Applicability of a hollow-cathode plasma jet for etching of Diamond-like Carbon (DLC) films

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Abstract

In this work, a new plasma tool based on the hollow-cathode discharge is introduced. Plasma jets are capable of operating at relatively low gas pressures, $10^{-4}$ Torr, what is in somehow advantageous in comparison with reactive ion etching (RIE) systems, because it reduces contamination from sputtered electrode materials, which eventually produces undesirable micromasks. On the other hand, the low intensity of the plasma jets limits the applicability of this technique for microelectronic purposes. To minimize this problem, a hollow-cathode system was developed in order to produce a dense beam, which was used to etch Diamond-like Carbon (DLC) films. The hollow-cathode plasma beam system revealed to be a reliable technique for DLC films processing, giving etching rate as good as those obtained with usual RIE systems, with the advantage of being a simple and low cost equipment and to proportionate a controlled process.

1. Introduction

Advances in very large scale integration (VLSI) have brought the industry to the point that small differences in process precision can have a large economic impact\textsuperscript{7}. An example is apparent in the area of microprocessor manufacturing. After fabrication, microprocessors today are sorted based on the maximum speed at which they will operate. This sorting is determined primarily by the precision in etching the gate and metal wiring levels. Relatively small losses in the precision of these etching steps result in slower devices. The sales price of a single chip can differ by hundreds of dollars between the fastest speed category and a slower one. Control of processes on the feature length scale, across the entire wafer, must be maintained over time scales that can range from seconds to many hours. During etching of a single wafer, short transients that might last on the order of seconds during the start or end-point of the etch can influence processing characteristics\textsuperscript{2}.

Partly in response to the challenges of etching high-aspect-ratio features, it is studied in this work a new plasma tool capable of operating at relatively low gas pressures, $10^{-5}$ Torr. The lower operating pressures improve etched feature profiles, for example, anisotropy by minimizing collisions between bombarding ions and neutral molecules in the sheaths. However, lower operating pressures tend to reduce etching rates, lowering wafer throughput and increasing the cost of operating the equipment\textsuperscript{7}.

In order to raise rates, in this work is used a hollow-cathode system, designed to sustain a higher plasma charged-particle number density. The properties of hollow-cathode glow discharge have been studied for many years\textsuperscript{4}. These discharges are traditionally used as light sources and active media for gas lasers\textsuperscript{5}. Owing to the hollow-cathode effect (HCE), the current density in a hollow-cathode discharge can exceed that in a planar discharge of the same voltage by orders of magnitude. Though the basic physical phenomena which contribute to this effect are still under discussion, its main features can be explained by fast electrons oscillating in the cavity (pendulum effect)\textsuperscript{6}.

Diamond-like carbon (DLC) films have been studied intensively in the last two decades, because of their attractive mechanical, optical, electrical, chemical and tribological properties\textsuperscript{7,8}. The combination of these properties makes possible the use of DLC films as protective coating for magnetic recordings\textsuperscript{9}, anti-reflective layer for silicon solar cells\textsuperscript{10}, solid lubricant coating for vacuum applications\textsuperscript{11}. For microelectronics purpose it can be used as gate dielectric, intermetal dielectric and passivation layer\textsuperscript{12}.

These films are usually deposited by plasma enhanced chemical vapor deposition (PECVD) or physical vapor deposition techniques, using different carbon precursors. In the present work the films were deposited on silicon substrate by magnetron sputtering using a high purity graphite target and argon as the discharge gas\textsuperscript{13}.

For some applications, such as microelectronic devices, it is usually necessary to etch part of the film. This is commonly done by a reactive ion etching (RIE) system\textsuperscript{14}, but sputtering of the electrode material can occurs and consequently the undesirable production of micromasking on the film.
2. Experimental

Non-hydrogenated carbon (a-C) films of 1.5 micrometer thick were deposited on p type, (100), 10 Ω.cm, silicon substrates, by a d.c. planar magnetron sputtering discharge, at a deposition rate of 15 nm/min. The target was a 100.6 mm diameter disk of graphite with 99.999% carbon content, placed at 45mm from the substrate. The gas used during the depositions was argon (flow rate = 5.0 sccm) at a pressure of 2.44x10⁻³ Torr. The electrical power input of the discharge was 200 W and the substrate temperature was 200°C. Details of the deposition system and processes can be found in reference [13]. The films obtained at these experimental conditions have the following characteristics: electrical resistivity: 5.10⁻⁶ Ω.cm, relative dielectric constant: 2.9, compressive stress: 9.5 GPa and rms roughness: 0.25nm.

The etching processes were performed in a home-built reactor (Figure 1). The hollow-cathode has 10 mm of internal diameter and 70 mm length. It is joined to the vacuum chamber, being the passage between the hollow-cathode and the vacuum chamber, a small center channel (1.0mm diameter and 2.0mm long) opened in the center of the ceramic wall, at the end of the hollow-cathode. A turbo molecular pump, backed by a rotary pump, is attached to the vacuum chamber through a connection in the end flange. Both metallic flanges serve as anode. The source is pumped down to about 1.0x10⁻⁶ Torr and then oxygen gas is fed in the hollow-cathode at a flow rate of 2.0 sccm. In the vacuum chamber, a pressure of operation of 4.4x10⁻⁵ Torr is attained.

A strong pressure gradient is established in the channel between the chambers, with the gas pressure in the vacuum chamber being at least three orders of magnitude lower than in the hollow-cathode. A supersonic gas jet, driven by the pressure gradient, emerges from the exit of the orifice and expands into the vacuum chamber.

During the etching processes, a part of the samples was 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 profile meter and the etch rates were determined.

The Raman spectra of the films, in the range of (1060-1930) cm⁻¹, were obtained by a Renishaw Raman Imaging Microscope System using 50 mW of 514.5 nm laser light. The spectra were decomposed in two Gaussian line shapes in order to analyze the shape, frequency position, width and integrated area of the D and G bands. The G band at 1550cm⁻¹ originates from the crystalline graphite and the D band at about 1370cm⁻¹ is associated with a disordered graphite lattice.

3. Results and Discussion

Figure 2 shows the etch rate of the DLC films for different distances between the expansion orifice and the substrate. The work conditions were: oxygen flow: 2.0 sccm, discharge current: 100 mA. A strong reduction in the etch rate is observed when the distance increases from 15 mm to 35 mm, however, the uniformity of the etch is increased.

The influence of current on the etch rate is shown in Figure 3. The curve shows a significant increase in the etch rate, from 120 nm/min to 400 nm/min, when the current is increased from 100mA to 300mA. This is an interesting behavior, because by controlling of an external parameter (discharge current) it is possible to obtain a good control of the etch rate. It is probably possible to attain a better etch rate levels and uniformity in our system using a multi-channel plasma jet. Other possibility of improvement is the addition of an axial magnetic field, with the advantage of having a much lower pressure in the processing chamber and absence of electrodes that could create impurities, micromasking and other undesirable effects. In a RIE etching there is no possibility of etch rate control by an independent operational parameter as we have here.
An analysis of the influence of the etching process on the atom-bonding configuration of the films was done by Raman spectroscopy. These films were gradually etched with a typical etch rate of 120 nm/min. Raman spectra of the film before etching and after etching steps of 136 nm, 216 nm and 456 nm, were recorded. These spectra were decomposed in the D and G bands. The results showed in Table 1 indicate that the atom-bonding configuration of the film was only slightly modified by the etching.

<table>
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<tr>
<th>Etch depth (nm)</th>
<th>D band</th>
<th>G band</th>
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<td>Width (cm⁻¹)</td>
<td>Position (cm⁻¹)</td>
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<td>1378</td>
<td>275</td>
<td>1575</td>
</tr>
<tr>
<td>456</td>
<td>1387</td>
<td>291</td>
<td>1575</td>
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</tbody>
</table>

Table 1 - Results of the Raman spectra analysis of the DLC films.

4. Conclusions

A high intensity oxygen plasma jet was used to etch diamond-like carbon (DLC) films. Etch rates in the range of (100-400) nm/min were obtained for typical operational conditions of the hollow-cathode discharge: current (200mA), O₂ flow rate (2.0sccm), pressure in the processing chamber (5.9x10⁻³ Pa).

The analysis of the Raman spectra indicate that this etching process does not affect the atom bonding (sp², sp³) configuration of the film, as desirable, for example, in microelectronic materials processing.

Control of the etch rate could be made by variation of the current or by the distance between the substrate and the output of the plasma stream. It is also possible to make this control by the variation of the gas flow. The etching of materials in a processing chamber at very low pressure is always an advantage of this system in comparison with RIE systems. It prevents contamination with sputtered electrode materials, which eventually produces undesirable micromasks. Other practical advantages are: a robust operation over a wide range of gas pressure of the hollow-cathode discharge, low cost, independent control of the etch rate by different operational parameters. The performance of the plasma jet etching has already shown to be suitable for microelectronic material processing, but etching uniformity can be further improved by making a plasma source with various channels, being necessary, in this case, to have a vacuum system of higher pumping speed to assure a low pressure in the processing chamber and the supersonic regime of the plasma stream.

Acknowledgements

The authors thank Drs. N. F. Leite, E. J. Corat and J. R. S. Sena of LAS-INPE for the use of the Raman system, the step height meter and helpful discussions. The financial support of FAPESP, CNPq, FINEP and CAPES is acknowledged.

References