Characteristics of a large gap uniform discharge excited by DC voltage at atmospheric pressure*

Li Xue-Chen(李雪辰)[a)b)†], Bao Wen-Ting(鲍文婷)[a)], Jia Peng-Ying(贾鹏英)[b)], Zhao Huan-Huan(赵欢欢)[a)], Di Cong(狄 聪)[a)], and Chen Jun-Ying(陈俊英)[b)]

[a)] *College of Physics Science & Technology, Hebei University, Baoding* 071002, *China*
[b)] *Key Laboratory of Photo-Electronics Information Materials of Hebei Province, Baoding* 071002, *China*

(Received 16 January 2014; revised manuscript received 10 March 2014; published online 16 July 2014)

A large-gap uniform discharge is ignited by a coaxial dielectric barrier discharge and burns between a needle anode and a plate cathode under a low sustaining voltage by feeding with flowing argon. The basic aspects of the large-gap uniform discharge are investigated by optical and spectroscopic methods. From the discharge images, it can be found that this discharge has similar regions with glow discharge at low pressure except a plasma plume region. Light emission signals from the discharge indicate that the plasma column is invariant with time, while there are some stochastic pulses in the plasma plume region. The optical emission spectra scanning from 300 nm to 800 nm are used to calculate the excited electron temperature and vibrational temperature of the large-gap uniform discharge. It has been found that the excited electron temperature almost keeps constant and the vibrational temperature increases with increasing discharge current. Both of them decreases with increasing gas flow rate.

Keywords: large-gap uniform discharge, plasma plume, plasma column, optical emission spectrum

PACS: 52.70.Kz, 52.80.Hc **DOI:** 10.1088/1674-1056/23/9/095202

1. Introduction

In recent years, considerable attention has been paid to atmospheric pressure uniform discharge (APUD) because it does not require a costly vacuum system,[1–4] which makes it possible to be used in the assembly line. The APUD has application prospects in a rich variety of fields, such as materials processing,[5] polymer deposition,[6] biological sterilization,[7] aircraft cloacking,[8] and so on.

So far, several methods were developed to generate APUD. Dielectric barrier discharge (DBD) was a traditional way to initiate APUD.[9,10] The APUD in parallel plate DBD configurations were extensively investigated. Massines *et al.* pointed out that the electrons and metastable density before the discharge were very important for the APUD in inert gases.[11] Rahel *et al.* investigated the APUD in atmospheric pressure air and found that the macroscopically uniform discharge was obtained by numerous radially expanding streamers that were temporally overlapping.[12] The APUD in flow argon was investigated in coaxial DBD configurations and the corona discharge around the inner electrode was important for the APUD.[13] Usually, the APUDs in DBD configurations were excited by power sources with several tens Herz. Shi investigated the radio-frequency DBD in atmospheric argon, and demonstrated that a stable glow discharge was obtained.[14]

The gas gap in DBD-based APUD mentioned above was not large enough. It is typically several millimeters, which was too small to be used in plasma processing for materials with large scale. Compared with the DBD, plasma jet could generate a uniform plasma plume with a relatively large length.[15–17] Algwari *et al.* investigated a DBD jet operated in helium and showed that the discharge was streamer.[18] Liu *et al.* found the electrical characteristics of a monofilament in DBD jet at atmospheric pressure.[19] Forster investigated an atmospheric pressure plasma jet by optical emission spectroscopy.[20] Kong *et al.* pointed out that the linear-field jet had higher chemical efficiency compared with the cross-field jet.[21] Plasma bullets with a very high velocity were often observed in the plasma jets operated in inert gases.[22,23] The fast moving bullets showed that a streamer discharge mechanism was usually involved in the uniform plume formation. The plasma bullets may damage the vulnerable materials, APUD in glow mode is more desirable.

In order to eliminate the onset of a steamer, the breakdown voltage needs to be lowered. Watanabe *et al.* used DBD as a pre-ionizer for the multi-hole micro-hollow cathode discharge, and found that the pre-ionization significantly reduced the sparking voltage and improved the spatial uniformity of the discharge.[24] Tang *et al.* developed a DBD enhanced plasma jet,[25] they found that the plasma generation was more effi-

*Project supported by the National Natural Science Foundation of China (Grant Nos. 10805013 and 51077035), the Funds for Distinguished Young Scientists of Hebei Province of China (Grant No. A2012201045), the Natural Science Foundation of Hebei Province of China (Grant No. A2011201132), the Department of Education for Outstanding Youth Project of China (Grant No. Y2011120), the Funds for Distinguished Young Scientists of Hebei University of China (Grant No. 2010J02), the Doctor Program of Hebei University of China (Grant No. 2012-241), and the Youth Project of Hebei University of China (Grant No. 2011Q14).

†Corresponding author. E-mail: wangny@bnu.edu.cn

© 2014 Chinese Physical Society and IOP Publishing Ltd

cient. The gap width is not large enough, with a maximum width of 1.5 cm. A kilohertz excited plasma jet was used as a pre-ionizer to generate a atmospheric-pressure microwave argon plasma discharge.[26] Although the plume length is several tens centimeters long, it can only be operated in a closed argon environment.

In this paper, a large-gap APUD was excited by a DC source in ambient air with atmospheric pressure argon used as working gas. The basic aspects of the large-gap discharge at atmospheric pressure are investigated by optical emission spectroscopy.

2. Experimental setup

A schematic diagram of the experimental setup is presented in Fig. 1. The discharge device is composed of two main parts. (i) a DBD-generating part to ignite the DC discharge. A tungsten electrode (12 cm in length and 1.5 mm in diameter) with a sharp end (about 200 μm in radius) is grounded, which is separated with a coaxially-placed water electrode by a glass tube with thickness of 1 mm. Argon (99.99%) flows along the gap between the tungsten electrode and the glass tube, and the gap width is about 3 mm. An alternating current (AC) power supply with a frequency of 40 kHz is used to excite the coaxial DBD. (ii) A large gap APUD-generating part is composed of the grounded tungsten needle and a plate copper electrode placed 5 cm away from the needle tip in the downstream region of the argon flow. The plate electrode is connected to the negative polarity output of a home-made DC power supply (maximal voltage is 15 kV) through a shunt resistor ($R = 500$ kΩ). The voltage across the plate cathode and the needle anode is measured by a high voltage probe (Tektronix P6015A). Light emission from the discharge is detected by photomultiplier tube (PMT) (ET 9085SB). The discharge current is obtained by the voltage on a small resistor

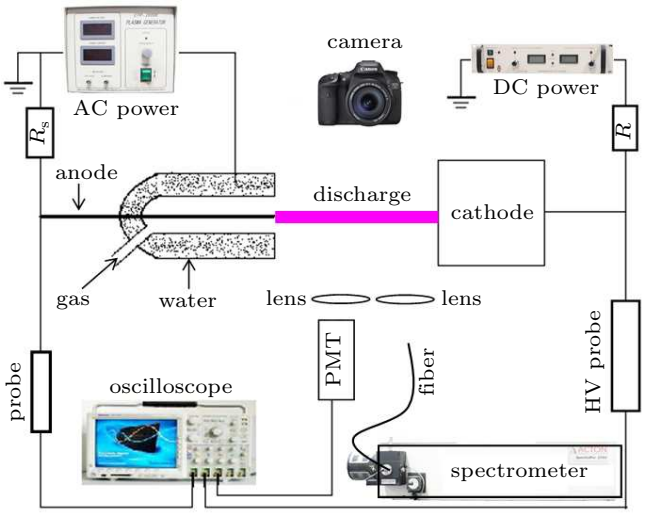


Fig. 1. (color online) Schematic diagram of the experimental setup.

(50 Ω) in series with the discharge device. The waveforms of the sustaining voltage, the light emission signal and discharge current are recorded simultaneously with an oscilloscope (Tektronix DPO4104). A digital camera (Canon EOS 7D) is used to record the discharge images. Emission of the discharge is transmitted into a spectrometer (ACTON SP2758, 1340×400 pixels) through an optical fiber.

3. Results and discussion

Two methods can be used to ignite the DC large-gap uniform discharge by the coaxial DBD. One is to increase the DC voltage to its maximal value, the DC discharge cannot initiate because of the DC voltage is not high enough. Then, increase the AC voltage to excite the coaxial DBD. At the same time, with the burning of the DBD, a large-gap uniform discharge is ignited between the needle anode and the plate cathode. The other is to excite the coaxial DBD first by increasing the AC voltage to its breakdown value, then, increase the DC voltage slowly. The large-gap uniform discharge can also be ignited between the needle anode and the plate cathode with increasing the DC voltage to a certain value (about 6 kV). After the burning of the DC uniform discharge, the coaxial DBD can be turned off and the large-gap discharge can operate stably. Active particles generated in the coaxial DBD, such as meta-stable molecules and radicals, can move along with the flowing argon to the downstream region. Furthermore, seed electrons can be generated in the downstream region through photo-ionization of ultraviolet (UV) and vacuum ultraviolet (VUV) that are emitted from the coaxial DBD. All the two factors contribute to lower the breakdown voltage in the downstream region. Consequently, a fairly-large-gap discharge initiates under a low DC voltage. Figure 2 presents some images of the large-gap discharge excited by DC voltage. It can be found that the large gap APUD consists of some characteristic regions. From the needle anode to the plate cathode, there are a plasma column, a plasma plume and a bright cathode spot (negative glow) at the vicinity of the plate electrode. A dark space is also evident between the negative glow and the plasma plume. The plasma column is bright, and the diameter of it is small. The plasma plume is diffusive and dim. Except the plasma plume, these characteristic regions are similar with those found in glow discharges at low pressure, and those in APUD excited by sinusoidal voltage[27] or saw-tooth voltage.[28] Furthermore, the voltage–current characteristic is also similar with that of the glow discharge at low pressure, as shown in Fig. 3. It can be found from Fig. 3 that the sustaining voltage decreases with increasing discharge current. From the discharge images, it can also be found that the length of plasma column increases with increasing current.

Figure 4 indicates the waveforms of the sustaining voltage across the needle anode and the plate cathode, the light emission signal from the plasma column and that from the plasma plume. The light emission signal in Fig. 4 is in arbitrary unit (a. u.). It is evident that the sustaining voltage and the discharge of the plasma column almost keep invariant with time, while there are some stochastic pulses for the plasma plume discharge.

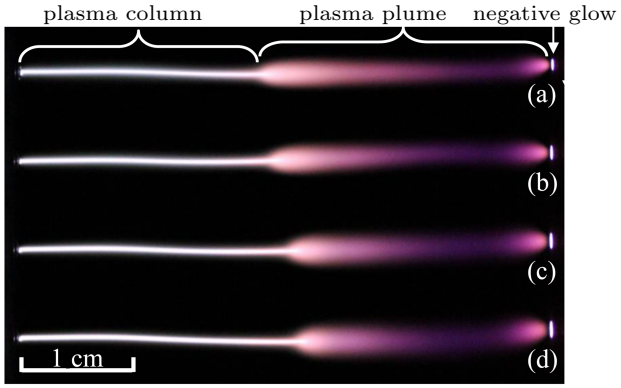


Fig. 2. (color online) Discharge images under different currents with exposure time of 4 ms. (a) 6 mA and 1.85 kV, (b) 9 mA and 1.70 kV, (c) 12 mA and 1.60 kV, (d) 15 mA and 1.50 kV. The distance from the pin anode to the plate cathode is 5 cm and the gas flow rate is 1 L/min.

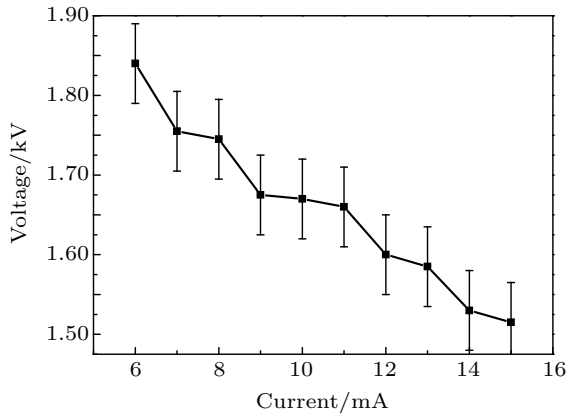


Fig. 3. Voltage–current characteristics of the APUD in a 5-cm gap with a gas flow rate of 1 L/min.

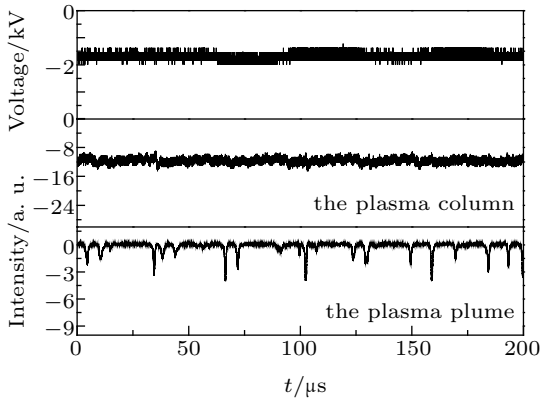


Fig. 4. Waveforms of the applied voltage (top), the total light emission signal from the plasma column (middle) and that from the plasma plume (bottom). The discharge current is 9 mA, voltage is 1.70 kV, and the gas flow rate is 1 L/min.

Optical collimators are used to collect the light emission signals at different positions with a detecting diameter of about 0.5 mm. PMTs behind the collimators are used to detect the light signals emitted from the discharge. The optical method used here is similar with that used in Refs. [29] and [30]. A coordinate system is established along the gas flow field and the needle tip of the anode is chosen as the x axis zero. From Fig. 5(a), it can be found that the light emission signals from the plasma plume (x value from 26 to 44) are intermittent. Obviously, there will be a pulse if the discharge passes the position. Therefore, the time lag of the signals at different positions in Fig. 5(a) indicates that a layer of light emission (plasma bullet) propagates from the plate cathode to the plasma column. The light emission from the plasma plume in Fig. 4 is stochastically intermittent, which means that the plasma bullets appear in time stochastically. Figure 5(b) indicates that the light emission signals at different positions of the plasma column are invariant with time. Consequently, the invariant plasma column implies that the plasma column is a continuous discharge, which means that the plasma column behaves like the positive column in low-pressure glow discharge.

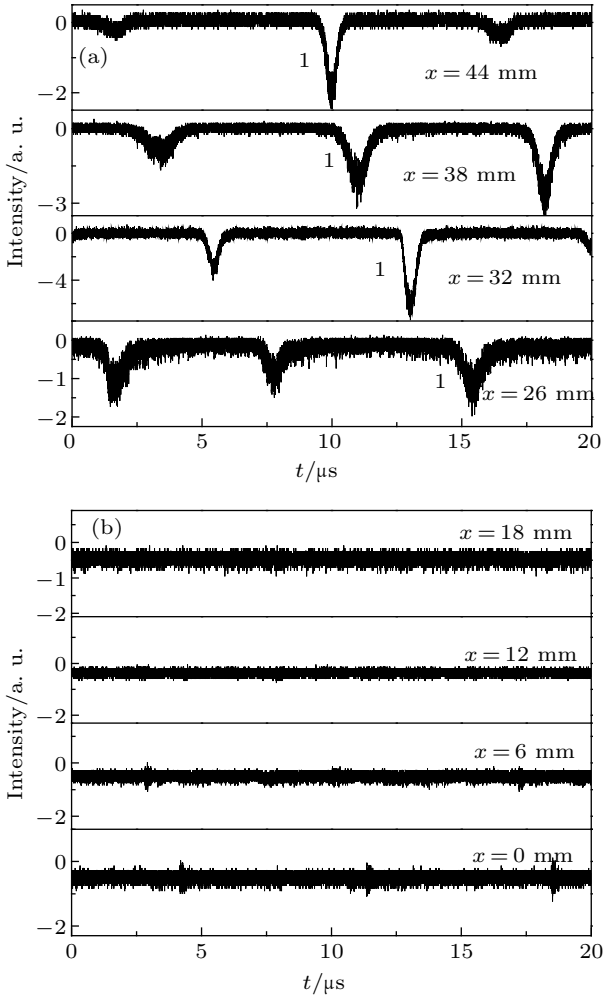


Fig. 5. The spatial resolved measurement of the light emission signals for the plasma plume (a) and the plasma column (b).

Figure 6 presents the optical emission spectra from the whole discharge. The spectra include the second positive system of nitrogen molecules and the emission lines from argon atoms and argon ions. For low-temperature plasma generated in gas discharge, local thermal equilibrium (LTE) is often supposed to hold. Under the supposition of LTE, Boltzmann plot method is used for determining the electron temperature from lines of the same element.[20] A plot of $\ln(I_{kl}\lambda_{kl}/(g_kA_{kl}))$ versus E_k should give a straight line with a slope of $-1/T_e$, where I_{kl} is the intensity of the emitting light, λ_{kl} is the wavelength, g_k is the statistical weight of the upper level, A_{kl} is the transition probability from level k to level l, E_k is the energy of the upper level, and T_e is the excited electron temperature. Figure 7 indicates a Boltzmann plot to estimate the excited electron temperature. Spectral parameters of Argon used in Fig. 7 to estimate the electron temperature are also shown in Table 1. Figure 8 shows T_e as a function of the current and the gas flow rate. It can be found that T_e almost keeps constant with increasing discharge current and it decreases with increasing gas flow rate.

Table 1. Spectral parameters of Argon used in Boltzmann plots to estimate the electron temperature.

Species	Wavelength/nm	A_{ki}/s^{-1}	E_k/eV	g_k
Ar I	706.7218	3.80×10^6	13.30222666	5
Ar I	727.2936	1.83×10^6	13.32785623	3
Ar I	763.5106	2.45×10^7	13.17177690	5
Ar I	772.4207	1.17×10^7	13.32785623	3
Ar I	419.8317	2.57×10^6	14.57594789	1

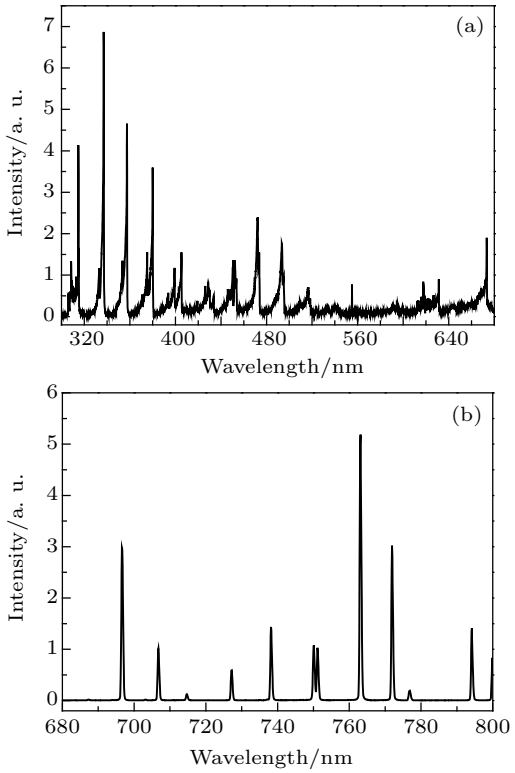


Fig. 6. Optical emission spectra of the APUD in the wavelength from 300 to 680 nm with an exposure time of 30 s (a) and that from 680 to 800 nm with an exposure time of 0.5 s (b). The discharge current is 10 mA, voltage is 1.65 kV, and the gas flow rate is 1 L/min.

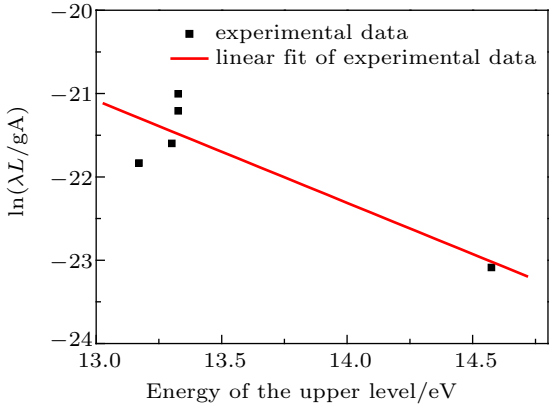


Fig. 7. (color online) Boltzmann plot to estimate the excited electron temperature. The experimental condition is the same as that in Fig. 6.

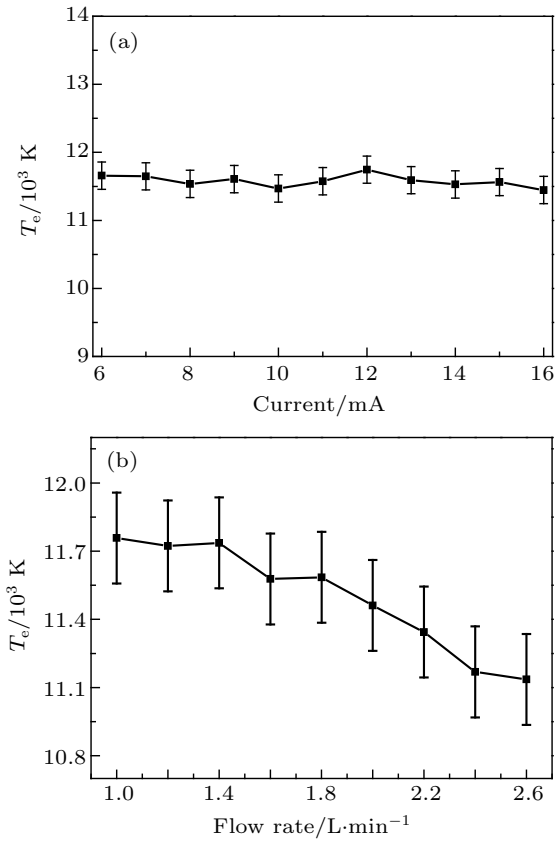


Fig. 8. Excited electron temperature as a function of the current (a) and that as a function of the gas flow rate (b). The gas flow rate in panel (a) is 1 L/min and the discharge current in panel (b) is 6 mA (voltage is 1.85 kV).

The plasma column is similar to the positive column in low-pressure glow discharge, which means that the electric field in the plasma column is low enough because the positive column is almost electro-neutral. Compared with the plasma column, the plasma plume has a much higher electric field because the discharge mechanism is a streamer. Therefore, the sustaining voltage across the needle anode and the plate cathode will decrease with increasing of the plasma column length. The length of the plasma column increases with increasing of the discharge current, as mentioned in Fig. 2. Therefore, the sustaining voltage decreases with increasing discharge current,

as shown in Fig. 3. The excited electron temperature of the whole discharge should be mainly determined by the electron energy in the plasma plume region because it is much higher in the plasma plume than in the plasma column. The net electric field in steamer discharge is the sum of the space charge (E') and applied electric field (E_0). According to Meek criterion, streamer mechanism is involved in when E' is comparable to E_0. That is to say, when the net electric field reaches its critical value, the streamer discharge begins to develop from the cathode to the anode. The critical value of electric field for the streamer discharge almost keeps constant with increasing discharge current. The electron temperature is determined by the net electric field for gas breakdown. Therefore, the excited electron almost keeps constant with increasing discharge current. The breakdown field of argon is lower than that of air because oxygen is electronegative. The content of air decreases in the working gas in the plasma plume region with increasing gas flow rate. Consequently, the critical value of electric field for gas breakdown decreases with increasing gas flow rate. As a result, the excited electron temperature decreases with increasing gas flow rate, as shown in Fig. 8(b).

The vibrational temperature (T_V) can also be calculated by fitting the second positive system of nitrogen molecules. Figure 9 presents T_V as a function of the discharge current and the gas flow rate. It can be found that T_V increases with increasing current under constant gas flow rate and it decreases with increasing gas flow rate under constant discharge current. This phenomenon can be explained as follows. During the discharge process, electrons collide with nitrogen molecules, which results in energy translation from electron to nitrogen molecules. With increasing discharge current, more electrons drift per unit of time from the cathode to the anode. The electron energy keeps invariant with time, however, the collision frequency increases with increasing discharge current. Therefore, more energy is transferred per unit of time to nitrogen molecules. Consequently, the vibrational temperature increases with increasing discharge current. Under constant discharge current, the electron temperature decreases with increasing gas flow rate. Hence, the energy transferred in every collision with electron decreases with increasing gas flow rate. Consequently, the vibrational temperature decreases with increasing gas flow rate.

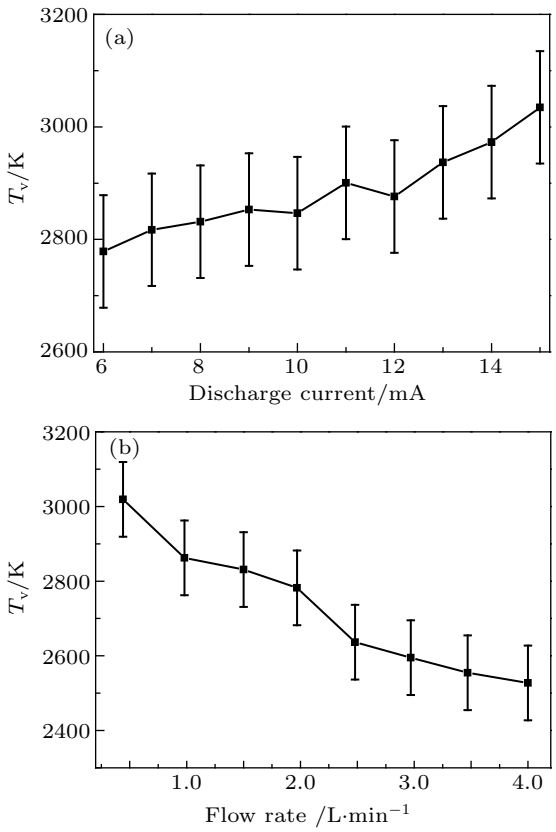


Fig. 9. Vibrational temperature as a function of current (a) and the gas flow rate (b). The gas flow rate in Fig. 9(a) is 1 L/min and the discharge current in Fig. 9(b) is 10 mA (voltage is 1.65 kV).

4. Conclusion

The characteristic of a large-gap uniform discharge between a needle anode and a plate cathode was ignited under a low sustaining DC voltage by a coaxial DBD in flowing argon. From the discharge images, a plasma column, a plasma plume and negative glow can be discerned in the discharge region. The large-gap APUD has the same characteristic regions with glow discharge at low pressure except the plasma plume. Sustaining voltage across the needle anode and the plate cathode as well as the light emission from the plasma column region almost keep invariant with time, while there are some stochastic pulses for the plasma plume discharge. The optical spectra scanning from 300 nm to 800 nm emitted from the uniform discharge include system of nitrogen molecular and the emission lines from argon atoms and ions. The excited electron temperature and the vibrational temperature are calculated based on the optical emission spectra. Results show that the excited electron temperature is almost constant and the vibrational temperature increases with increasing current. Both of the excited temperature and the vibrational temperature decrease with increasing gas flow rate.

References

[1] Li X, Di C, Jia P and Bao W 2013 *Plasma Sources Sci. Technol.* **22** 045007
[2] Okazaki S, Kogoma M, Uehara M and Kimura Y 1993 *J. Phys. D* **26** 889
[3] Tang J, Jiang W, Zhao W and Wang Y 2013 *Appl. Phys. Lett.* **102** 033503
[4] Eliasson and Kogelschatz U 1988 *Appl. Phys. B* **46** 299
[5] Benedikt J, Focke K, Yanguas-Gil A and von Keudell A 2006 *Appl. Phys. Lett.* **89** 251504
[6] Prat R, Koh Y J, Babukutty Y, Kogoma M, Okazaki S and Kodama M 2000 *Polymer* **41** 7355
[7] Lu X, Jiang Z, Xiong Q, Tang Z and Pan Y 2008 *Appl. Phys. Lett.* **92** 151504
[8] Vidmar R J 1990 *IEEE Trans. Plasma Sci.* **19** 733
[9] Fang Z, Qiu Y, Zhang C and Kuffel E 2007 *Plasma Sources Sci. Technol.* **40** 1401

[10] Yang D, Yang Y, Li S, Nie D, Zhang S and Wang W 2012 *Plasma Sources Sci. Technol.* **21** 035004
[11] Massines F, Rabehi A, Decomps P, Gadri R B, Segur P and Mayoux C 1998 *J. Appl. Phys.* **83** 2950
[12] Rahel J and Sherman D M 2005 *J. Phys. D* **38** 547
[13] Li X, Zhao N, Fang T, Liu Z, Li L and Dong L 2008 *Plasma Sources Sci. Technol.* **17** 015017
[14] Shi J and Kong M 2007 *Appl. Phys. Lett.* **90** 111502
[15] Lu X, Laroussi M and Puech V 2012 *Plasma Sources Sci. Technol.* **21** 034005
[16] Lu X, Jiang Z, Xiong Q, Tang Z, Hu X and Pan Y 2008 *Appl. Phys. Lett.* **92** 081502
[17] Cao Z, Nie Q, Bayliss D L, Walsh J L, Ren C S, Wang D Z and Kong M G 2010 *Plasma Sources Sci. Technol.* **19** 025003
[18] Algwari Q Th and O'Connell D 2011 *Appl. Phys. Lett.* **99** 121501
[19] Liu F, Wang W, Chang X, Wu Z, He L, Li Z, He Z and Liang R 2012 *EPL* **97** 65001
[20] Forster S, Mohr C and Viol W 2005 *Surf. Coat. Technol.* **200** 827
[21] Walsh J L and Kong M G 2008 *Appl. Phys. Lett.* **93** 111501
[22] Lu X and Laroussi M 2006 *Appl. Phys. Lett.* **100** 063302
[23] Walsh J L, Iza F, Janson N B, Law V J and Kong M G 2010 *J. Phys. D* **43** 075201
[24] Watanabe J, Ogino A and Nagatsu M 2007 *Appl. Phys. Lett.* **91** 221507
[25] Tang J, Li S, Zhao W, Wang Y and Duan Y 2012 *Appl. Phys. Lett.* **100** 253505
[26] Li S, Xu M, Zhang X and Zhang J 2012 *Appl. Phys. Lett.* **100** 174101
[27] Luo H, Liang Z, Lv B, Wang X, Guan Z and Wang L 2007 *Appl. Phys. Lett.* **91** 231504
[28] Li X, Niu D, Yin Z, Fang T and Wang L 2012 *Phys. Plasmas* **19** 083505
[29] Li X, Chang Y, Jia P, Xu L, Fang T and Wang L 2012 *Phys. Plasmas* **19** 093504
[30] Li X, Jia P, Yuan N and Chang Y 2012 *Chin. Phys. B* **21** 045204