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Gorin

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[54] **PLASMA REACTOR APPARATUS AND METHOD**

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[51] **Int. Cl.**³ **H01L 21/312;** B44C 1/22; C03C 15/00; C23F 1/02

[52] **U.S. Cl.** .... **156/643;** 156/646; 156/345; 204/192 E; 204/298

[58] **Field of Search** .... 204/298, 192 E, 164; 156/643, 646, 345, 657, 656, 659.1, 662, 665; 427/38, 39

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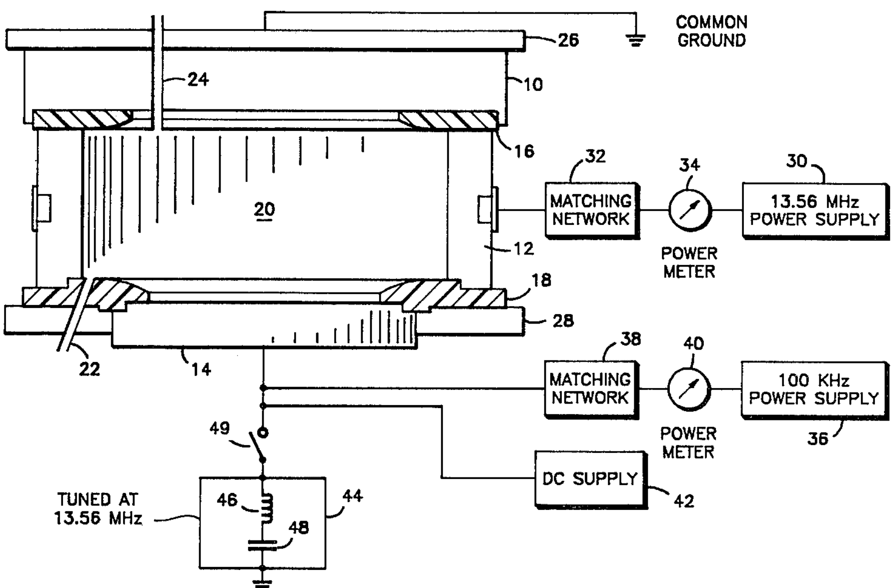
Primary Examiner—William A. Powell

[57] **ABSTRACT**

An improved plasma reactor apparatus and method are disclosed. Improved uniformity of etching and etch rate are achieved in a reactor through the use of electrodes powered at high and low frequencies. In one embodiment of the invention the workpiece which is to be etched rests on an electrode powered at a low AC frequency of about 100 KHz. A second electrode is powered at a high AC frequency of about 13.56 MHz. A third electrode is maintained at ground potential. High and low frequency AC fields acting on a reactant material optimize the dissociation of the reactant material and the ion energy of the plasma generated reactant species.

11 Claims, 4 Drawing Figures



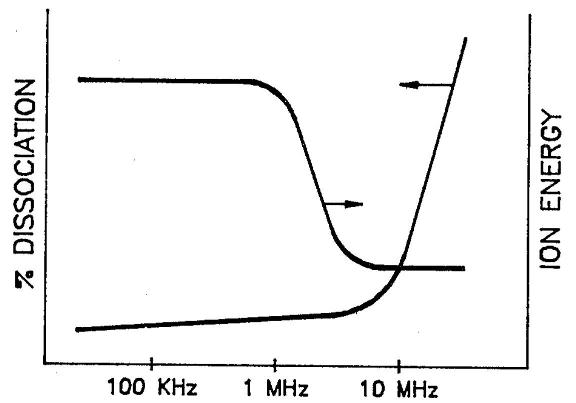


FIG. 1

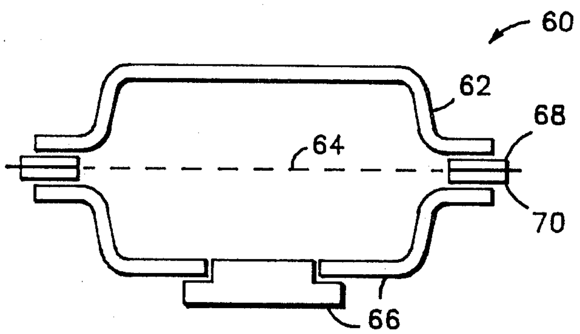


FIG. 3

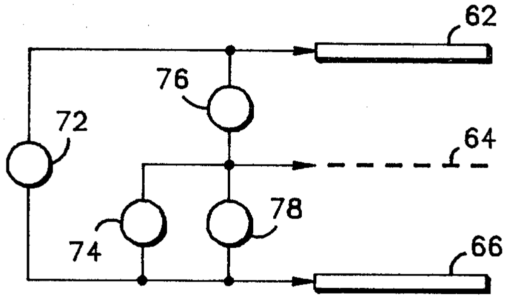


FIG. 4

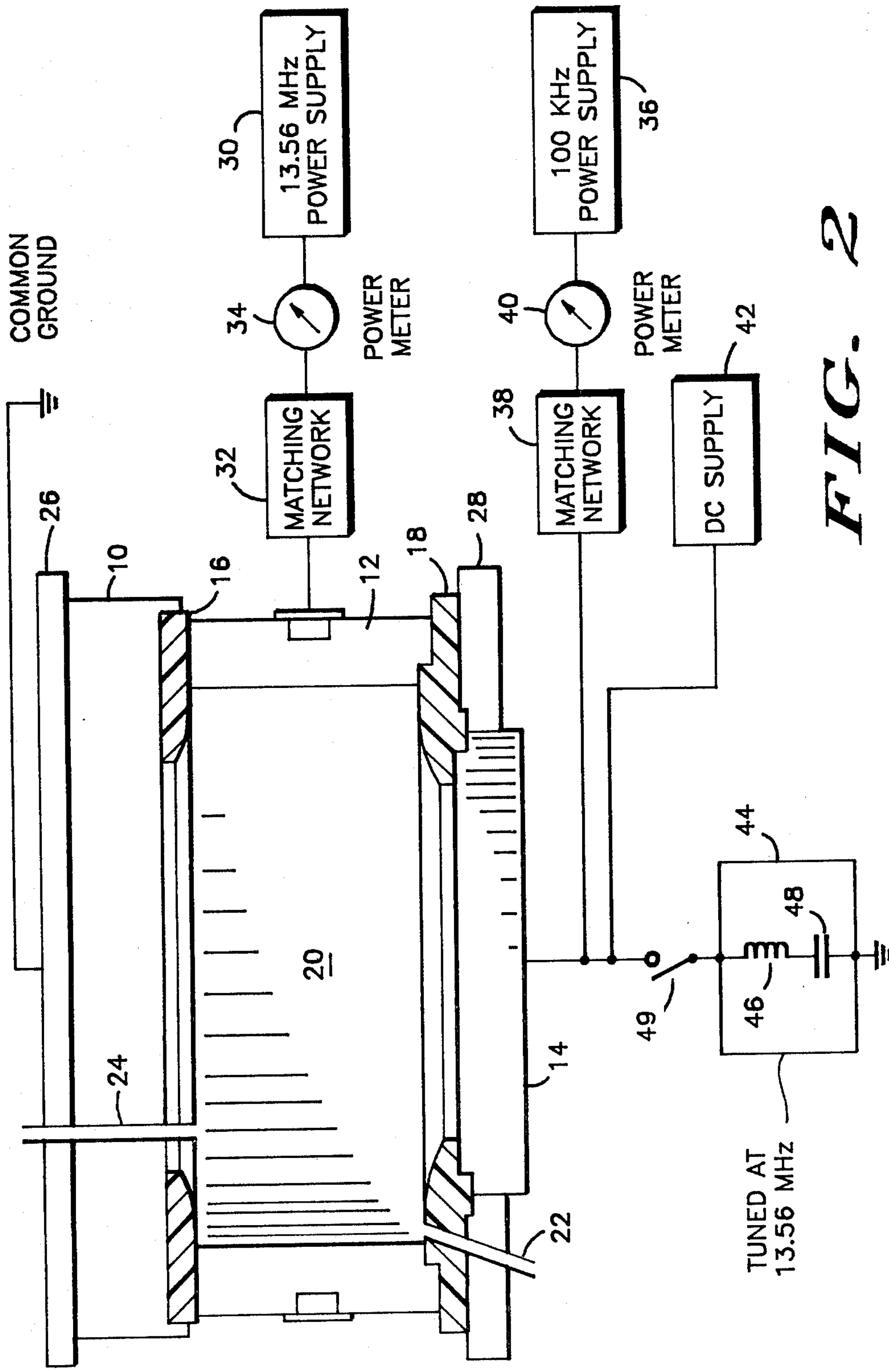

COMMON GROUND
13.56 MHz POWER SUPPLY
100 KHz POWER SUPPLY
POWER METER
POWER METER
MATCHING NETWORK
MATCHING NETWORK
DC SUPPLY
TUNED AT 13.56 MHz
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
49

FIG. 2

PLASMA REACTOR APPARATUS AND METHOD

BACKGROUND OF THE INVENTION

This invention relates to an improved plasma reactor apparatus and method, and more specifically to a multiple frequency plasma reactor apparatus and to a method for etching workpieces within that apparatus.

Plasma etching and reactive ion etching (RIE) have become important processes in the precision etching of certain workpieces such as in the fabrication of semiconductor devices. Differences in the two processes, which generally can be carried out in the same equipment, result from different pressure ranges employed and from the consequent differences in mean free path of excited reactant species. The two processes will herein be referred to collectively as plasma etching. Plasma etching is a "dry etching" technique and has a number of advantages over conventional wet etching in which the workpiece is generally immersed in a container of liquid etchant material. Some of the advantages include lower cost, reduced pollution problems, reduced contact with dangerous chemicals, increased dimensional control, increased uniformity, improved etch selectivity, and increased process flexibility. In existing plasma etch systems, however, it has not generally been possible to simultaneously achieve all of these advantages. A need therefore existed for equipment and process which would make several of the foregoing advantages simultaneously attainable.

It is therefore an object of this invention to provide an improved plasma reactor apparatus.

It is another object of this invention to provide an improved plasma etch process which enhances process flexibility.

It is another object of this invention to provide an improved plasma process which provides a higher degree of control over ion density and ion energy than previously practical.

It is a still further object of this invention to provide an improved plasma reactor apparatus, and a process for practice in that apparatus, which provides an improved uniformity of etch, improved etch selectivity, and improved dimensional control.

BRIEF SUMMARY OF THE INVENTION

The foregoing and other objects and advantages are achieved in the present invention through the use of a multiple frequency plasma reactor apparatus. The plasma reactor apparatus includes three electrodes. One of the electrodes is held at ground while the second is selectively coupled to a high frequency AC source and the third is selectively coupled to a low frequency AC source. A plasma generated by the high and/or low frequency electric fields established between the electrodes creates excited species of the reactants injected into the apparatus. The excited species act to precisely etch a workpiece positioned within the reactor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates percentage dissociation and ion energy as a function of plasma frequency;

FIG. 2 illustrates in cross section one embodiment of plasma apparatus in accordance with the invention;

FIG. 3 schematically illustrates a second embodiment of plasma apparatus in accordance with the invention; and

FIG. 4 illustrates coupling of the electrodes and power supplies of the second embodiment of the apparatus.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

In the nomenclature associated with plasma reactors and plasma processes, it is common to describe as "high frequency" any frequency greater than about 10 MHz. "Low frequency" is correspondingly used to describe any frequency less than about 1 MHz. The frequency of RF power applied to a reactant gas has an appreciable effect on the plasma that is generated from that gas. FIG. 1 illustrates, for example, the effect of frequency on the amount of dissociation that occurs in the reactant gas making up the plasma. The dissociation remains low until the frequency exceeds about 10 MHz. FIG. 1 also illustrates the effect of frequency on the energy of the ions generated in the plasma. The ion energy is generally high at low frequencies and falls off rapidly as the frequency is increased. The amount of dissociation of the reactant gas and the energy of the ions within the plasma have a marked effect on the uniformity of etching and also upon the rate of etching. The uniformity of etch is a strong function of the high frequency power while etch rate, for example in the case of oxide etching, is a strong function of low frequency power.

A high degree of etch uniformity and a high etch rate are achieved, in accordance with the invention, through the use of a plasma reactor apparatus employing three electrodes in combination with both a high frequency power source and a low frequency power source. One embodiment of apparatus in accordance with the invention is illustrated in cross section in FIG. 2. The apparatus includes a first electrode **10**, a second electrode **12**, and a third electrode **14**. The first and third electrodes are generally circular and the second electrode is ring-shaped. Ring-shaped ceramic insulators **16** and **18** provide electrical isolation between the first and second and the second and third electrodes, respectively. Together the three electrodes and two ceramic rings bound a generally cylindrical reaction volume **20**. Although not shown, the electrodes can be provided with temperature control means such as water cooling.

A gas inlet **22** provides for the ingress of reactants to the reaction volume. A gas outlet **24** provides for the egress of reaction products from the reaction volume under the influence of a vacuum pump (not shown). A top plate **26** and a clamp ring **28** mechanically hold the plasma reactor components together.

Lower electrode **14** is adapted for movement in the vertical direction. The electrode can be lowered to open the apparatus and to allow the placement of a workpiece within reaction volume **20**. The workpiece can be placed directly on the electrode, which functions as a workpiece holder, and then the electrode raised to the closed position.

In accordance with the invention, a high frequency power supply **30** and a low frequency power supply **36** are coupled to the second and third electrodes, respectively, so that high and low frequency electric fields can be established within the reaction volume to act upon reaction gases which enter the reactor through inlet **22**. In a preferred embodiment of the invention the top electrode **10** is coupled to ground. This electrode functions as the common ground for the system, being the ground reference for DC as well as high and low frequency AC supplies. The second electrode, the cylindrical ring electrode **12**, is coupled to a high frequency AC power supply **30** through a matching network **32**. Power, including both forward and reflected power, is monitored on a power meter **34**. Lower electrode **14** is coupled to a low frequency AC power supply **36** through a matching network **38**. Low frequency AC power is monitored on a power meter **40**. The high frequency power supply is preferably at a frequency of about 13.56 MHz (a frequency allocated for industrial uses by the FCC) and the low frequency power supply is preferably at a frequency of about 100 KHz.

In one embodiment of the invention the lower electrode is also coupled to a DC supply **42**. Use of a DC power supply allows the amount of DC biasing induced by the plasma to be changed, independently of pressure or power.

In a still further embodiment of the invention, a series circuit **44**, including, for example, an inductor **46** and capacitor **48**, tuned to the frequency of high frequency power supply **30**, is coupled between lower electrode **14** and ground. Switch **49** permits the selective coupling of series circuit **44** to electrode **14**.

During operation of the apparatus, in accordance with the invention, a workpiece, such as a semiconductor wafer, is placed on electrode **14** and the reaction volume is evacuated to a desired low pressure. Reactant gases are then admitted to the reaction chamber and the power supplies are energized. Either one or both AC power supplies can be energized, with or without the DC supply. Either AC supply creates a plasma within the reaction volume so that excited species of the reactant gas are created. Energizing high frequency supply **32** establishes an electric field which exists principally between upper electrode **10** and side electrode **12**. Energizing low frequency power supply **36** creates a low frequency field which exists principally between lower electrode **14** and upper electrode **10**. The combination of the two fields within the reaction volume and in proximity to the workpiece located on the lower electrode causes maximum dissociation of the reaction gas as well as imparting a high ion energy to the ions within the plasma.

The selective use of series circuit **44** by the closing of switch **49** has two effects. First, the tuned series circuit, which effectively places the lower electrode **14** at ground with respect to the high frequency supply, changes the electrode area ratio between the high frequency electrode and the ground electrode. This affects the plasma sheath potential above the wafer without physically changing the reactor. Second, coupling the series tank circuit to the lower electrode selectively couples the high frequency supply to the workpiece itself. This allows the optimizing of etch rates and etch selectivity for certain films. For example, the etch rate of silicon is high at low frequencies and drops off rapidly at high frequencies. In contrast, aluminum etches only slowly at low frequencies but etches rapidly at high frequencies. Thus, by selectively turning on or off the low frequency power supply and by selectively coupling or uncoupling the series circuit, the workpiece can be exposed to a high frequency, low frequency, or mixed frequency plasma.

FIG. **3** schematically illustrates a further embodiment of the invention. In this embodiment a plasma reactor **60** includes a first top electrode **62**, a screen electrode **64**, and a bottom electrode **66**. The bottom electrode can also function as a workpiece holder. Insulators **68** and

70 electrically isolate the three electrodes from each other.

FIG. **4** schematically illustrates one way in which the three electrodes can be powered. A high frequency power supply **72** such as a supply at 13.56 MHz is coupled between electrodes **62** and **66**. A low frequency power supply **74**, such as a supply having a frequency of about 100 KHz is coupled between electrodes **64** and **66**. In addition, DC supplies **76** and **78** are coupled between electrodes **62** and **64** and between electrodes **64** and **66**, respectively. Each of the supplies can be turned on or off or adjusted in power to create the desired plasma and to establish the desired DC bias on one or more electrodes.

The following are non-limiting examples which serve to further illustrate practice of the invention and to disclose preferred embodiments contemplated by the inventor.

EXAMPLE I

A plurality of silicon wafers were thermally oxidized to grow a silicon dioxide layer about 500 nm in thickness. Over the oxide layer was formed a layer of polycrystalline silicon, heavily doped with phosphorous and having a thickness of about 500 nm. A patterned photoresist etch mask was then formed on the layer of polycrystalline silicon. The wafers were divided into groups for the patterned plasma etching of the polycrystalline layer in a reactor as illustrated in FIG. **2**. The polycrystalline layer was first etched in a mixture of SF_6 plus 10% CCl_3F. The pressure in the reactor was maintained at 0.25 torr. The AC power between the top and side electrodes was maintained at 100 watts CW at 13.56 MHz. The polycrystalline silicon was etched until end point was detected, approximately 40 seconds. The polycrystalline silicon layer was then given an overetch in CCl_3F for about 18 seconds. During the overetch the high frequency power was maintained at 100 watts. One group of wafers was overetched with an additional DC bias of 100–150 volts applied to the wafer support electrode; one group was overetched without an additional DC bias. Wafers were examined after the etching. Those wafers overetched without a DC bias exhibited undercutting of the photoresist mask and a negative slope in the etched openings. That is, etched openings were narrower at the top of the polycrystalline silicon layer than at the bottom. Those wafers etched with a DC bias exhibited a decrease in undercutting and an increase in etched opening profile control. Additional groups of wafers were etched with a low frequency (100 KHz) supply coupled to the wafer support electrode. The low frequency plasma increased the anisotrophy of the polycrystalline silicon etch, but the etch selectivity of polycrystalline silicon over silicon dioxide decreased.

EXAMPLE II

A plurality of silicon wafers were thermally oxidized to grow a 500 nm thick layer of silicon dioxide. A layer of aluminum plus 4% copper was applied over the silicon dioxide to a thickness of 1000 nm. A patterned photoresist mask was formed over the Al/Cu layer. The wafers were divided into two groups for the etching of the alumimum. Both groups were etched in a CCl_4 plasma at 0.2–0.3 torr in a reactor as illustrated in FIG. **2**. One group was etched using only a 13.56 MHz plasma with the high frequency plasma maintained at 125 watts CW. The second group was etched using an

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