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Full Length Article

Effects of metallic interlayers on the performance of nanocrystalline diamond metal-semiconductor-metal photodetectors

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ABSTRACT

We have designed photodetectors based on a combination of nanocrystalline diamond (NCD) and bilayer metallic layers in a metal-semiconductor-metal (MSM) structure. The NCD films were deposited on silicon substrates which nucleated by different metallic layers (tungsten, molybdenum) and nanodiamond suspension. We found that the metallic layers not only significantly improve the nucleation density of the substrates but also reduce the surface roughness of the fabricated NCD films from 8.3 nm to 4.7 nm. Furthermore, the one-step fabrication of MSM photodetectors adopts metallic interlayers consisting of two functions (diamond nucleation site and back electrodes), which shows high detection efficiency and rapid response to UV irradiation in air ambient. The W/NCD/W structure exhibits good Ohmic contact characteristics and significant changes (~3 orders of magnitude) in photocurrent and stable reproducibility. The achievement of this research indeed demonstrates great prospects of photodetector applications of NCD films in the future.

1. Introduction

In the last decade, nanocrystalline diamond (NCD) films have emerged as a promising engineering material due to their unique characteristics as a combination of diamonds and nanoscaled structures [1,2]. Plenty of studies have been conducted to develop the potential applications of NCD films on machining, semiconductor, electrochemistry, and bio-engineering fields [3–6]. Recent developments in synthesis technique of intrinsic and doped NCD films with n- or p-type characteristics have opened up a potential to fabricate diamond-based devices aiming at the replacement of silicon and metallic materials, especially for such applications in harsh working environments [7,8]. Interestingly, these NCD films normally consist of diamond grains and grain boundaries which considered as non-diamond carbon phases and impurities, their electronic characteristics can be tuned through alteration in phase fractions, leading to high adaptability of the NCD films for the uses in electro-optical semiconductor devices.

Most of the diamond films are synthesized by conventional chemical vapor deposition (CVD) processes which used various activation methods including plasma [9] or thermal enhancement techniques [10,11]. It should be noted that diamond growth process on foreign substrates is difficult owing to their high surface energy which hinders the formation of stable diamond nuclei from the gaseous species and leads to non-continuous film [12]. In a typical CVD process, NCD film growth on a smooth surface of foreign substrates requires a high nuclei density as consequence of diamond nucleation enhancement procedure which also known as substrate surface pretreatment [13,14]. Since this pretreatment procedure was previously reported to result in severe destruction on the substrate surface, and thus leading to not only effects on the surface roughness of the NCD films but also hampers in functional junctions of a diamond-based device such as microelectromechanical, bio-sensor, and photovoltaic systems [13,15]. In other words, the fate of the aforementioned applications of NCD films is strongly depended on the performance of diamond nucleation enhancement stage; therefore, it is crucial to investigate and optimize this stage aiming at the high adaptability of the films for further applications. The method of bias-enhanced nucleation was studied and considered to achieve a high nucleation density, however, the requirement in conductivity substrate and formation of the higher fraction of amorphous carbon phase may limit the fabrication process of the diamond-based devices [16]. Mechanical abrasion and ultrasonically scratching are also developed for

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various non-diamond substrates which were reported to significantly enhance the diamond nuclei density and thus contribute to low surface roughness up to 8.5 nm rms (in the case of Si substrates) [3,4,17]. Nevertheless, the produced substrate surface damage, as a result of these mechanical agitations, usually lead to the requirement in physical strength of substrate materials, thus hindering potential fabrication of diamond devices. Note that the addition of nanodiamond nuclei layers on the highly smooth surface of substrates indeed increase the surface roughness of the film owing to solemn aggregation of nanodiamond particles in aqueous solution. Metallic interlayers for diamond nucleation was developed for CVD diamond growth on foreign substrates which was suggested to restrict the inter-diffusion of the deposited carbon atoms and thus contribute to the improvement of the adhesion of diamond films [18–21]. Besides, the produced metal carbide phases are considered to possess good electrical conductivity and work function which is corresponding to that of the CVD nanocrystalline diamond film [22,23], thus leading to potential applications of the metal carbide layers as back electrode materials for further fabrication of diamond-based devices. Therefore, in this research work, we develop a functionalized metallic interlayers aiming at twofold targets of diamond nucleation enhancement for CVD process and electrode for diamond-based ultraviolet range photodetectors. Furthermore, this present works also investigates the effect of tungsten and molybdenum element on the growth mechanism of nanocrystalline diamond film.

2. Experimental methods

In this research, mirror-polished *n*-type silicon (Si) wafer having electrical resistance of 3 Ω cm and size of 15 × 15 × 0.5 mm were used as the substrate for all experiments. Firstly, the substrates were successively rinsed with acetone and methanol for each 10 min using ultrasonic bath equipment and then dried by nitrogen flow at room temperature. Two types of metallic layers including of molybdenum (Mo) and tungsten (W) were deposited onto bare silicon (Si) substrates using unbalanced magnetron radio frequency (RF) sputtering technique. 3-inch-diameter Mo and W sputtering targets (purity: 99.99%) were kept 12 cm apart from the substrates, and argon (Ar, 99.99%) was used as working gas with a fixed flow rate of 20 sccm. Turbo and mechanical pumps were used to obtain a base pressure of 1.3×10^{-4} Pa in the vacuum chamber and working pressure was fixed at 0.66 Pa for all deposition processes of metallic layers. The RF sputtering power (13.56 MHz) was set at 50 and 100 W for both two metallic targets. During the deposition processes, a bias voltage of −100 V and temperature of 300 °C were applied to the substrates aiming at good adhesion of the metallic layers. The deposition time was controlled to obtain the thickness of 130 nm for all metallic layers. In order to enhance diamond nucleation for CVD diamond film growth, the as-coated substrates were then ultrasonically agitated in a suspension consists of 0.3 g nanodiamond particles (5–8 nm in diameter, Sigma Aldrich) and 20 ml ethanol. Also, another nucleation procedure was employed for bare Si substrates using the mixture of titanium and diamond nanoparticles suspension (named as (Ti + D) suspension) [24,25]. The nucleation stage is optimized for 30 min which assures a high nuclei density and minor effect to the surface roughness of the substrates [17]. After this, the nucleated substrates were ultrasonically cleaned in deionized water for 5 min and lastly dried by nitrogen flow.

In other stage, NCD films were grown on the as-pretreated substrates using a home-made microwave plasma jet chemical vapor deposition (MPJCVD) system and CH_4/H_2 gas mixture. The plasma jet was induced by microwave source (2.54 GHz) with an output power of 800 W for all experiments. Details of the MPJCVD process have been discussed in our previous studies [4,26]. The total gas flow rate and CH_4/H_2 concentration ratio were kept constant at 800 sccm and 8%, respectively. The diamond film growths were carried out under working pressure of 5.33 kPa and without substrate heating or bias voltage enhancement. Also, in situ optical electron microscopy (OES, B&WTEK BTC112E, USA) system was utilized to monitor the plasma condition as well as the gaseous species composition. For fabrication of the metal/diamond/metal

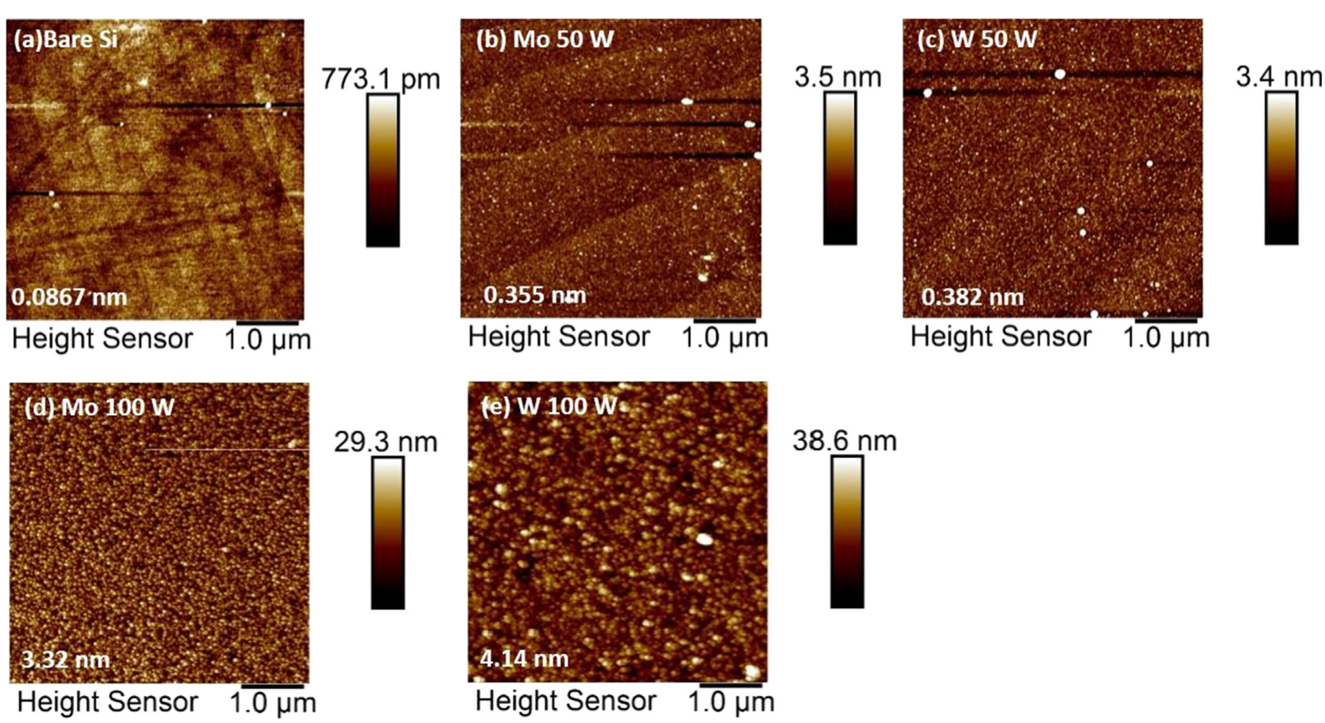

Fig. 1. AFM topographic images (5×5 µm^2) of bare Si substrates and the as-prepared metal layers.