Supplementary Information for 'Electron beam directed etching of hexagonal boron nitride'

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A comparison of a hBN flake before and after a plasma cleaning treatment is shown in figure S1, showing that no damage occurs to the hBN flake during the mild plasma treatment process. The plasma treatment is not necessary for the EBIE of hBN to occur but is used to minimise contaminantion and thus increase reproducibility of experiments.

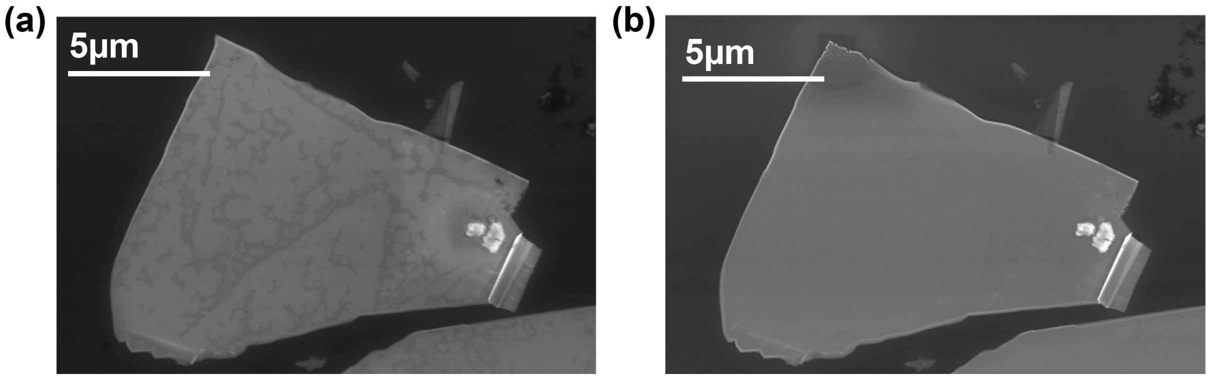

Figure S1: (a) SEM image of a typical hBN flake before plasma cleaning treatment. (b) Same hBN flake after a plasma cleaning treatment (note EBIE experimentation was undertaken in the top corner of the flake)

Figure S2 displays Raman spectra taken before and after EBIE in the rastered region labelled 'Area 1' in the inset. The hBN Raman line shows no shift, suggesting that no damage occurs to the hBN during electron beam irradiation and etching of the material.

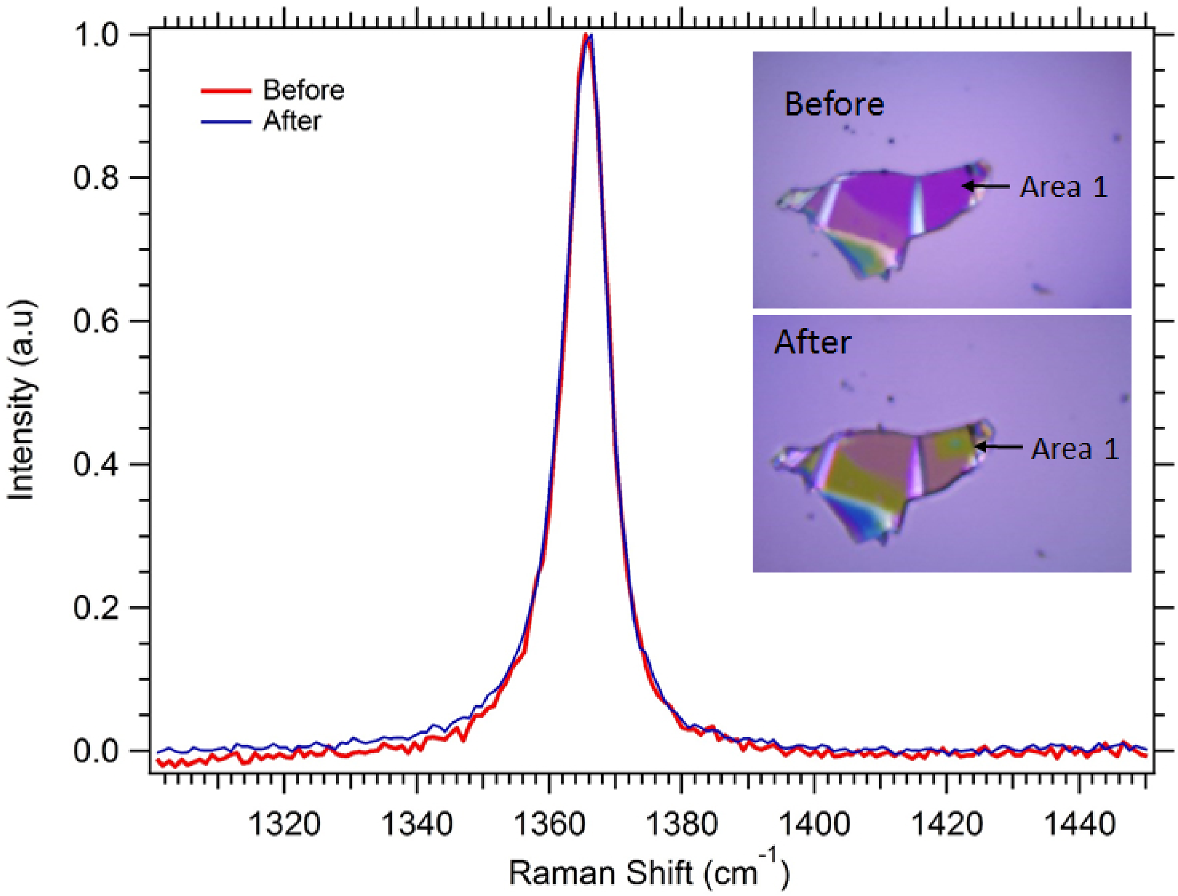

Figure S2: Raman spectra from hBN in Area 1 before and after EBIE processing. The Raman laser wavelength was 533 nm with a 2 micron diameter spot size.

Figure S3a shows reduced roughening in the region surrounding lines etched into the suspended hBN membrane compared to lines etched in the membrane-supported hBN. Within the red box the contrast has been enhanced to accentuate the suspended hBN lines, while in the blue box, the contrast has been enhanced to highlight the hBN on the Si membrane. It should be noted that a small amount of roughening or etching would be expected on the suspended lines as they were located and imaged using the electron beam. Figure S3b shows that some roughening of the hBN occurs at the interface of the Si membrane and hole due to backscattered electrons escaping from the side wall of the Si membrane. This roughening disappears further towards the centre of the hole.

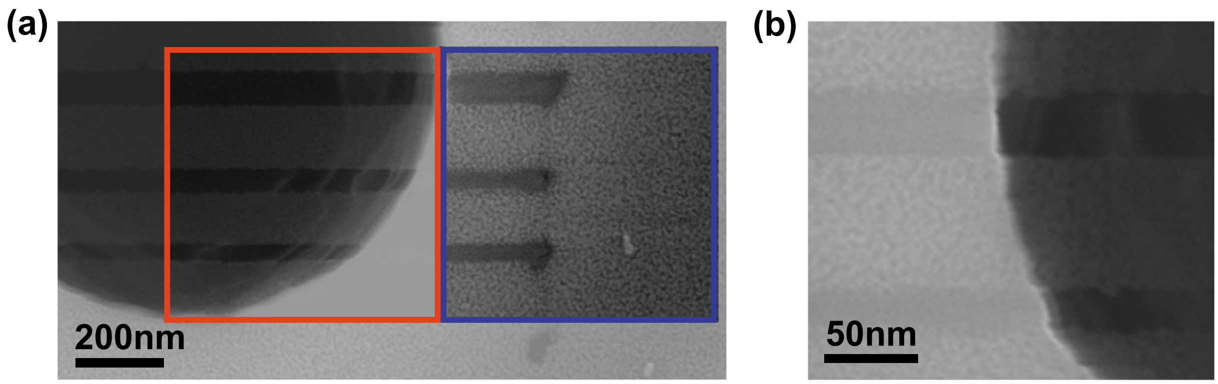

Figure S3: (a) SEM image of a series of horizontal lines etched into a hBN flake suspended over a 1.3 micron hole in a Si membrane. The hBN lines indicated within the blue box have been contrast enhanced to emphasize the increased surface roughening compared to the suspended lines within the red marked region. (b) Magnified SEM image at the interface of the Silicon and hole of the silicon membrane showing a gradient of reduced roughening as the hBN flake extends over the hole.

Monte Carlo simulations were carried out to show how both the BSE range and yield (electron hits per nm^{-2}) taper off dramatically away from the primary beam location when comparing hBN regions on the Si membrane (Figure S4a) and over a hole (Figure S4b). The substrate used in all 'on-membrane' simulations consisted of a 90nm thick oxide layer on a 500μ m Si membrane, which can be considered an infinite substrate. For the hBN over a hole, no BSEs were detected beyond a radius of 50nm from the primary beam axis for all accelerating voltages studied, indicating that the majority of etching of the hBN is due to primary and SE1 electrons.

Figure S5 shows SEM images of holes etched into hBN using a 10 and 5 kV primary electron beam. The observed range of roughening of the hBN at 10kV (Fig. S5a) and 5kV (Fig. S5b) on a silicon substrate matches the simulated BSE ranges of 800 and 300 nm respectively (Fig. S5c), providing further confirmation of the role of BSEs in causing surface roughening of the hBN outside the primary electron beam radius.

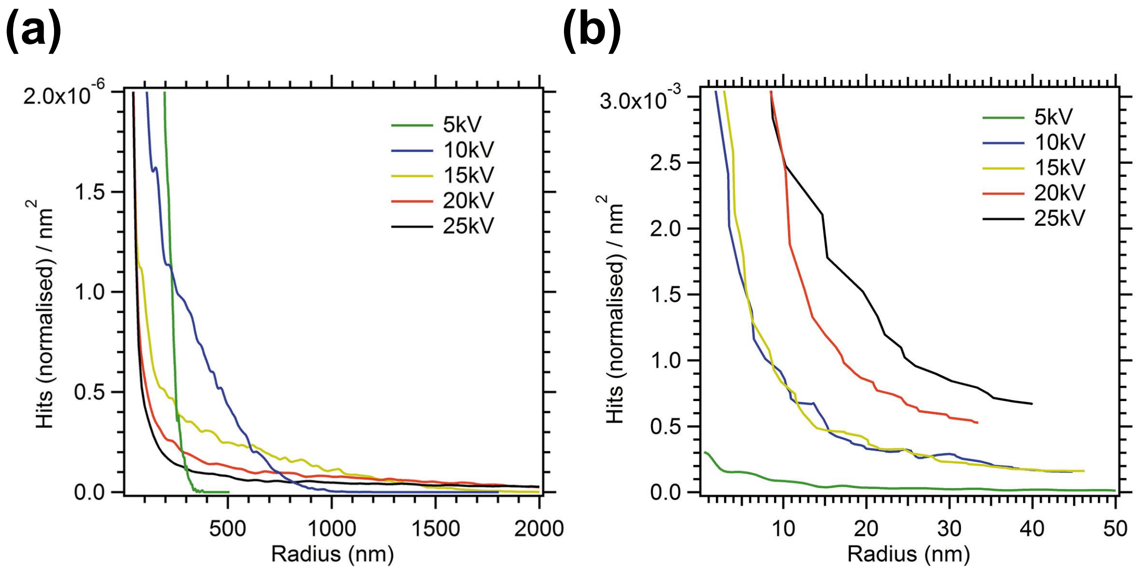

Figure S4: Monte Carlo simulations comparing the normalized hits (electrons per nm^2) on the (a) Si membrane-supported hBN and (b) unsupported hBN against the radial spread of BSEs for accelerating voltages between 5 and 25 kV. A large reduction in the BSE range can be seen when comparing the simulated hits on and off the Si membrane.

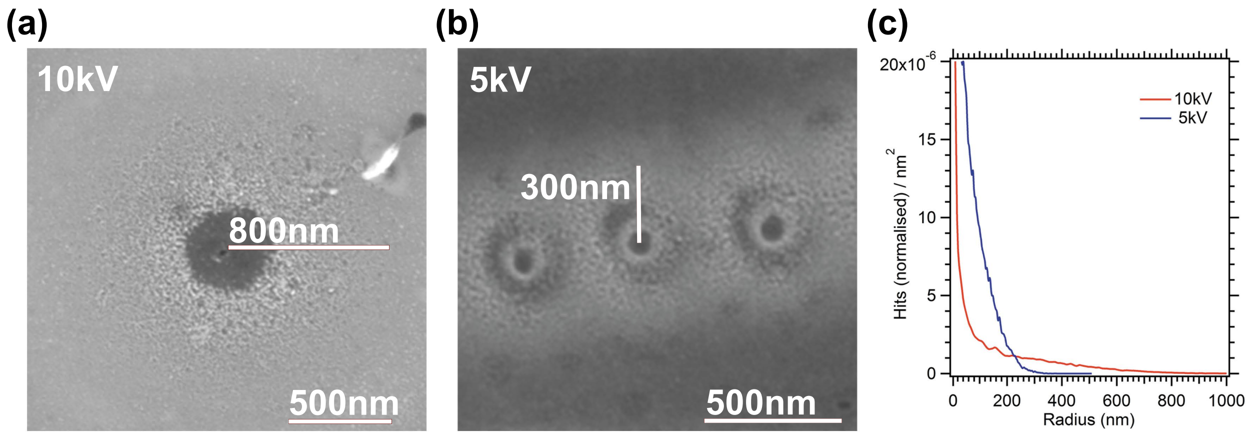

Figure S5: Correlation of radial extent of surface roughening as observed by SEM and expected BSE range at 10 and 5 kV primary beam energies. (a) SEM image of a single spot etched into a hBN flake at 10kV. The degree of roughening reduces with radial distance from the spot, extending to a distance of $\approx$ 800 nm. Similarly, (b) shows an SEM image of a series of holes etched into the same hBN flake at 5kV, showing that roughening is observed up to 300 nm from the primary beam location. (c) shows two Monte Carlo simulations comparing the normalized hits of electrons per nm^2 against the radial spread of BSEs at primary beam energies 5 and 10kV, showing good agreement with the observed range of surface roughening.