Influence of gas flow rate and entry point on ion charge, ion counts and ion energy distribution in a filtered cathodic arc


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Abstract

We report the results of an investigation in which we measured ion charge, ion counts and ion energy distributions of a titanium cathodic arc operated in a nitrogen atmosphere, using a Hiden mass selected ion energy analyser. Measurements were taken under standardised conditions of arc current and magnetic confinement. Two different gas entry points (over the cathode and in the main chamber close to the Hiden port), three different background gas pressures (2, 4 and 7.5 mtorr) and two different flow rates (23 and 71 sccm) were investigated. Counts were taken at 14, 24, 28, 48 and 62 amu, representing N or N , Ti or Ti , N or Ti and TiN , respectively. Ion energy was measured up to a maximum of 80 eV relative to vessel wall potential. Multiple data sets were collected for each combination of gas entry, gas pressure and flow rate. Ion counts, ion energy and mean charge all decrease as flow rate increases. For cathode entry, Ti ion counts increase greatly, N ion counts decrease slightly, mean ion energy increases and mean ion charge does not show a clear trend. Similarly, the responses of ion counts, ion energies and mean ionic charges to increases in pressure do not show a single, clear trend. The results of the study are reported and some implications for PBII processing are discussed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Cathodic arc; PBII; Mean ionic charge; Titanium; Nitrogen; Ion energy distribution

1. Introduction

Cathodic arcs are a widely used source of plasmas for the PBII (plasma based ion implantation) [1–9] processing of a wide range of metals, metal compounds and carbon films. Implantation of material derived from a cathodic plasma may be undertaken in a vacuum or in the presence of a reactive gas (e.g. N, O) or a non-reactive gas, such as He or Ar. While background or operating gas pressure is commonly reported, comparatively few authors have reported gas flow rate and gas entry position [10,11], or actively considered the possible effects of these factors in combination [8,9,12]. The study described in this paper indicates that gas entry point and gas flow rate may strongly influence film growth conditions by altering the relative quantities and range of ionic species available for PBII. This is especially true for the cathodic arc-generated plasmas, which have a significant directed velocity [2,4].

The aim of this work was to measure the ion counts, energy distributions and mean ionic charge of the principal ions derived from a cathodic arc plasma available in the region of the substrate for PBII production of TiN films. Knowledge of these factors was considered essential in finding the optimal stoichiometric conditions for film implantation and deposition, as changes to the relative abundance of ion species may well be relevant to implanted structures.

2. Experimental

The cathodic arc system with attached Hiden mass selected energy analyser is shown in Fig. 1. The arc system has been described in detail in an earlier paper [10]. The variables in the system were the background pressure (2, 4 and 7.5 mtorr), the flow rate (23 and 71 sccm) and the gas entry point (chamber or cathode). All other system parameters were kept constant. The vessel was evacuated via a rotary pump-backed diffusion pump situated directly below the main chamber. Gas pressure was measured prior to the ignition of the arc plasma. This background pressure is considerably greater.
than the pressure in the main chamber when the arc is operating.

Ultra-high purity nitrogen gas was introduced into the main chamber entry through a simple 6 mm pipe without a spreader or diffuser. The entry pipe was pointing at an angle of approximately $135^\circ$ away from the mass analyser (Hiden) port, and approximately $45^\circ$ into the plasma stream. The Hiden entrance port and the plasma stream are co-axial (see Fig. 1). At the cathode, nitrogen is introduced via a pair of entry ports in the cathode back plate. The entry ports face in opposite directions, parallel to the back plate and perpendicular to the axis of the cathode. A swirl chamber behind the cathode is formed in which the gas spirals circumferentially along the walls past the cathode and on down the plasma duct.

The energy distributions of the mass selected species were scanned using a Hiden system consisting of a model HA030 008 plasma probe and a SIMS PSU-1 analyser. The dwell time was 100 ms. Scans were taken at 14, 24, 28, 48 and 62 amu, representing $N^+$ or $N_2^+$, $Ti^{2+}$, $N_2^+$, $Ti^+$ and $TiN^+$, respectively. We are unable to distinguish between singly ionised atomic nitrogen and doubly ionised molecular nitrogen. Both appear at 14 amu. Ion energy was measured over the range of $20–80$ eV, relative to the vessel wall, which was at earth potential. Multiple data sets (between 7 and 10) were collected and averaged for each combination of gas entry (cathode or chamber), gas pressure (2, 4 or...
7.5 mtorr) and flow rate (23 or 71 sccm). The pumping speed of our vacuum system was not able to maintain 2 mtorr at 71 sccm, and so data for this particular combination of pressure and flow rate were not collected.

3. Results

The results are summarised in Fig. 2 (ion counts), Fig. 3 (ion energy) and Fig. 4 (ion charge).

3.1. Effect of gas flow rate

For cathode entry, all species show a decrease in ion counts as the flow rate is increased from 23 to 71 sccm. This trend also holds for chamber entry. The average ion energies for both nitrogen and titanium ions decrease as the flow rate increases, the effect being less pronounced for nitrogen. A similar, but weaker trend occurs with chamber entry. The mean charge for titanium ions (neglecting the Ti$^{3+}$ component, which was not measured) is dramatically lowered at the higher gas flow rate. For the 23 sccm flow rate, irrespective of pressure or gas entry point, the mean charge varied between 1.94 and 1.78. At 71 sccm, the range was 1.42–1.05, decreasing with pressure increase. The mean charge for nitrogen ions did not show the same degree of sensitivity to flow rate, but did decrease from 1.29 at 23 sccm to 1.15 at 71 sccm. Ion counts, ion energy and mean charge all decrease as flow rate increases.

3.2. Effect of gas entry point

At the low flow rate, total counts for both 24 amu (Ti$^{2+}$) and 48 amu (Ti$^{+}$) are much higher for cathode entry, but at 71 sccm, Ti ion counts are lowered slightly. Conversely, ion counts for both 14 amu and 28 amu are lower for cathode entry than for chamber entry, particularly at the combination of the lowest pressure and lowest flow rate. Both Ti species have much higher mean energies when nitrogen is injected at the cathode than in the chamber. For both N$_2^+$ /N$^+$ and for N$_2^+$, the energy distribution is shifted to a higher range when gas entry is behind the cathode than for gas entry at the chamber. With the exception of the lowest pressure, mean ion charge is less affected by gas entry point than by flow rate. For cathode entry, Ti ion counts increase greatly, N ion counts decrease slightly, mean ion energy
increases and mean ion charge does not show a clear trend.

3.3. Effect of gas pressure

Titanium and nitrogen ion counts decreasing with pressure is a general pattern for both gas flows and entry points. The exception, however, is cathode injection at the low flow rate, the counts for both nitrogen ion species increase with pressure. Mean titanium ion energies have a complex response to gas pressure, but generally trend downward with increasing pressure. With the cathode entry, low pressure, low flow rate as the exception, N ion energy changes very little with pressure. At low flow rates, the mean Ti ion charge decreases only slightly with pressure, but at the high flow rate, the mean Ti charge drops rapidly to near unity as pressure increases from 4 to 7.5 mtorr. Gas entry point is less important than pressure and flow rate for mean Ti charge. Except for cathode entry at the low flow rate, mean N charge does not greatly vary with pressure. The responses of ion counts, ion energies and mean ionic charges to increases in pressure do not show a single, clear trend.

4. Discussion

All ion energies are measured relative to the (earthed) vessel wall rather than the cathode, which was allowed to float relative to this reference potential. This accounts for the apparently negative energies of some of the ions; however, ion energy distribution is of less relevance in PBII where the plasma ion energies (a few eV) are overwhelmed by high voltage pulses. This is especially true for implantations/depositions where a high pulser duty cycle is employed.

In addition to the site of gas entry into the system, an important consideration is the manner in which the gas is introduced. In our system, there is no diffuser at the end of the chamber entry pipe, so the gas enters the plasma stream in a dense plume, which at higher flow rates visibly disrupt the plasma. In contrast, when nitrogen is introduced at the cathode, it spirals circumferentially along the walls of the cathodic duct. When the arc is in operation, the titanium plasma stream is co-axially surrounded by nitrogen gas diffusing into it. The mechanics of gas introduction may well be as important as the site.

A further complication is the changes in plasma beam diameter and position as pressure increases noted by Zhitomirsky et al. [4], for a system of somewhat similar layout to our machine. The position of the port to the mass selected energy analyser in our system is fixed, so if there were changes in beam position or diameter, we may well have been sampling different parts of the plasma beam at different background gas pressures. For high voltage PBII, however, slight changes in beam position should have a minimal effect.

Inspection of the plasma duct after nitrogen entry over the cathode revealed significant quantities of ‘gold’ TiN deposited on the walls of the duct. The deposits were all line-of-sight from the cathode and did not continue around the quarter torus. Ti macroparticles appear to be the most likely nitrogen ‘getting’ candidates as macroparticle production declines with increasing pressure [8], and at the low flow rate, total nitrogen ion counts increase rapidly as the background pressure increases from 2 to 4 mtorr (Fig. 2.). Singly ionised TiN$^+$ counts (62 amu) were very low for chamber entry, but were higher for cathode entry, suggesting at least some TiN$^+$ ionisation at the cathode.

The mean ionic charge for titanium ions was found to decrease with increasing gas flow rate and pressure. We note that at high pressures and flow rates for both chamber and cathode entry, the titanium ions are almost all singly ionised, an unexpected finding from the
Within the range of pressures studied, the nitrogen flow rate appears to be the most important parameter for the mean charge state of Ti ions. Low nitrogen flow rate produces high mean Ti ionic charge, and high flow rate produces a lower mean ionic charge. At the high flow rate, mean Ti charge decreases rapidly with pressure increase, an effect that is not seen at the low flow rate.

With the exception of cathode entry at 23 sccm, mean nitrogen ionic charge shows only minor changes with gas flow rate, entry point or pressure. Nitrogen in the region of the cathode appears to be both energised and ionised to levels approaching that of the Ti plasma, but the energised N\(_2\) ions lose energy and mean ionic charge through collisions with nitrogen molecules during flight down the plasma duct. However, once a ratio of 14:28 amu of approximately 0.4 is reached, an equilibrium is established where there is no further net down-conversion of 14–28 amu, despite increases in the energy loss collision rate.

5. Conclusions

Ion counts, ion energy and mean charge all decrease as flow rate increases. For cathode entry (compared with chamber entry), Ti ion counts increase greatly, N ion counts decrease slightly, mean ion energy increases and mean ion charge does not show a clear trend. Similarly, the responses of ion counts, ion energies and mean ionic charges to increases in pressure do not show a single, clear trend. The changes of ion counts and ionic charge state which occur with changes in flow rate, entry point and pressure have implications for both PBII processing and comparisons of results obtained on different machines with different internal layouts.

References