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Electrical contacts to nitrogen incorporated nanocrystalline diamond films

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ABSTRACT

The effect of surface plasma treatment on the nature of the electrical contact to the nitrogen incorporated nanocrystalline diamond (n-NCD) films is reported. Nitrogen incorporated NCD films were grown in a microwave plasma enhanced chemical vapor deposition (MPECVD) reactor using CH_4 (1%)/N_2 (20%)/Ar (79%) gas chemistry. Raman spectra of the films showed features at ~1140 cm^{-1}, 1350 cm^{-1}(D-band) and 1560 cm^{-1} (G-band) respectively with changes in the bonding configuration of G-band after the plasma treatment. Electrical contacts to both untreated and surface plasma treated films are formed by sputtering and patterning Ti/Au metal electrodes. Ohmic nature of these contacts on the untreated films has changed to non-ohmic type after the hydrogen plasma treatment. The linear current–voltage characteristics could not be obtained even after annealing the contacts. The nature of the electrical contacts to these films depends on the surface conditions and the presence of defects and sp^2 carbon.

1. Introduction

The formation of stable electrical contacts on conductive nanocrystalline diamond (NCD) films is necessary in order to integrate NCD into the nano/microelectronic industry. As well as exhibiting extraordinary mechanical and thermal properties, diamond has a low work function of 0.3 eV, high dielectric strength of 1.0×10^7 Vcm^{-1}, low dielectric constant of 5.7 and a wide band gap of 5.4 eV making it an ideal candidate for electronic and high temperature applications, such as radiation detectors [1,2]. Both p- and n-type conductivities have been successfully achieved in diamond films and their electrical properties have been investigated [3–5]. It has been reported that carbide forming metals such as Ti and Mo can form ohmic contacts to p-type polycrystalline diamond films after subsequent annealing at temperatures ~500 °C [6]. On the contrary, Ti could not form ohmic contact to n-type (phosphorous doped) diamond films even after annealing; the electrical contacts showed rectifying properties [7]. Hence the formation of ohmic contacts to n-type diamond films is not a straight forward process. This procedure is even more complex in nitrogen incorporated NCD films as the electrical conductivity is predominantly due to grain boundaries and the existence of disordered carbon.

J. E. Gerbi *et al.* have shown that ohmic contacts to nitrogen incorporated nanocrystalline/ultrananocrystalline diamond films can be formed by metals such as Al, Au, Cr, Cu and Pt [8–10]. It has been reported that the electrical properties of diamond films depend on surface treatments such as acid clean, exposure to hydrogen or oxygen plasma, in-vacuo heating and air annealing [11,12]. Yamazaki *et al.* have reported the effect of hydrogen plasma treatment at room temperature on the structural changes of high pressure-high temperature (HPHT) synthetic type IIA (001) diamond substrates [11]. The authors found that the hydrogen plasma exposure created a defective surface with the formation of a hydrogenated a: C like structure. All of these reports provide information on the surface treatment of undoped diamond films and single crystal diamond substrates; however, no significant study has been conducted on the post deposition plasma treatment of nitrogen incorporated NCD films and its influence on the formation of subsequent electrical contacts [13]. In this paper, we report the changes in the structural and electrical properties of the nitrogen incorporated NCD films before and after they were subjected to the hydrogen plasma. The effect of such surface treatment on the formation of electrical contacts was studied in detail.

2. Experimental section

The nitrogen incorporated NCD films were grown on n-type Si (100) substrates (resistivity: 10–15 Ω^{-1} cm) in a 2.45 GHz *Cyrannus I Iplas* microwave plasma enhanced chemical vapor deposition (MPECVD) reactor. Nucleation was initiated by ultrasonic scratching in nanodiamond (~4–5 nm) powder suspended in acetone. The nitrogen incorporated NCD films were grown in CH_4 (1%)/Ar (79%)/N_2 (20%) at a microwave power of 800 W, and a pressure of 100 Torr at a substrate temperature of ~750 °C for 3 hrs. As-grown films were then subjected to hydrogen plasma for 30 min at temperature ~750 °C. After performing the structural characterization on both as-grown and the plasma treated films, a bi- layer of Ti (~20 nm) and Au (~190 nm) was deposited by R.F. sputtering (*AJA PVD 100).* The deposition

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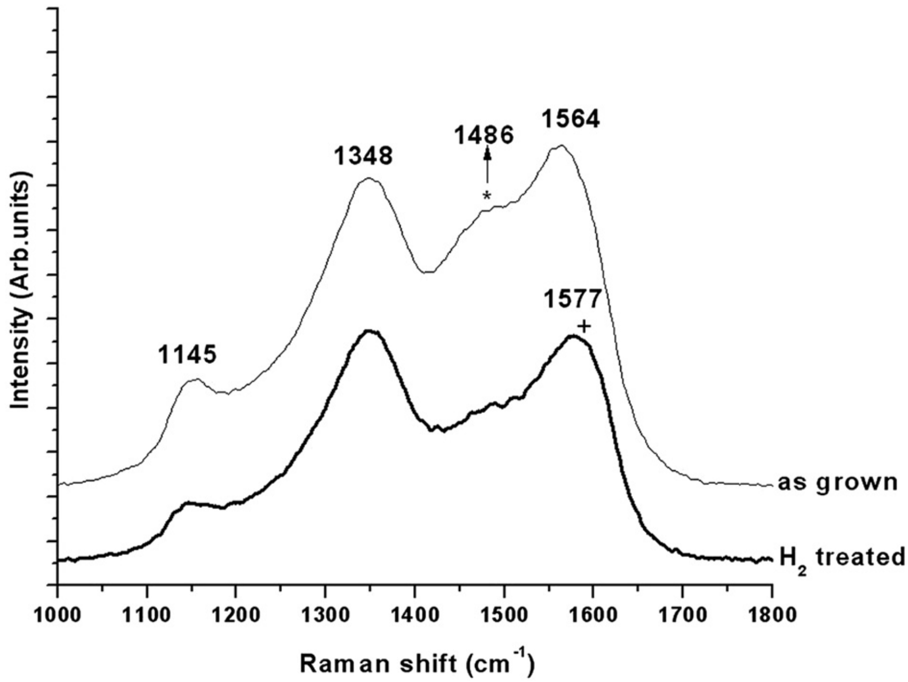

Fig. 1. Visible Raman Spectra of the as grown and hydrogen plasma treated films.

conditions were: pressure — 2 mTorr, R.F power — 360 W, substrate temperature — 25 °C. The metal contacts (area: 1000 µm × 1000 µm) to the films were achieved by a conventional photo-lithography technique. A blanket film consisting of Ti (~20 nm)/Au (~190 nm) was also deposited on the back side (unpolished Si surface) for establishing good electrical connection. After the metal contacts were formed, the samples were annealed in a vacuum furnace at 100 °C, 400 °C and 600 °C respectively, in an excess pressure of argon gas for 30 min. The nature of electrical contact to both as-grown and plasma treated films has been confirmed by studying the current–voltage characteristics before and after in-vacuo annealing.

The structural properties of the films were characterized by visible-Raman spectroscopy (*Renishaw 1000 Raman spectrometer* with an Ar laser at a wavelength of 514.5 nm, a laser spot size of 1 µm at a laser power of 25 mW) and scanning electron microscopy (*Hitachi-S4800* field-emission scanning electron microscope). The electrical properties of the metal/diamond/Si/metal multilayer structure were measured using a *Keithley* voltage source meter.

3. Results and discussion

3.1. Structural properties of as-grown and hydrogen plasma treated nitrogen incorporated NCD films

Fig. 1 shows the visible Raman spectra of both as-grown and hydrogen plasma treated nitrogen incorporated NCD films. It can be

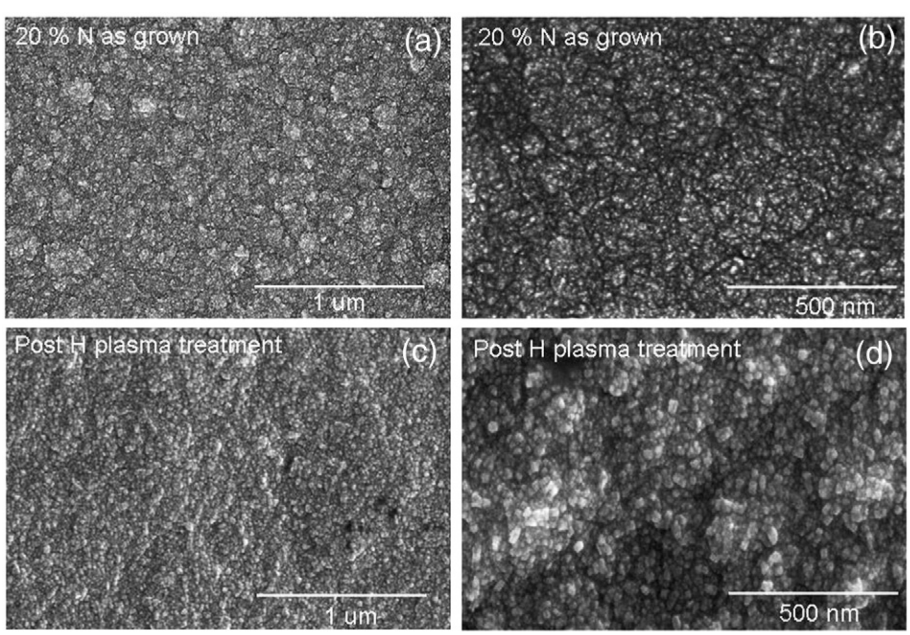

Fig. 2. Scanning electron micrographs of (a) as-grown — low resolution, (b) as grown — high resolution (c) Post hydrogen plasma treated — low resolution, (d) post hydrogen plasma treated-high resolution.