Enhanced Responsivity of Diamond UV Detector Based on Regrown Lens Structure

Zhangcheng Liu, Dan Zhao, Tianfei Zhu, Juan Wang, Wenyang Yi, Tai Min, and Hongxing Wang

***Abstract*— In this work, the regrowth method is used on lens-structure diamond ultraviolet (UV) detector to suppress the surface defects caused by the lens fabrication process. After the regrowth of thin diamond film, the structure of the lens remains. Therefore, in the UV region, the regrown lens detector exhibits the highest responsivity compared with the original lens detector and the regrown planar detector. Moreover, the regrown lens detector two response peaks at around 240 nm and 240 nm. Under 220 nm or 240 nm illumination, the regrown lens detector display a fast response speed without obvious persistent photoconductive effect. This provides an efficient way to extend the the detection range of diamond UV detector while not sacrificing the performance of transient response.**

***Index Terms*— Diamond, lens, UV detector, CVD regrowth.**

I. Introduction

NOWADAYS, ultraviolet (UV) detector have numerous applications, such as flame detection, engine monitoring, chemical sensing, and intersatellite communications [1]–[4]. Owing to its high carrier mobility, high thermal conductivity, low dielectric constant, high chemical inertness, and high radiation hardness, diamond is considered as a good candidate for UV detector fabrication [5]–[8], especially under an extreme condition. Meiyong Liao *et al.* investigated various planar diamond UV detectors such as interdigitated-finger metal-semiconductor-metal photodiode, conventional Schottky photodiode, and interdigitated-finger Schottky photodiode [9]–[11], which exhibit high signal-to-noise ratio, high spectral selectivity, high speed, and high stability.

In recent years, researches on diamond UV detectors have been mainly focused on a novel device design to further enhance the responsivity in the UV region. Minsong Wei *et al.* utilized graphene as the top electrode for fabricating a diamond UV detector with a vertical structure, fabricate vertical structure diamond UV detector, which exhibited high responsivity [12]. Kang Liu *et al* fabricated a groove-shaped diamond UV detector that exhibited enhanced responsivity compared with the planar structure detector [13]. Moreover, we investigated some diamond UV detectors with novel structures, such as the three-dimensional photovoltaic detector [14] and quasi one-dimensional detector [15], to efficiently improve the device performance. Theses new structures attempted to optimize the electric field distribution in the bulk of diamond, which was essential for the carrier collection.

On the other hand, localized surface plasmon-enhanced method was used on diamond UV detectors [16]–[18]. The existence of nanometal particles enhanced the coupling between light and conduction electrons, which resulted in a higher responsivity. To combine the electric field distribution optimization and light coupling enhancement, we developed a lens-structure diamond UV detector in our previous work [19]. The lenses were fabricated using the inductively coupled plasma (ICP) etching method, which introduced many surface defects, thus resulting in a lower responsivity.

Therefore, in this work, we attempt to use the regrowth method to suppress the etching defects while not destroying the lens structure. Moreover, regrown lens detector has been investigated, which exhibited higher responsivity compared with the detector based on original lenses.

II. Experimental

Figure 1(a) presents the cross-sectional diagram of a diamond UV detector with a regrown lens structure. A $3 \times 3 \times 0.3$ mm^3 high-pressure high-temperature Ib-type single crystal diamond was utilized as the substrate material. First of all, lens arrays were fabricated on the substrate using the conventional thermal reflow and ICP etching methods. The details of the fabrication process of lens arrays can be found elsewhere [20]. During etching, only the lens region has the photoresist mask. Therefore, half surface of the substrate is lens arrays, and the other half is the etched planar surface. After etching, about 20 nm intrinsic single crystal diamond thin film was grown on the etched surface using the microwave plasma chemical vapor deposition (MPCVD) method. The total gas flow rate, CH_4/H_2 ratio, chamber pressure, and substrate temperature were 500 sccm, 2%, 16 kPa, and 870 °C, respectively. Subsequently, the sample was treated by UV-ozone to change hydrogen termination into oxygen termination.

Finally, about 100 nm thick interdigitated-finger tungsten (W) electrodes were patterned on the lenses through standard photolithography, sputtering, and lift-off process. A sintered

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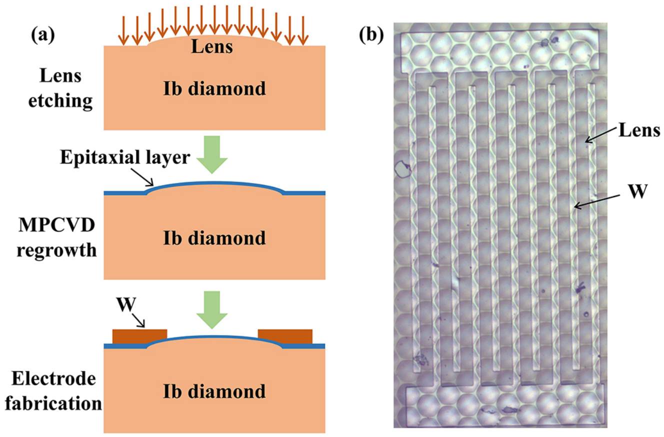

Fig. 1. (a) Cross-sectional diagrams of a diamond UV detector based on regrowth lens structure. (b) Optical image of the regrowth lens diamond UV detector.

W metal target (purity 99.99%; diameter 76.2 mm) was used as the source material, and Ar was used as the working gas. The background pressure, gas flow rate, working pressure, and radio frequency power were 7×10^{-5} Pa, 20 sccm, 0.13 Pa, and 150 W, respectively. W exhibited good adhesion to diamond, which is beneficial to the integrity of the electrodes. The electrodes were arranged between two adjacent lenses with 40 μm spacing and 26 μm width. Therefore, the photosensitive area is about 0.23 mm^2. The optical image of the regrown lens detector is shown in Fig. 1(b).

The surface morphology of the lens was characterized by scanning electron microscope (SEM). The electrical and photoresponse properties of the detector were evaluated using Agilent B1505A power device analyzer, a 1000 W Xe lamp source and a monochromator. The incident light power was measured by a commercial UV-enhanced Si detector. For comparison, the original lens detector, original planar detector, and regrown planar detector with the same electrode parameters on the same diamond sample were also investigated.

III. Results and Discussion

Figure 2(a) shows the SEM image of the regrown lenses. As can be seen from the figure, the regrowth of diamond thin film does not destroy the lens structure. Fig. 2(b) presents the outlines of the lens before and after epitaxial growth measured by a step meter along the red line shown in Fig. 2(a). The radius and height of the original lens before epitaxial growth are 38.8 μm and 842 nm, respectively. After epitaxial growth, the radius and height of the regrown lens change to be 39.25 μm and 814 nm, respectively.

It can be found that the radius increased and the height decreased after epitaxial regrowth. This is because the growth rates of diamond thin film on the lens-occupied surface are not uniform. The vertex has a (100) orientation, whereas the side wall and the valley deviate from the (100) orientation. Then, the growth rate at the vertex is smaller than that at the side wall and the valley [21]. Thus, to avoid destroying the lens structure, the regrowth of diamond thin film should be limited at a shorter time.

In Fig. 2(a), some white spots can be observed on the lens surface. This is in accordance with the sharp steps in the outline curve in Fig. 2(b). After etching with oxygen plasma,

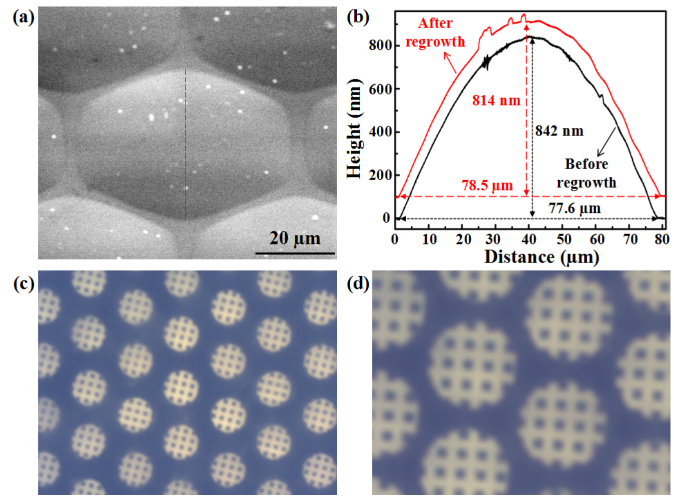

Fig. 2. (a) SEM image of the regrown lens. (b) Profile of the regrown lens and original lens. (c) Images projected by the regrown lenses. (d) Images projected by the original lenses.

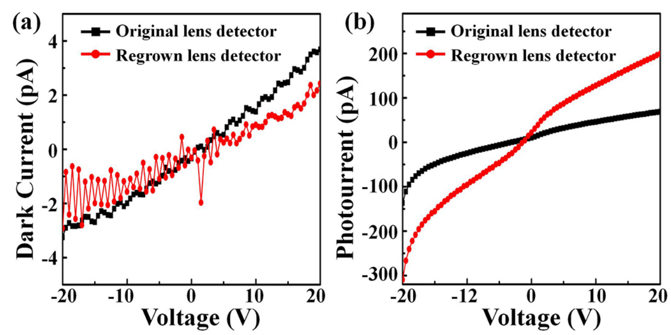

Fig. 3. I-V curves of the original lens detector and regrown lens detector (a) under dark condition and (b) under a 12.2-μW/cm^2 220 nm illumination.

some nanorods usually emerge on the diamond surface [22], and they remain after the regrowth of diamond thin film growth and appear as white spots in the SEM image.

To determine whether regrowth affects the optical properties of lens, projection experiments were conducted. Figure 2(c) and 2(d) display the images projected by the regrown lenses and original lenses, respectively. The images are similar, indicating that the regrown lenses maintain light convergence ability. This further confirms that the regrowth process of diamond thin film does not destroy the lens structure.

The I-V characteristics of the regrown and original lens detectors under dark condition are shown in Fig. 3 (a). Both detectors have extremely low dark currents, and it is clear that the dark currents of the regrown lens detector are smaller than that of the original lens detector. The regrowth of diamond thin film results in an effective reduction in the amount of surface defects for leakage current conduction.

Figure 3(b) compares the photocurrents of the two detectors under 12.2-μW/cm^2 220 nm illumination. As expected, due to the reduction of surface defects, more photogenerated carriers can be collected, which contributes to larger photocurrents for regrown lens detector. With lower dark current and larger photocurrent, the signal-to-noise ratio of the regrown lens detector is larger than that of the original lens detector. It should be noted that the photocurrent is large near −20 V. This may be because the scanning direction is from

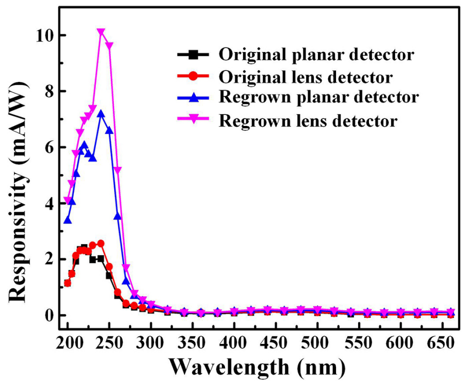

Fig. 4. Spectral response of the regrown lens detector, original lens detector, regrown planar detector, and original planar detector at 20 V bias.

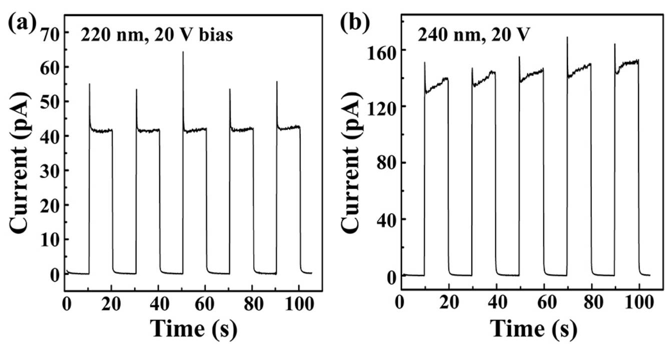

Fig. 5. Transient response of the regrown lens detector under (a) 220 nm and (b) 240 illumination at 20 V bias.

−20 V to 20 V. The sudden addition of a large voltage momentarily causes a strong electric field in the depletion region, thus enabling the tunneling of a larger amount of photogenerated carriers.

The responsivity of a UV detector is calculated using the equation $R = I_{ph}/AP$ [23], where I_{ph} is net photocurrent, A is active photosensitive area, and P is light power density. Accordingly, the responsivity of the regrown lens detector under 220 nm illumination at 20 V is calculated to be 6.99 mA/W. This value is three times larger than that of the original lens detector, which is 2.32 mA/W. This indicates that the suppression of the surface defects by the regrowth method can enhance photosensitivity.

Figure 4 exhibits the spectral response of the regrown lens detector, original lens detector, regrown planar detector, and original planar detector at 20 V bias. The regrown lens detector exhibits the highest responsivity, indicating the best photosensitivity. Furthermore, it can be observed that there exist two response peaks for the four detectors in the UV region. One response peak is around 220 nm and the other is around 240 nm. This phenomenon is different from the spectral response of a typical diamond UV detector, which has only one response peak at around 220 nm [24]. The response peak around 240 nm may be attributed to the response of the free excitons near the bandgap [25]. The existence of the free exciton response leads to the extension of the detection spectral range of the diamond UV detector.

Compared with the regrown planar detector, the regrown lens detector exhibits higher photosensitivity. This may be due to the enhancement of the electric field strength and light power for lens structure [20]. The larger light power indicates a larger incident photon number. Because the net photocurrent is decided by $I_{ph} = qF_0\eta\mu\tau E/d$ [26], where q is electron charge, F_0 is incident photon number, η is quantum efficiency, μ is carrier mobility, τ is carrier lifetime, E is electric field strength, and d is electrode space, a larger electric field E and larger incident photon number F_0 result in a larger net photocurrent.

However, it should be noted that before regrowth, the original lens detector is not better than the original planar detector. This indicates that surface defects can act as trap centers and thus degrade the $\mu\tau$ production, which leads to a lower photosensitivity. Through the regrowth process, the surface defects are repaired, then the surface trap centers are eliminated and the $\mu\tau$ production of the diamond thin film is almost the same. As a result, the regrown lens detector with optimized electric field and light power distribution exhibits higher photosensitivity than regrown planar detector. Therefore, diamond thin film regrowth is important to enhance the responsivity of lens detector.

Figure 5(a) presents the transient response of the regrown lens detector under 220 nm illumination at 20 V bias. When the light is turned on and off, the current rapidly increases and decreases, respectively, with little persistent photo conductivity. The rise time and decay time are extracted to be 115.5 ms and 157.1 ms, respectively.

The transient response under 240 nm illumination is also investigated, as shown in Fig. 5(b). The curve presents a high response speed, and no obvious persistent photoconductivity can be observed. This indicates that the spectral detection range of diamond UV detector in solar-blind UV region is extended without sacrificing the transient response performance. It should be noted that the photocurrents under 240 nm illumination may take some minutes before reaching a stationary value. This could be attributed to the conversion of more free excitons to free carriers with the increase in time, thus contributing to the slow increase in photocurrents.

IV. Conclusion

In this study, a diamond UV detector based on regrown lens structure has been investigated. The regrowth of diamond thin film can repair the surface defects caused by ICP etching while not destroying the lens structure. Thus, the regrown lens detector was found to have lower lark current and higher photocurrent compared with the original lens detector, which corresponds to a higher responsivity. Even though the lens structure enhances the electric field strength and light coupling efficiency, the regrowth process is essential because only when the surface defects are eliminated can the lens detector obtain higher responsivity than the planar detector. The detector has two response peaks around 220 nm and 240 nm, which can be attributed to the interband response and free exciton response of diamond, respectively. The regrown lens structure can further increase the free exciton response while not degrading the transient response performance. This provides an efficient way to extend the detection range of diamond UV detector.

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