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METHOD FOR ANISOTROPICALLY ETCHING TUNGSTEN USING SF_6, CHF_3, AND N_2

The present invention relates to a method for etching tungsten containing material on a substrate.

In integrated circuit fabrication, refractory metals, such as for example tungsten, tantalum, titanium, molybdenum, and their silicides, are used to form high density, high speed, electrically conductive interconnect lines and/or contact plugs for electrically connecting active semiconducting devices formed on silicon or gallium arsenide substrates. In a typical process, a blanket tungsten layer is deposited over an underlying titanium, titanium-nitride, titanium-tungsten, which serves as an barrier or adhesion layer. This is followed by a masking step in which patterned photoresist features are formed over the tungsten layer. To form interconnect lines on the substrate, an etch step is used to remove the tungsten material from the regions not covered by the photoresist features. Tungsten layers can also be used for filling openings to form electrically conducting contact plugs below interconnect wiring layers, by chemical vapor deposition of a blanket tungsten layer that fills the openings, followed by etching of the blanket tungsten layer to form the desired configuration of interconnect lines and/or plugs. Tungsten is desirable for both interconnect lines and contact plugs because (i) tungsten has a higher melting temperature of about 3410°C compared to aluminum which melts at 660°C, which allows high temperature processing of the substrate; (ii) tungsten exhibits reduced electromigration or diffusion when applied over a silicon layer, (iii) tungsten reacts with silicon at temperatures exceeding 600-700°C, whereas aluminum reacts with silicon at lower temperatures of 250°C, (iv) tungsten deposition generally provides more uniform filling of high aspect ratio contact plugs, better step coverage, and reduced formation of electrical discontinuities that cause shorts or breaks.

Conventional processes for etching tungsten containing layers use a capacitive RIE plasma of halogen-containing gases, and more typically fluorinated gases, such as CF_4, SF_6, $CBrF_3$, and NF_3. One problem with conventional etching processes lies in their inability to anisotropically etch tungsten containing layers to provide features having substantially vertical sidewalls which are not inwardly or outwardly tapered. Excessive etching at the sidewalls of the etched features results in the undesirable inwardly or outwardly sloped sidewalls.

Conventional tungsten etch methods that provide increased anisotropic etching use gases such as CBr, NF_3, or CHF_3 to form thick passivating deposits on the sidewalls of the etched features to reduce horizontal etching, as described in *J. Vac. Sci. Technol. B*, page 3272 (1985). However, these methods often result in etched features which have wider dimensions at the base due to the increased thickness of the passivating film that forms on the freshly etched sidewalls of the features as the etch process proceeds to completion. In yet another method, gas mixtures of $SF_6/CBrF_3$ or SF_6/CHF_3 are used to reduce undercutting, but these mixtures nonetheless yield isotropic profiles with substantial undercutting at the base of the etched feature, as for example, disclosed in Tennant, et al., *J. Vac. Sci. Technol. B*, page 71836 (1989). In yet another etching method, as described in U.S. Patent No. 4,992,136 to Tachi, et al., the tungsten film is etched using (i) an etchant gas such Cl_2 or SF_6; and (ii) a passivating film forming halogen gas containing C or Si to form deposits on the surface of the substrate during etching, such as CCl_4, CF_4, CHF_3, $CHCl_3$, SiF_4, or $SiCl_4$. However, this method generally provides tapered angles for the sidewalls of the etched features because it is difficult to precisely control the ratio of the etchant gas to the film forming gas during the etching process, particularly towards the completion of the etching process when a high concentration of volatile passivating polymeric species is formed in the etchant chamber.

Conventional etching processes also often fail to maintain the critical dimensions of the etched features, which are predefined and desirable dimensions of the etched features, used to determine the electrical properties of the etched features, in the design of integrated circuits. The critical dimensions are those dimensions that have a significant effect on the electrical properties of the etched features. In modern integrated circuits, the line widths of interconnect lines and diameters of contact plugs are becoming increasingly smaller to levels below 0.25 microns, to accommodate higher circuit densities. Because the electrical resistance of these features is proportional to the cross-sectional area of the etched features, it is important to maintain consistent and uniform dimensions without variations of across an etched feature or between different etched features. Tapering cross-sections, cross-sectional profiles that vary as a function of the spacing between the features, or other variations in the profile of the features is no longer acceptable in modern integrated circuits. The critical dimensions are typically measured as a ratio or difference between the width W_r of the resist features and the width W_e of the resultant etched features. The closer the width of the etched feature to that of the resist feature the more predictable and reliable are the electrical properties of the etched feature.

Thus, it is desirable to have a process for etching tungsten-containing layers which exhibits anisotropic etching and provides etched features having substantially straight sidewalls. It is further desirable for the etching process to provide etched features having consistent and reproducible critical dimensions. It is also desirable for the etching process to exhibit reduced and more controllable formation of passivating film deposits on the sidewalls of the etched features. It is further desirable for the etching process to have a large processing window tolerant of process fluctuations and provide a high process throughput.

The present invention provides highly anisotropic etching of tungsten containing layers on a substrate to provide low loss of critical

dimensions and prevent excessive deposition of thick passivating films on the etched features. In one aspect of the method, the substrate is placed in a plasma zone, and a process gas comprising SF_6, CHF_3, and N_2 is introduced into the plasma zone. A plasma generated from the process gas etches the tungsten containing layer on the substrate (i) substantially anisotropically, and (ii) without forming excessive passivating deposits on the substrate. The volumetric flow ratio of SF_6:CHF_3:N_2 is selected so that the tungsten containing layer is etched to provide etched features having sidewalls that form angles of at least about 88° with a surface of the substrate. Preferably, the volumetric flow ratio of SF_6:CHF_3:N_2 is from about 1:1:1 to about 8:1:1.

In another aspect of the present method, the substrate is placed in a process chamber comprising (i) process electrodes therein, and (ii) an inductor coil adjacent to the process chamber. A process gas comprising SF_6, CHF_3, and N_2 is introduced into the process chamber. The process gas is ionized to form plasma ions that energetically impinge on the substrate by (i) applying RF current at a first power level to the inductor coil, and (ii) applying RF voltage at a second power level to the process electrodes. The power ratio P_r of the first power level to the second power level is selected so that the tungsten containing layer is anisotropically etched without excessive deposition of passivating material on the substrate.

These and other features, aspects, and advantages of the present invention will become better understood from the following drawings and description, which show and describe examples of the invention, and from the appended claims, where:

Figure 1a is a schematic partial sectional view of a substrate having a tungsten layer and a patterned resist layer thereon;

Figure 1b is a schematic partial sectional view of the substrate of Figure 1a after etching of the tungsten layer showing substantially anisotropically etched features;

Figure 1c is a schematic partial sectional view of the substrate of Figure 1b after stripping the resist layer; and

Figure 2 is a schematic view in vertical cross-section of a process chamber suitable for practicing the etching process of the present invention.

The etching process of the present invention is useful for etching tungsten containing layers formed on a substrate **10** with high anisotropy and reduced passivating deposits, and good etch rates. With reference to Figures 1a to 1c, the present process is used to etch a substrate **10** made of any material, such as glass, ceramic, metal, polymer, or a semiconductor substrate, for example silicon or gallium arsenide wafers. A dielectric layer **15** such as doped or undoped silicon dioxide, silicon nitride, BPSG, or PSG (which is typically about 100 to 3000 Å thick) is formed on the substrate **10**. The substrate **10** is descummed to remove the native oxide layer on the silicon containing surfaces typically using an O_2 plasma. A thin barrier or adhesion layer **20**, such as a layer of titanium (Ti), titanium tungsten (Ti-W), or titanium nitride (TiN) having a thickness of 100 to 1000 Å can also be deposited on the substrate **10**. A tungsten-containing layer **25** is deposited on the substrate **10** by sputtering from a tungsten target, or by chemical vapor deposition from tungsten source gases, such as tungsten hexafluoride (WF_6). For example, commonly assigned U.S. Patent No. 5,500,249, to Telford et al., which is incorporated herein by reference, describes a chemical vapor deposition process for depositing WSi_x films via plasma enhanced chemical vapor deposition of tungsten hexafluoride and dichlorosilane. The tungsten containing layer **25** typically has a thickness of

about 500 Å to about 10000 Å, and is deposited by a low temperature RF biased sputtering processes.

Conventional photolithographic methods are used to form a patterned resist features **30** covering the tungsten containing layer **25**, the resist layer having features dimensioned according to the critical dimensions of the features desired to be etched in the tungsten containing layer. In this step, a layer of resist such as "RISTON" photoresist manufactured by DuPont de Nemours Chemical Company, is applied on the tungsten containing layer **25** to a thickness of about 0.4 to about 1.3 micron. The resist features **30** are defined using conventional lithographic processes in which the resist layer is exposed to a pattern of light through a mask that corresponds to the desired configuration of resist features **30**. After the etching process, the protective resist features **30** result in formation of the etched tungsten containing features **35**, as shown in Figure 1b. Thereafter, the residual resist features **30** are removed by conventional resist removing processes to provide a substrate comprising etched tungsten features **35**, as shown in Figure 1c.

The tungsten containing layer **25** is etched in a process chamber **50**, such as for example, a "DPS" chamber, schematically illustrated in Figure 2, and commercially available from Applied Materials Inc., Santa Clara, California. Portions of the process chamber are described in U.S. patent application serial nos. 08/597,445, entitled "RF Plasma Reactor with Hybrid Conductor and Multi-Radius Dome Ceiling" filed on February 2, 1996; and serial no. 08/389,889, filed on February 15, 1993 -- both of which are incorporated herein by reference. The particular embodiment of the process chamber **50** shown herein, is suitable for processing of a semiconductor substrate **10**, is provided only to illustrate the invention, and should not be used to limit the scope of the invention. For example, the etching process of the present invention can be used to simultaneously etch multiple substrates,

and can be used for manufacturing processes other than semiconductor fabrication.

To perform the etching process, the chamber **50** is evacuated to a low pressure, typically less than about 1 Torr, and a substrate **10** is placed on a support **52** within a plasma zone **55** in the chamber. At least a portion of the support **52** is electrically conductive and serves as a process or cathode electrode **60**. The cathode electrode **60**, in conjunction with sidewalls of the chamber **50** which are electrically grounded to serve as an anode electrode **65**, form process electrodes in the plasma zone **55** that form a capacitive electric field that generates or energizes the plasma in the chamber. The substrate **10** can be held in place during the etching process using a mechanical or electrostatic chuck with grooves in which a coolant gas, such as helium, is held to control the temperature of the substrate **10**. The substrate **10** in the chamber is typically maintained at a temperature of about -20 to 30°C, more preferably -5 to 15°C, and most preferably about 0 to 5°C, by flowing helium gas below the substrate **10** at a pressure of about 1 to 10 Torr. The lower substrate temperatures provide increased control of the cross-sectional profile of the etch features by reducing vaporization of the passivating film formed on the etch features.

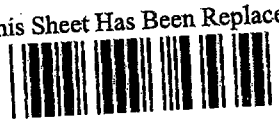
Process gas is introduced into the chamber **50** through a gas distributor **70** peripherally disposed about the substrate **10**, and the pressure in the chamber is regulated to about 1 to about 1000 mTorr, more typically from 5 to 30 mTorr, and preferably about 10 mTorr. A plasma is formed from the process gas using a plasma generator that couples an energetic electromagnetic field into the plasma zone **55**, such as an inductive, capacitive, or microwave field. Preferably, the plasma generator comprises both an inductive and a capacitive plasma source. The inductor coil **75** adjacent to the process chamber **50** that forms an inductive electric field in the chamber when powered by a coil power supply **76** operated using an RF

current at a first source power level that is preferably from about 100 Watts to about 3000 Watts; at preferably a frequency of about 2 MHZ.

Typically, a capacitive Rf electric field is formed in the chamber using the cathode and anode electrodes **60**, **65**, powered by an electrode power supply **78** operated using an RF voltage at a second power level of preferably about 100 to about 2000 Watts. The capacitive electric field is perpendicular to the plane of the substrate **10**, and accelerates inductively formed plasma species toward the substrate **10** to provide more vertically oriented anisotropic etching of the substrate. The frequency of the RF voltage applied to the process electrodes **60**, **65**, and/or the inductor coil **75** is typically from about 50 Khz to about 60 MHZ, and more typically about 13.56 MHZ.

Preferably, the process chamber **50** comprises a quasi-remote plasma zone **55** that provides enhanced plasma etching properties. The quasi-remote plasma zone **55** is defined by the region bounded by (i) the substrate **10**, (ii) chamber sidewalls **80** adjacent to the substrate, and (iii) the ceiling **85** of the chamber having an apex at a height H of from about 100 mm to about 175 mm (4 to 7 inches) above the substrate **10**. It should be noted that the ceiling height can vary for different diameter substrates, the ceiling height described herein being suitable for substrates having diameters of from about 150 mm to about 304 mm (6 to 12 inches). Preferably, the quasi-remote plasma zone **55** comprises a volume of at least about 10,000 cm^3, and more preferably from about 10,000 to about 50,000 cm^3. In the quasi-remote plasma zone, the plasma is formed directly below the ceiling **85** and immediately above the substrate **10**. Preferably, the quasi-remote plasma zone **55** has a center **88** located at a distance of about 50 to about 150 mm directly above the substrate **10**, and more preferably at a distance that is greater than about 75 mm and less than about 125 mm from the substrate **10**.

This Sheet Has Been Replaced



THIS SHEET HAS BEEN REPLACED

It is believed that the quasi-remote plasma zone **55** provides reduced recombination of active dissociated ions into inactive non-dissociated ions as compared to conventional remote plasma zones, such as for example, microwave plasma apparatus. When the center **88** of the plasma zone **55** is remote from the substrate **10** and the plasma ion has to travel a large distance (typically greater than about 30 cms) from the remote plasma source to the substrate **10**. Conversely, if the center **88** of the plasma zone **55** is too close to the substrate **10**, i.e., less than about 10 cms, the high power current applied to the plasma generator to increase dissociation causes the plasma ions to have excessively high kinetic energies which results in uncontrollable etching performance. Also, if the volume of the plasma zone **55** is too small, it is difficult to form dissociated plasma ions because the mean free path of the energized inert gas ions is excessively small, resulting in fewer collisions between the inert gas ions and the etchant gas molecules. If the center of the plasma zone is too far from the substrate **10**, or if the volume of the plasma zone **55** is excessively large, the dissociated ions in the plasma zone recombine to form non-dissociated species before they actually reach the substrate **10**. For these reasons, it is preferred to use the quasi-remote plasma zone **55** for etching of the substrate **10**.

The ceiling **85** of the process chamber **50** can be flat or rectangular shaped, arcuate, conical, dome-shaped, or multi-radius dome-shaped. Preferably, the process chamber **50** has a multi-radius dome-shaped ceiling **85** above the substrate **10** to provide a uniform distribution of plasma source power across the entire volume of the plasma zone **55** to increase dissociation of the etchant gas, as for example described in U.S. patent application serial no. 08/596,960, to Diana Ma, et al., entitled "Plasma Process for Etching Multicomponent Alloys," filed on February 5, 1996, which is incorporated herein by reference. The multi-radius dome-shaped ceiling **85** reduces dissociated ion recombination losses near the substrate **10** to less than those experienced with a flat ceiling, so that

plasma ion density is more uniform across the substrate **10**. This is because ion recombination losses are affected by the proximity of the ceiling **85**, and the dome-shaped ceiling is further from the substrate center than a flat ceiling.

Preferably, the inductor coil **75** is wrapped around the sidewall **80** of the process chamber **50** in the form of a multi-radius dome-shaped inductor coil having a "flattened" dome shape that provides more efficient use of plasma source power and increased plasma ion density directly over the substrate **10** center. This is because ion density is affected by local ionization near the inductor coil **75**, and a multi-radius inductor coil is closer to the substrate center than a hemispherical coil. In another preferred embodiment, the ceiling **85** comprising a multi-radius dome having at least a center radius R and a corner radius r less than the center radius R, wherein R/r is from about 2 to about 10.

The plasma formed in the quasi-remote plasma zone 55 can also be enhanced using magnetically enhanced reactors, in which a magnetic field generator, such as a permanent magnet or electromagnetic coils, are used to apply a magnetic field in the plasma zone **55** to increase the density and uniformity of the plasma. Preferably, the magnetic field comprises a rotating magnetic field with the axis of the field rotating parallel to the plane of the substrate **10**, as described in U.S. Patent No. 4,842,683, issued June 27, 1989, which is incorporated herein by reference. The magnetic field in the chamber **50** should be sufficiently strong to increase the density of the ions formed in the plasma, and sufficiently uniform to reduce charge-up damage to features such as CMOS gates. Generally, the magnetic field as measured on a surface of the substrate is less than about 500 Gauss, more typically from about 10 to about 100 Gauss, and most typically from about 10 Gauss to about 30 Gauss.

Spent process gas and etchant byproducts are exhausted from the process chamber **50** through an exhaust system **95** capable of achieving a minimum pressure of about 10^{-3} mTorr in the process chamber **50**. A throttle valve **100** is provided in the exhaust for controlling the pressure in the chamber **50**. Also, an optical endpoint measurement technique is often used to determine completion of the etching process for a specific layer by measuring the change in light emission of a particular wavelength corresponding to a detectable gaseous species. A sudden decrease or increase in the amount of the detectable species, such as silicon species, that results from chemical reaction of the process gas with the silicon dioxide layer **26**, indicates completion of etching of the tungsten containing layer **25** and start of etching of the underlying layer.

The etching process gas composition of the present invention provides highly anisotropic etching of the tungsten containing layers **30** with high etch rates and good etching selectivity relative to the underlying silicon dioxide layer **15**. The etching process uses a process gas comprising (i) sulfur hexa-fluoride (SF_6), (ii) methyl trifluoride (CHF_3), and (iii) nitrogen (N_2). The SF_6 gas dissociates in the plasma to form dissociated atomic fluorine-containing species that chemically etch the tungsten containing layer **25** on the substrate **10**. For example, tungsten containing material is etched by fluorine-containing ions and neutrals to form volatile WF_x species that are exhausted from the chamber **50**. It is believed that SF_6 gas provides a high ratio of dissociated fluorine ions relative to non-dissociated fluorine ions in the quasi-remote plasma zone of the present apparatus, that enhances etching anisotropy and etching selectivity.

Preferably, the process gas consists essentially of SF_6, CHF_3, and N_2. It has been discovered that the addition of CHF_3 and N_2 gas to the SF_6 gas provides significantly higher anisotropic etching of the tungsten containing layer **25** with little or no change in the critical dimensions of the etched features **35**. The critical dimensions ("CD") are the predefined and

desirable dimensions of the etched features, which are used to determine the electrical properties of the etched features, in the design of integrated circuits. The critical dimensions are dimensions of etched features that can have a significant effect on its electrical properties. For example, the electrical resistance of metal interconnect lines is proportional to the cross-sectional area of the etched features, particularly, the height and width of the etched features. As the dimensions of etched features are diminished due to advances in etching technology, the cross-sectional area of the interconnect lines becomes a critical dimension that should be maintained as close to the desired dimensions as possible to provide the required electrical resistance levels. Thus, tapering cross-sections, cross-sectional profiles that vary as a function of the spacing between the features, or other variations in the profile of the features is no longer acceptable in modern integrated circuits. Critical dimension measurements are typically made using cross-sectional scanning electron micrographs of the substrate before and after etching. The average width (W_r) of resist features 30 formed on the blanket tungsten layer 25 is measured prior to etching; and after etching a second width (W_e) of the etched features 35 is measured. The critical dimension loss is the difference between the two dimensions of $W_r - W_e$; and the % critical dimension loss is $(W_r - W_e)/W_r \times 100\%$. The minimum critical dimension is the average value of the smallest width across the cross-sections of the etched features 35. It is desirable to maintain critical dimension loss of less than 300 Å, and more preferably, less than 100 Å. It is further desirable to provide a percent critical dimension loss of less than 4% and more preferably less than 2%.

The present gas chemistry provides excellent control of the critical dimensions of the etched features and highly anisotropic etching of the features. It is believed that process gas consisting essentially of SF_6, CHF_3, and N_2, forms a sufficient amount of "passivating" polymeric species (typically $C_xO_yN_z$ containing polymeric species) in the plasma to form passivating films that protect the etched sidewalls 40 of the features 35, and reduce isotropic etching, tapering, and undercutting of the etched features

35. At the same time, the thickness of the passivating film is controlled to prevent formation of excessively thick passivating films on the etched tungsten features. It is difficult to measure the thickness of the passivating polymeric film formed on the etched features, however, it has been found that excessively thick passivating films provide etched features having a tapered profile which is thicker at the bottom and thinner at the top. Although controlling the thickness of the passivating film deposits, the CHF_3 and N_2 gas addition does not reduce etching selectivity (which is reduced when the rates of etching of the silicon dioxide underlayer 15 are increased). It is believed that the nitrogen gas significantly increases the rate of dissociation of the SF_6 and CHF_3 gases. The increased number of dissociated ions and neutrals increases the rate of etching of the tungsten containing layer 25, and also increase the amount of $C_xO_yN_z$ passivating species that are deposited on the sidewalls 40 of the freshly etched features 35 thereby maintaining the critical dimensions of the etched feature. Because the atomic and molecular constituents of an active plasma are difficult to analyze, the nature or composition of the volatile passivating species is difficult to determine with accuracy.

Thus, the ratio of the flow rate of SF_6 to the combined flow rate of the CHF_3 and N_2 gases is selected to provide a controlled etch rate, highly anisotropic etching, and to limit the thickness of passivating film deposited on the etched features 35. An excessively high flow ratio of SF_6 relative to the combined flow rate of the CHF_3 and N_2 gas provides etching rates that are uncontrollable, particularly at the end of the etching process, due to the large number of dissociated fluorine species. However, an excessively low flow ratio of SF_6 relative to the combined flow rate of the CHF_3 and N_2 gas can cause isotropic etching of the features by removing the passivating deposits formed on sidewalls 40 of the etched features 35 to provide cone shaped tapered features. Thus, the flow rate of the SF_6 relative to the combined flow rate of the CHF_3 and N_2 gas is maintained at a level that provides a sufficient ratio of dissociated etching fluorine-containing

species to non-etchant passivating species to rapidly etch the tungsten containing layer **25** with the desired level of anisotropy and etch rate control.

The composition and volumetric flow ratios of different constituents of the process gas are also selected to provide anisotropically etched features **35** having sidewalls **40** with smooth surfaces that form angles (α) of at least about 88° with a plane of the substrate **10**, and more preferable angles from about 89° to about 90°. Anisotropically etched features **35** result when the tungsten containing layers are etched substantially vertically to provide features having straight sidewalls **40**. Excessive etching at the sidewalls **40** of the etched features **35** results in undesirable inwardly or outwardly sloped walls. A high degree of anisotropic etching is obtained when dissociated species in the etchant gas combine to deposit passivating layers on the sidewalls **40** of freshly etched features **35** to limit further etching of the sidewalls **40**. Anisotropic etching is also obtained by the highly directional kinetic energy of the charged species in the etchant plasma (in the electric field perpendicular to the substrate **10**), that causes the plasma species to energetically impinge upon and remove substrate material in the vertical etching direction. However, different materials are sputter etched by highly energized plasma species at the high etch rates to provide little or no control over etching selectivity. For these reasons, it is difficult to obtain highly anisotropic etching in combination with high etching selectivity ratios for etching tungsten containing material relative to underlayers of other materials.

For these reasons, the volumetric flow ratio of the process gas is also selected to etch the tungsten containing layer **25** at a high etching selectivity ratio relative to the underlying silicon dioxide layer **15**. The etching selectivity ratio is the ratio of the rate of etching of the tungsten containing layer **25** to the rate of etching of the underlying silicon dioxide layer **24**. It is particularly desirable have high etching selectivity ratio for tungsten containing structures having a partially convoluted topography,

where portions of the tungsten containing layer **25** are thicker across the substrate **10**. Toward completion of the etching process, the thinner portions of the tungsten containing layer **25** are etched through and etching of the underlying silicon dioxide layer begins, while the thicker portions of the tungsten containing layer **25** are still being etched. This effect requires that the silicon containing underlayer below the thinner tungsten containing layer **25** portions be etched at a sufficiently slow etch rate relative to the tungsten containing etch rate that the silicon dioxide layer is not etched through, before completion of etching of the thicker tungsten containing layer **25**. it is desirable to etch the tungsten containing layer **25** at a faster rate relative to the rate of etching of the silicon dioxide layer **15**. Preferably, the etching selectivity ratio relative to the underlying silicon dioxide layer **15** is at least about 1.2, and more preferably at least about 1.5.

Preferred volumetric flow ratios of SF_6:CHF_3:N_2 are from about 1:1:1 to about 8:1:1, and more preferably, from about 2:1:1 to about 5:1:1, and most preferably about 4:1:1. The ratio of the volumetric flow of SF_6 to the combined volumetric flow of CHF_3 and N_2 is typically from about 0.5:1 to about 3:1, and more preferably about 2:1. For the process chamber size illustrated herein, preferably, the flow rate of SF_6 is preferably from about 30 to about 120 sccm; the flow rate of CHF_3 is from about 10 to about 40 sccm; and the flow rate of N_2 is from about 10 to about 50 sccm. Also, it is preferred to maintain the flow rate of N_2 to within about $\pm$ 50% of the flow rate of CHF_3 and more preferably within about 20 sccm of the flow rate of CHF_3. For the chamber size described herein, preferably, the total flow rate of the process gas is from about 100 to 200 sccm. It should be understood, however, that process gas flow rates are dependent upon the size of the process chamber and flow rates for different sized chambers that provide the equivalent function and/or etching properties are encompassed within the scope of the present invention.

In certain processes, it may be desirable to add argon to the SF_6 to promote the stability of the plasma formed from the highly electronegative SF_6 gas. This is sometimes desirable for etching elemental tungsten layers or substrates, which cause plasma instabilities, in the highly electronegative sulfur hexafluoride gas. By plasma instability, it is meant a sporadic or intermittent formation of bright and dark plasma glow regions that are caused by unstable electron and ion levels in the plasma. It is believed that the argon gas promotes plasma stability by providing additional energetic species that strike upon, ionize, and/or dissociate the process gas molecules. However, the argon gas addition may not be desirable when the plasma is sufficiently stable without the additional inert gas.

It has also been discovered that the quasi-remote plasma generator when operated at a particular ratio of source power to bias power serves to balance the etching rate to the rate of deposition and removal of the passivating deposits to provide highly anisotropic etching. The power ratio P_r of the first (or source) current power level applied to inductor coil **75** to the second (or bias) voltage power level applied to the process electrodes **60, 65** is also selected to enhance the ability of the etchant plasma to anisotropically etch the tungsten containing layer **25** without excessive deposition of passivating film on the etched features **35**. A high power ratio P_r (obtained by increasing the first power level of the current applied to the inductor coil **75** or reducing the second power level of the voltage applied to the bias process electrodes) increases the amount of dissociated fluorinated etchant species to provide more isotropic etching of the features. Conversely, a low power ratio P_r (obtained from a low first power level to the coil or a high bias electrode power level) can cause excessive and nonuniform sputtering of the deposited passivating film and insufficient dissociation of the etchant gas resulting in more isotropic etching. Typically, increasing the second power level of the RF voltage applied to the process electrodes **60, 65** provides increased kinetic bombardment energy to the plasma species, causing more sputtering of the substrate **10** and deposited

passivating film. A preferred power ratio P_r of source to bias power is at least about 4:1, and more preferably from about 8:1 to about 40:1. More preferably, the plasma is formed by applying a current at a first power level of about 200 to 2000 Watts, and more preferably about 1400 ± 200 watts, to the inductor coil **75** adjacent to the plasma zone **55**. The plasma ions are attracted to the substrate **10** by applying a voltage at a power level of about 5 to 500 Watts, and more preferably about 40 Watts, to process electrodes **60, 65** in the plasma zone.

Scanning electron micrographs were taken showing sectional and perspective views of the features etched in a tungsten layer on a substrate **10**. These SEM micrographs demonstrated the unexpected results obtained using the process gas composition of the present invention. In these experiments, a 6-inch silicon wafer covered by a silicon dioxide layer was used as the substrate **10**. The substrate **10** was coated with a blanket tungsten layer having a thickness of about 600 nm. After the process gas was introduced into the chamber, the chamber pressure was maintained at 10 mTorr. The substrate **10** was maintained at a temperature of 5°C by flowing helium at a pressure of 8 Torr below the substrate **10**. The source power level of the inductor coils was maintained at 1400 Watts, and the bias power level of the process electrodes was maintained at 60 Watts. After etching, the residual resist layer on the features was removed using conventional resist removal methods.

Table I shows the dimensions measured on cross-sections of the features etched on the present substrates. Critical dimension measurements were made using cross-sectional views of scanning electron micrographs of the substrate before and after etching. SEM micrographs were used to measure the average width (W_r) of resist features **30** formed on the blanket tungsten layer prior to etching. After etching, a second width (W_e) of the etched features **35** was measured. The critical dimension loss was the difference $W_r - W_e$, and the % critical dimension loss was

$(W_r - W_e)/W_r \times 100\%$. The minimum critical dimension was measured as an average value of the smallest width across the cross-sections of the etched features **35**.

Scanning electron micrographs were taken of the cross-sectional profile of tungsten features etched using a process gas comprising 60 sccm SF_6 and 30 sccm CHF_3. No nitrogen was added to this etchant gas. It was seen from these SEM micrographs that the sidewalls **40** of the etched features **35** were generally tapered and sloped outwardly from the top of the feature to the bottom of the feature, which is undesirable. In addition, the etched features have a narrower bottleneck region, at approximately three-quarters the height of the feature.

TABLE I

	Example 1	Example 2	Example 3
Minimum Critical Dimension	0.24 μm	0.30 μm	0.32 μm
Critical Dimension Loss	-800 Å	-200 Å	<50 Å
% Critical Dimension Loss	25%	6.3%	<1.5%
Profile	Bowing	Tapered	Vertical
Profile Angle	N/A	87°	89-90°

The dimensional measurements made on the etched features **35** of Example 1 are shown in Table I, which demonstrate that a process gas comprising SF_6 and CHF_3 without addition of nitrogen, results in more isotropic etching and critical dimensions that have a smaller width than the overlying resist feature. Specifically, the etched features **35** had a minimum critical dimension of 0.24 μm, a high loss of critical dimension of about -800 Å., and a % critical dimension loss of 25%. Such a high critical dimension loss is undesirable because they are reflective or narrowing and non-uniform cross-sections of the etched features **35**. The narrow cross-sections increase the resistivity of the etched feature by providing a smaller

area. The relatively large loss of critical dimension also prevents the ability to accurately design engineer the integrating circuits formed on the substrate **10**.

In Example 2, an etchant process gas comprising 60 sccm SF_6 and 30 sccm N_2 was used. No CHF_3 gas was added to this process etchant gas. This process gas composition provided better results than that of Example **1** showing etched features **35** having sidewalls **40** that taper only slightly outwardly from the top of the feature to the bottom of the feature. This indicates a slightly higher degree of anisotropic etching. The dimension measurements of these etched features **35**, as shown in Table I, include a minimum critical dimension of 0.30 μm, a critical dimension loss of 200 Å, and a % critical dimension loss of 6.3%. The profile angle of the sidewalls **40** of the features was measured to be about 87°. This profile angle is relatively low, and angles exceeding 88° and preferably 89 to 90°, are more desirable. The etched features **35** also had rough sidewalls **40** and exhibited a high loss of critical dimension.

In Example 3, the tungsten features were etched using the process gas composition of the present invention, namely 60 sccm SF_6, 15 sccm, CHF_3, and 15 sccm N_2. SEM micrographs taken of the substrate **10** reveal the unexpected highly anisotropic etching of the features provided by this process gas composition. In these examples, the features have substantially perpendicular sidewalls **40** with substantially no tapering from the top of the feature to the bottom of the feature. The minimum critical dimension loss was relatively low at 0.32 μm, and the critical dimension loss was less than 50 Å. The % critical dimension loss was 1.5%, which is about 4 to more than 10 times lower than the % critical dimension loss provided by the other etchant gas compositions. Profile angles in the desired 89 to 90° range were obtained and the profiles comprise substantially uniformly vertical sidewalls **40**. The sidewalls **40** of the etched features **35** were relatively smooth without serrated edges. These unexpected results of

the anisotropic etching and excellent cross-sectional profile of the etched features **35** demonstrate the advantage of the present process.

Although the present invention has been described in considerable detail with regard to the preferred version thereof, other versions are possible. For example, the plasma can be formed using a microwave plasma source, and equivalent gases can be substituted for the gases described herein. Therefore, the appended claims should not be limited to the description of the preferred versions contained herein.



What is claimed is:

1. A method of anisotropically etching a tungsten containing layer on a substrate, the method comprising the steps of:

(a) placing the substrate in a plasma zone;

(b) introducing into the plasma zone, a process gas comprising SF_6, CHF_3, and N_2; and

(c) forming a plasma from the process gas to etch the tungsten containing layer on the substrate.

2. A method according to claim 1 characterized in that the volumetric flow ratio of SF_6:CHF_3:N_2 is selected to substantially anisotropically etch the tungsten containing layer to provide etched features having a critical dimension loss of less than 4% and sidewalls that form angles of at least about 88° with a surface of the substrate, and without forming excessive passivating deposits on the substrate.

3. A method according to claim 2 characterized in that the volumetric flow ratio of SF_6:CHF_3:N_2 is from 1:1:1 to 8:1:1.

4. A method according to claim 3 characterized in that the volumetric flow ratio of SF_6:CHF_3:N_2 is from 2:1:1 to 5:1:1.

5. A method according to any one of claims 1 through 4 characterized in that the process gas consists essentially of SF_6, CHF_3, and N_2.

6. A method according to claim 1 in which the process gas is ionized to form plasma ions that energetically impinge on the substrate by (i) applying RF current at a first power level to the inductor coil, and (ii) applying RF voltage at a second power level to the process electrodes,

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characterized in that the power ratio P_r of the first power level to the second power level is at least 4:1.

7. A method according to claim 6 characterized in that the power ratio P_r is from 8:1 to 40:1.

8. A method according to claim 7 characterized in that the first power level is from 200 to 2000 Watts and the second power level is from 5 to 500 Watts.

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