ABSORPTION OF MICROWAVE POWER IN NITROGEN PLASMA AT MODERATELY LOW PRESSURE

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Key words: plasma; reflected power; matching; power transfer; energy absorption; electron motion

Abstract: The efficiency of microwave absorption by nitrogen plasma has been studied. Plasma was created within a quartz glass tube mounted perpendicular to a microwave cavity. The cavity was powered by a microwave generator operating at a standard frequency of 2.45 GHz and adjustable nominal power up to 1200 W. Plasma was created at low pressure. The quartz tube was pumped with a two stage rotary pump with a nominal pumping speed of 33 m^3/h. A valve was mounted between the tube and the pump in order to adjust the effective pumping speed. The pressure of nitrogen in the quartz tube was thus varied between 100 Pa and 2500 Pa. The experiments were performed at the gas flow of 20 l/h. The nominal and adsorbed powers were measured with appropriate power meters. At low nominal power the reflected power was rather low but it kept increasing with increasing nominal power. The reflected power also depended on the pressure. The reflected power decreased monotonously with increasing pressure. At the highest pressure the reflected power was about 5 times lower than at the lowest pressure. The results were explained by energy accumulation of electrons at elastic collisions during oscillation in EM field.

Absorpcija mikrovalovne moči v dušikovi plazmi pri nizkih tlakih

Kjučne besede: plazma, odbita moč, uskladitev, prenos moči, absorpcija energije, gibanje elektronov

Izvleček: Preučevali smo učinkovitost absorpcije mikrovalov v plazmi dušika pri nizkih tlakih. Plasma je bila ustvarjena v cevi iz kvarčnega stekla, ki je bila nameščena pravokotno na mikrovalovni resonator. Resonator je bil napajan z mikrovalovnim generatorjem, ki deluje na standardni frekvenci 2,45 GHz in ima nastavljivo nazivno moč do 1200 W. Razelektritveno cev smo črpali z dvostopenjsko rotacijsko črpalko z nazivno črpalno hitrostjo 33 m^3/h. Med cevjo in črpalko je bil nameščen ventil, s katerim smo uravnavali efektivno črpalno hitrost. Tlak dušika v razelektritveni cevi je tako bil med 100 Pa in 2500 Pa. Eksperimenti so bili izvedeni pri pretoku plina 20 l/h. Nominalno in adsorbirano oz. odbito moč smo merili z ustreznimi merilniki moči. Pri nizki nominalni moči je bila odbita moč sicer majhna, vendar je z naraščajočo nominalno močjo naraščala. Odbita moč je bila odvisna tudi od tlaka. Odbita moč je monotono padala z naraščajočim tlakom. Pri največjem tlaku je bila odbita moč približno 5-krat nižja kot pri najnižjem tlaku. Rezultate smo pojasnili s kopičenjem energije elektronov pri elastičnih trkih med nihanjem v EM polju.

1. Introduction

Low pressure gaseous plasma is nowadays widely used for treatment of different materials /1-9/. Depending on specific needs plasma is created by various electrical discharges. Basically we can distinguish between two types of discharges: those where charged particles are accelerated in sheet region next to the electrodes, and those where charged particles are accelerated in electrical field presented in the volume. Examples of the first type of discharges include a simple DC glow discharge /10,11/, capacitively coupled RF discharge /12,13/ and hot-cathode as well as hollow cathode discharges /14/. The second type of discharges includes a variety of resonance discharges such as the popular electron cyclotron resonance (ECR) discharges /15,16/, inductively coupled RF discharges /6,9,17/ and MW discharges /18-22/. The absorption of energy supplied by an appropriate power supply is usually very high at surface discharges, but in volume discharges they may or may not be that high. If conditions for resonant acceleration of charged particles in electromagnetic fields are met, the power absorption is usually pretty high. On the other hand, the absorbed power could be very low and many authors use expressions like unmatched or unbalanced plasma. The problem of insufficient power absorption is particularly severe in devices for modification of the properties of solid materials since the optimal conditions for power absorption can not be made due to particular requirements regarding the samples that are treated. In such cases a compromise between the requirements and the power absorption should be made. A pretty good example is plasma created in a microwave cavity. In this paper we present results on systematic measurements of the reflected power in order to show the right conditions for plasma generation.

2. Experimental

Experiments were performed at solar facilities of PROMES-CNRS laboratories for treatment of materials in Font Romeu through the FP7 program SFERA. The experimental reactor MESOX is used for characterization of high-temperature materials properties after exposure to gaseous plasma at extreme conditions. Samples are heated by concentrated light at maximum power of 5 kW concentrated on a spot area of about 1 cm2 and simultaneously heated by gaseous plasma. A schematic of the experimental system is shown in Fig. 1. Plasma is created in the discharge chamber which is 50 cm long quartz glass tube with the diameter of 5 cm. The tube is pumped with the two stage rotary pump with the nominal pumping speed of 33 m^3/h. There is a variable valve between the pump and the discharge chamber. The valve serves for adjusting the effective pumping speed at the exhaust of the discharge chamber. Depending on the valve adjustment the pumping speed can be decreased down to about 1 m^3/h. Gas is leaked into the discharge chamber on the other side through flow controller. The maximum throughput of the controller is 20 l/h. Pressure is measured between the discharge chamber and the variable valve as shown in Fig. 1. The pressure in the discharge chamber depends on the position of the leak valve as well as the variable valve. At current experiments we created plasma in pure nitrogen.

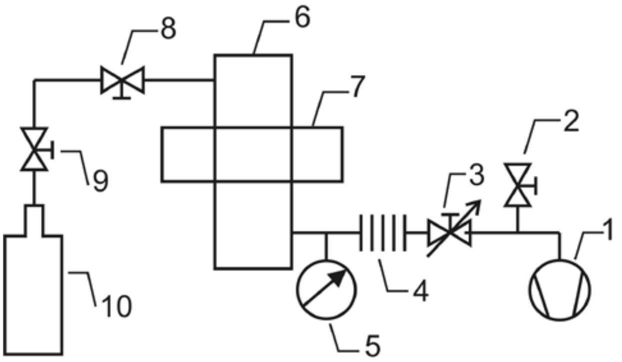

Fig. 1: Schematic of the experimental vacuum system: (1) rotary pump, (2) venting valve, (3) adjustable valve, (4) bellows, (5) absolute vacuum gauge, (6) discharge chamber, (7) MW cavity, (8) leak valve with flow meter, (9) high pressure valve, (10) nitrogen flask.

Plasma was created by a microwave (MW) generator. A detail about plasma system is shown in Fig. 2. The discharge chamber is placed perpendicularly to the microwave cavity which is made from copper and has standard dimensions of 9×4×15 cm^3. The cavity is powered with the MW generator operating at the standard industrial frequency of 2.45 GHz and at adjustable power up to 1200 W. On the other side of the microwave cavity there is manually operating matching unit. At our experiments the matching unit was optimized at the maximal effective pumping speed (practically equal to the nominal pumping speed of the vacuum pump) and was kept at that position during all experiments. The MW generator is equipped with a MW power meter, while the wave-guide between the MW generator and the cavity is equipped with a meter of the reflected power, as shown in Fig. 2.

Experiments were performed at different pressures in the microwave cavity corresponding to different effective pumping speeds. Pressure was measured with an absolute vacuum gauge. Depending on the opening of the variable valve the pressure in the discharge chamber was between 100 Pa and 2500 Pa. At each pressure we performed measurement of the reflected power versus the nominal power of the microwave generator. At high pressure it was possible to perform measurements up to the nominal power of 800 W, but at lower pressure measurement up to lower power were realized because of the automatic switch-off function of the MW generator. Results of systematic measurements are summarized in Fig. 3.

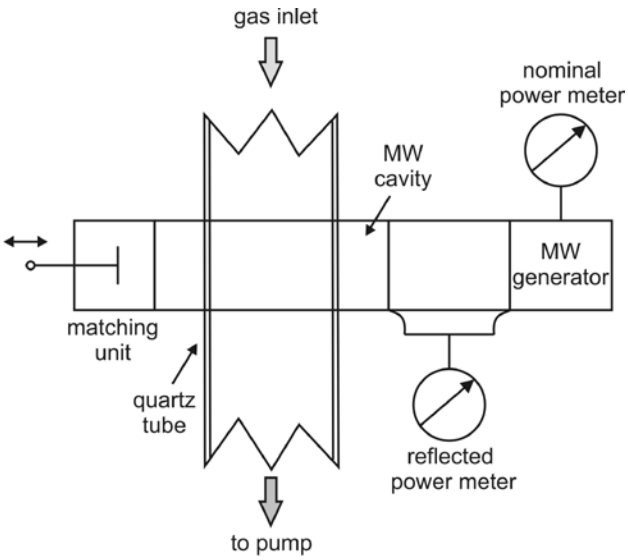

Fig. 2: Detail of the discharge chamber with MW apparatus.

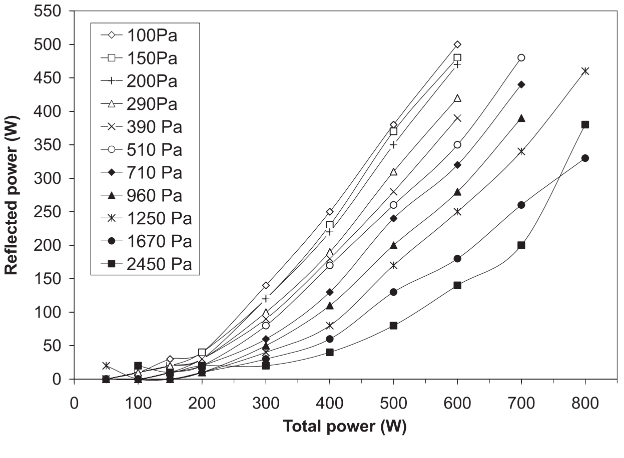

Fig. 3: Reflected power versus the nominal power of the MW generator. The parameter is the nitrogen pressure in the discharge chamber.

3. Discussion

The results of the measurements of the reflective power shown in Fig. 3 reveal some interesting features. As a general rule the reflected power increases with increasing the nominal power. At low power up to about 200 W the reflected power is much lower than the nominal power indicating rather good matching of the microwave generator. As the total power is increased, the reflected power is increased too. The increase of the reflected power depends enormously on the pressure. At low pressures the increase of the reflected power is pretty steep while at higher pressures a pretty good matching is observed at the total power of say 500 W. Such a huge discrepancy in matching between different pressures is explained by transfer of energy between the electromagnetic field and free electrons in nitrogen plasma.

Charged particles are accelerated in electric field. The energy gained from the field does not depend on the type of charged particle (electrons or ions) in the DC field. Namely, the energy gained is just $e \cdot U$, where e is the charge of the charged particle and U is the voltage, $U = E \cdot x$. Here, E is the electric field and x is the path. This also holds for AC electrical field as long as the frequency is low. As the frequency of the electrical field increases, the charged particles may not rich the walls of the chamber but they start oscillating in the electrical field. The oscillation of a charged particle with mass m in high-frequency electrical field is described by the basic equation /23//23/:

$$m\ddot{x} = eE_0 \cos\omega t \tag{1}$$

The kinetic energy of charged particles depends on the frequency (ω) and the mass of the charged particle (m) and is determined as:

$$W_k = \frac{1}{2} m\dot{x}^2 \tag{2}$$

where $\dot{x}$ is the velocity, i.e.

$$\dot{x} = \frac{eE_0}{m\omega} \sin\omega t \tag{3}$$

The oscillation amplitude is determined by integration of the Eq. (1) and is:

$$x = -\frac{eE}{m\omega^2} \cos\omega t \tag{4}$$

The Eqs. (1-4) reveal important fact about oscillations of charged particles in high-frequency electrical field. First, the oscillation amplitude and the energy gained depend on the mass of the charged particle. Massive particles gain much less energy than particles with a low mass. The mass of nitrogen molecules is about 30.000-times larger than the electron mass. From Eqs. (1-4) it is clear that charged nitrogen molecules can not follow the oscillations of the electromagnetic field when the frequency is moderately high. In practical cases this often happens at the frequency of about 1 MHz. The frequency of the electrical field in our MW discharge is over 1.000-times larger at 2.45 GHz. Massive ions practically do not feel such high frequency electrical field so they gain practically no energy. On the other hand electrons are much lighter so they are still capable of oscillating with a reasonably large amplitude and kinetic energy. Electrons oscillating in vacuum cannot accumulate energy from the electrical field. Namely, when they reach maximal kinetic energy the electric field is transversed so they are slowing down instead of accelerating. An electron can only accumulate the kinetic energy if suffering an elastic collision with a heavy particle at the time when it has the maximum kinetic energy obtained from the electric field. Namely, at elastic collision the kinetic energy of the electron is preserved, but the direction of the velocity becomes opposite. The electron is thus capable to take advantage of further accelerating in the electric field. If such collisions happen each time when the electric field is changed, the electron can accumulate a lot of energy. In the ideal case, the path between the two collisions should be equal to the oscillation amplitude. In such a case the electron would be able to keep accumulating its kinetic energy so it could gain energy much larger than the maximum energy according to Eq. (2).

The path between two collisions depends on several parameters, but the major one is the pressure. The mean free path decreases linearly with increasing pressure. At the pressure of 100 Pa the mean free path is roughly 10^{-4} m. This is at least of order of magnitude larger than the oscillation amplitude of electrons at 2.45 GHz and power of the order of 100 W. At low pressure obviously the electrons cannot gain much energy from the oscillating electromagnetic field. As the pressure increases the mean free path decreases so the accumulation of kinetic energy by electrons become more and more efficient. The electrons can thus accumulate energy at higher pressure and this accumulation is illustrated as better matching between microwave field and nitrogen plasma. The decrease of the reflected power with increasing pressure is demonstrated in Fig. 3. is therefore explained by better accumulation of the electron kinetic energy.

The upper consideration explains a huge difference in the reflected power versus pressure at high nominal power. Let us now discuss a rather good absorption of MW power at low discharge power. At the nominal power of about 100 W the absorbed power is almost perfect. As mentioned above the matching unit was adjusted just to have best matching at such conditions. The pretty good absorption of MW power at low powers cannot be explained by accumulation of electron kinetic energy at collisions but other effects should be taken into account. As mentioned earlier the heavy particles are not accelerated in the microwave field so their velocity is orders of magnitude smaller than the electron velocity. The consequence of such huge difference between positive ions and electron velocities is depletion of plasma since electrons escape on the walls leaving positive ions in the gas phase. Plasma becomes positively charged against the walls of the discharge chamber. The potential difference between the gas phase and the surface obviously depends on the ratio between electron and ion velocities, but is typically of the order of 10 V. This voltage prevents further depletion of the electrons and causes acceleration of ions towards the surface of the discharge chamber. The typical thickness of the sheath between the wall and unperturbed plasma is of the order of the Debye length /24/. This holds for chamber walls far from any electrode. In practice however there are always electrodes present and the voltage between plasma and the wall backed by an electrode can be as high as several

100 V. Such voltage is high enough to cause acceleration of positive ions onto the wall surface where they may emit a free electron. Electron enters the sheath and is accelerated to an energy which is large enough for sustaining the discharge. A rather good matching at low powers is therefore explained by such surface effects rather than by acceleration of charged particles in the volume.

Here, it is worth mentioning that formation of sheath is only possible when we already have charged particles in the gas phase. Charged particles can be only obtained by multiplication at ionization collisions which is possible only if electrons accumulate their energy. The discharge at low voltage therefore cannot be ignited. This is sound with experiments performed in any lab with MW plasma: the ignition of the discharge is only possible at high power. As mentioned earlier our experiments were performed in such a way that a discharge was ignited at maximum power and once plasma was established, the power was decreased. Opposite procedure would never be possible.

4. Conclusions

The absorption of MW power by nitrogen plasma was studied versus the pressure. While the absorption was pretty good and it did not depend much on pressure at low power, huge differences were observed at large power. The power absorption at low pressure and large power was only about 20% of the available power. At larger pressure, the absorption of MW power became reasonably good also at larger nominal powers. The huge differences in the absorption ability were explained by oscillations of electrons in the electromagnetic field and accumulation of kinetic energy at elastic collision with gaseous particles. At low power, on the other hand the energy accumulation was rather poor so pretty good power absorption was explained by effects in the sheath between the unperturbed plasma and the surface of the discharge tube. The results clearly indicate that high pressure is more suitable for plasma generation by MW discharge. If there is a need for nitrogen plasma generation at lower power one is recommended to use discharge at a lower frequency, such as inductively coupled RF discharge.

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