Effect of an Ultraflat Substrate on the Epitaxial Growth of Chemical-Vapor-Deposited Diamond

The performance of diamond power devices depends on the crystalline quality of the drift layer, which is a semiconducting diamond layer. Because the layers of diamond power devices are usually grown by chemical vapor deposition, it is important to analyze the critical factors determining crystalline quality during this process. An important related issue is the reduction of the density of dislocations in the epitaxial layer: the density of dislocations increases during chemical vapor deposition. We show that, when using an ultraflat substrate, existing dislocations remain in the epitaxial layer but no new dislocations are formed.

Semiconducting diamond has attracted considerable attention as a material for power devices owing to its high breakdown characteristics and high carrier mobility in high-temperature, high-voltage environments [1]. Recently, the development of a diamond Schottky barrier diode (SBD) that exhibited stable performance at temperatures greater than 200°C has been reported [2-4]. However, the reported performances of diamond power devices are poorer than expected. For the development of high-performance devices, the density of defects is thought to be critical, especially in the drift layer [5, 6].

The permissible defect concentration can be determined using Murphy's yield model [7]. For example, using the model, one can obtain the permissible defect density for a high-current device. By setting the electrode size to $1{\times}10^{-4}$ cm^2 and using Murphy's yield model, while assuming the performance of the electrode deposited on a threading dislocation to be poor, one can find the dislocation density. If the dislocation density is approximately 10^4 cm^{-2}, most of the electrodes (more than 60%) will be inferior. The results of calculations based on Murphy's yield model suggest that a high-quality diamond, which has a defect density of less than 10^3 cm^{-2}, is essential for developing actual devices.

In the case of diamond SBD, a lightly boron-doped diamond layer (p^- layer) is deposited as the drift layer, and the SBD breakdown characteristics will depend on the quality of this layer.

Some researchers have suggested that pretreatment of the substrate is effective for improving the quality of epitaxial diamond [8, 9], so we investigated the effect of an ultraflat polished substrate on the quality of the p^- layer using X-ray topography (XRT) images. For comparison, a scaife-polished substrate was used as a conventional technique.

Since we assumed that the quality of the epitaxial layer might depend on the dislocation density and variations in the distribution of defects in the substrate, we used the same substrate throughout the experiment. This was done to evaluate the effect of the substrate surface flatness on the epitaxial growth of the CVD diamond layer.

The polished substrate was a type-Ib diamond (001) plate. Each p^- layer was deposited using microwave-plasma-assisted chemical vapor deposition. Hydrogen, methane, carbon dioxide, and trimethyl borate were used as the source gases. The thickness of the p^- layer was 10 μm.

UV-assisted polishing is basically mechanical polishing combined with a UV-induced photochemical reaction. This is an effective method of polishing diamond to an ultraflat finish. The carbon atoms at the surface of the diamond layer are oxidized by active species such as oxygen radicals and removed in the form of CO and CO_2. Details of this system were reported previously by Touge *et al.* and Kubota *et al.* [10, 11]. The average roughness, Ra, of the scaife-polished surface and the ultraflat surface was 70.0 Å and 21.5 Å, respectively.

XRT produces two-dimensional images of X-ray diffraction intensities, and these images can provide a projective distribution map of the defects in a single crystal [12]. The bright areas represent areas virtually free of all defects. XRT-based measurements were carried out at BL-15C [13]. Figure 1 is a schematic representation of the experimental set-up for XRT. Exposure time is adjusted by the shutter. The geometry of the sample and detector is asymmetric Bragg-case diffraction. The diffraction plane is (-404) because the diffraction intensity is sufficient to detect XRT images with clear contrast and the incident angle of the X-ray is too shallow to measure the surface-sensitive XRT for observation of the epitaxial layer. XRT images of a scaife-polished surface and p^- layer deposited on this substrate are shown in Figs. 2(a) and (b), respectively. The circles denote areas containing the discussed dislocations. In the yellow dashed circles, a threading dislocation from the substrate to the p^- layer was observed. In the red open circles, no defects were observed, as can be seen from Fig. 2(a); however, new dislocations that grew from the interface were observed in Fig. 2(b). Figures 2(c) and (d) show the XRT images of the ultraflat polished substrate and the p^- layer on this substrate taken under the same conditions as those for the images shown in Figs. 2(a) and (b). The observed area is the same as in Figs. 2(a) and (b). In this case, no dislocations were observed in the red circle.

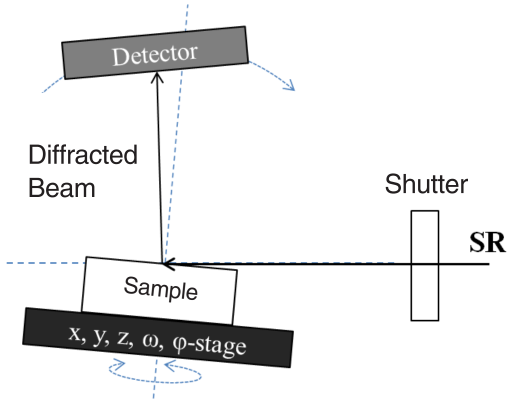

Figure 1: Schematic representation of the experimental setting.

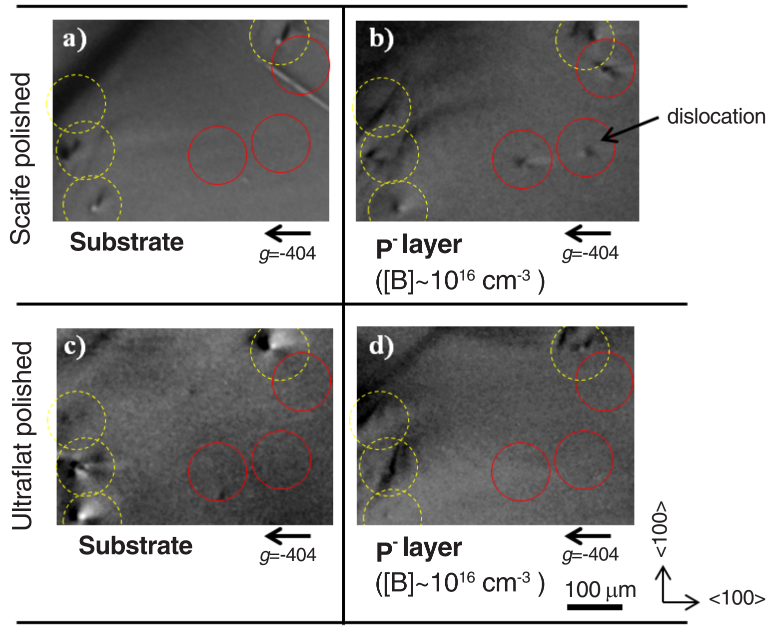

Figure 2: XRT images of the substrates and their p^- layers ($g = -404$). Each circle represents the area that contained the discussed dislocations. (a) scaife-polished substrate, (b) p^- layer on the scaife-polished substrate, (c) ultraflat polished substrate and (d) p^- layer on the ultraflat polished substrate.

To summarize, although the density of all types of dislocation could not be controlled using the ultraflat substrate, the polished substrate was led to a reduction in the growth of new dislocations from the interface. It was found that the ideal surface roughness, Ra, is less than 21.5 Å. In this study, we used UV-assisted polishing to obtain a substrate with an ultraflat surface. Other techniques for smoothening surfaces have been reported, including for (110) or (111) surfaces grown by CVD [14, 15], however, these techniques have not been applied to (001) surfaces grown by CVD, with this particular orientation being the one commonly used for diamond devices.

In a future study, we intend to perform a quantitative analysis of the effect of decreasing the dislocation density by using a substrate exhibiting a low defect density.

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