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Measurement of Anisotropic Dielectric Strength of Hexagonal Boron Nitride

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Abstract

In this work, an anisotropic dielectric breakdown strength (E_{BD}) for hexagonal boron nitride (h-BN) was measured under a well-controlled relative humidity. The in-plane and out-of-plane E_{BD} values were measured to be 3 and 12 MV/cm, respectively.

1. Introduction

Dielectric breakdown has historically been of great interest from the perspectives of fundamental physics and electrical reliability. Although h-BN is considered an ideal substrate for two-dimensional material devices, research on the insulating properties of h-BN has been limited. The anisotropy of dielectric breakdown has not been extensively discussed because the well-studied SiO_2 is amorphous to minimize the leakage path. To date, there have been only a few reports on such anisotropy, for example, the existence of a preferred breakdown direction in alkali-halide crystals and the anisotropic E_{BD} observed in power device applications of SiC. Moreover, we have observed layer-by-layer breakdown behavior, suggesting the existence of strong anisotropy in the dielectric breakdown originating from the layered structure [1]. At present, however, the experimental data are quite limited. Here, we present a complete characterization of the dielectric breakdown strength of high-quality h-BN bulk single crystals in the directions both normal and parallel to the c axis ($E_{BD\perp c}$ & $E_{BD//c}$) to reveal the overall picture of the anisotropy in the dielectric breakdown of this material. The E_{BD} value obtained here can be regarded as the standard for qualifying the crystallinity of large-area h-BN layers grown via chemical vapor deposition (CVD) for electronic applications.

2. Dielectric breakdown in the in-plane direction

Figure 1(a) shows a schematic of device for $E_{BD\perp c}$ measurements. These devices were prepared via the mechanical exfoliation of bulk h-BN and conventional electron beam lithography. High-quality synthetic fused silica (ES grade for optical use) was used as the substrate because the E_{BD} of the substrate must be higher than that of the h-BN. The gap length (L_{gap}) should be in the range of 200 nm to 1 μm. The maximum voltage of the source meter needed to precisely measure the leakage current (< 1 nA) is 210 V. The relative humidity was carefully controlled using a humidifier and monitored by a hygrometer placed near the prober.

Because the sample in the fabricated device is exposed to an ambient, the effect of adsorbed water on the dielectric breakdown was invested carefully by four kinds of experimental setups. **Figure 1(b)** shows the I-V measurements recorded for L_{gap} ~450 nm and an h-BN thickness of $10 - 60$ nm. When the relative humidity was ~68 %, the current flow was quite unstable, exhibiting several peaks. V_{BD} could be clearly defined as 92 V, as indicated by an arrow, because the electrode was broken by the melting and evaporation induced by the high current density that formed at breakdown with perceivable light emission. Next, I-V measurements were performed in Flourinert, an insulating oil, under atmospheric pressure to prevent creeping discharge. The V_{BD} value increased, and the leakage current before breakdown was reduced, although it still remained. When the adsorbed water was removed under vacuum, the leakage current decreased below the detectable level. Finally, the sample was annealed at 200 °C for two hours using the stage heater in the vacuum prober. The V_{BD} value did not change from that observed in vacuum, suggesting that the effect of the adsorbed water was negligible. **Figure 2** shows V_{BD} as a function of L_{gap} for h-BN on a fused silica substrate. The colors of the lines correspond to those used in **Fig. 1**. The E_{BD} value observed at a relative humidity of 68 % was 1 MV/cm, whereas the other three
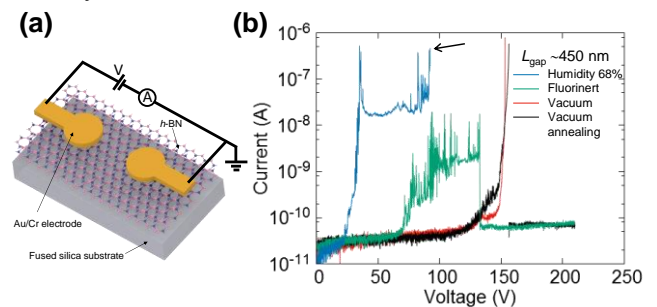

Fig. 1 (a) Schematic diagram of the measurement setup for $E_{BD\perp c}$. **(b)** I-V curves for h-BN with L_{gap} ~450 nm.
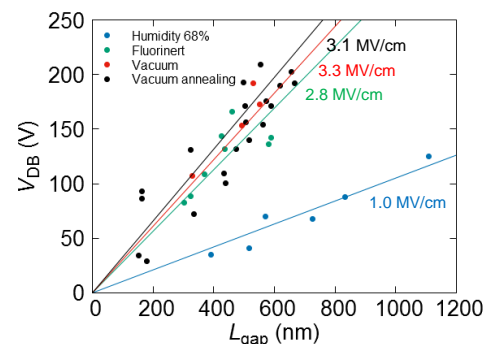

Fig. 2 V_{BD} as a function of L_{gap} for h-BN on a fused silica substrate.

cases yielded values of approximately 3 MV/cm; all of these values are smaller than that of the fused silica substrate. Based on these data, it can be concluded that for the investigated device structure, the value of $E_{BD\perp c}$ for h-BN is ~3 MV/cm.

Next, we analyzed the morphology of the h-BN after breakdown. **Figure 3(a)** shows an optical image of a typical sample after breakdown. **Figure 3(b)** shows an atomic-force microscopy (AFM) image corresponding to the region indicated by the white-dashed rectangle in **Fig. 3(a)**. The white broken lines in **Fig. 3(b)** indicate the edges of the electrodes before breakdown. Small particles with a diameter of less than 200 nm are evident in the gap. The energy-dispersive X-ray spectrometry measurement suggests that these particles were formed by the melting of the metal electrodes due to the high current density. **Figure 3(c)** shows the height profile along the broken green line in **Fig. 3(b)**. Interestingly, the heights of the h-BN in the gap and below the electrode were reduced by ~4 nm, and the remaining h-BN surface was still flat. In the case of the breakdown of the fused silica substrate without h-BN, the surface in the gap region became rough. The flatness of the h-BN after breakdown appears to be a consequent of its layered structure. After many breakdown tests, the upper h-BN layers of 4 – 15 nm in thickness were found to have melted.
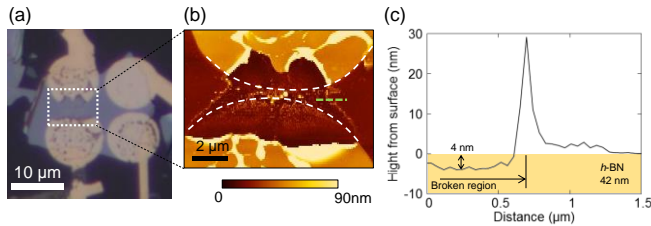

Fig. 3 (a) Optical microscopy image of h-BN after dielectric breakdown. (b) AFM image corresponding to the region indicated by the white-dashed rectangle in a. (c) Height profile corresponding to the green-dashed line in b.

3. Dielectric breakdown in the out-of-plane direction

Figure 4(a) shows a schematic drawing of a typical device fabricated on the same type of fused silica substrate used in the previous tests. h-BN with a thickness of 10 – 100 nm was sandwiched between upper and lower Cr/Au electrodes to form a metal-insulator-metal (MIM) structure. The overlap area was designed to be 25 μm^2. The conditions for the annealing before the test. And the $E_{BD//c}$ was measured
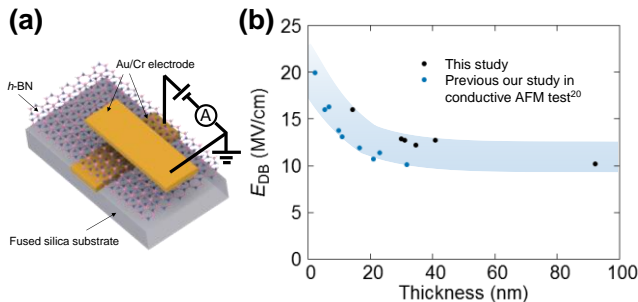

Fig. 4 (a) Schematic diagram of the measurement setup for $E_{BD//c}$. (b) $E_{BD//c}$ as a function of the h-BN thickness.

by the I-V measurements in the same system as those for the $E_{BD\perp c}$ tests. $E_{BD//c}$ is plotted as a function of the h-BN thickness in **Fig. 4(b)**. The $E_{BD//c}$ results exhibit a similar trend to those observed in our previous study using a conductive AFM, supporting the validity of the present measurement. The value of $E_{BD//c}$ was determined to be ~12 MV/cm.

4. Anisotropy in E_{BD} of h-BN

Empirically, E_{BD} has been found to be inversely related to ε_r in well-studied insulators. Insulators with strong covalent bonding have higher E_{BD} and lower ε_r, whereas those with ionic bonding exhibit larger ε_r because of their higher polarization. This relationship can be simply converted into that of the band gap energy vs. ε_r. **Figure 5** shows E_{BD} as a function of ε_r for various materials, along with the present h-BN data. h-BN exhibits strong anisotropy in ε_r; $\varepsilon_{r//c}$ and $\varepsilon_{r\perp c}$ are 3.38 and 6.61, respectively [2]. Therefore, it is interesting that for h-BN, both $E_{BD\perp c}$ and $E_{BD//c}$ follow the empirically established relationship between E_{BD} and ε_r. Here, it should be emphasized that the value of $E_{BD//c}$ = ~12 MV/cm for h-BN is indeed quite large, as seen from the fact that it is comparable to or slightly larger than the ideal value of ~10 MV/cm for diamond. The large $E_{BD//c}$ of h-BN can be understood by considering the structure change from sp^3 of h-BN to sp^2 of cubic-BN. The $E_{BD\perp c}$ of h-BN is decreased with respect to the E_{BD} of c-BN, whereas the $E_{BD//c}$ of h-BN is increased with respect to the E_{BD} of c-BN [3]. The origin of this large $E_{BD//c}$ for h-BN is the small value of $\varepsilon_{r//c}$ due to the layered structure.
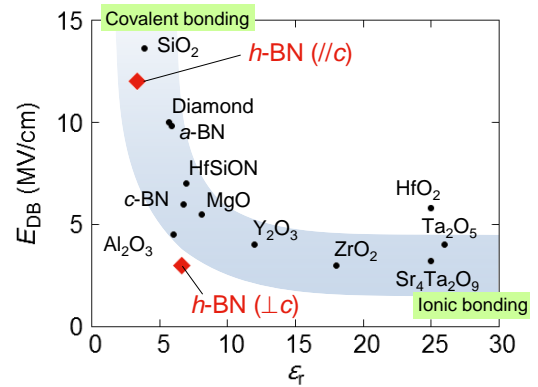

Fig. 5 E_{BD} as a function of ε_r for various materials, along with the present h-BN data.

5. Conclusions

$E_{BD\perp c}$ was measured to be 3 MV/cm in the investigated device structure, in which a pair of electrodes were fabricated on the surfaces of the h-BN. By contrast, the value of $E_{BD//c}$ measured in an MIM structure was 12 MV/cm. The origin of this large $E_{BD//c}$ for h-BN is the small value of $\varepsilon_{r//c}$.

References [1] Hattori, Y. et al., *ACS nano*, **9**, 916 (2015). [2] Ohba, N. et al. *PRB* **63**(11), 115207 (2001). [3] Brożek, T. et al., *Diamond and Related Materials* **3**(4-6), 720 (1994).