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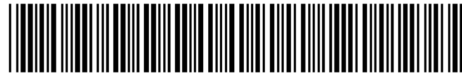

(11) Publication number : **0 665 575 A1**

(12) EUROPEAN PATENT APPLICATION

(21) Application number : **95300449.6**

(51) Int. Cl.[6] : **H01J 37/34**

(22) Date of filing : **25.01.95**

(30) Priority : **28.01.94 US 188287**

(43) Date of publication of application :
02.08.95 Bulletin 95/31

(84) Designated Contracting States :
AT BE CH DE ES FR GB GR IE IT LI NL SE

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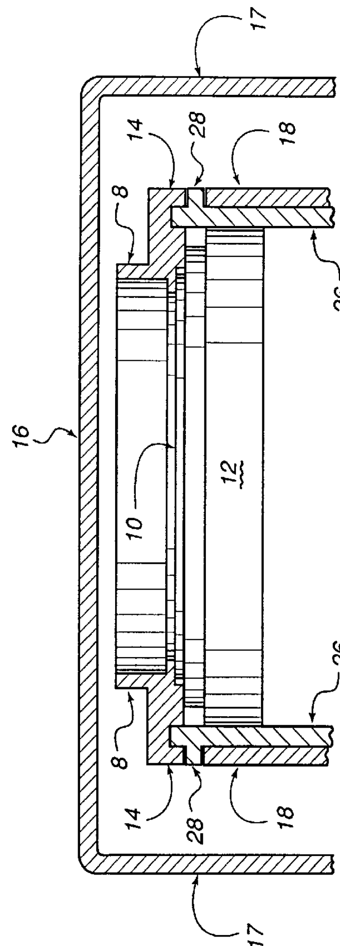
(54) Plasma processing systems.

(57) A reactive ion etching or magnetically enhanced reactive ion etching system consists of a cathode support structure (12), a shield structure (18) disposed around the cathode, an insulator (26) disposed between the cathode and the shield structure, and a clamping ring capable of mating with the top edge of the insulator. The insulator (26) has a generally cylindrical shape with a flange (28) that extends outward between the shield structure (18) and the clamping ring (14). A gap (24) between the clamping ring and the top edge of the insulator is controlled to 20 thousandths of an inch or less to restrict an RF coupling path between the shield and the cathode. In addition, the flange acts to interrupt the plasma conduction path between the shield structure and the cathode. By inhibiting plasma conduction between the shield and the cathode, reactive ion etching systems in accordance with the present invention operate in a higher pressure, higher power regime without arcing or exciting a secondary plasma.



EP 0 665 575 A1

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The present invention relates to plasma-based processing systems.

Etching operations are frequently used in the formation of modern semiconductor devices. Typically, layers within device structures are formed by depositing a thin film layer of material on the semiconductor substrate, forming a photoresist mask on the thin film layer, and then removing the material left exposed by the photoresist mask in an etching step. A number of characteristics of the reactive ion etching (RIE) technique make it better suited to the extreme demands of modern device processing than many of other etching techniques. Because of the high level of directional selectivity achieved with reactive ion etching, its use enables device structures of greater density to be formed. In addition, the relatively low temperatures at which RIE is performed make such process steps compatible with even the later stages of device processing.

The process of forming a photoresist mask and then etching to remove material is repeated many times in the formation of semiconductor devices. Thus, the etching process has a substantial impact on the processing time required to produce semiconductor devices, as well as on the yields for those processes. As with many of the processing steps employed to form modern semiconductor devices, there is a need to reduce the time needed for etching steps so that process through put can be increased. There is a similar need to improve the reliability and predictability of etching processes.

Reactive ion etching, and the related technique of magnetically enhanced reactive ion etching (MERIE), removes that portion of a thin film layer not protected by a photoresist mask through a combination of physical bombardment, chemical etching and chemical deposition. In these reactive ion etching processes, a chemical etchant from a plasma created above the etching substrate is transferred to and then absorbed onto the surface of the material to be etched. Ion bombardment provides additional energy to bring the absorbed etchant species to a higher energy state and to accelerate the surface reaction. Chemical etchants are typically chosen so that etching occurs predominantly at the exposed portions of the thin film layer rather than on the surfaces of the photoresist mask. Reacted material, which is typically volatile, is removed from the surface of the device through a vacuum exhaust line. An RIE or MERIE system typically uses a single, RF-powered cathode for generating a capacitively coupled plasma. Accordingly, the etching system walls, including the top lid, are typically grounded in such a system to define the extent of the RF field and the region in which a plasma is generated.

Optimizing the reactive ion etching environment typically includes optimizing the operational pressure within the etching chamber. When chlorine chemistry (*e.g.*, based on Cl_2), fluorocarbon chemistry, or other, similar chemistry is used in the etching system, it is desirable to operate at relatively high pressures (between about 100 milliTorr and about 250 milliTorr) to obtain a good balance between the effects of physical bombardment and chemical etching. When chemically strong etchants, such as SF_6 or NF_3, are used, lower pressure operation is desirable. Higher operating pressures can increase both the density of etchants within the plasma and the rate of transport of etchants to the surface of the etching substrate. In many circumstances, higher operating pressures may improve the selectivity between the photoresist mask and the material being etched. Higher operating pressures require a correspondingly higher level of RF power input to maintain a suitable DC bias to obtain good etch profiles. RIE and MERIE systems also exhibit greater stability and reduced etch residues at higher operating pressures.

Two types of cathode structures are typically used to deliver RF power into reactive ion etching systems. The "isolated cathode" structure uses a cathode separated from the chamber walls primarily by insulation. Although this cathode structure is simple and relatively reliable, the RF power input to the cathode may couple to the chamber wall through vacuum, giving rise to an undesirable secondary plasma. A second type of cathode structure places a shielding structure between the cathode and the walls of the etching system. In typical implementations of this "shielded cathode" design, a shield, typically in the form of a grounded cylinder, is placed around the cathode. An insulating cylinder, also typically cylindrical, physically and electrically separates the cathode from the shield. The grounded shield prevents the creation of a secondary plasma between the cathode and the walls of the etching chamber. Under some conditions, however, arcing may occur between the RF-powered cathode and the grounded shield. In particular, high operating pressure and high RF input power often causes arcing, probably because of the high potential drop over the short distance between the powered cathode and the grounded shield. The thinner plasma sheath associated with high pressure, high input power operation may make the generation of a secondary plasma more likely in the narrow space between the RF-powered cathode and the grounded shield.

One preferred embodiment of the present invention is an etching system including a cathode capable of exciting a plasma. A shield structure, which may be maintained at an electrical potential different from the cathode, is disposed adjacent to and about at least a portion of the cathode. An insulating structure is disposed between the cathode and shield. Any gaps within the insulating structure, or between the insulating structure and the cathode or shield, which may define a gas conduction path between the cathode and shield, are limited over at least a portion of any such gas conduction path to less than the threshold thickness which would allow the generation of a secondary plasma.

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Another preferred embodiment of a reactive ion etching system in accordance with the present invention includes a cathode coupled to a high frequency power source capable of exciting a plasma. A shield structure is disposed adjacent to at least a portion of the cathode, and the shield structure can be maintained at an electrical potential different from the cathode. An insulating structure is disposed between the cathode and the shield structure so that an edge of the insulating structure extends beyond either a surface of the cathode or an edge of the shielding structure. The edge of the insulating structure has a cap disposed upon it so that the cap defines at least a portion of a gas conduction path between the shield structure and the cathode. A flange extends from the insulating structure to interrupt the gas conduction path.

In another preferred embodiment of the present invention, a cathode is coupled to a high frequency power source capable of exciting a plasma. A shield structure is disposed adjacent to at least a portion of the cathode, and the shield structure is maintained at an electrical potential different from the cathode. An insulating structure is disposed between the cathode and the shield structure so that an edge of the insulating structure extends beyond either a surface of the cathode or an edge of the shielding structure. A cap structure is disposed adjacent to an edge of the cathode and is fitted to the insulating structure so that the cap structure is separated from the insulating structure by a sufficiently thin gap so that a secondary plasma is not generated within said gap at operating pressures in excess of 150 milliTorr. In a further aspect of this preferred embodiment, a gap equal to or less than 20 thousandths of an inch separates the cap structure from the edge of the insulating structure.

In yet another preferred embodiment of the present invention, a cathode is coupled to a high frequency power source capable of exciting a plasma. A shield structure is disposed adjacent to at least a portion of the cathode, and the shield structure is maintained at an electrical potential different from the cathode. An insulating structure is disposed between the cathode and the shield structure so that an edge of the insulating structure extends beyond either a surface of the cathode or an edge of the shielding structure. The etching system further includes means for restricting plasma conduction between the cathode and the shield structure at operating pressures of 150 milliTorr or greater.

The following is a description of some specific embodiments of the invention, reference being made to the accompanying drawings, in which:

Fig. 1 is a cross section of a prior art reactive ion etching system;

Fig. 2 is a detailed view of a portion of the reactive ion etching system of Fig. 1;

Fig. 3 is a detailed view of a portion of a reactive ion etching system in accordance with the present invention; and

Fig. 4 is a cross section of a reactive ion etching system in accordance with the present invention.

The present invention generally relates to reactive ion etching (RIE) systems and magnetically enhanced reactive ion etching (MERIE) systems. For convenience, these systems will be collectively referred to herein as reactive ion etching (RIE) systems. Prior art RIE systems are typically unable to maintain the higher operating pressures that are desirable for greater operating stability, improved etching rates, improved selectivity, and reduced residue levels. The present inventor has identified what is believed to be the primary mechanism for electrical breakdown in the shielded cathode configuration of prior art RIE systems. Apparently, a mechanical fitting becomes sufficiently loose during normal operation so as to allow ionized gas to flow between the system cathode and a grounded shielding structure within the system. By lengthening or restricting the path along which the ionized gas (*i.e.*, the plasma) must travel to conduct electricity, the likelihood that breakdown will occur by this mechanism can be greatly reduced, allowing for higher pressure operation in a shielded cathode RIE system. In a preferred embodiment of the present invention, the plasma conduction path can be interrupted by extending an insulating flange to divert plasma flow away from the normal conduction path between the cathode and the shielding structure. In another preferred embodiment of the present invention, the plasma conduction path is restricted by reducing the size of the gap between the insulating structure and the clamping ring structure used to hold the etching substrate in place. By substantially improving the machining tolerances for this mechanical joint, the likelihood of creating a sufficient plasma conduction path to allow arcing to occur is greatly reduced.

Fig. 1 illustrates a prior art RIE system in cross section. The illustrated etching system consists of an etching substrate 10 disposed on a support structure 12. Most often, the etching substrate 10 is a semiconductor wafer at some intermediate stage of processing. The etching substrate is preferably mounted in a temporary but rigid manner with respect to the support structure 12. For example, the support structure may be an electrostatic chuck that holds the etching substrate in place by inducing a large electrostatic attraction between the dielectric etching substrate and a charge established within the electrostatic chuck. Alternatively, the etching substrate may be held in place by a clamping ring 14, as illustrated in Fig. 1.

During etching operations, the support structure 12 preferably acts as a cathode for the etching system. Generally, the anode for the system is primarily the upper surface 16 (*i.e.*, the lid) of the etching chamber, but

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the walls 17 of the etching chamber also act as part of the system anode. Both the lid 16 and the walls 17 of the etching chamber are preferably grounded. In operation, a molecular gas such as BCl_3, Cl_2, HBr, SF_6, C_2F_6 or CF_4 is introduced to the region between the cathode 12 and the lid 16 of the etching chamber. RF power is applied to the cathode 12, so that the RF power capacitively couples to and excites the molecular gas, partially or completely ionizing the gas to create a plasma. The molecular gas is chosen so that it ionizes to yield an etchant species that is suitable to etch the desired material from the surface of the etching substrate 10. The difference between the surface area of the cathode 12 and the surface area of the lid 16 and walls 17 of the etching chamber (collectively the system anode) means that the etching system's RF circuit is asymmetric. Consequently, when RF power is applied to the cathode, a DC bias will be induced on the cathode. This induced DC bias is typically negative and tends to accelerate positive ions toward the etching substrate. An additional DC field may also be applied to further accelerate the ionized etchant gases toward the etching substrate 10. The induced and applied DC fields improve the etching rate by increasing the transport of etchant to the surface of the etching substrate 10 and by increasing the kinetic energy of the etchant molecules reaching the surface of the etching substrate.

High plasma density and high ionization levels are favorable to improved etching rates. Producing a high density plasma or a high ionization level requires very high input power levels. As a practical matter, the plasma for etching must be contained within a well-defined region of the processing chamber. If the plasma is not adequately contained, there may be insufficient power density to maintain the plasma, even if powerful RF generators are used to excite the plasma. To facilitate the formation of a stable plasma, a number of measures are taken within the processing environment to contain both the plasma itself as well as the electric field used to create the plasma. Often, the lid 16 of the etching chamber and the support structure 12 are spaced closely together and the plasma gases may be physically confined in other manners. For example, a ring 8 may extend from the clamping ring 14 to partially confine the plasma gas within the region adjacent to the etching substrate 10.

In shielded cathode RIE systems, the RF electric field used to create the plasma is also contained to prevent power dissipation in ways that do not contribute to the formation of an etching plasma. An example of such containment is illustrated in Fig. 1. A shield structure 18 is disposed around the cathode support structure 12 to contain the RF driving field. The shield structure 18 is typically disposed as closely as possible to the cathode support structure 12 and is generally maintained at ground potential. Accordingly, the shield structure 18 also acts, to some extent, as an anode for the reactive ion etching system. The close proximity of the shield structure 18 to the cathode support structure 12, coupled with the presence of ionized gases from the plasma, makes electrical conduction between the shield structure 18 and the cathode support structure 12 likely unless appropriate measures are taken. Such electrical conduction is an effective short circuit, allowing the input RF power to be drawn away and causing the plasma to break down.

To prevent conduction between the shield structure 18 and the cathode support structure 12, a dielectric insulator 20 is disposed between shield structure 18 and the cathode support structure 12. Often the dielectric insulator 20 is formed from quartz because of the durability, toughness and good insulating properties of quartz. Other dielectric materials can also be used, including such dielectric ceramics as alumina. For the geometry shown in Fig. 1, the dielectric insulator 20 has a cylindrical or pipe-like shape. In addition to providing a dielectric insulator 20 between the shield structure 18 and the cathode support structure 12, it is typical to use a close fitting cap over the dielectric insulator 20 to further electrically isolate the shield structure 18 and the cathode support structure 12. For example, when a clamping ring structure is used, the clamping ring 14 may be formed with a groove having a rectangular cross section that mates with the edge of the dielectric insulator 20. The joint between the dielectric insulator 20 and the clamping ring 14 illustrated in Fig. 1 is shown in greater detail in Fig. 2. Here, and in all of the figures discussed herein, the same numbers are used to indicate the same or similar components of the illustrated systems.

Fig. 2 illustrates the mechanical joint between shield structure 18, dielectric insulator 20, cathode support structure 12 and clamping ring 14. A channel 22 having a rectangular cross section is formed in clamping ring 14 to fit over the edge of the dielectric insulator 20 that extends above the shield structure 18 and the edge of the cathode 12. The channel 22 is designed to fit around the edge of the dielectric insulator 20. Using the clamping ring 14 as an end cap for the dielectric insulator 20 has the effect of further electrically isolating the shield structure 18 from the cathode support structure 12. However, the gap 24 which is left between the channel 22 and the edge of the dielectric insulator 20 upon assembly of the clamping ring 14 to the dielectric insulator 20, generally has not been well controlled in embodiments of the Fig. 1 geometry. Consequently, the typical gap 24 has ordinarily been on the order of between about 40 and 60 thousands of an inch.

Despite the measures taken to electrically isolate the cathode support structure 12 from the shield structure 18 and to contain the plasma field within the region in which the etching operation is to be performed, existing reactive ion etching systems cannot be reliably operated at high pressures. For example, the use of

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pressures above about 150 milliTorr results in plasma instability and arcing in existing shielded cathode designs of reactive ion etching systems. Table 1 illustrates the arcing problems of an RIE system of the general configuration indicated by Fig. 1. This Table shows the level of DC bias (in Volts) induced on the cathode for a variety of different input RF power levels for a number of different operating pressures. Either two or three trials were made at each combination of input RF power and operating pressure. Typical DC biases for non-arcing conditions are between -300 V and -500 V. The shaded boxes indicate trials in which arcing was observed within the 50 second trial period.

TABLE 1

DC BIAS (Volts) -- PRIOR ART CONFIGURATION					
PRESSURE (mTorr)	RF Power Input to Target				
	400W	450W	500W	550W	600W
150	-448	-465	-497	-540	-540
	-450	-465	-504	-530	-540
				-540	-540
200	-150	-392	-140	-134	-100
	-380	-398	-420	-430	-100
			-418	-134	
250	-320	-340	-140	-100	
	-320	-340	-356	-370	
				-100	
300	-260	-290	-138	-100	
	-113	-295	-308	-320	
			-305	-330	

Previous efforts have been unable to improve upon the performance indicated in Table 1. The present inventor has identified what is believed to be the most common breakdown path in existing shielded cathode reactive ion etching systems. By reducing the likelihood of electrical breakdown along this path, the present invention overcomes some of the disadvantages of existing reactive ion etching systems. The resulting system has achieved stable operation at considerably higher operating pressures and has achieved greater stability at those pressures than has been obtained with existing reactive ion etching systems.

The present inventor has observed that in existing shielded cathode etching systems, the shield structure 18 is insufficiently insulated from the cathode support structure 12, giving rise to the arcing and plasma breakdown indicated in Table 1. The present inventor has determined that, despite the presence of an insulating structure 20 and the presence of an isolating clamping ring structure 14, electrical breakdown occurs in shielded cathode etching systems by plasma conduction between the shield structure 18 and the cathode support structure 12. This conduction is mediated by the presence of ionized gas within a gap 24, indicated in Fig. 2, between the clamping ring channel 22 and the dielectric insulator 20. In existing RIE systems, the channel 22 is typically machined so that the gap 24 remains on the order of between 40 and 60 thousandths of an inch. Gap 24 may open further during the normal operation of the reactive ion etching system due to the differential

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