ABSTRACT: A passive impedance-matching network specifically designed to provide an interface between a fixed radio frequency power output of a generator and the capacitive electrodes of the gaseous plasma chamber of a plasma-generating apparatus, the network having the particular characteristic of providing a close impedance match over a relatively wide changing impedance range of the plasma in accordance with a known program.
Fig. 3

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The invention relates to plasma-generating machines and more particularly to an impedance converter for connecting the radio frequency power output of the generator to the plasma-producing electrodes. Electrode-gas excitation devices, more popularly referred to as plasma machines, operate to provide a relatively low temperature gas plasma. These machines are used for a variety of programs such as low temperature ashing of organic samples for analysis and diagnostic work, the removal of photoresist from silicon wafers in the process of manufacturing solid state components, and other applications.

The plasma-generating apparatus consists briefly of a glass or quartz tube or envelope providing a plasma chamber and having inlet and discharge passages adapted for connection to a gas source and a vacuum pump for flowing gas through the chamber at controlled flow rates and pressures, electrodes mounted externally of the envelope for exciting the gas in the chamber to form the plasma, and a radio frequency generator for supplying high frequency power to the electrodes. In the instance of plasma ashing, for example, the species in the plasma are chemically "consumed" in the ashing process, and optimum ashing conditions require a predetermined program of a proper balance of power, gas flow and pressure. By a series of experiments, a program may be evolved for ashing a given species which involves the controlling, with time, of varying amounts of power, gas flow, and pressure, and degree of sample temperature and ashing rate. In a similar manner, a program may be evolved for varying these same parameters for the removal of photoresist from silicon wafers, and the like.

Changes in the operating parameters of the plasma, gas flow rate, pressure and power affect the load impedance of the plasma as seen at the capacitive electrodes. Accordingly, an impedance converter is customarily inserted between the generator output and the plasma electrodes so as to provide an impedance match therebetween. As will be understood, an impedance mismatch between the generator and the plasma results in loss of power and efficiency. Such a converter usually includes a variable capacitor and a variable inductor which are required to be varied during the operation of the program to provide impedance matching. The periodic and critical manual tuning of these variable impedances is difficult to accomplish quickly, and consequently the processing program must be constantly interrupted while the operator searches for impedance settings required to minimize the reflected power as the above parameters are changed.

What is equally disconcerting is the far lack of dependable repeatability in subsequently reproducing the earlier set of balanced conditions. The actual amount of energy delivered to the gas will not always reproduce precisely with the result that even though records are kept of the impedance adjustments made, satisfactory impedance matching may not result by returning such impedances to the same settings in subsequent processing cycles. The problem is further complicated by the use of different gases in the plasma, a placing of solids in the system, and the release of vapors into the plasma.

It is accordingly an object of the invention to provide an impedance-matching network for plasma-generating apparatus which will automatically provide, without any required manual adjustment whatever, substantial impedance matching between the generator and capacitive electrodes of the gaseous plasma chamber continuously and throughout a range of changing parameters required to carry out a known plasma-chemical process.

Another object of the present invention is to provide an impedance-matching network of the character above which functions in a passive manner to provide automatic matching without necessitating, except for initial adjustment, the need for any moving parts.

A further object of the present invention is to provide an automatic impedance-matching network of the character described which is interchangeable with the existing manually operable converter.

Further and more specific objects and advantages of the present invention are made apparent in the following specification wherein a preferred form of the invention is described with reference to the following drawings.

In the drawings:

FIG. 1 is a diagrammatic representation of a plasma-generating apparatus embodying the improvement of the present invention.

FIG. 2 is a schematic diagram of an impedance-matching network constructed in accordance with the present invention and shown connected to the plasma chamber.

FIG. 3 is a chart showing processing parameters of the power, pressure and gas flow for which the present device will provide satisfactory and automatic impedance matching.

With reference to the accompanying drawing, the plasma-generating apparatus comprises briefly a gaseous plasma chamber 11 provided by a glass or quartz tube or envelope 12 formed with inlet and discharge connections 13 and 14 adapted for connection, as by conduits 16 and 17, to a source 18 of gas under pressure and a vacuum pump 19 respectively, and to provide a flowing of gas through chamber 11. The electrodes 21 and 22 are located externally on envelope 12 for exciting the gas therein; and means 23 for supplying radio frequency power via a converter 24 to electrodes 21 and 22; the converter functioning to provide an impedance matching between the output of the generator 23 and the plasma as seen at electrodes 21 and 22. Conventionally also a wattmeter 31 is inserted in the line 32 between generator 23 and converter 24 in order to measure and indicate the forward and reflected power; the electrical connections between these components being preferably provided by coaxial conductors 32 and 33, and between converter 24 and electrodes 21 and 22 by conductors 26 and 27.

Radio frequency (sometimes hereinafter abbreviated RF) generators employed to provide power for plasma machines customarily operate on an F.C.C. preset frequency of 13.56 MHz., and must be designed to deliver power under widely changing load impedance conditions. A preferred generator construction is disclosed in my copending application, U.S. Ser. No. 753,474, for RADIO FREQUENCY GENERATOR CIRCUITS AND COMPONENTS THEREFOR. The equivalent circuit for the generator may be represented by the equivalent resistance (see resistor 36 in FIG. 2) equal to the internal plate impedance of the generator at resonance. The generator's own internal network transposes the relatively high plate impedance of its power tube to the equivalent of a relatively low impedance, say 50 ohms, for feeding into a 50 ohm coaxial line 32. Thus, for present purposes, the equivalent circuit of the generator may be considered as that of the coaxial line 32—33 connected to the converter, or with reference to FIG. 2 as that of resistor 36 representing a 50 ohm output generator supplying radio frequency energy to the input of the matching network.

Wattmeter 31 should be designed to provide a showing of both forward and reflected power, the latter evidencing a mismatch between the output impedance of the generator and the plasma load. The wattmeter must have the further characteristic of being insertable in the transmission line without itself significantly changing the load impedance conditions. A preferred wattmeter construction is disclosed in my copending application U.S. Serial No. 753,681, for RADIO FREQUENCY WATTMETER.

Plasma-generating apparatus, including the several above-described components, and having a manually tunable converter to provide impedance matching between the RF generator and the plasma chamber are commercially available, as for example, the Plasma Machine Model 1101 manufactured by International Plasma Corporation of Hayward, California.

The plasma equivalent circuit as shown in FIG. 2 of the drawing may be reduced to a parallel connected capacitor 30...
The capacitance in the absence of a plasma is of a very small magnitude, being the capacitance across electrodes 21 and 22, and is in the order of 20 pico farads—perhaps 1 percent. The capacitance of the loading coil is shown as resistor 39. During operation of the plasma, the capacitance may be in the order of 2000 pico farads, but will vary with gas flow rate and pressure, and power. As illustrated in FIG. 1, a manually controlled valve 66, pressure meter 67, and flow rate meter 68 are customarily incorporated in the gas conduit 16 leading to the plasma chamber for controlling and regulating the gas flow rate and pressure. Generally, as more power is applied, the given quantity of gas, greater ionization results with an increase in capacitance and a decrease in resistance. On the other hand, at a constant power, say, 1000 watts, the impedance will change with the flow rate and pressure at a relatively high vacuum of a few microns, say, 10 microns, the capacitance may be on the order of perhaps 100 pico farads and the effective resistance high, say, several hundred ohms. At the other extreme, let’s say a pressure of 50,000 microns, the resistance will be in the order of a few ohms, perhaps 3 or 4 ohms, and the capacitance several thousand, perhaps 5000 or 6000 pico farads.

The matching network which is the improvement of the present invention is here provided with input and common line terminals 43 and 44 adapted for connection to the generator output terminals 43 and 44, and output and common line terminals 46 and 47 adapted for connection to input terminals 48 and 49 of the plasma electrodes 21 and 22. The network comprises briefly an inductor 51 having one end 52 connected by conduit 53 to input terminal 41; a second inductor 56 having one end 57 connected to the other end 58 of inductor 51 and also connected to output terminal 46; inductors 51 and 56 being mounted in mutually coupled relation to provide an air core transformer; a capacitor 61 having its opposite sides connected, respectively, to input terminal 43 and common terminal 42; and a capacitor 62 having its opposite sides connected respectively to the junction 63 between inductors 51 and 56 and the common line terminal 42—47, the common line here being a common ground and being generally identified by numeral 64.

The basic network as above described will be seen as two mutually coupled networks which cointegrate with the input and load impedances to automatically provide close impedance matching between the output of the generator and the plasma. As a result, the Q of the inductors, circulating losses and time constants involved in the foregoing all operating in a complex integral relationship which stabilizes for a given set of plasma parameters to provide the substantial impedance matching described, but which make a complete explanation of the operation of the circuit most complex and difficult.

The automatic response of the circuit is broadened measurably by the introduction of a resistance, shown as resistor 71, connected in parallel across capacitor 62. In practice this resistor may be obtained by using a very lossy ceramic capacitor. Resistor 71 functions to stabilize and shape the Q of the network to correspond to that of the plasma and also tends to limit to some extent the change in Q of the plasma, because its Q is determined also by some of the reactance coupled from the network.

In order to obtain an initial setting of the network, capacitor 61 is selected of a variable type; a trimmer inductor 76 is connected across inductor 51 to adjust the effective reactance thereof; and a trimmer capacitor 77 is connected in parallel across capacitor 62. These variable components are factory-adjusted with the plasma in operation under a predetermined set of parameters until the reflected power substantially disappears for such operation. Thereafter a change in the parameters of the plasma over a known program for which the network is suited will not materially affect the amount of reflected power. For most programs the network of the present invention will effect a delivery of better than 95 percent of the applied power to the plasma.

Another important feature of the present network is the ability to handle very high amounts of reflected power which occurs on initiating operation and prior to the establishment of a plasma within chamber 11. This feature is provided by an inductor 78 which is connected across capacitor 62 and serves to protect the capacitor against arcing under the impact of the high standing wave energy which accompanies the complete mismatch condition prior to initiation of the ionized plasma. Inductor 78 is preferably wound like a radio frequency choke and has an inductance very much higher than inductors 51 and 56 so as to present a substantial circuit under normal operating conditions but still being sufficiently low so as to provide the desired protection for capacitor 61.

By way of example, inductor 78 may be in the millihenry range while inductors 51 and 56 are in the microhenry range. A specific example follows using for purposes of illustration a plasma generating apparatus having a plurality, in this case six 3"x6" long plasma reaction chambers; an RF generator output of up to 1000 watts at 13.56 MHz and a gas flow of up to 1000 cc per minute over a pressure range of about 700 to 10,000 microns of Hg. A plasma was established using oxygen gas and, with the generator and gas controls set to deliver approximately 400 watts of power and a gaseous flow rate of about 400 cc., the variable reactances 61, 76 and 77 were tuned to provide less than 1 watt of reflected power. The component values selected and thus arrived at were as follows: inductor 51 15 microhenrys inductor 76 2 microhenrys inductor 56 1.8 microhenrys inductor 78 1 millihenry capacitor 61 17 pico farads capacitor 62 100 pico farads capacitor 77 560 pico farads resistor 71 approximately 50 megohms (here being the internal resistance of capacitor 62)

The performance of the foregoing apparatus is illustrated in FIG. 3 showing the chart of an envelope of parameters within which the reflected power was found to be less than about 5 percent of the forward or applied power. In FIG. 3 applied power over a range of up to 1000 watts is plotted as the ordinate and gas flow rate ranging up to 1000 cc. per minute as the abscissa. The corresponding gaseous pressure ranging up to 10,000 microns Hg is also shown along the abscissa. It will be observed that the envelope of operating parameters for which the converter of the present invention is best suited, generally follows the relationship of 1 watt of power for each cc per minute gas flow, which is a generally recommended relationship for various plasma-chemical processes. It will be observed that in all 1-to-1 power to gas flow relationships the automatic impedance-matching network of the present inven-
tion will transmit 95 percent or better of the applied power. However, the apparatus is capable of automatic accommodation to other plasma parameter relationships. For example, with applied power of 500 watts there will be less than 5 percent reflected power for gas flow rates of 150 and 500 cc. per minute. Similarly, at 100 watts the flow rate may vary from about 200 to about 800 cc. per minute; at 500 watts from about 300 to 900 cc. per minute; at 600 watts from about 350 to about 950 cc. per minute; and at 700 watts from about 500 cc. per minute. Other permissible power, gas flow rate and pressure relationships resulting in a delivery of at least 95 percent of the applied power may be readily taken from the chart.

A present automatic converter is designed for direct interchangeability with existing manually tunable converters, thus facilitating a user's exploring of diverse applications of his plasma machine and also to enable the user to establish the optimum power-gas-flow rate for a given plasma-chemical process which may thereafter be carried out with the automatic impedance matching network of the present invention.

I claim:

1. In a plasma-generating apparatus including an RF generator having substantially a resistive impedance and a fixed frequency power output, a gaseous plasma chamber and means for flowing gas therethrough and capacitive electrodes for exciting the gas therein, the improvement comprising an impedance-matching network having input and common line terminals adapted for connection to said generator output and said electrodes, a first inductor having one end connected to said input terminal, a second inductor having one end connected to the other end of said first inductor and its other end connected to said output terminal, said inductors being mounted in mutually coupled relation, a first capacitor having its opposite sides connected respectively to said input and common line terminals, and means providing a second capaci-

tor having its opposite sides connected respectively to the junction between said inductors and said common line terminal.

2. The impedance matching network as defined in claim 1, said means providing a resistor in parallel with said second capacitor.

3. The impedance matching network as defined in claim 1, and a third inductor of relatively high impedance compared to said first and second inductors and being connected in parallel across said first capacitor for the protection thereof prior to initiation of a plasma in said chamber.

4. A plasma-generating apparatus comprising: means providing a gaseous plasma chamber and means for flowing gas therethrough and capacitive electrodes for exciting the gas in said chamber, a substantially fixed frequency RF generator having a substantially resistive output impedance having one side connected to one of said electrodes, an air core transformer having mutually coupled windings having first ends connected to place said windings in series and opposite ends connected to the other side of said generator output and the other of said electrodes, respectively, a capacitor connected across said generator output and means providing a second capacitor having its opposite sides connected to said first winding ends and said first named generator side.

5. The apparatus as defined in claim 4, said last named means providing a resistor in parallel with said second capacitor.

6. The apparatus as defined in claim 5, a third inductor of relatively high impedance compared to said windings and being connected in parallel across said first named capacitor, said inductor having an inductance sufficiently high to exhibit a substantially open circuit characteristic during operation of a plasma in said chamber and sufficiently low to provide protection for said first named capacitor prior to initiation of said plasma.