Charging of dielectric substrate materials during plasma immersion ion implantation

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Abstract

We have investigated the electrostatic charging effects of dielectric substrate materials during plasma immersion ion implantation. The results demonstrate that the time-dependent surface potential (negative) may be reduced in magnitude due to the charging effect of the dielectric surface, leading in turn to a reduction in the energy of the incident ions and a broadening of the implanted ion energy spectrum. The charging effect is greater during the plasma immersion bias pulse rise-time, and the electrostatic potential charging may be as large as 75\% of the total applied (pulse) potential. This is due to abundant charge movement both of ions and secondary electrons, and has been confirmed by computer simulation. The plasma sheath capacitance has a small influence on the surface potential, via the bias pulse rise-time. Processing parameters, for example voltage, pulse duration, plasma density, and pulse rise-time, have a critical influence on the charging effects. Short pulse duration, high pulse frequency and low plasma density are beneficial from the viewpoint of maximizing the implantation ion energy. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Plasma immersion ion implantation (PIII) has received much interest because of its capabilities for batch processing, high throughput, and reduction in line-of-sight limitations [1–3], and has been well investigated for the implantation of metal and semiconductor substrate materials [4].

The method has also been used for ion implantation into polymer materials; for example the wetting properties of ethylene terephthalate have been improved [5,6], and the surface hardness of polymers has been increased by carbon and by nitrogen PIII [7,8]. As an insulating material, the polymer substrate that is positioned on a conducting target holder cannot rise to the full (negative) pulse bias potential that is applied to the holder, and consequently, the energy of the incident ions is less than that expected from the pulse bias voltage. This can be attributed to insulator charging effects and to the capacitance of the insulator. A number

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of researchers have carried out theoretical investigations of PIII into insulating substrates [6,9–11]. The processing parameters, including applied voltage, plasma density, pulse duration, etc., have a critical influence on the end results of the surface modification [10,11]. In fact, surface charging will further broaden the energy distribution of incident ions in addition to the effect of the rise- or fall-time of the negative pulses [10]. Up to now all the prior investigations have been theoretical. In this paper, we report on our experimental studies of the surface charging effects of dielectric substrate materials and discuss the charging dynamics implied by the experimental results and by computer simulation.

2. Experimental setup

The experimental setup shown schematically in Fig. 1 has been described in details elsewhere [12]. The target holder is 152 mm in diameter and 56 mm in thickness. A thin copper plate 120 mm in diameter was placed on the top surface of the dielectric sample, which in turn was positioned on the target holder. The substrate materials investigated included glass, polyethylene, single-crystal silicon wafer, and silicon with a layer of silicon oxide. The target holder was biased to an applied voltage that was measured using a Pearson type 305A capacitance divider, and the potential of the copper plate on the dielectric sample was measured using another capacitance divider of the same kind. A Tektronix model 360 oscilloscope was used to record the probe potential information as well as the total implantation current. A hydrogen plasma was generated by an inductively coupled radio-frequency (RF) plasma source with a magnetic field coil installed between the plasma source and the main region of the vacuum chamber was used to adjust the plasma density.

3. Effectiveness of measurement system

Measurements were first carried out in the absence of plasma, with a glass substrate of dimensions 75 mm × 25 mm × 1 mm. The relationship between the substrate surface potential and the applied voltage is shown in Fig. 2(a). The (negative) surface potential is of smaller magnitude (less negative) than the potential applied to the target holder, and changes linearly with the applied potential. The potential difference between the two sides of the glass is equal to one-third of the total applied potential, and cannot be accounted for by a simple capacitance in vacuum but can be attributed to the inherent capacitance of the capacitive voltage divider (18 pF) [13], which is much greater than the vacuum capacitance. The capacitance of the glass sample may be some tens of pF, and the total system including glass and capacitive voltage divider would become another capacitive divider as shown in Fig. 2(b). Thus it is not strange that the potential of the glass surface increases substantially, because of the similarity of the capacitances of the glass substrate and the capacitive divider. Although the measurement system may induce a change in the potential of the dielectric surface, the charging effect is nevertheless defined by the potential change through the relationship ΔV = Q/C. Thus during the charging experiments, the initial surface potential of the dielectric sample can be assumed to be equal to that measured without plasmas. During processing of the dielectric samples, the surface potential may be influenced by the insulator composition, size, thickness,
etc. The clean silicon wafer and the wafer with a 0.2 μm oxide layer do not lead to an increased surface potential. This is consistent with the simulation results of Qin et al. [11]. The charging effect is small when the insulating layer thickness is less than 100 μm, for a plasma density of \(1 \times 10^{16} \text{ m}^{-3}\).

4. Theoretical potential rise on dielectric surface

In practical PIII processing of dielectric surfaces (without an associated measurement system), there will necessarily exist a surface potential rise. This rise can originate from both plasma sheath capacitance effects and insulator surface charging effects.

During the PIII process, the plasma fills the space between the chamber wall and the target. When a negative potential is applied to the target, a plasma sheath forms with an associated plasma sheath capacitance, \(C_{\text{plasma}}\) [10,14,15],

\[
C_{\text{plasma}} = \frac{\varepsilon_0}{S_t},
\]

where \(\varepsilon_0\) is the permittivity of free space and \(S_t\) is the sheath thickness. The potential rise (\(\Delta V\)) of the dielectric surface induced by this capacitance is given by

\[
\Delta V = C_{\text{plasma}} \frac{V_{\text{target}}}{C_{\text{plasma}} + C_{\text{dielectric}}}.
\]

During the ion implantation phase, charge is accumulated on the dielectric surface because of its low electrical conductivity. This also leads to a potential difference, given by

\[
\Delta V = \frac{Q_{\text{charge}}}{C_{\text{dielectric}}},
\]

\[
Q_{\text{charge}} = \int_0^t j_t (1 + \gamma) \, dt,
\]

where \(\gamma\) is the secondary electron emission coefficient determined by the material and the incident ion species [16–18] and \(j = (4/9)\varepsilon_0 \sqrt{2e/M(V_{3/2}/S_t^2)}\) is the implantation current density.

Fig. 3 shows the time-dependent ion current and potential drop induced by the plasma sheath.
for a hydrogen plasma of density $1.0 \times 10^9$ cm$^{-3}$, a pulse bias voltage of 10 kV with a 1.5 μs rise-time, and a glass substrate ($\varepsilon_r = 4.0$) with thickness 1 mm. We assume that the surface potential increases linearly with time during the rise-time. The results indicate that the potential difference induced by the plasma sheath gradually increases from zero and reaches a maximum at the end of the pulse rise. However, this potential difference is not significant. In contrast, the initial current jump that occurs because of the high initial ion flux and after which the current that increases only gradually until the end of the pulse rise [19], has a critical influence on the charging dynamics. We now consider these effects.

5. Charging effects

5.1. Charging dynamics

Fig. 4(a) shows the time-dependent surface potential during the pulse-on period for hydrogen plasma. The surface potential rapidly increases once the negative voltage is applied to the target holder. This may be attributed to plasma-induced charging effects and to a change in the equivalent capacitance, which together produce a potential difference between the two sides of the glass substrate. The potential difference can be calculated from Fig. 4(a) as shown in Fig. 4(b). Initially, the potential difference increases rapidly with the applied voltage until the end of the pulse rise-time, after which the potential changes only slowly. That is, surface charging occurs mainly during the initial time period. For example, for a pulse duration of 10 μs, at the end of the pulse rise-time, the accumulated charge is 75% of the total charge accumulation. Our one-dimensional simulation shows that the contribution from the plasma sheath capacitance to the potential difference is very small, as shown in Fig. 3. Thus, we can infer that charge movement is mainly responsible for the initial charging, not the plasma sheath capacitance. An initial current jump leads to rapid charge accumulation. After this, a secondary electron flux can occur because of ion bombardment, which will increase the charging effect. Although the charging effect induced by the incident ions decreases with time, the effect of secondary electrons gradually increases. During the voltage plateau, charge accumulation slows because the ion current decreases.

5.2. Effect of applied voltage

The applied voltage has a critical influence on surface charging. A higher implantation voltage may induce a greater incident ion flux and also emission of secondary electrons according to the Child–Langmuir law. Hence, the greater the applied voltage, the greater the charging effect is as shown in Fig. 5. When the potential difference is sufficiently great, arcing may occur, which may

![Fig. 4. (a) Surface potential during plasma ion implantation. (b) Time-dependent potential difference and charge rate-of-change.](image-url)
damage the substrate surface and other hardware. In our case, arcing takes place at a potential difference of 13 kV. This means that one must use a shorter pulse duration when implanting insulators at higher voltage. Although a higher voltage may give rise to a greater charging effect, this is still preferable from the viewpoint of maximizing the ion energy.

5.3. Effect of plasma density

We speculate on the various factors influencing the ion implantation current and their effects on surface charging. As shown in Fig. 6(a), the maximum potential obtained by the insulator surface is also influenced by the plasma density. When the externally applied confining magnetic field is switched off, the plasma density decreases, leading to a reduced implantation flux and subsequent insulator charging. Fig. 6(a) also demonstrates the influence of the voltage and plasma density on charging during the pulse duration (comparing curves 1, 2 and 4). A low voltage or density may lead to a low potential because of a low incident flux. A higher plasma density may lead not only to higher total charging but also to a higher ratio of charge obtained during the rise-time to that during the total pulse duration, as indicated in Fig. 6(b). This will substantially reduce the average implantation energy. Therefore a lower plasma density may be beneficial for plasma implantation of insulators. However, this may also give rise to a thicker plasma sheath and consequently non-uniform implantation for some substrate geometries. A large vacuum chamber is also beneficial so as to avoid propagation of the sheath to the plasma source and consequently plasma extinction. The solution may be to use a small pulse width, which is consistent with reducing the magnitude of surface charging.

5.4. Effect of pulse rise-time

The pulse rise-time is an important processing parameter in plasma implantation of dielectric materials. On one hand, the ion current is high during the rise-time, and consequently most of the surface charging happens during this time. On the
other hand, the difference between the capacitance of dielectric materials and the capacitance of the plasma sheath is not great. The effect of the capacitive voltage divider due to the plasma sheath should not be ignored, and thus the pulse rise-time should be considered when processing dielectric materials. With increasing rise-time, charging induced by the plasma sheath capacitance decreases, while that induced by the incident ion flux and secondary electron emission increases. The effect of the plasma sheath capacitance increases with a lower rise-time. Limitations on short rise-time due to physical hardware constraints provide a fortuitous limit to this effect; otherwise the initial surface potential would be very high for very short rise-time. Our simulation also demonstrates that a lower density will reduce the sensitivity of the charging effect to the rise-time (Fig. 7). Generally speaking, a small rise-time is preferable. This is consistent with the conventional PIII of conducting materials, although arrived at for different reasons.

5.5. Discharge of the charged surface

During the pulse-off period, the dielectric surface will be discharged by electrons in the plasma. Therefore, the magnitude of the surface charging can be monitored via the tail waveform shape when the substrate bias voltage pulse is switched off. During the pulse-off time, the surface potential gradually returns to zero and may even become positive. This is because a finite time is needed for the electrons in the plasmas to discharge the positive substrate charge while the potential due to the insulator capacitance effect vanishes. This is similar to the case of a target immersed in a plasma, with a bipolar alternating pulse bias voltage. A longer time is needed for discharge, about 20 μs in our case as indicated in curve 3 of Fig. 6(a). This experimentally obtained time scale is of great importance for understanding the mechanism of PIII of insulators. A higher voltage, higher plasma density, or longer pulse duration (see Figs. 5 and 6) all lead to a higher positive potential.

6. Conclusion

We have conducted investigations of surface charging effects of insulating substrate materials during PIII. The experimental results indicate that the energy carried by the incident ions is reduced due to the static capacitance effect of the insulator. Surface charging is also brought about by the incident ions and secondary electron emission because of the low electrical conductivity of the dielectric materials. The discharge time scale of the charged insulator surface can be of order 20 μs. A combination of short pulse duration, high pulse frequency, and low plasma density can be beneficial from the viewpoint of obtaining maximum ion implantation energy. The experimental results obtained provide some insight into the mechanisms of plasma implantation of dielectrics, and can be applied to the case of metal PIII and deposition (MePIIID) [20].

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