Extended Abstracts of the 2017 International Conference on Solid State Devices and Materials, Sendai, 2017, pp465-466

Random Telegraph Noise in *h*-BN under Constant-Voltage Stress Test

Yoshiaki Hattori[1], Takashi Taniguchi[2], Kenji Watanabe[2], and Kosuke Nagashio[1,3]

[1]The University of Tokyo7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656 Japan
[2]National Institute of Materials Science, 1-1 Namiki, Tsukuba, Ibaraki, 305-0044 Japan
[3]PRESTO-JST, Japan
E-mail: hattori@adam.t.u-tokyo.ac.jp

Abstract

In this work, constant-voltage stress test for high-quality single crystal hexagonal boron nitride (*h*-BN) was performed. The complex random telegraph noise (RTN) was observed in the test, which indicates the onset of the impact ionization process for dielectric breakdown.

1. Introduction

h-BN has gained a great deal of attention as an ideal substrate for 2-dimensional van der Waals heterostructure devices to improve their performance. From the point of view of device applications, the characterization of the insulating properties is important.

Breakdown strength (E_{BD}) is the most representative insulating properties to evaluate the film quality. E_{BD} of exfoliated single crystal *h*-BN has been reported as 10–12 MV/cm in the out-of-plane direction and ~3 MV/cm in the in-plane direction, respectively [1, 2]. On the other hand, it has been reported that the out-of-plane E_{BD} of the scalable *h*-BN grown by various growth methods is lower than exfoliated sample, and limited to ~4 MV/cm due to the defects, impurities and/or grain boundaries.

Judging from the comparison with E_{BD} of other materials, E_{BD} for the exfoliated single crystal *h*-BN is considered to be very close to the ideal value. However, the presence of the oxygen and carbon impurities of less than 10^{18} cm^{-3} and nitrogen vacancy has been experimentally confirmed by scanning tunneling microscope or secondary ion mass spectrometry measurements [3, 4]. For now, the correlation between these defects and insulation properties has not been clarified yet in spite of its importance.

Here, constant voltage stress test is expected to allow the quality evaluation of *h*-BN film more sensitively than E_{BD} evaluation because the time evolution of the failure can be detected. In this study, constant voltage stress test was performed using high-quality single crystal *h*-BN sample.

2. Device structure and current uniformity

Figure 1(a) shows the optical image of the device, where *h*-BN flake is sandwiched by two metal electrodes vertically. The schematic of the device structure and measurement setup is illustrated in **Fig. 1(b)**. The electrical measurement was performed in vacuum (~5.0×10^{-3} Pa) at room temperature in the prober. The bottom electrode was grounded in all measurement. Array-type electrodes enable multiple electrical measurements at different places in the same flake. To investigate the time-dependence current quantitatively, it should be confirmed that current flows uniformly in the overlap area. For this reason, different area of electrodes in the same flake were tested in the *I*-*V* measurement.

Figure 2(a) shows the current density (j) versus electrical field (E) for different electrode area. It is noted that the electrons are always injected from the top electrode. All measurements match well, which indicates the uniform current. Therefore, quantitative evaluation of the current is possible using the metal electrode device. **Figure 2(b)** shows the Fowler-Nordheim (F-N) plot for the *I*-*V* character. The straight relationship in the figure indicates that F-N tunneling current is dominant leakage current in the *I*-*V* test.

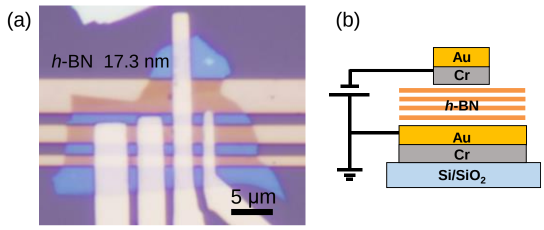

Fig. 1 (a) Optical image of the typical device. **(b)** Schematic diagram of the device and measurement setup.

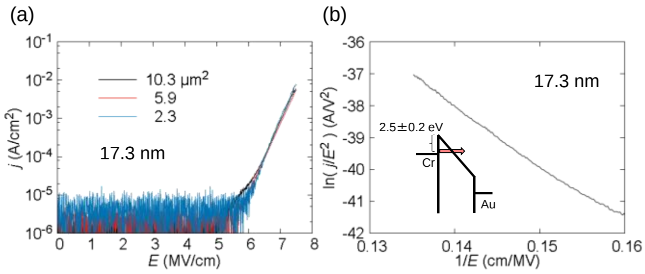

Fig. 2(a) Current density versus electrical field for different electrode area **(b)** F-N plot for the *I*-V character. The slope of the line gives the barrier height of 2.5±0.2 eV for Cr electrode.

3. Repeated *I*-*V* test and the constant voltage test

Figures 3(a) and **(b)** show the *I*-*V* measurement repeated ten times and the constant voltage stress test, respectively. The sampling time for the constant-voltage test is 0.1 s. The current decreases with the iterative number of *I*-*V* measurements, especially, first five times. The degradation of current was also confirmed in constant-voltage test for 8.1 MV/cm and 8.3 MV/cm. Interestingly, the spike-like fluctuation appears in current over ~8.3 MV/cm, which will be discussed later. It should be noted that *h*-BN could tolerate the 8 MV/cm for more than 1 hour, suggesting the high crystallinity. By contrast, the strong electrical field over ~10 MV/cm increases current after decreasing current for initial 30 s, and finally leads to the dielectric breakdown.

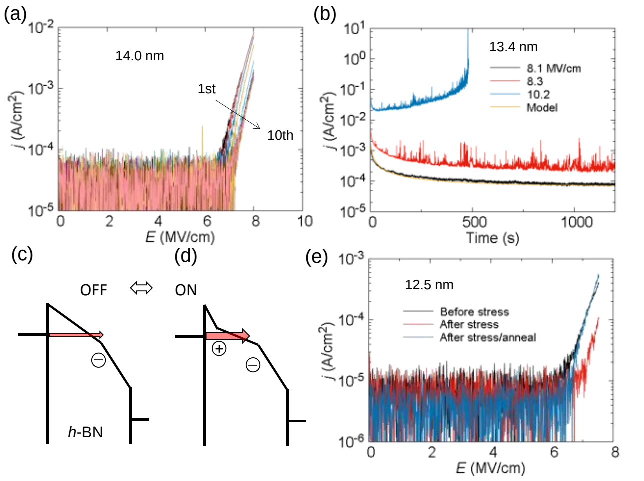

Fig. 3(a) *I-V* measurement repeated ten times. The figure is converted to current density and field. **(b)** Constant-voltage test with different field. **(c)** Band diagram for electron trap **(d)** Band diagram for electron and hole trap **(e)** *I-V* measurement before and after applying the stress in 7.0 MV/cm for 1800 second. The shifted *I-V* character is recovered by annealing due to the thermal detrap.

Next, the origin of the current degradation was investigated. Because the decreased current recovers over ~90 % of the initial value by just leaving the sample at atmospheric pressure for several days, the origin is expected to the accumulation of electrons trapped in the insulator, as shown in **Fig. 3(c)**, not forming the permanent defects. It indicates that the trapped electron lower the cathode field, resulting current decrease. The numerical simulation based on the model [5] is in good agreement with the experiment. Thus, the removal of the accumulated electrons was attempted by thermal annealing. **Figure 3(e)** shows the effect of annealing at 200 °C for 2 hours in the Ar/H_2 forming gas. The *I-V* character degraded by applying the electrical stress of 7.0 MV/cm for 1800 second was recovered by subsequent annealing due to the thermal detrapping. From these experiments, it is concluded that the current reduction is attributed to the electron trapping.

4. Random telegraph noise

The unique spike-like noise observed in constant-voltage test for over ~8.3 MV/cm was focused in detail using faster sampling time with 4 ms. **Figure 4(a)** shows the time-dependent current for 8.5 MV/cm in certain time range. It was found that the spike-like noise was random telegraph noise (RTN) with multiple states. The RTN was also observed in the graphite/*h*-BN/Au structure device shown in **Fig. 4(b)**. Because the graphite electrode provides an ideal van der Waals interface with *h*-BN, it is expected that the RTN is attributed to the intrinsic properties of the present *h*-BN itself, not to the interface states or defects in the Cr electrode.

Figure 5 shows the constant-voltage test at different electrical fields. The RTN is observed for $E > 8$ MV/cm in the equilibrium state after current decrease, but the current fluctuates significantly for $E \geq 9$ MV/cm. Therefore, it is expected that the origin of RTN is trapped holes produced by the impact ionization process at high electrical field. **Figure 3(d)** indicates the band diagram when both electron and hole are trapped. The accumulation of holes enhances the cathode field, which in turns current increase. Because the observed RTN is constructed with random current increase in a short time, it is expected the trapping and detrapping of hole occurs near cathode everywhere in the electrode. The situation corresponds to **Fig. 3(c) and (d)** as OFF/ON states, respectively.

In the impact ionization process, an electron with kinetic energy larger than band gap creates an electron-hole pair, but not necessary though band-to-band impact ionization. It is possible with lower energy by the presence of defect states in the band gap. It means that the threshold electrical field for RTN shown in **Fig. 5** reflects the crystallinity of the *h*-BN film. In other words, the measurement of RTN might be used for the quality evaluation of *h*-BN film.

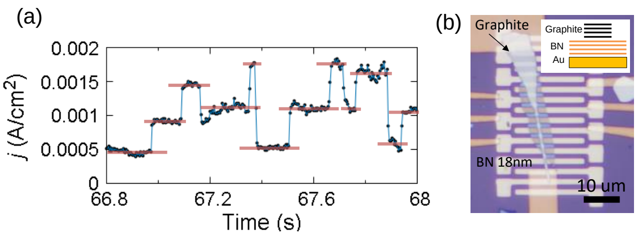

Fig. 4(a) RTN with multiple states in constant-voltage test. **(b)** Optical image of the graphite/*h*-BN/Au device.

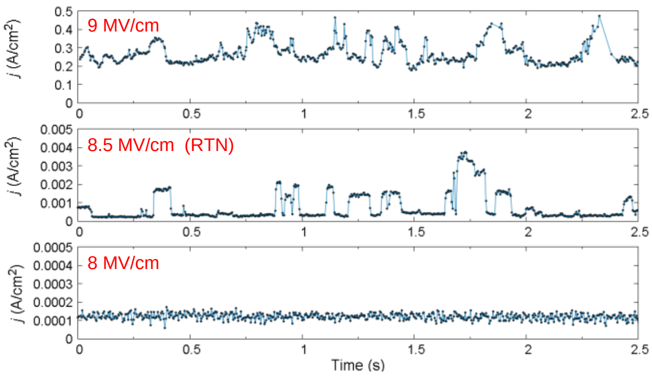

Fig. 5 Character of noise in constant-voltage measurement depends on field.

5. Conclusions

Single crystal *h*-BN film can tolerate the constant high electrical field stress with 75% of E_{BD} for more than 1 hour, which indicates the high electrical reliability. The RTN in the constant-voltage test implies the presence of the initial defects in the film. It is possible that the measurement of the RTN allows the crystallinity evaluation of *h*-BN film more sensitively than the measurement of E_{BD}.

Acknowledgements
This research was supported by the JSPS Core-to-Core Program, JSPS KAKENHI Grant Numbers JP17K14656, JP25107004, JP26886003, JP16H04343 & JP16K14446, Mikiya Science and Technology Foundation, and Mizuho Foundation for the Promotion of Sciences.

References

[1] Hattori, Y., *et al.*, *ACS Nano*, **9**, 916 (2015).
[2] Hattori, Y., *et al.*, *ACS appl. mater. interfaces*, **8**, 27877 (2016).
[3] Taniguchi, T., *et al.*, *J. Crystal Growth*, **303**, 525 (2007).
[4] Wong, D., *et al.*, *Nature Nanotechnol.* **10**, 949 (2015).
[5] Chen I. C., *et al.*, *IEEE Trans. Electron Dev.*, ED-**32**, 413(1985).