crystalline diamond and clear polycrystalline diamond FETs."

Most research on diamond-based devices is based on white polycrystalline or single-crystal material. Polycrystalline silicon is widely used for thin-film transistors in displays.

Undaunted by the "unappealing large grain boundaries and cracks" of BPD, the researchers believe the material is worth further research into its full potential. "Breakdown and stress voltages of BPD in an FET have not been previously studied," they add.

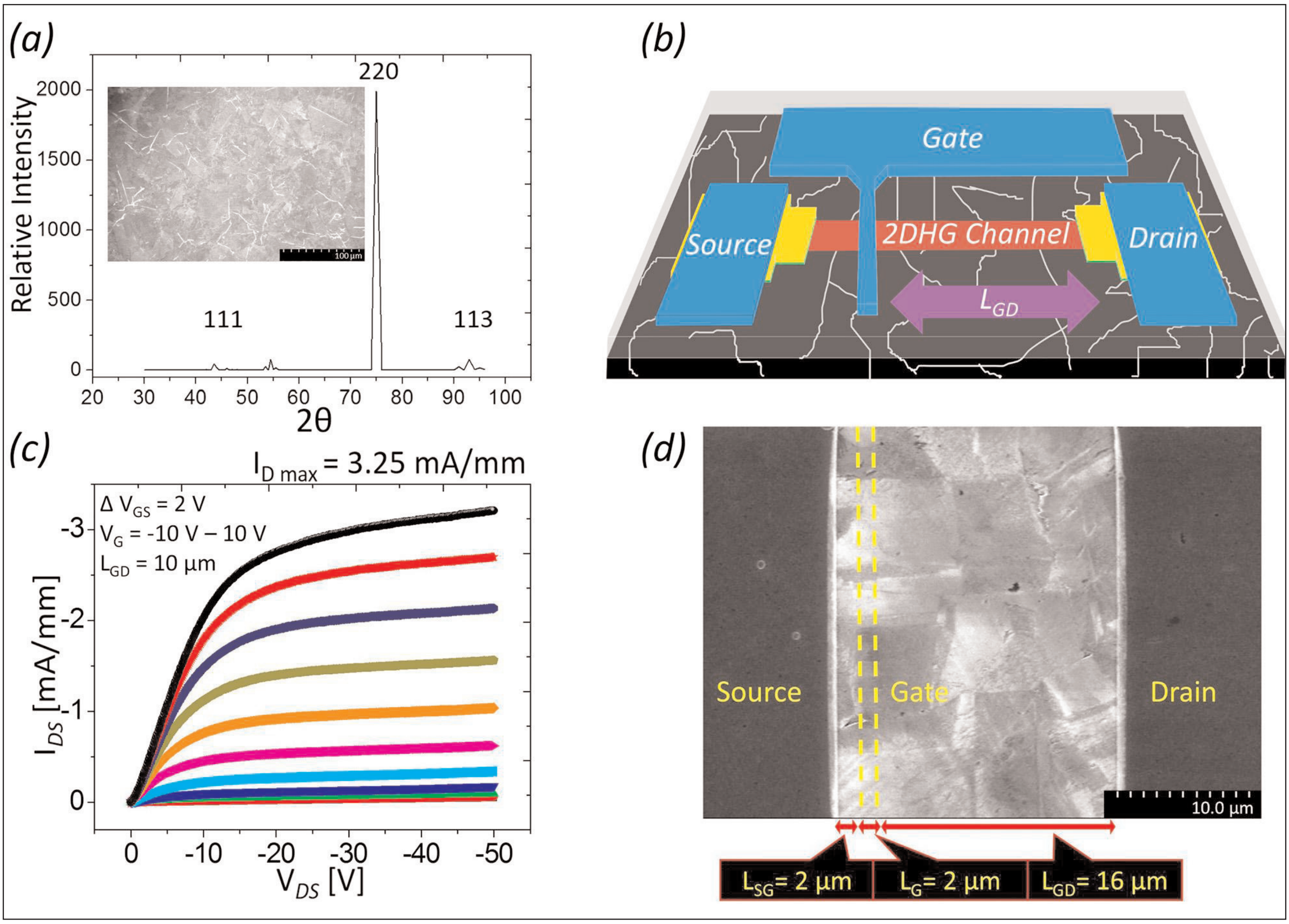

Figure 1. (a) X-ray diffraction pattern of BPD. Inset: field-emission scanning electron microscope image of rough BPD surface. (b) Diagram of BPD-FET. (c) Drain current–voltage (I_{DS}–V_{DS}) characteristics in vacuum at room temperature with L_{GD} of 10μm. (d) Field-emission scanning electron microscope image of region between the source and drain of the BPD-FET after stripping metallization and Al_2O_3 passivation.

The devices (Figure 1b) were fabricated on 10mmx10mmx0.5mm commercial BPD substrates produced by chemical vapor deposition (CVD). According to atomic force microscopy (AFM), the roughness was 2.72nm and grains covered 98% of the surface.

Source–drain contacts consisted of gold/titanium layers. The electrodes were annealed at 450°C for 30 minutes in hydrogen. This formed a layer of titanium carbide (TiC) between the titanium contact and carbon material of the BPD. After annealing, the sample was heat treated with hydrogen plasma at 600°C for 6 minutes.

A narrow 25µm-wide horizontal two-dimensional hole gas (2DHG) channel was defined with photoresist. The 2DHG was created using treatment involving ultraviolet light and ozone, giving a partially carbon–oxygen (C–O) bond surface termination. This gave a potential barrier of 2eV between the carbon–hydrogen bonded 2DHG region and the surrounding C–O terminated areas, giving electrical isolation of the channel.

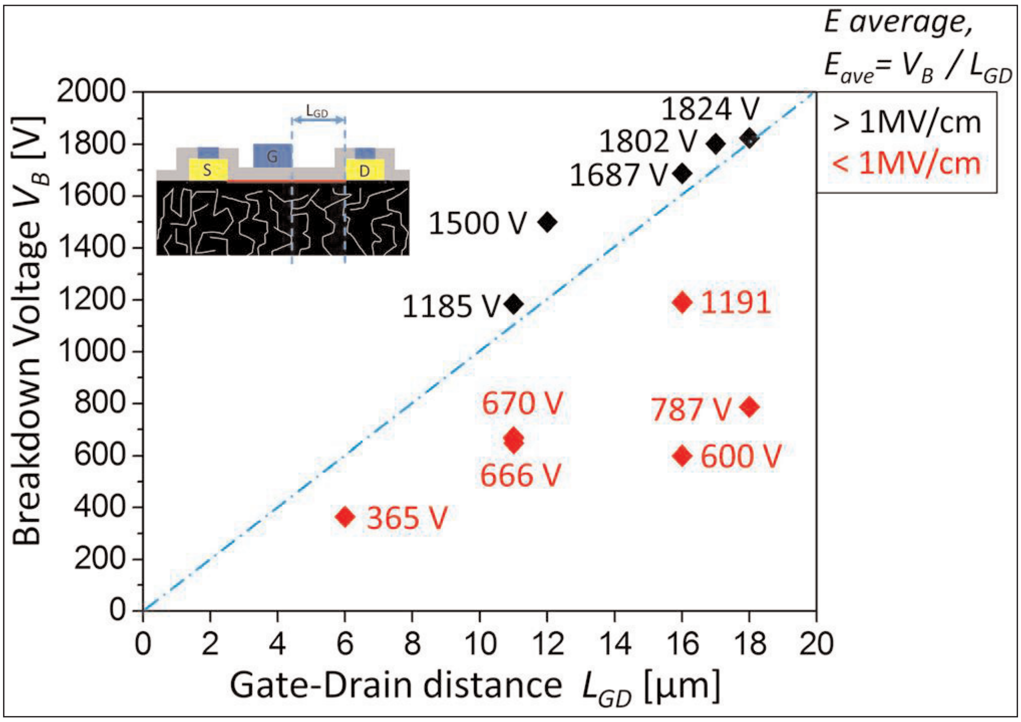

Figure 2. Breakdown voltage versus L_{GD} — those above the dashed line satisfy V_B/L_{GD} greater than 1MV/cm.

The photoresist was removed and then a 200nm aluminium oxide (Al_2O_3) gate dielectric layer built up using alternate exposures to trimethyl-aluminium and water (H_2O) at 450°C.

The device was completed with the removal of Al_2O_3 from the source–drain areas and deposition of the aluminium gate electrode.

Measurements (Figure 1c) were made on a device with 10µm gate-drain distance (L_{GD}), 2µm gate length (L_G) and 2µm source-gate distance (L_{SG}) in vacuum. "The characteristics of the saturation curves, including the pinch-off and saturation region, were similar to those of single-crystalline or clear-type polycrystalline diamond FETs, exhibiting nearly perfect modulation," the team comments.

The maximum drain current (I_{Dmax}) was 3.25mA/mm. The researchers point out: "The maximum drain current was unusually high for BPD considering the room-temperature operation and 25µm channel width. This value is also nearly three times higher than the boron-doped metal-semiconductor field-effect transistors (MESFETs) and junction field-effect transistors (JFETs)."

Increasing L_{GD} to 18µm enabled a breakdown voltage (V_B) of 1824V with I_{Dmax} of 1.1mA/mm. The team claims: "These findings indicate that our BPD-FET has the highest breakdown voltage of any diamond FET reported to date. The breakdown voltage was more than 300V higher than boron-doped diamond FETs and three times greater than JFETs."

Over a range of devices with varying L_{GD} values, the average electric field at breakdown (V_B/L_{GD}) reached as high as 1.25MV/cm. Values greater than 1MV/cm are taken as indicative of high-voltage robustness in FETs, according to the researchers. Out of ten devices presented in the paper, five met this criterion (Figure 2).

Aluminium gallium nitride barrier/gallium nitride (AlGaN/GaN) channel FETs have achieved values of V_B/L_{GD} up 1.7MV/cm. The researchers comment that their devices have demonstrated among the highest values for planar FETs, adding: "Performance of our BPD-FETs exceeded those of Ga2O3, SiC and AlGaN/GaN based devices, which have shown V_B/L_{GD} values of 0.5, 0.8, and 1MV/cm, respectively."

The researchers also studied the degradation of the devices after subjecting them to harsh voltage stresses. The degradation in I_{Dmax} after 500V stress was 6% for a 16µm L_{GD} from 2.42mA/mm, before, to 2.28mA/mm, after. A 1000V stress reduced I_{Dmax} further to 1.81mA/mm (25% down on the original value). Breakdown occurred at 1191V. Voltage stress of 2000V destroyed the device.

The team believes that better understanding of the effect of polycrystalline grain boundaries on high voltage breakdown could lead to further improvements in BPD-FET devices. ■

http://dx.doi.org/10.1063/1.4967999

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