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Enhanced ultraviolet photoresponse of diamond photodetector using patterned diamond film and two-step growth process

Zhangcheng Liu[a,b,c], Dan Zhao[a,b], Jin-Ping Ao[c], Wei Wang[a,b], Xiaohui Chang[a,b], Yanfeng Wang[a,b], Jiao Fu[a,b], Hong-Xing Wang[a,b,*]

[a] Institute of Wide Bandgap Semiconductors, Xi'an Jiaotong University, Xi'an 710049, China
[b] Shaanxi Key Lab of Information Photonic Technique, Xi'an Jiaotong University, Xi'an 710049, China
[c] Institute of Technology and Science, The University of Tokushima, Tokushima 770-8506, Japan

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ABSTRACT

In this study, we report ultraviolet photoresponse enhancement of diamond photodetector by applying patterned diamond film design and two-step growth process. Diamond stripes are fabricated on the surface and inter-digitated electrodes are set perpendicular to them. Before second step growth, surface defects induced during etching process affect the responsivity of supra-band gap light. After second step growth, the surface defects are suppressed, then the responsivity of photodetector on diamond strips are larger than that of photodetector on continuous diamond film. The larger responsivity could be attributed to the quasi-one-dimensional carrier transport and large surface to volume ratio. In additionally, a large electrode space is helpful in enhancing ultraviolet photoresponse while suppressing the visible response.

1. Introduction

Ultraviolet (UV) photo detection is becoming increasingly important in modern life for its variable applications such as flame detection, engine monitoring, chemical sensing and intersatellite communications [1]. Many wide bandgap semiconductor materials such as GaN, ZnO, β-Ga_2O_3 and TiO_2 have been widely used to fabricate UV photodetectors [2–5]. Diamond is known as an excellent semiconductor material with many extraordinary properties such as wide bandgap (5.5 eV), high carrier mobility (4200 $cm^2/V\,s$ for electron, 3800 $cm^2/V\,s$ for hole), high thermal conductivity (22 W/cm K), low dielectric constant (5.7), high breakdown electric field (> 10 MV/cm), high Johnson index and Baliga index,high radiation hardness and high chemical stability [6–8]. Due to these properties, diamond can be used in many electronic devices such as field-effect transistors, diodes, detectors and so on [9–11]. Obviously, diamond is also very suitable for UV light detection. Its wide bandgap provides a natural selectivity between UV light and visible light, and the intrinsic carriers is extremely low. Moreover, the highest thermal conductivity, high chemical stability and high radiation hardness allow the diamond-based detectors to be efficient in extreme environments. Early diamond UV photodetectors are mainly based on chemical vapor deposition (CVD) polycrystalline diamond film on silicon [7,12]. With the breaking through of homoepitaxial synthesis technique, CVD single crystal diamond has been widely applied to UV photodetectors [13], and the results demonstrate a satisfaction for 5S requirements of UV photodetector [14]. In order to further enhance the performance of diamond detectors, surface engineering has been enrolled in these years. Benoit Caylar et al. applied graphite channels in the bulk of diamond to perform as buried within electrodes to optimize the electric field distribution, and the charge collection efficiency was enhanced compared with planar configuration [15]. Forneris et al. etched diamond surface to form stripes array, then applied inter-digitated metal electrodes parallel to these stripes. As a result, the charge collection efficiency was enhanced [16]. This idea inspired some attempts to apply surface modification in diamond UV photodetectors, demonstrating an enhancement of photoresponse [17–19].

In the last decade, one-dimensional or quasi-one-dimensional (Q1D) structures have been widely researched in UV photodetector for other materials, presenting a high sensitivity to light due to the unique physical properties of low-dimensional systems [20]. Thus, it is possible to combine surface modification with confined structure to further enhance the responsivity of diamond photodetector. There exists two characteristics when considering electron transport in a semiconductor: the electron mean free path (λ_{MFP}) and the electron diffusion length (λ_{DL}) [21]. When the size of structured diamond is between λ_{MFP} and λ_{DL}, Q1D carrier transport occurs. λ_{MFP} is the average length that the

* Corresponding author.
E-mail address: hxwangcn@mail.xjtu.edu.cn (H.-X. Wang).

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electron can travel freely before a elastic collision. It is related to momentum relaxation time (τ_m) and average drift velocity (υ) via $\lambda_{MFP} = \upsilon\tau_m$. Generally, the momentum relaxation time is about dozens of femtosecond [22,23], and the average drift velocity in CVD diamond is about 10^7 cm/s [24]. Therefore, the λ_{MFP} is less than a few nanometers. The diffusion electron length λ_{DL} is related to the diffusion coefficient (D_n) and electron lifetime (τ_n) via $\lambda_{DL} = \sqrt{D_n\tau_n} = \sqrt{\frac{kT}{q}\mu_n\tau_n}$, where k is Boltzmann constant, T is temperature, q is electron charge and μ_n is carrier mobility. For CVD single crystal diamond, $\mu\tau$ product is about 10^{-3} cm^2/V [25], then the λ_{DL} is calculated to be about few ten micrometers. This means that Q1D transport can be achieved in micrometer scale for diamond material.

In this work, we attempt to develop a Q1D designed diamond UV photodetector with electrodes set perpendicular to diamond stripes. In this device, diamond stripes are three-side surrounded by electrodes, and the carriers are confined by the three diamond surfaces.

2. Experimental methods

A $3 \times 3 \times 0.3\,mm^3$ high-pressure high-temperature IIa-type single crystal diamond was used as the substrate material. At first, about 250 nm diamond homoepitaxial layer was grown on this substrate through microwave plasma chemical vapor deposition (MPCVD) method. The epitaxial layer surface was oxidized in boiling acid solution (H_2SO_4:HNO_3 = 1:1 by volume, 250 °C) and Ti stripes with 10 μm width and 5 μm spacing were patterned on it through standard photolithography and magnetron sputtering method. After inductively coupled plasma (ICP) etching and removing of Ti mask, 10 μm wide and 200 nm high diamond stripes have been achieved with a space of 5 μm. Then, interdigitated 30/120 nm thick Ti/Au electrodes were patterned perpendicular to diamond stripes to form photodetectors. After optoelectronic performance measured, Ti/Au electrodes were removed with acid solution, and the diamond sample was again put into MPCVD chamber for a thin layer diamond growth with the same parameter. The second layer thickness is about 30 nm. Sequentially, the surface was oxidized and interdigitated 30/120 nm thick Ti/Au electrodes were again patterned perpendicular to diamond stripes to form photodetectors. These photodetectors were named as Q1D PDs, and the first step Q1D PDs were denoted as 1st-Q1D PDs, and second step Q1D PDs were denoted as 2nd-Q1D PDs. The electrode width and length of 1st-Q1D PDs and 2nd-Q1D PDs were 5 μm and 200 μm, respectively, and the spaces were 5 μm, 10 μm, 20 μm and 30 μm. For comparison, traditional planar photodetectors were also fabricated on the same sample and they were denoted as 1st-Planar PDs and 2nd-Planar PDs. The electrical and photoresponse properties of the photodetectors were evaluated by Agilent B1505A power device analyzer, 1000 W Xe lamp source and monochromator. The incident light power was measured by a commercial UV-enhanced Si detector. Time response behaviors were measured by repeatedly switching on and off the UV light with a metal shutter.

3. Results and discussion

Fig. 1(a) shows a schematic of the novel Q1D structure photodetector. A high quality homoepitaxial layer is necessary for the fabrication of diamond stripes and the etching depth is less than the epitaxial layer thickness. In this condition, the diamond stripes are all on the homoepitaxial layer. The Ti/Au electrodes are set perpendicular to the diamond stripes, resulting in field lines extending along the stripe direction. Fig. 1(b) is the scanning electron microscope (SEM) image of a fabricated 1st-Q1D PD with 20 μm electrode space. It can be clearly observed that the electrodes are well patterned on diamond stripes. In this novel Q1D geometry, the width and height of the diamond stripes are 10 μm and 200 nm. The two values are between λ_{MFP} and λ_{DL}, indicating that the carriers will be restricted in the stripes. As a result, quasi one dimensional transport is achieved and very high internal gain can be achieved [21].

Fig. 2(a) and (b) present the scanning electron microscope (SEM) images of the structured diamond stripes before and after second step growth, respectively. It can be observed that before the second step growth, there exist many nanorods in the edge of the sidewall. This indicates that some defects will be induced during ICP etching process. After the second step growth, the nanorods disappeared and the sidewall surface becomes smooth. This indicates that a second growth step is helpful in repairing the surface defects. In actual, the optimization of the surface plays an important role in enhancing the device performance.

The IV characteristics of 1st-Q1D PDs and 1st-Planar PDs with 30 μm, 20 μm and 10 μm electrode space are shown in Fig. 3(a)-(c). With the decrease of electrode distance, the dark currents of 1st-Planar PDs are around 200 fA, indicating an independence on electrode distance and voltage. This could be ascribed to that the dark currents are lower than the detection limit of the instrument, presenting a high resistivity of diamond. As for 1st-Q1D PDs, the dark currents increase slowly with voltage increase and electrode space decrease. In addition to that, the dark currents of 1st-Q1D PDs are larger than that of 1st-Planar PDs. This could be ascribed to increased surface conductivity for 1st-Q1D PDs. The extra surface conductivity paths stem from surface defects in the grooves and sidewalls, as demonstrated in Fig. 2(a).

Under 0.366 $\mu W/mm^2$ 210 nm light illumination, the photocurrents of these detectors increase a lot compared with their dark currents. There exists a tendency that the photocurrents decrease with electrode

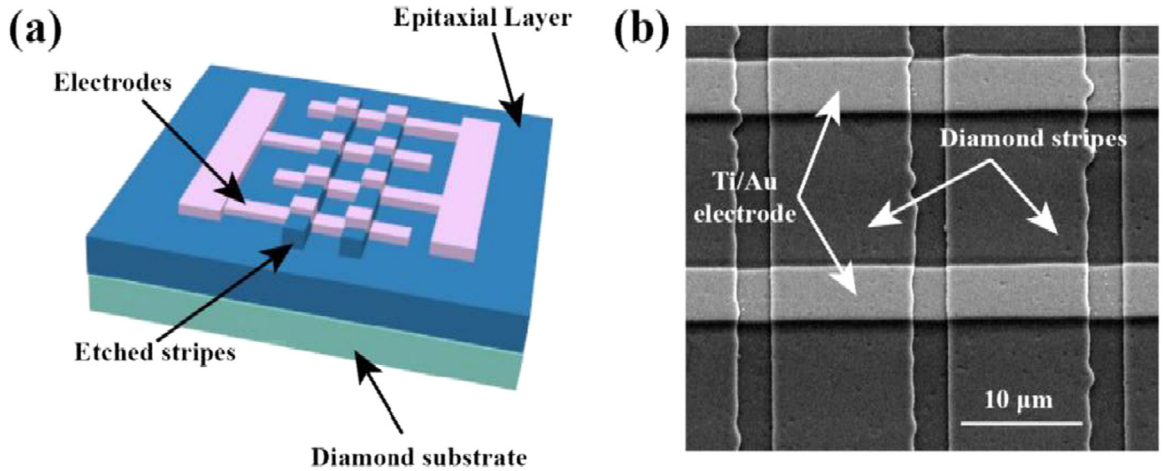

Fig. 1. (a) Schematic of Q1D photodetector. (b) SEM image of a 1st-Q1D photodetector with 20 μm electrode space.