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Etching of DLC films exposed to a plasma jet

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In this work, an argon plasma jet was used to etch diamond-like carbon (DLC) thin films which were grown on silicon (100) substrates by magnetron sputtering. The etching rates of the DLC material were investigated with respect to the ion energy, ion density, magnetic field intensity and plasma power for both perpendicular and inclined incidence of the plasma jet on the substrate. It was observed that the DLC etching rates (around 2-20 nm/min) increased up to 7-fold when the magnetic field in the jet plasma region increased from zero to 6 mT. Also, at a fixed cathode potential, a reduction in the etching rates was observed for angles of incidence lower than 90°. In order to explore in detail the surface changes due to the etching process, on a nanometric scale, the DLC films were analyzed by atomic force microscopy. The results indicated that by using this etching technique it was possible to reduce the formation of needle-like structures on the etched DLC surface.

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1. Introduction

Diamond-Like Carbon (DLC) films exhibit particular physical-chemical properties that make them promising materials for the micro and nano electronics industries [1]. Etching processes are needed to make the applications of this material reliable [2]. Reactive ion etching (RIE) reactors are usually used for this purpose [3, 4], but sputtering of the electrode material can occur, consequently leading to the undesirable production of micro-masking on the film. Additionally, sometimes undesirable needle-like structures are formed in the etched surface. The use of a low pressure plasma jet has been shown to be an alternative for these problems [5].

In this work, we extend the studies of the etching of DLC films with a plasma jet system [5]. For this, DLC films were grown on silicon (100) substrates by magnetron sputtering. The etching rates of the DLC material were investigated with respect to the ion energy, ion density, magnetic field intensity and plasma power, for both perpendicular and inclined incidence of the plasma jet on the substrate.

2. Experimental set-up

Fig. 1 shows a schematic view of the experimental set-up. The etching system consisted basically of two chambers working at different pressures (at least 2-3 orders of magnitude), connected by a narrow channel (0.2 mm diameter). In one of the chambers, namely the source chamber, an argon hollow cathode discharge (HCD) was produced. Differential pumping through the channel promoted a plasma flow towards the second one, namely the processing chamber, where an expanding plasma jet was produced.

The processing chamber was evacuated by a combination of rotary and turbo-molecular pumps to achieve a residual pressure of 10^{-6} Torr. The argon gas was introduced through a mass flow controller. The gas was fed directly into the processing chamber through the source chamber, at a flow rate of 90 sccm and a fixed pressure of 5 mTorr. The HCD was operated in direct current (DC) mode with a voltage (U) in the range 400-600 V and a current in the range 100-250 mA.

At a distance of 6 cm from the source chamber, a substrate holder was positioned, which was biased with a negative polarization V_p (150-400 V)

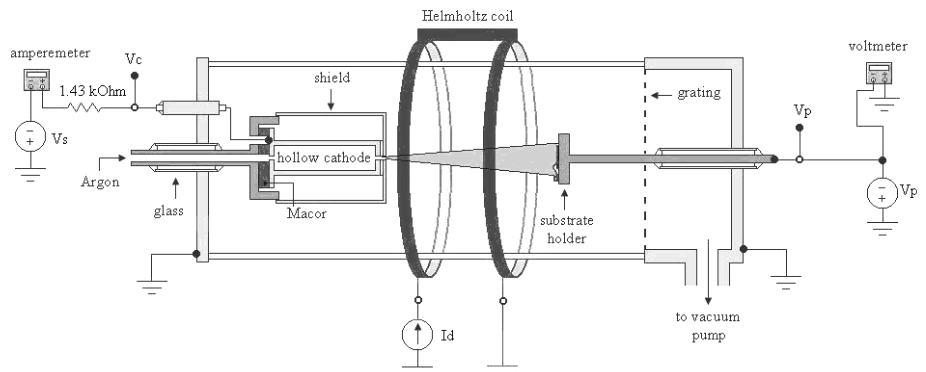


Fig. 1. The experimental set-up. The substrate shutter is not shown.

in order to extract and accelerate ions towards the substrate. In addition, a Helmholtz coil was placed outside the vacuum recipient in order to provide magnetic confinement of the plasma flux and to strengthen the ion bombardment effect.

DLC films were deposited by 150 W DC magnetron sputtering of a graphite target, with the discharge produced in an Ar atmosphere at a working pressure of 5 mTorr. The target-substrate distance was kept at 6 cm. During the etching processes, parts of the samples were covered with a mechanical mask to produce a step between the etched and non-etched regions. This step was measured by an Alpha-Step 500 profilometer, and the etching rates were determined. The surface of the films was examined by atomic force microscopy (AFM) in order to verify the quality of the final surface obtained after etching.

3. Results and discussion

Fig. 2 shows the etching rates (ER) for a DLC film as a function of the substrate polarization or the accelerating voltage, taken at different magnetic fields. The curves indicate that the etching rate can be increased when the polarization voltage changes from -100V to -300V, for all magnetic field values. It also shows that the value of the magnetic field acts directly on the efficiency of the etching process, since an increase in the slope of the curves is observed. The electrons are repelled from the cathode, confined by the magnetic field, and repelled again from the substrate holder. They oscillate towards the electrode, performing ellipsoidal trajectories, and contribute to effective gas ionization.

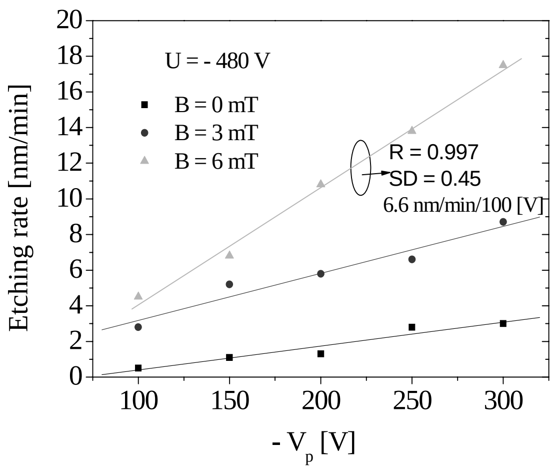


Fig. 2. DLC etching rates at different magnetic fields and a cathode voltage of -480V.

Fig. 3 has been taken with the same set of variables as Fig. 2, the only difference being the higher discharge voltage value, fixed at -600V. As already mentioned, both the cathode and anode (substrate holder) were negatively charged, and the less polarized could be considered as relatively positively charged. Regardless of the higher discharge applied power, and consequently the higher ionization efficiency inside the HC, the leaving positive ions were considerably reduced in number, due to the higher negative bias. This reflects on the etching efficiency – the results taken at higher magnetic fields show that the rate per 100 eV equaled 2.25 nm/min/100 eV, whereas the etching rate taken at a discharge voltage of -480 V was about 3 times higher. SD signifies the standard deviation.

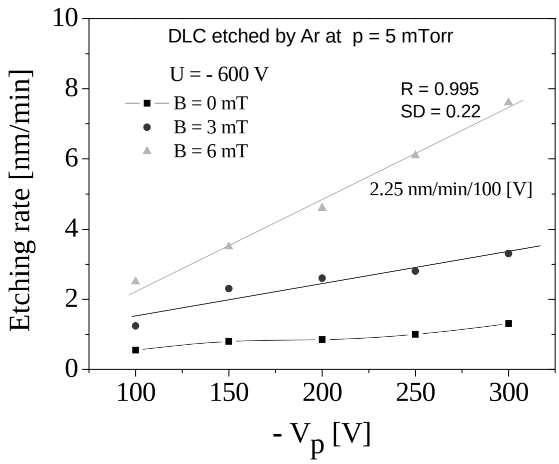


Fig. 3. DLC etching rates at different magnetic fields and a cathode voltage of -600V.

In Fig. 4, in a more visible way, the plasma power influence is shown at a constant magnetic field of 3mT at different accelerating voltages: -250V and -300V. In this graph, three regions could be distinguished; the first one, below -480V, is where the substrate polarization has almost a null effect on the ER because the number of particles leaving the HC is limited due to inferior plasma excitation; the second region, beyond -480V, is where the excitation probability was found to be maximal – only a 50eV higher polarization contributes in a decisive way. The third region involves cathode voltages higher than -540V – in this case the cathode polarization surpasses by a few times the polarization of the anode, which finally limits strongly the particle density which takes part in the process. In the curve drawn at V_p = -250 V, at a cathode difference of only -100 eV (from -500 to -600 eV) the ER drops exponentially, by a factor of 4. It is worth noting here that if this graph was taken at B = 6 mT, the curves would be considerably enhanced in the second region.

Some materials have a pronounced angular sputtering dependence, which is why we studied the ER at an incident ion angle of 45^o, using the same experimental method. As shown in Fig. 5, the magnetic field had a strong influence on the etching rate and increased it by ~ 4 times.

Surprisingly, the anode polarization influence was insignificant, which was not the case when perpendicular incidence is employed. The latter could be explaining simply by the fact that incoming energetic ions at glancing angles contribute to near surface sputtering, without making cascades into the film. Most of them (neutrals) are reflected and their contributions

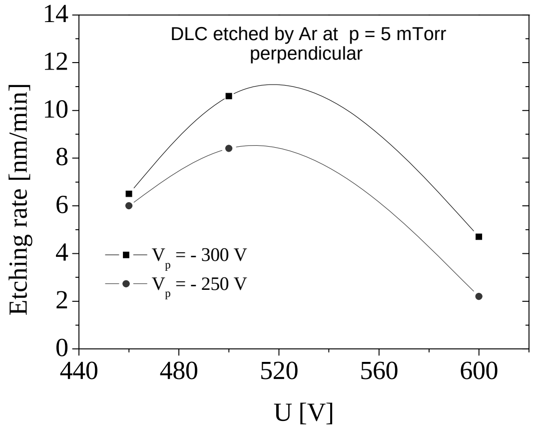


Fig. 4. Etching rates as a function of the cathode polarization at a constant magnetic field B = 3 mT.

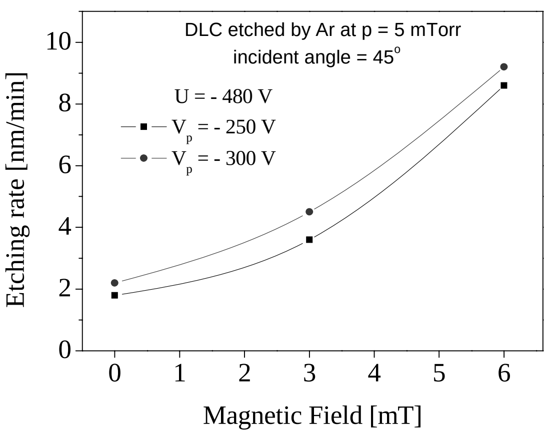
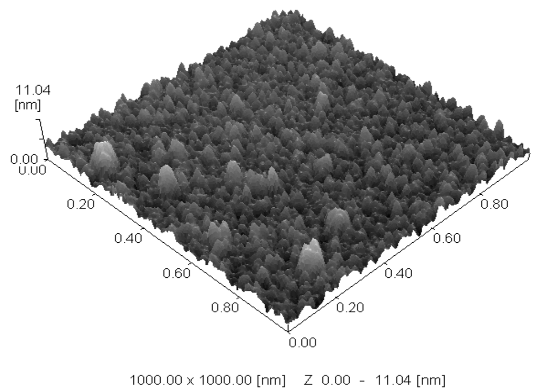


Fig. 5. Etching rates as a function of the magnetic field B = 0, 3, and 6 mT (I = 0, 2 and 4 A).

consist mainly of single surface atom ejection. That is why the variation of the incident particle energy did not result in a significant yield, whereas the perpendicular incidence created a cascade regime and higher energy ions resulted in a higher number of sputtered atoms.

In order to explore in detail the surface changes due to the etching process on a nanometric scale, the DLC films were analyzed by Atomic Force Microscopy (AFM). A comparison between an as-deposited DLC film and a treated one was made (see Figure 6) under the following plasma conditions: discharge cathode voltage V_d = -500V; substrate polarization V_p = -250V; magnetic field B = 3mT; discharge current I = 175mA; argon gas pressure p = 5 mTorr; distance between the sample and the channel d = 50 mm; process time t = 600 s. The results show that the as deposited surface presented a root-mean-square (rms) roughness of 1.2 nm and an average grain diameter of 14 nm. The treated sample presented a substantial reduction in the rms roughness to 0.4 nm, and an increase in the average grain diameter to 30 nm. These results indicate that by using this etching technique it is possible to reduce the formation of needle-like structures on the etched DLC surface, also suggesting a peculiar manner for smoothing the film surface.

a)



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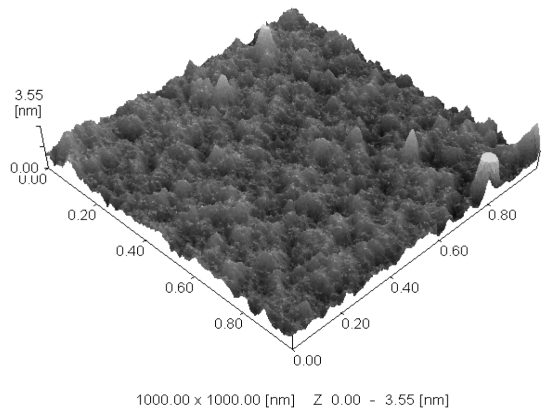

Fig. 6. AFM scan in dynamic mode of: a) non-treated and b) treated DLC thin films.

4. Conclusions

In this work, an argon plasma jet was used to etch high-quality DLC thin films sputtered on silicon (100) substrates, and the following important conclusions could be noted:

i) The magnetic field applied to the processing chamber acts strongly on the efficiency of the etching process. It was observed that it is possible to increase the ER up to 7-fold when the magnetic field increases from zero to 6 mT in the jet plasma region. This is an important result, because it makes it possible to control the ER of the samples by controlling an external parameter, namely the current in the Helmholtz coil.

ii) We have established a discharge-power region which results in a maximum ER efficiency of the hollow-cathode system, and depends in specific ways on the substrate polarization.

iii) AFM analysis indicated that by exploring the proposed etching technique, one can significantly reduce the formation of needle-like structures on the DLC surface, suggesting a particular manner of smoothing of the as-deposited film surface.

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