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Reduced influences of the HPHT substrates on the electronic quality of homoepitaxial CVD diamond layers and on their ultraviolet detector performance ☆

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ABSTRACT

We have carried out a detailed estimation of the influences of the high-pressure/high-temperature-synthesized (HPHT) Ib substrate on the crystalline quality of the homoepitaxial diamond and on the performance of the ultraviolet (UV) detector. The H3 center related luminescence peaks were observed even from the homoepitaxial diamond film having a thickness of 250 μm on a HPHT Ib substrate, suggesting that carriers excited in the epitaxial diamond layer can diffuse over a rather long distance to the HPHT substrate when the quality of the epitaxial layer is sufficiently high. Furthermore, we have attempted to efficiently reduce the long-distance carrier diffusion phenomenon by inserting a boron-doped layer between the epitaxial layer for the detection and the HPHT Ib substrate. The electrically-floating B-doped layer inserted between the homoepitaxial layer and the HPHT substrate efficiently reduced the long-distance carrier diffusion phenomenon, and substantially improved the performance of the UV detector fabricated on a low-quality HPHT Ib substrate.

1. Introduction

Diamond has several interesting physical properties such as large bandgap, high carrier mobilities, extremely high breakdown electric field, highest thermal conductivity and low thermal expansion coefficient near room temperature (RT). Thus, diamond is expected as a potential material for high-performance electronic devices such as high-power and high-speed devices [1, 2], ultraviolet (UV) detectors [3] and UV light-emitting diodes [4]. For the development of diamond-based electronic applications, it is essential to develop a high-rate growth process suitable for diamond films with sufficiently high quality to fabricate such electronic devices. Currently, the microwave-plasma chemical-vapor-deposition (MWPCVD) method is recognized as the most promising fabrication technique for producing such high-quality diamond films at low costs. So far, a number of achievements in the deposition processes for such high-quality diamond films have been reported. Nevertheless, these high-quality diamond films can be deposited only at rather low growth rates much less than 1 μm/h. In recent years, fortunately, some research groups developed a high-rate growth process suitable for diamond films with sufficiently high quality [5–7]. We also have successfully developed a high-rate (>4 μm/h) growth process for such high-quality homoepitaxial diamond films on high-pressure/high-temperature synthesized (HPHT) Ib (001) substrates by using a high-power-density MWPCVD method [8–13]. Furthermore, it was reported that the substrate off-angle effectively improves various characteristics of the homoepitaxial diamond films, such as significant (or complete) reduction of surface hillocks and substantial increases in both the growth rate and the doping efficiency [14–16]. On one hand, these homoepitaxial diamond films can yield strong free-exciton (FE) recombination radiation even at RT, indicating that the films have a reasonably high crystalline quality. On the other hand, it turned out that low-quality HPHT Ib diamond substrates substantially degrade the performance of the devices fabricated homoepitaxially on them [17, 18]. Silva et al. reported in detail the influence of the HPHT substrate on the characteristics of the homoepitaxial diamond films [19]. It was suspected that the observed degradation of the device performance was due to the carrier diffusions to the low-quality HPHT substrate from the homoepitaxial film where hot carriers were created by electrons or UV photons. Therefore, it is desired to diminish the influences of such low-quality HPHT substrates to improve the performance of diamond-based electronic devices under such situations that frequently occur.

In this study, thus, we have carried out a detailed estimation of the influences of the HPHT Ib substrate on the electronic quality of the homoepitaxial diamond layers and on the performance of the UV detector, and have attempted to efficiently reduce the long-distance carrier diffusion phenomenon by inserting a B-doped layer between the epitaxial layer for the detection and the HPHT Ib substrate.

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2. Experimental

For the estimation of the influences of the HPHT substrate on the crystalline quality of the homoepitaxial diamond, thick undoped diamond layers were homoepitaxially grown on mechanically polished HPHT Ib (001) diamond substrates using a high-power microwave-plasma CVD apparatus [8]. The size of the substrates employed was $3.0\times3.0\times0.5$ mm^3. The source gas used was CH$_4$ diluted with H$_2$, and the microwave power, total gas pressure, substrate temperature, and CH$_4$/H$_2$ ratio employed were 3.8–4.2 kW, 120–130 Torr, 1020 °C, and 4.0%, respectively. The samples thus grown were characterized at RT using some methods described below after every ≈50-μm thick additional growth. The total thicknesses of these undoped diamond films were ≈300 μm. Then, with a laser cutting technique the HPHT substrates were removed to obtain self-standing CVD diamond films. Finally, both surfaces of each self-standing film thus separated were mechanically polished to obtain sufficiently flat surfaces (with roughness <0.3 nm defined by the root mean square) [20]. The surface morphology of the homoepitaxial films was characterized using a Nomarski-type optical microscope (OM), a scanning electron microscope (SEM) and an atomic force microscope (AFM). Steady-state cathodoluminescence (CL) spectra and images were taken using the SEM additionally with a photon detection apparatus. An accelerating voltage of 15 kV and a probing current of 2×10^{-6} A were used for CL measurements. Time-resolved photoluminescence (PL) spectra were measured with a gated photon detection system using 20–30 ps laser pulses with a wavelength of 220 nm. The laser pulses were generated by means of a Nd:YAG-laser-based system combined with an optical parametric generator.

In order to study the effect of inserting a B-doped layer on the long-distance carrier diffusion phenomenon, the following two specimens were prepared. The one had a 60-μm thick undoped diamond layer. The undoped layer was grown on the HPHT substrate under the conditions mentioned above. The other one had homoepitaxial undoped buffer, B-doped and undoped top layers whose thicknesses were 10, 10 and 40 μm, respectively, in this order on the HPHT substrate. The doping gas used for the B-doped p-type diamond growth was 100 ppm trimethylboron [B(CH$_3$)$_3$] diluted with H$_2$, whose flow rate was set to yield a B(CH$_3$)$_3$/CH$_4$ ratio of 5 ppm. To fabricate the UV detector, the coplanar TiN electrodes were deposited on the top layer using a dc magnetron sputtering apparatus with Ti target, Ar gas, and N$_2$ gas. Using a high-performance source-measure unit (Keithley model: 617), the performance of the UV detectors was studied for UV lights monochromatized from a Xe lamp in a wavelength region from 220 to 550 nm. The incident photon number per unit time was calibrated using a UV-enhanced Si photodiode. All the measurements were performed at RT.

3. Results and discussion

Fig. 1 shows CL intensities of the broad emission band centered at ≈420 nm, called as A-band emissions, and the H3 center related emissions peaked at 525 nm as a function of the thickness of undoped homoepitaxial layers on a HPHT Ib substrate. The signal intensity of the A-band emissions increased with an increase of the homoepitaxial undoped layer thickness. Fig. 2 shows a typical OM image taken from the homoepitaxial diamond layer with a thickness of ≈100 μm (estimated from the growth rates and deposition periods). An irregular growth was observed at the sample edges which had not been observed at the early growth stage. It is thought that this irregular growth originated in a disordered crystalline growth (for example, hillock and defect generation) in the sample edge. The A-band emissions, whose origin is assigned to the dislocations in the diamond film, were observed mainly in the area grown in an irregular growth mode. The irregular growth mode more strongly governed with the increasing growth period, and finally extended to the whole sample surface. These results indicated that the growth mode of the homoepitaxial diamond had great influence on the crystalline quality. Therefore, the growth mode control is critical to obtain such device-quality thick diamond films. In our previous work, it was reported that the substrate off-angle effectively suppressed the irregular growth mode related to characteristic growth hillocks and improved the crystalline quality of the homoepitaxial diamond layer [20].

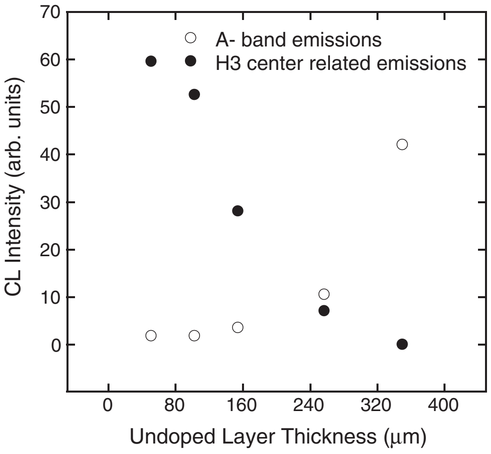

Fig. 1. RT CL intensities of the A-band emissions (centered at ≈420 nm) and the H3 center related emissions (peaked at 525 nm) as a function of the total thickness of undoped homoepitaxial layers on a HPHT Ib substrate.

On the other hand, the signal intensity of the H3 center related emissions, whose origin is assigned to the H3 center in the diamond film, decreased with an increase of the undoped homoepitaxial layer thickness. By contrast, no H3 center related emission peak was observed from the self-standing CVD diamond film separated by laser-cutting the thick CVD sample between the homoepitaxial layer and the HPHT Ib substrate. Fig. 3 shows a typical steady-state CL spectrum obtained from a self-standing homoepitaxial diamond film in the regions close to the HPHT substrate removed. The inset shows the spectrum only in the near-band-edge region. This CL spectrum had strong sharp-emission lines due to the FE peaks. It should be noted that RT FE emissions can be used as a measure of the crystalline quality. These results indicated that the high-quality layers were grown even at a rather initial stage of the homoepitaxial growth on a (low-quality) HPHT Ib substrate, and moreover, that the H3 center related emissions originated from the HPHT Ib substrate and/or the interface region between the HPHT Ib substrate and homoepitaxial film. The H3 center related signals were still observed even at an

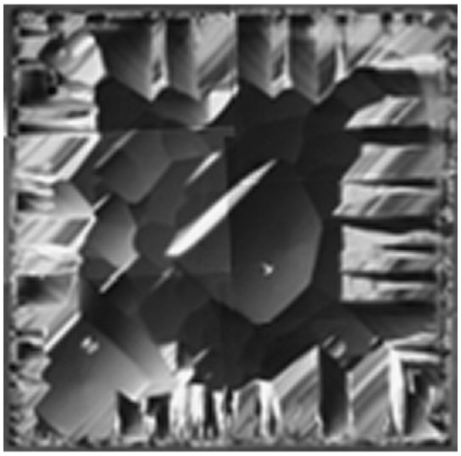

Fig. 2. Typical OM image taken at a growth stage of a homoepitaxial layer thickness of 100 μm on a HPHT Ib substrate.