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# Study on the transition from filamentary discharge to diffuse discharge by using a dielectric barrier surface discharge device*

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Discharge characteristics have been investigated in different gases under different pressures using a dielectric barrier surface discharge device. Electrical measurements and optical emission spectroscopy are used to study the discharge, and the results obtained show that the discharges in atmospheric pressure helium and in low-pressure air are diffuse, while that in high-pressure air is filamentary. With decreasing pressure, the discharge in air can transit from filamentary to diffuse one. The results also indicate that corona discharge around the stripe electrode is important for the diffuse discharge. The spectral intensity of $N_2^+$ (391.4 nm) relative to $N_2$ (337.1 nm) is measured during the transition from diffuse to filamentary discharge. It is shown that relative spectral intensity increases during the discharge transition. This phenomenon implies that the averaged electron energy in diffuse discharge is higher than that in the filamentary discharge.

**Keywords:** dielectric barrier surface discharge, diffuse discharge, optical emission spectroscopy
**PACC:** 5280H, 5200, 5270K

## 1. Introduction

Gas discharge has important applications in many fields, such as the growth of thin films, modification of materials, and plasma display panels, etc.[1,2] Moreover, carbon monoxide, nitrogen oxides, and sulfur oxides, etc., released by various sources, which are the main cause of acid rain and urban smog, can be decomposed and removed finally in gas discharge. This is beneficial to the environment of ozone generation, sterilization of water, removal or degeneration of harmful gases, etc.[3]

Dielectric barrier discharge (DBD) is a kind of typical non-equilibrium gas discharge. An experimental device for DBD generally consists of two electrodes, at least one of which is covered by a thin layer of dielectric. There are two basic configurations for generating DBD: volume DBD and surface DBD. In volume DBD,[4] the discharge is executed in a gas gap between two parallel plates or concentric cylindrical electrodes covered dielectric. In surface DBD, the discharge is along the dielectric surface, and the electrodes can be arranged at two sides of the dielectric layer or on the same side. Compared with the volume discharge, the surface discharge is more desirable in applications, such as plasma display panels, backlight sources for liquid crystal displays, surface treatment, aerodynamics, and plasma clocking for aircraft, etc.[5,6]

DBD often operates in filamentary mode and discrete micro-discharge filaments can be observed.[7] Filamentary DBD is less used in material processing because disposal of materials will be nonuniform. Obviously, uniform glow discharge of DBD (also referred to as diffuse DBD) is more desirable. Diffuse DBD under atmospheric pressure was first reported by Kanazawa *et al* in 1988.[8] Kanazawa *et al* found that the discharge current waveform of diffuse DBD is one discharge pulse (about 1 $\mu$s) per half-cycle of the applied voltage, while that of filamentary DBD consists of many short-lived pulses (about 10 ns) per half-cycle.[9,10]

So far, diffuse discharge in the volume discharge configuration has been studied with many gases such as helium, neon, nitrogen, argon, etc,[11−14] and the

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results show that the efficiency of producing free radicals in diffuse discharge is much higher than that in filamentary discharge.[15] As stated in Ref.[4], volume DBD has been investigated intensively, while investigations of surface discharge are rare. Although a macroscopically uniform plasma generated in a surface DBD has ever been reported in Ref.[6], however, the discharge is still in filamentary mode, judged from the discharge current waveform. So far, little reference papers can be found of diffuse discharge in surface discharge device.

This paper aims at realizing diffuse discharges in helium at atmospheric pressure and in air at low pressures with a surface discharge device. The different characteristics of filamentary mode and diffuse discharge under different pressures are investigated. Waveforms of discharge current and applied voltage are recorded during the transition from filamentary to diffuse discharge. Spectral characterization is presented also.

## 2. Experimental setup

The experimental setup is shown in Fig.1, and the surface discharge device used in our experiment consists of one tungsten stripe electrode and one rectangular metallic electrode, as shown in Fig.1(b). Tungsten stripe with a width of 1 mm and length of 30 mm is situated on a layer of rectangular ceramic dielectric (36 mm × 16 mm) with a thickness of 1 mm. The rectangular metallic layer (25 mm × 9 mm) is attached to the other side of the ceramic layer. The stripe electrode is covered with a protective ceramic dielectric layer (its thickness is about 0.1 mm) and connected to high voltage output, and the other electrode is grounded through a small resistor. A sinusoidal ac power supply having a maximum peak voltage of 10 kV with a frequency of 80–100 kHz is used. The applied voltage can be measured by a high voltage probe (Tektronix P6015A, 1000X) and recorded with an oscilloscope (Tektronix TDS3054B, 500 MHz). The discharge current is measured with the small resister ($R = 50\,\Omega$) in series with the grounded electrode. Helium (99.9%) and air are used as working gases. A digital camera (Canon Powershot G1: 3.24 mega pixels) is used to record the images of the discharge, and the exposure time is 8ms in our experiments. Optical emission spectroscopy is used to measure the emission spectra from the discharge. Emission of the discharge is focused on one end of an optical fibre, the other end of which is connected to the entrance slit of a spectrometer equipped with a CCD detector (ACTON research Spectropro2785, 1340 × 400 pixels) with a grating of 2400 grooves $mm^{-1}$. The entrance slit opening and the integration time of the CCD detector are maintained at 0.5 mm and 3 s, respectively.

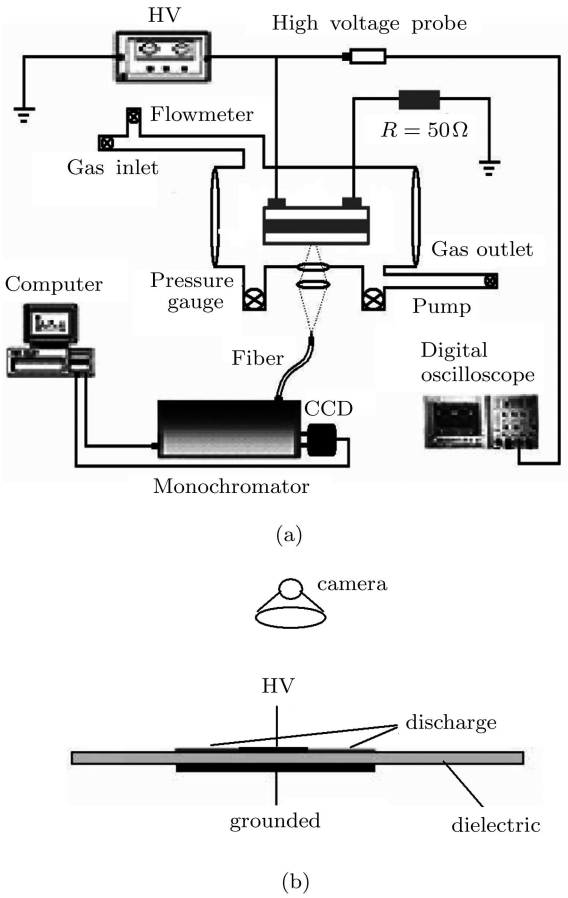



**Fig.1.** (a) The schematic diagram of the experimental setup, and (b) configurations of the surface discharge device.

## 3. Results and discussions

### 3.1. Diffuse discharge in helium at atmospheric pressure

Raising the voltage of power supply to higher than 600 V, uniform diffuse discharge can be ignited in atmospheric pressure helium, as shown in Fig.2(a). From Fig.2(a), it is obvious that gas breakdown takes place on the stripe electrode in spite of the discharges on its both sides. The gas ignition on the stripe electrode may be related to a low breakdown voltage of helium, and ultraviolet radiation or electrons provided

by the discharges in other regions. No discharge filaments can be seen in Fig.2(a), although there are non-uniformity. The non-uniformity near the stripe electrode may result from cathode sputtering, and the non-uniformity far away from the stripe electrode may be related to the edge effect of the grounded electrode. Typical waveforms of the applied voltage and discharge current in the diffuse discharge in atmospheric pressure helium are shown in Fig.3. The discharge current is characterized by only one discharge pulse per half cycle and the width of each pulse is larger than 1 $\mu$s, which is similar to that of uniform diffuse discharge in volume discharge configurations. If the applied voltage is increased further, it is also found that two or more discharge pulses per half cycle appear in the discharge current waveforms.

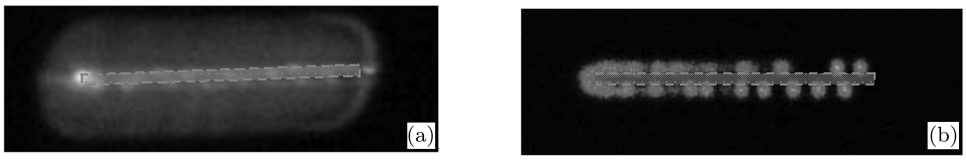



**Fig.2.** Images of uniform glow discharge (a) and filamentary discharge (b).

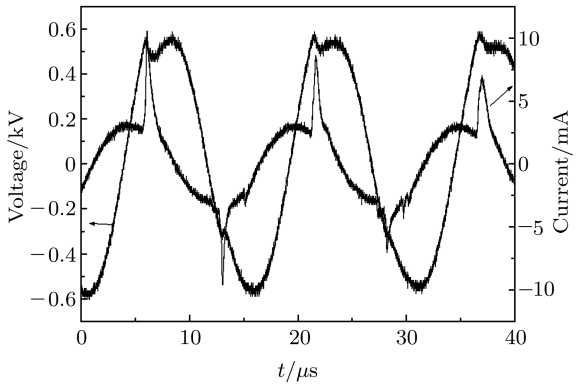



**Fig.3.** Typical oscillogram of the voltage and discharge current in the glow discharge in helium at atmospheric pressure.

The diffuse discharge in helium at atmospheric pressure can be realized at a flow rate more than 3$l$/min. At a lower flow rate, the discharge is nonuniform. A similar phenomenon was found in Ref.[14] and was attributed to the restraining heat instability through the flow of the gas.

It is commonly believed that Penning ionization between metastable helium molecules and nitrogen molecules is important for the realization of the uniform diffuse discharge in atmospheric pressure helium. The other factor resulting in uniform diffuse discharge may be the electrodes configurations. The electrodes are asymmetric in our experiments, and the electric field near the stripe electrode is higher than elsewhere. Corona discharge near the stripe electrode can provide electrons for the breakdown of the whole gas gap, therefore, the discharge of the gap can be ignited at a lower voltage. A little of heat given out by the discharge can prevent the discharge from transit to arc. Consequently, low breakdown voltage helps the realization of uniform diffuse discharge.

## 3.2. Discharge transition from filamentary mode to diffuse mode in air at different pressures

When the applied voltage is slightly above the critical value for breakdown, discharge filaments can be observed in atmospheric pressure air, as shown in Fig.2(b). Discharge filaments are restricted in a narrow region near the stripe electrode. Typical waveforms of the applied voltage and discharge current in the filamentary discharge in atmospheric pressure air are shown in Fig.4(a). The discharge current waveform consists of many discharge pulses with a width of about 10 ns, which are distributed randomly. At a higher voltage, the whole area is filled by discharges. Although the discharges are also uniform in this circumstance, judged by naked eye, the waveforms of the voltage and discharge current are similar to those shown in Fig.4(a). Therefore, the discharge in atmospheric pressure air at a higher voltage applied is still filamentary. The number density of filaments, however, is so high that the filaments cannot be seen any more because the number of filaments increases with applied voltage.

Diffuse discharge can be ignited in air when the pressure is very low (less than 2000 Pa). The image of uniform diffuse discharges in low-pressure air is similar with that shown in Fig.2(a). Figure 4(b) shows the

waveforms of voltage and discharge current for uniform diffuse discharges in low-pressure air. By comparing Fig.3 with Fig.4(b), it is obvious that the diffuse discharge in low-pressure air is ignited at a lower voltage and the discharge current pulse is smaller than that in atmospheric pressure helium.

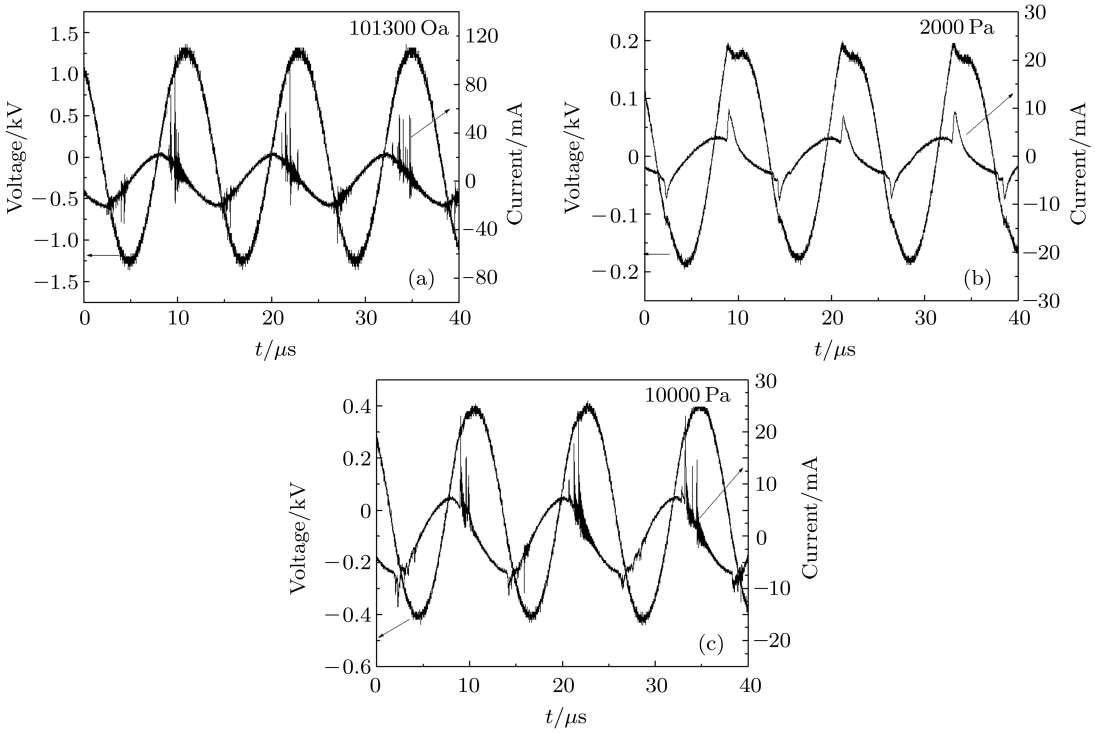



**Fig.4.** Different oscillograms of the voltage and discharge current in air: filamentary (a), glow discharge (b) and transition from filamentary to glow discharge (c).

As mentioned above, the discharge in air is filamentary at high pressures and uniform at very low pressure, that is to say, with decreasing air pressure, the discharge can transit from filamentary to diffuse mode. Figure 4(c) shows the typical waveforms of the voltage and discharge current during the transition. From Fig.4(c), it can be found that there is almost only one discharge pulse with a width of about 1 $\mu$s during the negative half cycle and there are many pulses with a width of about 10 ns during the positive half cycle. This phenomenon implies that the discharge is filamentary in positive half cycle and diffuse in negative half cycle. This result may also come from the asymmetric configurations of the electrodes. When the stripe electrode is an instantaneous cathode, corona discharge around the stripe electrode can provide electrons to lower the breakdown voltage for the whole gas gap, as mentioned before; consequently, uniform diffuse discharge is easier to realize. However, electrons will disappear on the stripe electrode when it is the instantaneous anode, and the corona discharge cannot provide electrons for the whole gas gap, accordingly, the breakdown voltage will be high and uniform diffuse discharge is hard to realize.

## 3.3. Characterization of relative spectral intensity in different discharge modes

In order to compare the characteristics of different discharge modes, optical emission spectra of discharges at different air pressures are recorded in the range of 300–800 nm. The emission spectral lines have been normalized at 337.1 nm (the second positive system of nitrogen molecules: $(C^3\Pi_u)_{\nu'=0} \rightarrow (B^3\Pi_g)_{\nu''=0}$) and the emission spectra of the first negative system of $N_2^+((B^2\Sigma_u^+) \rightarrow (X^2\Sigma_g^+))$ in the wavelength range of 387–392 nm at different pressures are shown in Fig.5(a). Figure 5(b) shows the relation between relative intensity of $N_2^+$ 391.4 nm spectral line $((B^2\Sigma_u^+)_{\nu'=0} \rightarrow (X^2\Sigma_g^+)_{\nu''=0})$ and the discharge pressure, from which it can be concluded that the relative spectral intensity ratio of $N_2^+$ to $N_2$ increases with decreasing pressure.

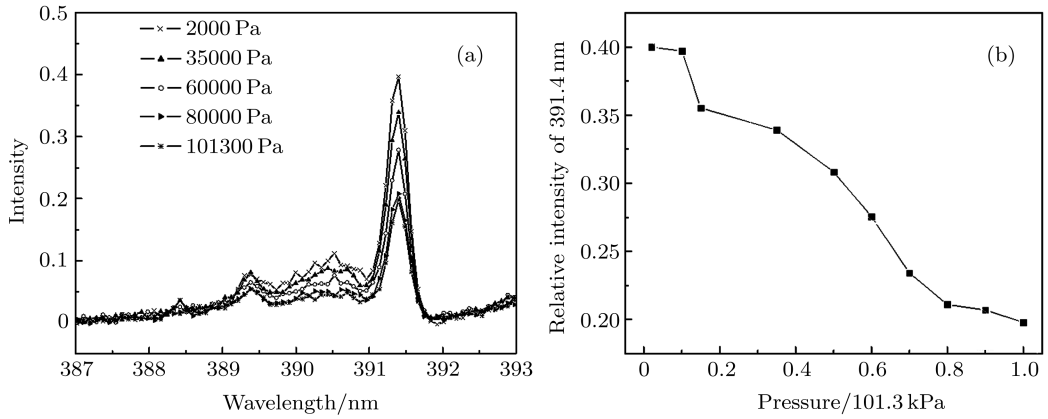



**Fig.5.** (a) Emission spectra of the first negative systems of $N_2^+$ at different pressures, (b) the relative intensity of 391.4nm spectral line as a function of pressure.

During the discharge, electrons collide with other particles such as molecules and ions, and these collisions result in excitations. These excited particles emit radiations during transition to the ground state. Therefore, radiation can reflect the numbers of different excited particles. For the discharge in gases including nitrogen, nitrogen molecules in the ground state are mainly excited to the second positive system of $N_2$ by direct impact with electrons of energy higher than 11 eV. And the excited state of the first negative system of $N_2^+$ is mainly populated by direct impact ionization with high energy electrons (higher than 18.7 eV). Therefore, the radiation can reflect the averaged energy of electrons. If the relative intensity ratio of 391.4 nm ($N_2^+$) to 337.1 nm ($N_2$) is changed, it means a change in averaged electron energy. From the above analysis, it can be concluded that the averaged electron energy is higher when the relative intensity of 391.4 nm spectral line is stronger. Consequently, the lower the pressure is, the higher the averaged electron energy is. Because diffuse discharge and filamentary discharge are generated at low pressure and high pressure respectively, Figure 5 also indicates that the averaged electron energy is higher in diffuse discharge than that in filamentary discharge. This may be the reason why the reaction efficiency in glow discharge is higher than that in filamentary discharge, as proposed in Ref.[15].

Figure 6 shows the emission spectra of the first negative system of $N_2^+$ in the wavelength range of 387–392 nm in uniform diffuse discharges in helium at atmospheric pressure and in air at low pressure respectively. From Fig.6, it can be found that the relative spectral intensity of $N_2^+$ in helium discharge is higher than that in air discharge at low pressures. The higher relative intensity in diffuse discharge in helium may be the results of Penning ionization.

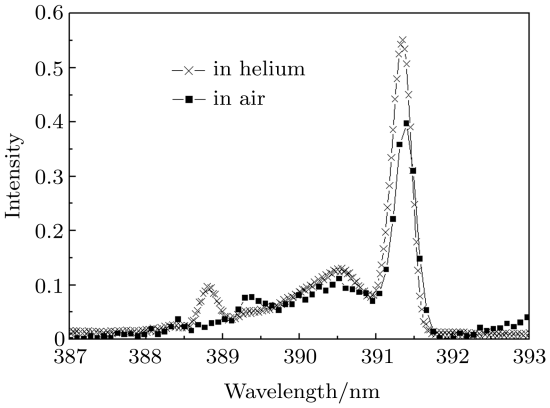



**Fig.6.** Emission spectra of the first negative systems of $N_2^+$ of the discharges in atmospheric pressure helium and low pressure air (2000 Pa).

# 4. Conclusion

Uniform diffuse discharge in helium at atmospheric pressure has been achieved with a dielectric barrier surface discharge device. In order to clarify the physical mechanism of diffuse discharge, the transition process from filamentary discharge to uniform diffuse discharge in air at different pressures has been investigated. The results show that filamentary discharge occurs at high pressures and uniform diffuse discharge at low pressures. Through analysis, it is believed that corona discharge around the stripe electrode is important for the diffuse discharge. Optical

emission spectroscopy is used to study the characteristics of discharges during the transition. It has been found that the relative spectral intensity of $N_2^+$ to $N_2$ increases with decreasing pressure. This experimental phenomenon indicates that the averaged electron energy is higher in diffuse discharge than in filamentary discharge.

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