Ignition System To Generate Microwave Plasma Torch At Atmospheric Pressure

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Abstract

Microwave-generated plasmas at atmospheric pressure have greatly expanded for industrial purpose. By designing a waveguide the electric field as a source generating plasma is calculated. Using a magnetron 700W and a nozzle injecting nitrogen gas test the waveguide experimentally to ignite the system. The test has been achieved successfully for few seconds.

Keywords : Design, Cavity, Design, Microwave, Plasma

1. Introduction

Plasma sources using microwaves have been developed in the last 50 years following investigations of break down with a microwave discharge in rare gas [1]. Numerous experimental and theoretical works on the electric field breakdown at microwave frequencies have been reported in the literature [2,3]. A relatively new applications area is surface processing in the semiconductor industry using microwave discharges [4,5]

Nowadays, microwaves have an important role in generating plasmas, especially at higher pressure. The advantages are a wide range of gas pressure may be used. There is no electrode erosion and consequent contamination of plasma, and the low cost of power supply, which is useful in a commercial product. Microscopically, when field are applied across a gas, electrons move only short distances before the direction of the field changes [6]. Therefore electrons are not swept out of the discharge region by the field, but leave with relatively low speeds and produce essentially no secondary effects at the surfaces of the container. For this reason microwaves can make it possible to study interactions between electrons, atoms and ions without disturbance of electrode phenomena.

Plasma at atmospheric pressure has some advantages and disadvantages. The advantages are large areas, no vacuum vessel is required so the process can be continuous, low cost and a simple source. However, some disadvantages are a high electric field is required to break down the gas. We have to make a certain region where the electric field can concentrate highly. In addition there are complications because of the mixture of gases. In addition electric field calculation for breakdown may be less than that of experimental results.

A microwave plasma torch is designed to improve accessibility of plasma. It is necessary to match the microwave source to a plasma load. In section 2 and 3, a waveguide is designed and calculated along transmission lines to concentrate the electric field in a rectangular waveguide in small volume. Coupling structure and gas feed are arranged at an antinode wave of waveguide to obtain breakdown. Section 3 describes calculation of electric field by changing guide impedance and then calculation and experimental result shown in section 4, finally discussion and conclusion in section 5 are summarised.

2. Waveguide Coupling Circuit, Coupling Structure and Gas Feed Arrangement

A schematic diagram of a typical plasma source configuration shows the parts in figure 1. The plasma source's overall efficiency is defined as the fraction of power delivered by the generator at the source input which is absorbed by electrons and ions [7]. As well as incident power, the electric field is the source for breakdown plasma. It can be concentrated by a waveguide design. The waveguide must be a small volume by reducing the height of waveguide hence the electric field can be obtained very highly. It is also to avoid limitations of skin-depth where the electric field not only travels through the boundary of waveguide but also for the whole volume.

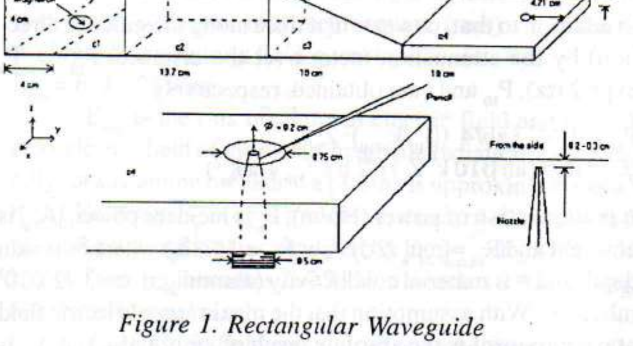

Figure 1. Rectangular Waveguide

A rectangular guide, made from aluminium formed a waveguide. The advantages of this are simplicity in guiding the power and producing plasma continuously in air, small area and low cost. This waveguide is also designed to maximise power and minimise absorption. It shown in figure 1, region c1 is connected to the magnetron source of power. It is based on a commercial product type FV-MZ 0138 WRWO (2M172AJ/L1 made in Japan), powered output of around 700W at 2.45

GHz and a half wave rectified output at 100 Hz, with 10 ms gaps between the pulses, variable down to around 400W. Region c2 is connected to a 1-port circulator. The circulator was used to protect the magnetron from damage due to reverse power. Region c3 was a connector to increase the electric field by reducing the height. Region c4 was the main region applied for breakdown plasma with the highest electric field at a quarter wave 4.71cm in distance from the end of the waveguide forming a point at antinode at which the electric field was intensified. On the bottom there was a nozzle 0.2cm in diameter made of steel injecting nitrogen gas. Nitrogen gas is commonly used for industrial processing, as it is very cheap and unreactive, making it suitable as a process carrier gas [8]. The nozzle was adjusted by a screw thread and breakdown initiated by a sharpened rod. The leakage from the cavity is very small (<0.1 mW/cm) [8].

3. Calculation of Electric Field by Changing Guide Impedance

Transverse Electric field, TE10 [9] is the mode that can propagate in a rectangular guide, and also the most commonly used. When the waves propagate along a waveguide, some magnitudes of which physical parameters will change such as wave number, kc, wave impedance, Z_h and constant phase, β. They are calculated as follows

$$k_o = 2\pi/\lambda\ ;\ k_c = \pi/a\ ;\ \beta = [k_o^2 - k_c^2]^{1/2} \qquad (1)$$

Free space wavelength, λ_o=0.1224 m, k_o = 51.33m-1 for microwave frequency 2.45 GHz. A guide wavelength will change when travelling to rectangular guide due to change of width, a. λ_g can be determi[illegible]

$$\lambda_g = 2\pi/\beta = \lambda_o/[1 - (\lambda_o/2a)^2]^{1/2} \qquad (2)$$

The magnitude of both electric field (E) and magnetic field (H) oscillate toward x, y and z direction. Ey component at z direction is written by

$$Ey = -j\,AZ_h\,\beta/k_c \sin \pi x/a \exp(-j\beta z) \qquad (3)$$

$Z_h = -E_y/H_x = k_o/\beta\ Z_o$, where wave impedance in free space, Z_o = 377ohm.

In addition to that, power will reduce along the guide (z direction) by the attenuation factor over the distance, $P_{10} = P_o \exp(-2\,\alpha z)$, P_{10} and (are obtained, respectively

$$P_{10} = |A|_{10}^2\, ab/4\ (\beta_{10}/k_{c,10})^2 Z_{h,10}$$
$$\alpha = \{R_m/(ab\,\beta 10\,k_o Z_o)\}(2\,b\,k_{c,10}^2 + a\,k_o^2)$$

α is attenuation of power (Np/m), P_o is incident power, $|A_{10}|$ is constant and $R_m = (\omega\mu_o/2\sigma)^{1/2}$, or $R_m = 1/(\sigma\,\delta_s)$ where δs is skin depth and σ is material conductivity (aluminium, σ= 3.72 x 10^7 mhos/m). With assumption that the maximum of electric field at y component is the absolute result of amplitude, and A_{10} is absorbed into $|Ey|$, hence equation (3) becomes

$$P_{10} = ab/4\ (|Ey|^2/Z_h) \qquad (4)$$

The other parameter influencing the power and electric field are impedance matching presented to the waveguide. The quantity characterising both the impedance mismatches in a transmission line terminated by the material impedance Zm and the wave reflection level within it is the reflection coefficient [10]

$$\gamma l = (Z_m - Z_h)/(Z_m + Z_h\} \qquad (5)$$

Z_h is wave impedance at that rectangular size. With the finite conductivity σ, the waveguide wall may be characterised as exhibiting surface impedance given by [9]

$$Z_m = (1+j)/(\sigma\delta s) = (1+j)\,R_m$$

The electric field lines terminate in an electric charge distribution on the inner surface of the upper and lower waveguide walls. This charge oscillates back and forth in the axial and transverse directions.

4. Calculation and Experimental Result

Electric field is calculated by equation (1) to (5) and the results are shown in table 1. The wave is launched at z=0 (c1 at z=6cm) and propagates along the waveguide. The power $P_{(z)}$ decreases with z but α is very small. Pr is calculated at the short circuit at c4. From c1 to c4 each value of attenuation is less than 5 percent or 0.0054 x 8.686 = 0.0469 dB/m. This means the waveguide did not influence the power and electric field significantly. For c3 and c4, E_y is higher than that of c1 and c2. In table 1, c45 is the wave in region c4 before reflection and c46 is the wave after reflection occurring in region c4. The value of E_y depends on parameter a and b but k_c, β and Z_h do not depend on the size of b and c.

TABEL 1. Electric Field and Power Calculation

a(cm)	b(cm)	c(cm)	Z_h(ohm)	β	k_c(m-1)	α(Np/m)	P(W)	E(V/m)
8(c1)	4	6	582.72	33.32	39.27	0.0026	699.63	2.26x10^4
8.2(c2)	4.1	13.7	564.15	34.42	38.31	0.0024	699.32	2.17x10^4
8(c3)	4-0.25c	10	582.72	33.32	39.27	0.0054	698.56	3.68x10^4
8(c4)	1.5	5.29	582.72	33.32	39.27	0.0054	698.16	3.68x10^4
8(c45)	1.5	10	582.72	33.32	39.27	0.0054	697.81	3.68x10^4
8(c46)	1.5	4.71	582.72	33.32	39.27	0.0054	698.16	3.68x10^4

Impedance is quite high, but P_z and E_y are influenced by the rectangular size, hence the reduction of these numbers is very small.

Figure 2 represents the calculation result for region c4 for superposition wave,
$E_{total} = E_{incident} + E_{reflection}$ is determined by equation (3)

$$E_{yt} = E_{yi} + E_{yr}$$
$$E_{yi} = -j\,AZ_h\,\beta k_c \sin(\pi x/a)\exp(-j\beta z)$$
$$E_{yr} = j\,AZ_h\,\beta/k_c \sin(\pi x/a)\exp(j\beta z)$$
$$E_{yt} = -2A\,Z_h\,\beta/kc \sin(\pi x/a)\sin(\beta z) \qquad (6)$$

The value of $\beta = 2\pi/\lambda_g$, where λ_g = 0.1886m at c4. Since P_z and other parameters are known so E_y can be calculated. From equation (6) E_y at c4 and c46 is 73.6 kV (at z= 0.529 cm from c4). This is the maximum amplitude for E_y. The amplitude term of this equation is absorbed by calculation of equation (6), so that A vanishes.

Reflections contributing the waveguide with impedance Z_h=582.72 ohm, Z_m=0.0161 ohm have (l almost equal to -1. This means almost all the incident power is reflected from aluminium boundary. Therefore E_{yr} amplitude is assumed similar to E_{yi} amplitude. The reflection that required in this experiment is the reflection from the end (short circuit), perpendicular to z direction. E for the first half wave is positive and for the second half wave is negative. It does not influence the position of the nozzle. The nitrogen flow rate is neglected because gas flows slowly.

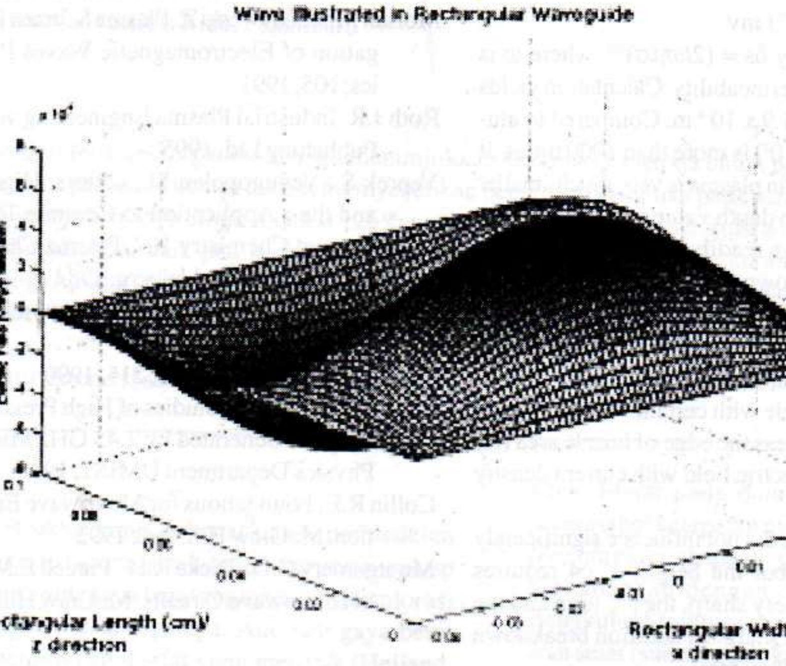

Figure 2. Electric field at c4

There are two procedures for ionising nitrogen. Firstly, the discharge did not start breakdown until voltage variable was adjusted to 255V roughly. The current delivered from 0.1A to 5.8A while voltage increased slightly. Graph 3 shows current and voltage result. From 240 V the discharge would start intermittently emerge shown by noise from some points close to nozzle, and finally between 250 to 260V plasma broke down. After that, for next few tests it was found that breakdown could not be produced readily. Secondly, a sharpened rod inserted into the waveguide near the nozzle having the effect of concentrating the field at that point. The rod was placed near the nozzle and the discharge was produced at 255V.

The height of nozzle over the top of waveguide is set 0.2-0.3 mm roughly. If this distance is adjusted well, the discharge can be sustained a few seconds as long as the nozzle and rod are not burnt. Sometimes the plasma sustained longer after initiation if the rod was kept away from the nozzle.

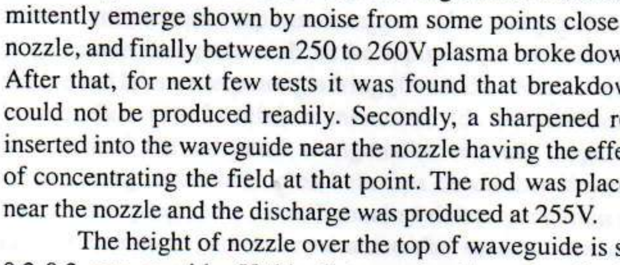

Figure 3, Voltage and Current Measurement

5. Discussion and Conclusion

At each collision the electron velocity vector is randomised and a part of the energy gained (or lost) from the electric field of microwave is transferred to directions perpendicular to the wave field and retained until the next collision. So far as the electron is concerned, the microwave appears as an oscillating field, hence for plasma breakdown the electric field is calculated on average.

The breakdown of nitrogen gas by microwave radiation occurs when the root mean square (rms) value reaches the breakdown electric field given by:

$E_{rms} = E_{yt} / \sqrt{2}$ (V/m)

E_{rms} is the rms breakdown electric field and E_{yt} is the peak electric field of the electromagnetic radiation, experimentally for sustaining breakdown plasma is approximately 60kV/m [8]. However, E_{yt} at δ_b=3 mm (the distance of the nozzle to the top of the waveguide) is calculated by $E_{yt(3mm)} = E_{yt} \times b/\delta_b = 368$ kV/m. Thus, E_{rms} becomes 260.2 kV/m which is 4.3 times larger than experimental result.

The Electric field calculation on previous section does not consider for sustaining the plasma because the electric field will change in presence of plasma. Part of the wave is transmitted into the plasma where it may be absorbed and part reflected. This experiment did not measure electron density and collisions rate so that electric field wave in the plasma is not known.

However, by assuming electron density (n_e) of order 10^{23} m^{-3} and collision rate, ν of order 10^{12} s^{-1} [8], the conductivity and skin depth can be calculated. Electrons interact to the electric field and produce current with equation

$$eE = m\, v_d\, \nu$$

$$J = \sigma E = n_e\, e\, (v_d/E)$$

where vd is drift velocity, m is electron mass, (is conductivity, and J is current density. By two equations the conductivity is

$$\sigma = n_e\, e^2 / m\nu$$

and skin depth is determined by $\delta s = (2/\omega\mu\sigma)^{1/2}$, where ω is microwave frequency and μ is permeability. Calculation yields $\sigma = 2.81 \times 10^3$ mho/m and $\delta_s = 1.9 \times 10^{-4}$ m. Compared to aluminium conductivity (of order 10^7) is more than 1000 times. It means reflection of electric field in plasma is very much smaller than transmission part. The skin depth value is reasonable, so that electric field can break down readily.

Experimentally breakdown was enhanced by some factors: a trigger rod and the edge of the nozzle, and also the distance either rod to nozzle or the nozzle to the top of the waveguide. The trigger rod multiplies electric field (E) where a distance (d) is the height of nozzle with certain voltage (V) can be expressed as $E = V \times d$, whereas the edge of nozzle area (A) has inversely proportional to electric field with current density $J = \sigma E$.

The length of waveguide did not influence significantly since the small power decay but the height of c4 requires smaller. Since the antinode is very sharp, the position and the size of nozzle must be tiny and sharp. In addition breakdown was also influenced by the N_2 flow rate.

In microwave development, the arc discharge is difficult to identify as well because the point where breakdown starts on the surface of the nozzle is not consistent, and the surface of the nozzle is large, hence the performance of the arc will be different for every breakdown. Measurement of both density and temperature is not carried out.

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