Microarcing instability in RF PECVD plasma system

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Abstract

Microarcing at the chamber wall in RF plasma is studied in PECVD type system. A Langmuir probe is used to measure the plasma potential. This system and procedure allows us to create reproducibly microarcing by increasing the plasma potential. The wall arcing threshold of the plasma potential in this system is in the vicinity of 50 V. In this system, the charging process, which is about a few tens of milliseconds or more, is much slower compared to the microsecond discharge. The time constant for sheath charging can be reduced if less sheath area is responsible for the potential recovery. The arcing frequency strongly depends on the plasma potential, the grounded surface area of sheath, and the pressure. This work demonstrated that the microarcing in the RF deposition and reactive etching plasmas depends on plasma potential, gas pressure, surface area of grounded wall, and chamber conditions.

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1. Introduction

Microarcing during plasma sputtering, PECVD deposition, or plasma reactive ion etching is not desirable because it causes unstable plasma reproducibility, roughened surfaces, possible destructive damage, and the introduction of the wall material into the vapor phase. For more than half a century, many studies have been carried out on DC discharge and sputtering processes [1–6]. In particular, microarcing in reactive sputtering of oxide and nitride materials is a well-known and troublesome phenomenon, in which the mechanism responsible for the arcing in such systems is generally accepted to be the electrical breakdown of an insulating layer building up on an electrode [3,7], with a resulting positive charge accumulating on the dielectric layer to such an extent that the electric field exceeds the breakdown strength of the dielectric layer.

Relatively few studies have been carried out on detailed microarcing in plasma thin film deposition systems using either DC sputtering or RF PECVD. Perhaps, the most extensive studies relevant to this topic are those reported by Cho et al. at NASA research centers related to space shuttles, satellites, or rockets traveling in low Earth orbit [8–10]. The primary concern in their study is that microarcing frequently occurs due to exposure of parts to the ionosphere environment, causing either local destructive damage or interfering with electronic circuits. Of course, the ionosphere plasma environment of low Earth orbit is dramatically different from that found in conventional plasma deposition and etching reactors. For example, the plasma density is about six orders of magnitude lower, which suggests the plasma sheath is about three orders of magnitude larger. The pressure at low Earth orbit is at least about two orders of magnitude less than that in laboratory reactors resulting in fewer collisions, and the above studies conclude that the arcing is generally not caused by high plasma potential but rather by high surface charging or biasing. Although different conditions exist between the terrestrial plasma systems we are interested in and the moving environment in ionosphere plasma, the research done on the microarcing in ionosphere plasma systems has...
indeed provided us with detailed information of relevance to the present experiment on microarcing phenomenon in RF plasma PECVD.

In thin film deposition, both researchers and power supplies manufacturers have made extensive efforts to avoid the occurrence of microarcing. For example, for arc detection through the power supply circuit, the power supply is turned off for a predetermined period of time, followed by reapplication of the power [11]. Another approach is concentrated on preventing positive charges accumulating on insulating layers and keeping electrical fields lower than its dielectric strength [12–14] by either pulsing the DC power or continuously switching deposition between two electrodes.

Compared to DC discharge, very few studies of such microarcing have been reported on RF plasma systems. However, arcing in RF plasma processes such as plasma etching and deposition is one of the major concerns in industries, as it can result in a high density of microparticles and a metallic vapor from the microdischarge depositing on the substrate and vacuum system surfaces. For example, great attention has to be paid in microelectronic manufacturing industries to RF plasma systems by monitoring the microarcing and applying conservative equipment maintenance procedures that is often requested by machine manufacturers, which results in higher running cost and lower effective machine use and hence high Cost Of Ownership.

For the experiments presented here, an RF hollow electrode plasma system was constructed to increase the plasma potential and to analyze the dependence of microarcing on plasma potential. The results also show that the plasma potential is a useful parameter and a convenient method to monitor microarcing.

2. Experimental setup and procedures

The hollow electrode system consists of an 80-mm-long tube with 26-mm inner diameter one end of which is sealed by a piece of insulator. The distance between the top planar electrode and the top surface of the hollow electrode is 25 mm. The RF power supply and matching network are ENI OEM-12 and ENI Matchwork 5, respectively, and a single RF power supply drives both the upper electrode and the hollow electrode and avoids the complexity of RF phase shift control between the two electrodes. A DC and RF blocking unit is connected to the bottom cylindrical hollow electrode to filter DC signal for the hollow electrode (i.e., DC-grounded) and to block the DC signal from the top planar electrode. The stainless steel chamber is connected to the ground. The Langmuir probe consists of a 0.20-mm diameter tungsten wire passing through an ALSINT-sintered alumina ceramic tube in a stainless steel tube (connected to the grounded chamber) and is positioned at the center of the two electrodes. All Langmuir probe data of floating potential are collected using nitrogen plasma, although in some circumstances, other gases such as argon were also used to confirm the measurements. Base pressure in the vacuum system is less than $2 \times 10^{-6}$ Torr. A Pfeiffer QMS 200 residual gas analyzer is also connected to the vacuum chamber via a leak valve to detect impurity level. The flow rate of the 99.999% pure nitrogen used in this study is 10.0 sccm, and comparing typical outgassing or leak rate of chamber walls in this vacuum system, this nitrogen flow rate is approximately about four orders of magnitude higher.

Chamber conditioning procedure was performed prior to data collection as following: the procedure applied is first to pump the system to base pressure for over 2 h, then to flow argon for 20 min, followed by argon RF plasma clean for 10 min with electrode self-biasing negatively at approximately 300 V. After the argon plasma clean, the chamber is pumped down to base pressure, and RGA analysis is then performed to ensure no significant argon outgassing from the walls. Nitrogen gas is then let into the chamber at a pressure of 60 mTorr, and microarcing conditioning of the chamber wall is performed for about 10 min. After the procedure of the chamber conditioning, we found that the plasma potential was reasonably stable, and microarcing was reproducible in the range of measurements performed in this work.

3. Results and discussion

Fig. 1 shows the floating potential for four different modes of RF configurations as a function of RF power. Mode A has the top planar electrode connected to RF with DC floating, and the hollow electrode is DC-floated without RF; mode B has the top planar electrode connected to RF with DC floating and the hollow electrode DC grounded with RF; mode C has the top electrode with DC floating and no RF, and the hollow electrode is DC floating with RF; and mode D is the same as mode C except that the hollow electrode is DC-grounded.

![Fig. 1. Floating potential as a function of RF power for different RF configurations.](image-url)
It is convenient to present the result as a function of floating potential instead of plasma potential because the plasma potential or electron temperature cannot be conveniently determined when microarcing occurs in the plasma. The difference $U$ between the plasma potential and the floating potential can be estimated from Ref. [15]:

$$U = T_e \ln \left( \frac{M}{2\pi nm} \right)^{0.5}$$

(1)

Where $T_e$ is the electron temperature in eV, $M$ is the mass of the nitrogen ions (assuming $N_2^+$ ions), and $m$ is the mass of the electron. The electron temperature was found to be about 3 eV determined at conditions without microarcing. Because the range of plasma potential variation in this work is from a few tens to over 100 V, small variations of electron temperature should not cause significant uncertainty.

In both DC floating modes A and C, the floating potential is almost constant in the range of RF powers employed. In the case of mode D, however, the floating potential ramps up with increasing RF power. The DC-grounded hollow electrode forces the plasma potential to increase since in this asymmetric system, there is no biasing capacitor. In the case of mode B, the floating potential is between the floating case A and the grounded configuration D. This can be understood, as the DC floating RF electrode creates a negative bias to force the plasma potential downwards comparing with mode B.

There was no arcing for the case of the floating antenna, and the plasma was very quiet. Arcing can be produced for modes B and D when the floating potential is greater than or equal to 30 V. This corresponds to plasma potential about 50 V. The floating potential is fluctuating when microarcing occurs, and thus for floating potentials higher than about 30 V, an average value is taken. No arcing has been observed for cases A and C in good agreement with Ref. [16]. When the arcing was observed by the naked eye, it occurred at the chamber walls with possibly relatively higher frequency on nonflat surfaces. An attempt was made to reduce the arcing at the walls by cleaning the chamber, and with prolonged gas flow or plasma, but no noticeable improvement was found. This is strong evidence that the arcing is not caused by a charge build up on an insulating film on the surface [17,18] but rather is a result of the sheath breakdown.

The temporal behavior of the arcing was recorded, and Fig. 2 shows some examples for mode D corresponding to different levels of RF power or floating potentials. It is straightforward to see from the spectra that the arcing frequency increases as the floating potential increases. The discharge time is much shorter than that of charging, and the discharge time is of the order of microseconds, suggesting that the discharge cycle follow a different mechanism from the charge cycle. The discharging mechanism in this system may be related to the so-called unipolar arcing in DC discharge. It has been suggested [19] that DC unipolar plasma arcing discharge is caused by secondary electron emission and enhanced by thermionic emission. Because the microarcing occurred at RF plasma, the mechanism of the arcing or sheath breakdown may need further investigation.

In our experimental configurations, the discharge does not pull the plasma potential down to ground, which could indicate that the wall sheath recovery takes place and forces the arc to die away prior to fully discharged. It is possible that, at the spot of a localized arc, the high-flux electron emission results in local wall plasma sheath vanishing, which draws a large electron current to the plasma. The high flux of emission current reduces the plasma potential and, consequently, the sheath voltage. At a certain potential, arcing stops, followed by a slow recharging of the plasma potential and sheath. The relative drop of floating potential in Fig. 2 is larger with higher average floating potential. This seems to support the DC unipolar discharging mechanism [19] that a positive feedback occurs, in which higher plasma potential would cause larger positive feedback to enhance electron emission. The charging process to rebuild the plasma potential or plasma sheath is rather slow, although the exact recovery time constant cannot be determined accurately at this stage, particularly for large

![Fig. 2. Floating potential spectra of arcing for mode D at different RF power levels.](image1)

**Fig. 2.** Floating potential spectra of arcing for mode D at different RF power levels.

![Fig. 3. Arcing frequency as a function of floating potential for different pressures.](image2)

**Fig. 3.** Arcing frequency as a function of floating potential for different pressures.
floating potential because the floating potential is not saturated before the next arcing occurs.

The dependence of arcing frequency is plotted as a function of floating potential as shown in Fig. 3 for 60 and 7 mTorr, respectively. An approximate exponential dependence of arcing frequency with floating potential is found with a threshold potential value of about 30 V. The arcing frequency also depends on the gas pressure: for lower pressure, the arcing frequency is higher. This may be explained as shown above due to lower pressure resulting in lower collision frequency. Nevertheless, this needs further investigation.

The relationship between microarcing formation and plasma potential is supported by negatively DC biasing the top planar electrode, while the hollow electrode is connected to a DC floating RF power. It is found, as expected, that arcs occur at the top electrode only, since the plasma potential or the sheath voltage of the rest of chamber does not exceed the threshold arcing potential and remains less than about 20 V. The potential difference between plasma and the planar electrode increases when the negative biasing increases. At a potential difference greater than the microarcing threshold potential, arcing occurs as expected. A DC-grounded RF power generator was also connected to the hollow electrode while negatively DC biasing the top electrode without RF. Plotted in Fig. 4 is an example of the temporal arcing behavior, in which the hollow electrode is RF-powered with DC grounded and the top electrode is DC biased negatively at 60 V.

Two major differences were found in the temporal behavior compared to those in Fig. 2. Firstly, the arcing frequency (about 10 Hz) is much smaller. Secondly, the charging “time constant” is much shorter, about 8 ms. We interpret these differences as resulting from much reduced surface area of plasma sheath responsible for the charging–discharging process. During arcing, the plasma floating potential can drop as low as to about 50 V. In this case, the potential of the grounded chamber wall is higher than that of the plasma, which would allow electron current flow to ground from the negatively biased electrode when the plasma potential is negative, speeding up the charging process. This would support the argument that the charging time constant dominantly represents the charging of the appropriate plasma sheath. This argument is supported by observation that microarcing was found when the condition of the chamber wall was “poorly” grounded by performing a prolonged period of deposition of silicon dioxide resulted in a layer of insulating coating on a significant part of the chamber walls. In this case, the RF source was DC floating. The coating on the wall resulted in a poor ground, and the plasma potential thus increases, resulting in microarcing. The microarcing was found dominantly at corners or places on the chamber walls where plasma deposition has not occurred, rather than at those “dirty” or coated areas. The frequency of microarcing (about 1 Hz) is much less than the frequencies when the chamber walls are well grounded, as shown in Fig. 5.

4. Conclusions

In this work, the experiments presented are somewhat different to conventional experiments on microarcing, as we make the plasma potential sufficiently positive to create the microarcs instead of negatively biasing the electrode. We have been able to reproducibly produce microarcing by increasing the plasma potential in an RF plasma system. The wall microarcing threshold for the plasma potential is in the vicinity of 50 V. This low value is very close to the plasma potential in conventional RF etching or deposition systems, depending on system and plasma conditions, thus indicating that microarcing in those systems could be a troublesome phenomenon unless extra care is taken. The arcing frequency strongly depends on the plasma potential and chamber conditions such as grounded wall area and gas pressure. The microarcing is due to the breakdown of the plasma sheath on the grounded wall or that at lower potential. Whereas the microarcing discharge is a rapid
process, the recovery of the plasma potential is determined by recharging the plasma sheath due to an ambipolar drift of ions. The time constant for charging is dependent on the area of the sheath in the recovery of the plasma potential. This work showed that the microarcing instability in RF plasma systems is not necessarily caused by dielectric breaking down but by discharge through wall sheath due to high plasma potential.

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References