Plasma propagation in the microwave window breakdown at the air/dielectric interface

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Abstract

The microwave window breakdown due to the plasma formation greatly limits the power handling capability of high-power microwave systems. However, the experimentally-observed fast plasma propagation cannot be explained using previous theory or simulation results. In this paper, the photoionization is considered to investigate the mechanism of microwave window breakdown at the air/dielectric interface by particle-in-cell simulation. The results show that photoelectrons produced by high-speed photons can profoundly promote discharge above the air/dielectric interface. Then a fast plasma formation and propagation occurs. The speed of plasma propagation can reach $1 \times 10^6$ m s$^{-1}$, which agrees well with experiments. As a result, the transmitting power is attenuated more seriously than the case without the photoionization. Furthermore, the effects of size of microwave window, gas pressure, strength of microwave electric field and distribution of microwave electric field on the plasma propagation are investigated. The results show that the total number of electrons is nonlinearly increasing with the size of microwave window when a uniform microwave electric field is applied. The speed of the plasma propagation exponentially increases with the strength of microwave electric field. Therefore, the photoionization is an indispensable process in the microwave window breakdown with high-strength microwave electric field.

Keywords: microwave window breakdown, photoionization, plasma propagation, particle-in-cell

1. Introduction

Plasma that results from gas discharge near a surface is a fundamental and important phenomena that causes microwave window breakdown [1–4]. This is one of the main factors that limits high-power microwave (HPM) transmission and radiation [3, 5]. The range of plasma observed in experiments [6, 7] can reach several millimeters for nanosecond pulses, which is much larger than the scale of plasma obtained using the former particle-in-cell and Monte Carlo collision (PIC-MCC) simulation results [8–10]. A theoretical model for plasma propagation in vacuum window breakdown was proposed by Wang [11]. However, because the electrons have a smaller free path and larger collision frequency at the high gas pressure atmosphere, that model cannot explain plasma propagation in the microwave window breakdown at the air side of an air/dielectric interface. Therefore, the mechanism of plasma propagation in the microwave window breakdown at air/dielectric interfaces requires additional understanding.

Photoionization is one of the essential processes when considering the mechanisms of streamer discharges [12, 13]. This process can provide extra electron–ion pairs to promote
ions, photons travel at a faster speed, allowing the plasma to expand to a large scale within several nanoseconds. In the past theory and simulation results, only the collision ionization is taken into account. Therefore, in this paper, the photoionization is considered using a 3D PIC-MCC model to investigate the process of plasma propagation in the microwave window breakdown at the air/dielectric interface.

2. Model

A scheme of the microwave window breakdown at the air/dielectric interface is shown in figure 1. The microwave frequency is 10 GHz. The background gas is air (80% $N_2$ and 20% $O_2$) at a pressure of 100–760 Torr. The photoionization model proposed by Jang is used in the proposed model [14]. The lifetime of high excited states of $N_2$ is considered.

Collision reactions considered in PIC-MCC simulation are shown in table 1. The excitation cross-sections for the high excited states of $N_2$ are derived by Itikawa [15]. The elastic, low state excitation and ionization cross-sections are taken from the Morgan database [16]. The most common assumption on photoionization in air is that $N_2$ is excited by electrons and photons emitted by excited $N_2$ ionize $O_2$ [17]. The probability of multilevel photoionization is very small [18]. Therefore, the photoionization process of $N_2$ is neglected. In our model, each of the high excited states is tracked as an individual particle species. Generation of high excited states of $N_2$ is mainly attributed to electron impact excitation. Excited molecules undergo electron collision quenching and radiate photons to return to a ground state or a lower excited state. The deactivation process of excited molecules is very complicated. It is further assumed that the excited molecules that suffered collision quenching will return to the ground state and the number of collision quenching is proportional to the number of radiation [14]. Photon radiation is the result of excited nitrogen molecules for the high states ($b^1\Pi_u$, $b^1\Sigma_u^+$, and $c^1\Sigma_u^+$). The photons have wavelengths from 98 to 102.5 nm and are mainly absorbed by oxygen molecules, which ionizes them. The radiative lifetimes of low excited states of $N_2$ are tens of nanoseconds [19, 20]. However, compared with the low excited states, the radiative lifetimes of high excited states of $N_2$ are much shorter. The measured radiative lifetimes of high excited states of $N_2$ are derived by Wu [21]. The average lifetime of $b^1\Pi_u$ state, the $b^1\Sigma_u^+$ state and $c^1\Sigma_u^+$ state are $2.184 \pm 0.26$ ns, $1.13 \pm 0.17$ ns, $0.9 \pm 0.2$ ns, respectively. The mean free paths of the
photons emitted by $b^3\Pi_u$, $b^1\Sigma_u^+$, and $c^1\Pi_u$ are approximately 78.6 $\mu$m, 47.4 $\mu$m, and 83.3 $\mu$m, respectively, at atmosphere pressure [14]. Besides, the speed of photons is the speed of light. Compared with the lifetimes of high excited molecules, the lifetime of photons is very short. Therefore, the motion and lifetime of photons are ignored in our model.

The seed electrons are set on the first grid above the dielectric surface at a density of $5 \times 10^{12}$ m$^{-3}$. In our model, the electrons are divided into two types: (1) electrons, which include the seed electrons and those obtained from collision ionization; and (2) photoelectrons, which are obtained from photoionization. As secondary electron emission is completely suppressed at high gas pressures [8], this phenomenon is neglected in our model. The grid size is 20 $\mu$m, and the time step is 10 fs.

3. Results and discussion

The density distributions of electrons and photoelectrons at $t = 3.75$ ns calculated for a uniform microwave electric field of $E_{\text{rf}} = 6$ MV m$^{-1}$ applied along the y-direction are shown in figures 2 and 3. The size of microwave window is $1 \times 1$ cm and the gas pressure is 760 Torr. When only collision ionization is considered, as figure 2 shows, the thickness of the plasma extends to 0.3 mm. When the effect of photoionization is considered, the front of plasma in figure 3(a) can reach 3.96 mm, which is in agreement with past experiments [6, 7]. At the beginning, the high excited states molecules and photons are produced near the dielectric surface. Photons are emitted isotropically and propagate at the speed of light in the gas until being absorbed [14, 22]. Compared with the high excited states molecules, photons can travel longer distances in the same amount of time. It will create new electron–ion pairs in the further position. Photoelectrons will get energy from the microwave electric field and collide with neutral gas molecules in this position. So high excited states molecules will form in this position. Again, photons will be produced and propagate to a further position. Therefore, the photoionization is the main reason to cause the fast plasma propagation in the microwave window breakdown. As shown in figures 3(a) and (b), the density of photoelectrons is smaller than the density of electrons by seven orders of magnitude at $z < 0.1$ mm. The density of electrons in figures 2 and 3(a) are nearly same at $z < 0.1$ mm. Due to the influence of the plasma sheath, the maximum density of electrons locates 40 $\mu$m above the dielectric surface and equals to $5.52 \times 10^{20}$ m$^{-3}$. Therefore, the growth of the plasma distribution near the dielectric surface is caused primarily by the collision ionization. The photoionization can provide photoelectrons to trick the discharge in a higher position away from the dielectric surface. As figures 3(a) and (b) shows, the densities of electrons and photoelectrons are nearly the same at larger distances from the dielectric surface.

Figure 4 shows the average density distribution of electrons in $z$ direction with different moments. The speed of plasma propagation at the beginning is fast. During 1.25 ns,
the front of plasma can reach 0.14 mm (without the photoionization) and 1.62 mm (considering the photoionization), respectively. Therefore, the speed of plasma propagation is $1.12 \times 10^5$ m s$^{-1}$ and $1.29 \times 10^5$ m s$^{-1}$. The speed of plasma propagation depends on the density gradient of plasma. The density gradient of plasma is large at the beginning, then gradually decreases. The speed of plasma propagation when only considering the collision ionization reduces to $0.64 \times 10^5$ m s$^{-1}$ when $t > 1.25$ ns. The photoionization can generate more electron–ion pairs to promote the discharge. Besides, the speed of photons is much larger than electrons and ions. Therefore, the speed of plasma propagation decreases slightly, which equals to $0.94 \times 10^5$ m s$^{-1}$ when $t > 1.25$ ns. The light emission observed in experiment is concentrated in a 2 mm layer above the dielectric surface within 2 ns [7]. The speed of plasma propagation in experiment is $1 \times 10^5$ m s$^{-1}$. It is equal to the average speed of plasma propagation from 0 to 3.75 ns in our model ($1.06 \times 10^5$ m s$^{-1}$).

With the development of discharge, the HPM power is absorbed and reflected by the plasma. The transmitting power efficiency $\eta$ is calculated using [23]

$$\eta = \exp(-2 \int_0^{z_0} \alpha(z) dz),$$

where $z_0$ is the height of the plasma; $\omega$ is the microwave frequency; $c$ is the speed of light in vacuum; $\nu_e$ is the collision frequency between the electrons and the neutral gas molecules; $\beta = \frac{\nu_e}{(\nu_e^2 + \omega^2)\frac{1}{2}}$ and $\omega_p$ is the plasma frequency. As shown in figure 5, $\eta$ equals to 100% when $t < 2.75$ ns. The density of plasma is small in the meantime. With the growth of density of plasma, $\eta$ quickly decreases during 1 ns. When only considering the collision ionization, $\eta$ equals to 34% at $t = 3.75$ ns. The photoionization can promote the discharge, so the transmitting power decays more quickly. When $t = 3.75$ ns, $\eta$ is only 80% of it when the photoionization is neglected, which equals to 27.3%.

It can be known from the results that the photoionization is an essential process in the microwave window breakdown to describe the image obtained from experiments. Later, we will discuss the effect of microwave window size, gas pressure, strength of microwave electric field and distribution of microwave electric field on the plasma formation and propagation in the microwave window breakdown when the photoionization is considered.

### 3.1. Size of microwave window

The density distributions of electrons and photoelectrons with different microwave window size ($0.1 \times 0.1$ cm, $0.3 \times 0.3$ cm, $1 \times 1$ cm and $3 \times 3$ cm) when $t = 3$ ns are shown in figures 6 and 7. A uniform microwave electric field of $E_{rf} = 6$ MV m$^{-1}$ are applied along the y-direction. Because the influence of photoionization near the dielectric surface is small, the density of electrons locates at the dielectric surface ($z < 0.1$ mm) keeps as a constant with different microwave window size. However, the density of electrons above the dielectric surface ($z > 0.1$ mm) mainly depends on the number of photoelectrons. With the increasing size of microwave window, the more photoelectrons are generated. At the beginning, there are a few photoelectrons above the dielectric surface ($z > 0.1$ mm). The average density of photoelectrons above the dielectric surface increases with the size of microwave window. The photoelectrons will be the seed electrons to trick the discharge above the dielectric surface. The number of total electrons exponentially increases with the development of discharge. As the size of microwave window increases, the discharge above the dielectric surface ($z > 0.1$ mm) becomes more intense. As figures 6 and 7 show, the density of electrons and photoelectrons at $z > 0.1$ mm when the size of microwave window is $3 \times 3$ cm are larger than it is when the size of microwave window is $0.1 \times 0.1$ cm. Because photons are emitted isotopically, photons produced above the dielectric surface will also propagate back to the dielectric surface. The maximum density of photoelectrons locates at the dielectric surface ($z < 0.1$ mm), it also increases with the size of microwave.
As figure 7 shows, the maximum density of photoelectrons is $5.75 \times 10^{12}$ m$^{-3}$, $1.70 \times 10^{13}$ m$^{-3}$, $5.89 \times 10^{13}$ m$^{-3}$, and $1.84 \times 10^{14}$ m$^{-3}$, respectively. Therefore, the total number of electrons is not linearly increasing with the size of microwave window.

The speed of plasma propagation also increases with the size of microwave window. When $t = 3$ ns, as figure 6 shows, the front of plasma can reach 1.66 mm, 2.64 mm, 3.1 mm and 3.84 mm, respectively. The average speed of plasma propagation can reach $1.28 \times 10^6$ m s$^{-1}$ in figure 6(d). The size of discharge area observed in experiment can reach 4 cm [7]. Therefore, the speed of the plasma propagation is quicker than it is in figure 6(d).

3.2. Gas pressure

The density distributions of electrons with different gas pressure when $t = 0.5$ ns are shown in figure 8. A uniform microwave electric field of $E_{rf} = 3$ MV m$^{-1}$ are applied along the y-direction. The size of microwave window is 3 x 3 cm. The results show that the gas pressure can strongly affect the discharge. With the decreasing of gas pressure, the free path of electrons becomes larger. Therefore, the average energy of electrons increases. Figure 9 shows the average energy of electrons with different gas pressure when $t = 0.5$ ns. The average energy of electrons is 4.6 eV when gas pressure is 100 Torr, which is the three times of it is when the gas pressure is 400 Torr. The collision ionization rate increases with the average energy of electrons when the average energy of electrons is less than 50 eV. As a result, the density of electrons exponentially decreases with the growth of gas pressure $P$. When $P = 100$ Torr, the maximum density of electrons can reach $3.46 \times 10^{17}$ m$^{-3}$. It is five orders of magnitude larger than the initial density of electrons. However, when $P = 400$ Torr, the maximum density of electrons is only $4 \times 10^{12}$ m$^{-3}$, which is smaller than the initial density of electrons. At the beginning, the effect of ionization is small. The number of electrons absorbed by the dielectric surface is larger than the number of electrons generated by the ionization. With the development of gas discharge, the number of electrons generated by the ionization increases, and the maximum density of electrons can reach $3.48 \times 10^{14}$ m$^{-3}$ when $t = 3$ ns.

With the decreasing of gas pressure, the photoionization rate increases. Therefore, the number of photoelectrons and the speed of plasma propagation both grow. As figure 8(a)
shows, the front of plasma can reach over 6 mm during 0.5 ns when \( P = 100 \) Torr. So the speed of plasma propagation can be over \( 1 \times 10^7 \) m s\(^{-1}\). When \( P = 400 \) Torr, as figure 8(d) shows, electrons almost locate at the dielectric surface, the front of plasma can reach 0.64 mm. The speed of plasma propagation is only \( 1.28 \times 10^6 \) m s\(^{-1}\).

### 3.3. Strength of microwave electric field

Compared with the microwave window breakdown under microsecond pulse, a larger microwave electric field is needed to cause the breakdown under nanosecond pulse. Figure 10 shows the density distributions of electrons with different strength of microwave electric field when \( t = 1 \) ns. The size of microwave window is 3 × 3 cm. The gas pressure is 760 Torr. With the increasing of microwave electric field, electrons obtain more energy from the electric field force. The rates of collision ionization and photoionization both increase. The maximum density of electrons in space is \( 3.64 \times 10^{16} \) m\(^{-3}\), \( 3.87 \times 10^{14} \) m\(^{-3}\), \( 1.82 \times 10^{13} \) m\(^{-3}\) and \( 3.56 \times 10^{12} \) m\(^{-3}\), respectively.

Figure 7. Density (m\(^{-3}\)) distributions of photoelectrons at the XOZ plane with different size of microwave window when \( t = 3 \) ns.

As figure 11 shows, the speed of plasma propagation is also strongly influenced by the strength of microwave electric field. When \( E_{rf} = 7 \) MV m\(^{-1}\), the front of plasma can reach 2.68 mm. When \( E_{rf} = 4 \) MV m\(^{-1}\), the furthest distance of plasma can reach is only 0.96 mm. We define the characteristic time \( t_c \) as when the front of the plasma is 1 mm away from the dielectric surface. As shown in figure 11, the \( t_c \) exponentially decreases with the growth of the microwave electric field. This is why the fast plasma propagation can only be observed in HPM systems with high-strength microwave electric fields. As mentioned above, the transmitting power efficiency reduces more severely when the photoionization is considered. As figures 10 and 11 show, the effect of photoionization on the breakdown is more obviously with the growth of microwave electric field.

### 3.4. Distribution of microwave electric field

The development of the plasma discharge depends on the distribution of the microwave electric field. In experiments, the microwave electric field is not uniformly distributed. The microwave mode is \( \text{TE}_{10} \) or \( \text{TE}_{11} \) [6, 7, 24], and the
breakdown always starts from the center of the window where the strength of the microwave electric field is maximum. Therefore, a microwave electric field in TE_{10} mode is used in this part to investigate the effect of distribution of microwave electric field on the process of microwave window breakdown at the air/dielectric interface. The size of microwave window is 3 × 3 cm. The microwave electric field is $E_{ef} = E_{\text{peak}} \cdot \sin(\omega t)\sin(\pi x/a + a/2)y$, where $a$ is the size of the microwave window along the y-direction, and $E_{\text{peak}}$ is the peak value of the microwave electric field (6 MV m⁻¹). Figure 12 shows the space distributions of the electrons, $N_2^+$, and $O_2^+$ when $t = 1$ ns and $t = 3$ ns. When $t = 1$ ns, positive ions only appear at the center of the microwave window, and electrons and positive ions are mainly distributed at the dielectric surface. Only a few particles locate far from the dielectric surface. The furthest distance that $N_2^+$ can reach from the dielectric surface is 1.5 mm. The effects of ionization allow the furthest distance that $O_2^+$ can reach from the dielectric surface to be larger than 1.9 mm. With the development of the discharge, as shown in figure 12(b), the plasma at the center of the microwave window expands quickly. However, the width of the plasma shows limited changes, which is consistent with previous experiments [7]. The space distributions for electrons and positive ions are in agreement with the space

Figure 8. Density (m⁻³) distributions of electrons at the XOZ plane with different gas pressure when $t = 0.5$ ns.

Figure 9. Average energy of electrons with different gas pressure when $t = 0.5$ ns.
distribution of the microwave electric field. When \( t = 3 \text{ ns} \), the furthest distance that electrons can reach from the dielectric surface is 3.8 mm.

Figure 13 shows the density distributions of electrons and photoelectrons when \( t = 1 \text{ ns} \) and \( t = 3 \text{ ns} \). When \( t = 1 \text{ ns} \), the density of electrons and photoelectrons are small as most electrons are distributed within 0.1 mm of the dielectric surface. Compared with electrons, photoelectrons have a smaller density but expand further away from the dielectric surface. As the discharge develops, photoelectrons collide with neutral gas molecules and collision ionization occurs. When \( t = 3 \text{ ns} \), electrons and photoelectrons are distributed nearly equally. The microwave electric field at the center of the microwave window is much higher than in any other position, where the maximum electron density can reach \( 1.55 \times 10^{19} \text{ m}^{-3} \). The number of photoelectrons depends on the number of excited nitrogen gas molecules, and the density of excited nitrogen gas molecules is proportional to the density of electrons. Therefore, the maximum density of photoelectrons is also at the center of the microwave window. However, because the motion of photons is random and quick, the area of high-density photoelectrons \( (1.74 \times 10^{14} \text{ m}^{-3}) \) is larger than that for electrons.

Figure 10. Density \( (\text{m}^{-3}) \) distributions of electrons at the XOZ plane with different strength of microwave electric field when \( t = 1 \text{ ns} \).

Figure 11. Characteristic time \( t_c \), when the front of the plasma is 1 mm away from the dielectric surface.
Figure 12. Space distributions of the electrons, N\textsubscript{2}\textsuperscript{+}, and O\textsubscript{2}\textsuperscript{+} when \( t = 1 \) ns and \( t = 3 \) ns (blue is electrons, red is N\textsubscript{2}\textsuperscript{+}, pink is O\textsubscript{2}\textsuperscript{+}).

Figure 13. Density (m\textsuperscript{−3}) distributions of electrons (left column) and photoelectrons (right column) at the XOZ plane when \( t = 1 \) ns and \( t = 3 \) ns.
4. Conclusion

In summary, the evolution of the microwave window breakdown at an air/dielectric interface is investigated through the space and density distributions of the particles. It is found that photoionization is the main reason for fast plasma formation and propagation, which agrees well with previous experiments. As a result, the transmitting power is attenuated more seriously than the case without the photoionization.

The effects of size of microwave window, gas pressure, strength of microwave electric field and distribution of electric field on the plasma formation and propagation are investigated. The results show that the total number of electrons is non-linear increasing with the size of microwave window. With the decreasing of gas pressure, the density of plasma and speed of plasma propagation both grow. The strength and distribution of microwave electric field can strongly influence the density and distribution of plasma. Besides, the speed of plasma is exponentially increasing with the microwave electric field. Therefore, the photoionization is an indispensable process in the microwave window breakdown with high-strength electric field. Our works thus provide an extended understanding to the mechanism of microwave window breakdown and a guidance to design the microwave window.

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