The role of vibrational temperature variations in a pulsed dielectric barrier discharge plasma device

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Abstract
The use of dielectric barrier discharge (DBD) plasmas has become a practical way to carry out surface treatment where precise control of the plasma parameters, such as rotational and vibrational temperatures ($T_{\text{rot}}$ and $T_{\text{vib}}$), is required. As the $T_{\text{vib}}$ of an atmospheric pressure plasma jet appears to be the most important parameter related to the improvement of surface treatments, in this work, we analysed two methods to increase the values of $T_{\text{vib}}$ in a DBD plasma jet device. One of the methods is to reduce the exit size ($\phi$) of the DBD reactor, which results in an increase in the measured $T_{\text{vib}}$ values, due to an increase in the pressure inside the reactor. The other method is to change the gas flow rate (GFR) used to produce the plasma jets. This leads to a $T_{\text{vib}}$ reduction when the GFR is increased in the case of using helium or nitrogen as the working gas, but the opposite happens (an increase in the $T_{\text{vib}}$ values) when argon is used, with different phenomena causing the variation of $T_{\text{vib}}$ in each situation.

KEYWORDS
DBD plasma, plasma spectroscopy, rotational temperature, vibrational temperature

1 INTRODUCTION

Cold plasmas produced at atmospheric pressure and in open environments have received considerable attention in recent years due to their versatility, easiness of operation, and low cost compared to plasmas produced in a vacuum environment. The plasmas are characterized by low temperature that is especially important for the modification and/or activation of surfaces of soft materials, such as polymers or biological tissues, without damaging them. A plasma generated using dielectric barrier discharge (DBD) is one kind of atmospheric pressure plasma in which the discharge is produced between two electrodes, with at least one of them covered with a dielectric material (glass or ceramic in most cases).

Most DBD devices that operate at atmospheric pressure and in open environments can use many different gases as the working gas. Depending on the working gas, the resulting plasma presents different values for parameters such as vibrational and rotational temperatures, electron density, delivered power, and so on, and the variation of these plasma parameters can affect surface treatment processes. We can also change the plasma parameters for a given working gas if the operation conditions are changed, like varying the gas flow rate, the gas pressure, and/or the voltage applied on the electrodes.

The variation of plasma rotational and vibrational temperatures with operation parameters such as gas flow rate and gas pressure was the subject of study by some authors, but in none of these studies was a theoretical model proposed to explain the results. Yuji et al. showed that, in tests of surface wettability, the values of the water contact...
angle in poly(ethylene terephthalate) decrease when surface treatments using plasmas with higher rotational temperature are performed, but that study did not take into account the effects of $T_{\text{vib}}$ values. Although it is known that both $T_{\text{rot}}$ and $T_{\text{vib}}$ contribute synergistically during the surface treatment process, studies relating chemical reactions between gases and surfaces have shown that the impact of $T_{\text{vib}}$ on surface treatment using plasma jets should be more significant than the impact of $T_{\text{rot}}$.[18,19] This statement was verified in a work on the treatment of poly(dimethylsiloxane) (PDMS) surfaces for adhesion between treated samples, with adhesion being more efficient for higher $T_{\text{vib}}$ values.[20]

In this work, we analyse two ways to control the vibrational temperature of the DBD plasma. One is by reducing the exit size of the DBD reactor or, in other words, putting a smaller amount of the plasma generated inside the reactor in contact with the surrounding air. The other is by changing the gas flow rate used to produce the plasma. In the first case, we verified that the larger the exit size, the lower the vibrational temperature, but in the last case, the behaviour of vibrational temperature as a function of gas flow rate depends on the working gas used to produce the plasma. We also propose explanations for the reasons that lead to the increase or reduction of the vibrational temperature in both cases.

2 | THEORETICAL BACKGROUND

2.1 | Vibrational excitation

In DBD plasmas, there are some processes that can change the number density of $N_2$ molecules in vibrationally excited states, increasing the vibrational energy of the gas: collisions with electrons, collisions with metastable atoms and ions, energy transfer by collisions between vibrationally excited molecules, and conversion of vibrational energy into translational and/or rotational motion of the molecules.[21–26]

In Figure 1, we can see that metastable helium He(2 $3S$) and argon ion Ar$^+(3P_{3/2})$ have enough energy to ionize $N_2$ molecules to states $N_2^+(A^3\Pi_u$ and $B^2\Sigma^+_u)$ for He and $N_2^+(X^2\Sigma^+_g)$ for Ar$^+$. The $N_2^+$ ions and argon metastable states Ar$^+(3P_2$ and $3P_0$) can collide with $N_2$ and produce excited states $N_2(C^3\Pi_u$ and $B^3\Pi_g)$ and metastable states $N_2(A^3\Sigma^+_u$ and $\alpha^1\Sigma^+_u$). Collisions between two metastable $N_2$ and between an $N_2^+$ with a ground-state $N_2(X^1\Sigma^+_g)$ can also produce excited $N_2$ ($N_2^*$) molecules. Table 1 summarizes the most important of the possible reactions that can produce excited $N_2$ molecules and their rate coefficients at room temperature. In Table 1, Penning ionization of $N_2$ by argon metastable (Ar$^M$) and by $N_2(A^3\Sigma_u^+)$ are neglected because the energies of Ar$^M$ and $N_2(A^3\Sigma_u^+)$ are considerably lower than the ionization energy of $N_2$ as can be seen in Figure 1. Penning ionization due to collisions between metastables $N_2(A^3\Sigma_u^+)$ and $N_2(\alpha^1\Sigma_u^-)$ is neglected because its contribution is very small when compared with other processes that can occur with these metastables.[33] Penning excitation of $N_2$ by helium metastable (He$^M$) can also be neglected because the energy of He$^M$ is considerably higher than the energy of the $N_2(C^3\Pi_u)$ state. The reaction $e + N_2 \rightarrow 2e + N_2^+$ is neglected because its cross section is very small for the electron energies that can be found in a DBD plasma.[34]

Neutral $N_2$ molecules are vibrationally excited by electron impact at a rate of $4 \times 10^{-9}$ cm$^3$/s at a typical electron temperature of 1 eV.[35] In addition, an electronically excited $N_2$ molecule ($N_2^*$), produced by any of the reactions shown in Table 1, lies on a vibrationally excited state $v'$ as metastables, ions, and excited molecules are able to perform vibrational excitation on the $N_2$ molecules.[36,37]

Observing the data in Table 1, we notice that reaction number 10 is one of the most important sources of $N_2^*$ because it has the highest reaction coefficient related to $N_2^*$ production in plasmas at room temperature, and as it depends on reaction 6 or 9, we see that there are two ways to produce a plasma with a high vibrational energy in an open environment. One is using a working gas that is able to produce a large amount of $N_2^+$ ions. Comparing the energy levels of $N_2^+$ ions with those of He(2 $3S$) and Ar$^+(3P_{3/2})$ (Figure 1), we can infer that the helium gas is the best choice in order to produce a plasma with a high degree of vibrational excitation. The other way is to use a working gas that is able to produce a large amount of $N_2^M$ metastables, which can be carried out using pure nitrogen or argon as working gases, as suggested by the energy level diagram shown in Figure 1.

2.2 | Vibrational temperature

The total energy $E$ of an excited $N_2$ molecule is given by equation:

$$E = E_e + E_{\text{trans}} + E_{\text{vib}} + E_{\text{rot}}$$ (1)
where $E_e$ is the electron energy, $E_{\text{trans}}$ is the translational energy, $E_{\text{vib}}$ is the vibrational energy, and $E_{\text{rot}}$ is the rotational energy.

Assuming a Boltzmann distribution for the number density of molecules in a rotational–vibrational excited state $N_{\nu',J'}$, we can write\textsuperscript{[38,39]}:

$$N_{\nu',J'} = N_0 \alpha(\nu',J') \exp(-E_{\nu}/k_BT_{\text{vib}}) \exp(-E_{J}/k_BT_{\text{rot}})$$  \hspace{1cm} (2)

where $N_0$ is the number density of $N_2$ molecules that are not excited (neutral), $\alpha(\nu',J')$ is a constant of the state $\nu'$-$J'$, $E_{\nu}$ is the energy of the vibrational state $\nu'$, $E_{J}$ is the energy of the rotational state $J'$, $k_B$ is the Boltzmann constant, and $T_{\text{vib}}$ and $T_{\text{rot}}$ are the vibrational and rotational temperatures, respectively. For non-equilibrium plasmas, the rotational temperature is known to be approximately equal to the gas temperature ($T_{\text{rot}} \approx T_{\text{gas}}$)\textsuperscript{[40–42]}

The $N_2$ molecules that enter the plasma have a partial pressure $P_0$ and are subjected to the gas thermalization process in the plasma. When working at atmospheric pressure and in an open environment, we can assume that the $N_2$ gas is an ideal one, which allows us to use the ideal gas equation, $P_0 = N_0 k_B T_{\text{gas}}$, together with the approximation $T_{\text{gas}} \approx T_{\text{rot}}$. In order to write the vibrational temperature in terms of $P_0$, $N_{\nu',J'}$, and $T_{\text{rot}}$ after substituting all this in Equation (2), resulting in:

$$T_{\text{vib}} = \frac{E_{\nu}}{k_B} \left[ \ln \left( \frac{P_0 \alpha(\nu',J')}{N_{\nu',J'} k_B T_{\text{rot}}} \right) - \frac{E_{\nu}}{k_B T_{\text{rot}}} \right]^{-1}$$  \hspace{1cm} (3)
Table 1. The most important possible reactions that can produce excited N₂ molecules and their rate coefficients at room temperature.

| Number | Reactiona | Rate coefficient | Reference |
|--------|------------|------------------|-----------|
| 1      | Ar⁺ + N₂ → Ar + N₂⁺ | 2.9 × 10⁻¹¹ (cm³/s) | [27] |
| 2      | Ar⁺ + N₂ → Ar + N₂⁺ | 0.1–6.6 × 10⁻¹¹ (cm³/s) | [22] |
| 3      | He⁺ + N₂ → He + (N₂⁺⁺, N₂⁺⁺) | 0.63–1 × 10⁻¹⁰ (cm³/s) | [21] |
| 4      | N₂ + N₂ → N₂ + N₂⁺ | 1.9 × 10⁻¹³ (cm³/s) | [24] |
| 5      | N₂⁺ + N₂ → N₂ + N₂⁺ | 1.5–2.6 × 10⁻¹⁰ (cm³/s) | [28–30] |
| 6      | N₂⁺⁺ + N₂ → N₂⁺ + e | 1–5 × 10⁻¹¹ (cm³/s) | [31] |
| 7      | N₂⁺ + N₂ → products | 3.7–8.2 × 10⁻¹⁰ (cm³/s) | [21,28,32] |
| 8      | e + N₂ → e + N₂⁺ | 3.4 × 10⁻¹⁰ (cm³/s) | [25] |
| 9      | N₂⁺ + N₂ → N₄⁺ + N₂ | 6.8 × 10⁻²⁹ (cm⁶/s) | [26] |
| 10     | N₄⁺ + e → N₂⁺ + N₂ | 3.2 × 10⁻⁷ (cm³/s)b | [26] |

Note. * = Electronically excited; + = ionized.

a M = metastable state.
b For an electron temperature of 1 eV.

From Equation (3), we can see that \( T_{\text{vib}} \) decreases if \( P_0 \) is increased and increases if \( N_{\nu'} \) and/or \( T_{\text{rot}} \) are increased. If \( P_0 \) is increased, the mean free path for collisions between N₂ molecules in the plasma becomes smaller, which reduces the vibrational energy transferred in each collision, and then, \( T_{\text{vib}} \) is reduced. When neutral N₂ molecules enter the plasma they start to collide with energetic electrons and the vibrationally excited N₂ molecules, which may result in a larger number of vibrationally excited molecules and, consequently, in a higher \( T_{\text{vib}} \) if the amount of neutral N₂ molecules entering the plasma is not so large, otherwise that energy coming from the energetic electrons and excited N₂ molecules will be divided between the neutral ones, so the \( T_{\text{vib}} \) values will remain constant or decrease. The gas temperature gives more kinetic energy to the molecules in the plasma; then, the higher \( T_{\text{gas}} \), the higher \( T_{\text{vib}} \).

3 | EXPERIMENTAL PROCEDURE

The experimental set-ups used to measure both \( T_{\text{vib}} \) and \( T_{\text{rot}} \) of DBD plasmas are shown in Figure 2. The basic functioning of the device is as follows: a continuous gas flow is injected inside the poly(vinyl chloride) (PVC) tube, and high-voltage pulses are applied to the electrode inside the glass tube. A primary plasma discharge is formed in the region between the glass tube and the PVC tube producing a plasma jet leaving the tube exit.

The pulsed voltage applied to the electrode had peak values of 15 kV when Ar and He gases were used and 30 kV when the N₂ gas was used. The frequency of plasma pulses was 60 Hz in all cases. The distance \( d \) between the end of the PVC tube and the surface of the dielectric plate was kept constant and is equal to 5 mm in all experiments performed in this work.

In order to obtain the temperatures as a function of the diameter \( \phi \) of the PVC tube exit, the changeable part of the device (dashed part in Figure 2) is replaced by another one with a different exit diameter.

Both \( T_{\text{vib}} \) and \( T_{\text{rot}} \) were determined using the SpecAir software and measurements of spectral emissions were performed using an Andor 303i spectrometer equipped with an iStar DH720 ICCD detector and a 1200 lines/mm grating. The light emitted by the plasmas was collected with a lens and transported to the spectrometer through an optical fibre. The vibrational temperature of N₂ molecules was determined by comparing a simulated spectrum that best fits the experimental one. In order to obtain rotational and vibrational temperatures of N₂ molecules, we use emission lines from the second positive system, C \(^3\Pi_g\), \( \nu' \rightarrow B \) \(^3\Pi_g\), \( \nu' \), where C \(^3\Pi_g\) and B \(^3\Pi_g\) denote electron configuration, and \( \nu' \) and \( \nu' \) denote the vibrational state. Each vibrational band comes from a transition of a different vibrational state (\( \nu' \rightarrow \nu' \)).

4 | RESULTS AND DISCUSSION

Figure 3a shows curves of the variation of \( T_{\text{vib}} \) as a function of the diameter of the PVC tube exit obtained for plasmas produced using Ar, He, and N₂ as the working gases, and Figure 3b shows the respective curves obtained for \( T_{\text{rot}} \).
FIGURE 2  DBD scheme used for temperature measurements and for plasma treatment of PDMS samples. \( \Phi_e \) and \( \Phi_i \) refer to external and internal diameters, respectively. \( \Phi_{\text{el}} \) is the diameter of the electrode. The elements are out of scale.

FIGURE 3  Vibrational (a) and rotational (b) temperatures as a function of the diameter of the PVC tube exit using a gas flow rate of 4 L/min.
As we can see in Figure 3a, the $T_{\text{vib}}$ values for Ar and He plasmas decrease if the diameter of the PVC tube exit ($\varnothing$) is increased. The larger variation occurs for the He plasma. The $T_{\text{vib}}$ values for $N_2$ plasma do not change significantly when $\varnothing$ is increased. From Figure 3b, we can see that the $T_{\text{rot}}$ values do not change significantly with the size of the PVC opening when He and $N_2$ gases are used but tends to decrease when Ar is used.

When $\varnothing$ is increased, the gas pressure inside the PVC tube is reduced, and the surrounding air tends to have more contact with the primary plasma inside the PVC tube. Then, we observe an increase in the amount of $N_2$ molecules, which come from the air, inside the plasma, which increases the number density of molecules in all vibrationally excited states and results in a reduction in the vibrational temperature when Ar and He are used to generate plasmas, which is in agreement with theory and also with the results shown in.[3] The reduction of the pressure of Ar and He gases inside the PVC tube allows an increase in the partial pressure of $N_2$ molecules coming from air, and it also contributes to the reduction of the $T_{\text{vib}}$ values.

When the $N_2$ gas is used, the reduction in the gas pressure inside the PVC tube due to the increase in the size of the exit opening is accompanied by a reduction of the number of $N_2$ molecules that are compressed in the PVC tube, which results in a lower number of molecules in higher vibrational states, and then, the $T_{\text{vib}}$ values do not change significantly.

In another experiment with an atmospheric pressure plasma jet, Yuji et al.[10] increased the amount of nitrogen gas in the plasma, increasing the $N_2$ gas flow rate in an Ar/$N_2$ gas mixture, keeping the Ar flow rate constant. As a result, they obtained a curve which showed that the $T_{\text{vib}}$ values increase as the $N_2$ gas flow rate increases. Once the neutral molecules enter the plasma, they become excited, and $T_{\text{vib}}$ is increased, and this confirms the dependence of $T_{\text{vib}}$ with $N_{e,r,f}$ predicted by Equation (3).

In an experiment by Masoud et al.,[3] in which the rotational temperature was measured as a function of working pressure in a cylindrical DBD device, for a constant input power into the device and using neon as the working gas with trace amounts of $N_2$, it was found that, at pressures above 200 Torr ($\sim$ 0.26 atm), the $N_2$ molecules in the $N_2(C^3\Pi_u)$ state tend to be in thermodynamic equilibrium with the surrounding gas, and then, $T_{\text{rot}}$ tends to be constant, while the pressure is varied. As we worked using pressures close to 1 atm (760 Torr), and the variation in diameter $\varnothing$ does not lead to larger variations in the working pressure, the hypothesis of thermodynamic equilibrium between the plasma jet and the surrounding gas explains the behaviour of $T_{\text{rot}}$ as a function of $\varnothing$ observed here, which is almost constant for all three gases used and also extends the validity of the results in[3] to pressures of up to 1 atm and for larger amounts of $N_2$.

Figure 4a shows curves of the variation of $T_{\text{vib}}$ as a function of the gas flow rate obtained for plasmas generated using Ar, He, and $N_2$ as working gases, and Figure 4b shows the respective curves obtained for $T_{\text{rot}}$.

From Figure 4a, we can see that the $T_{\text{vib}}$ values for He and $N_2$ plasmas decrease as gas flow rate is increased, but those for Ar plasma do the opposite. In Figure 4b, we can see that the increment of the gas flow rate does not significantly affect the $T_{\text{rot}}$ values for He and $N_2$ plasmas but results in an increment of this parameter when Ar is used.

There is a different explanation for the behaviour of $T_{\text{vib}}$ in relation to the gas flow rate for each gas used. For the cases of operation with Ar and He gases, if the gas flow rate is increased, the total gas pressure inside the PVC tube increases, but the partial pressure of $N_2$ (and the number density of $N_2$ molecules) decreases, also reducing the number of $N_2$ molecules vibrationally excited. Then, the reduction of the $T_{\text{vib}}$ values with the gas flow rate for He plasmas should be related to the reduction of the number of $N_2$ molecules vibrationally excited, present in the plasma.

For the case of operation with $N_2$ gas, the gas pressure inside the reactor increases with the gas flow rate, while many neutral $N_2$ molecules are introduced into the plasma. The increment in pressure causes a reduction in the $T_{\text{vib}}$ values due to the lowest mean free path for collisions in the plasma. Due to the high gas flow rate, the number of neutral $N_2$ molecules entering into the plasma is very large; thus, their collisions with excited $N_2$ and energetic electrons are not sufficient to increase the population of $N_2$ molecules in excited states and, in this way, do not contribute to increase $T_{\text{vib}}$. Both He and $N_2$ cases are in agreement with theory.

For the Ar plasma, the increment in $T_{\text{vib}}$ values as a function of the gas flow rate is related to the increment in the respective $T_{\text{rot}}$ values, and this is in agreement with predictions given by Equation (3). There is also a variation of the gas pressure inside the PVC tube with the gas flow rate, but it is lower than the variation of $T_{\text{rot}}$ values.

The behaviour of the $T_{\text{vib}}$ as a function of the gas pressure for He and $N_2$ plasmas is in agreement with that reported by Masoud et al.,[3] in which the $T_{\text{vib}}$ values decrease when the gas pressure increases.

The increment in $T_{\text{rot}}$ (or $T_{\text{gas}}$) values when the gas flow rate is increased in the case where Ar is used as the working gas was also observed by Moon et al.[16] using an atmospheric microwave-induced plasma. This behaviour is in contrast to the expected one because, if other parameters such as the applied voltage and pulse frequency are kept constant, an increase in the gas flow rate usually tends to cool down a discharge due to the increase in the number of particles in the plasma. Some authors reported an increment in the electron density by increasing the gas flow rate when working with
As we can see in Figures 3a and 4a, the higher values of $T_{\text{vib}}$ were obtained using helium as the working gas, and these values are considerably higher than in the cases in which argon or nitrogen is used. In order to investigate the reasons for such differences, we obtained the emission spectrum of the plasmas formed using the three gases. The results are shown in Figure 5.

From Figure 5, we notice that only the plasma created using the He gas presents detectable molecular line emissions from the $N_2^+$ ion (N$\!_2$ II) at 391.4 and 427.8 nm. If we compare the intensities of the molecular line emissions from $N_2$ molecule (N$\!_2$ I), we observe that they are higher in the He plasma. Then, considering the higher $T_{\text{vib}}$ values obtained with He gas, we observe that the Penning ionization process by metastable helium plays an important role in the increment of vibrational excitation of $N_2$ particles in the plasma. From Figure 5, we can also deduce that the Penning ionization processes associated with $N_2$ and Ar metastables are negligible in DBD plasmas at atmospheric pressure as there are no detectable line emissions from the $N_2^+$ ion in the emission spectra of the plasmas created with these gases. The lower $T_{\text{vib}}$ values obtained for operation with Ar and $N_2$ gases indicate that reaction 6 (see Table 1) does not contribute significantly to the generation of $N_4^+$ species, which are used in reaction 10 to generate excited $N_2$ molecules, in DBD plasmas.

5 | CONCLUSIONS

According to the results of $T_{\text{vib}}$ as a function of $\phi$, where we find that the $T_{\text{vib}}$ values decrease when $\phi$ is increased, if the plasma inside the reactor has less contact with the environment due to the smaller size of the device opening, it results
in higher $T_{vib}$ values. This happens regardless of which working gas is used to produce the plasma, and according to the theoretical model, that behaviour is associated with the reduction of the gas pressure inside the reactor due to the increment of the exit diameter, which allows more N$_2$ molecules from the environment to be in contact with the primary plasma discharge.

In addition, it was also verified that the behaviour of the $T_{vib}$ values as a function of the gas flow rate are similar – the higher the flow rate, the lower the $T_{vib}$ values – when He or N$_2$ are used to produce the plasmas, but that parameter increases when Ar is used. All the $T_{vib}$ results obtained by variation of the gas flow are in agreement with the predictions made in the theoretical model and also confirm its validity.

The use of He is essential to achieve the highest $T_{vib}$ values in DBD plasmas because, among the gases used in this work, only this gas has metastable states with energy high enough to ionize a large number of N$_2$ molecules, forming N$_2^+$ ions, which seem to be primarily responsible for the reactions that lead to increased $T_{vib}$ values in the plasma jets. It is not possible to reach higher values of $T_{vib}$ using argon and nitrogen gases because the production of N$_2^+$ ions is negligible in these cases.

REFERENCES

[1] S. Y. Moon, W. Choe, B. K. Kang, *Appl. Phys. Lett.* **2004**, *84*, 188.
[2] X. Lu, G. V. Naidis, M. Laroussi, K. Ostrikov, *Phys. Rep.* **2014**, *540*, 123.
[3] N. Masoud, K. Martus, M. Figus, K. Becker, *Contrib. Plasma Phys.* **2005**, *45*, 30.
[4] P. Rajasekaran, N. Bibinov, P. Awakowicz, *Meas. Sci. Technol.* **2012**, *23*, 085605 (8pp).
[5] M. Bashir, J. M. Rees, S. Bashir, W. B. Zimmerman, *Phys. Lett. A* **2014**, *378*, 2395.
[6] M. Machida, *Braz. J. Phys.* **2015**, *45*, 132.
[7] U. Kogelschatz, B. Eliasson, W. Egli, *J. Phys. IV* **1997**, 7(C4), C4.
[8] T. C. Corke, C. L. Enloe, S. P. Wilkinson, *Annu. Rev. Fluid Mech.* **2010**, *42*, 505.
[9] F. Nascimento, S. Parada, S. Moshkalev, M. Machida, *Ipn. J. Appl. Phys.* **2016**, *55*, 021602.
[10] T. Yuji, Y. Suzuki, T. Yamawaki, H. S. Akaue, H. A. Katsuka, *Ipn. J. Appl. Phys.* **2007**, *46*, 795.
[11] S. Keller, P. Rajasekaran, N. Bibinov, P. Awakowicz, *J. Phys. D: Appl. Phys.* **2012**, *45*, 125202.
[12] S. Müller, T. Krähling, D. Veza, V. Horvatic, C. Vadla, J. Franzke, *Spectrochim. Acta Part B* **2013**, *85*, 104.
[13] N. K. Bibinov, A. A. Fateev, K. Wiesemann, *Plasma Sources Sci. Technol.* **2001**, *10*, 579.
[14] G. Faure, S. M. Shkol’nik, *J. Phys. D: Appl. Phys.* **1998**, *31*, 1212.
[15] J. L. Walsh, F. Iza, N. B. Janson, V. J. Law, M. G. Kong, *J. Phys. D: Appl. Phys.* **2010**, *43*, 075201.
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