

SILICON DIOXIDE DEPOSITION METHOD AND APPARATUS

Technical Field

This invention relates to methods and apparatus for depositing silicon dioxide and, more particularly, to methods for depositing silicon dioxide over
5 conductors of an integrated circuit having a relatively high aspect ratio.

Background of the Invention

The technology of integrated circuits has been characterized by a continuing increase in the density with which devices can be formed in a silicon semiconductor chip or substrate. The interconnection of such high density devices
10 requires the formation on the chip surface of conductors that are extremely small and spaced closely together, and conductive patterns that overlap, or, in the terminology of the technology, are vertically spaced at different conductor levels. The use of two or more levels of conductors requires a deposition of a dependable insulation such as silicon dioxide on the lower or first level of conductors so that the overlying upper
15 level or second level can be made without the risk of accidental short circuits or other conductive anomalies.

A favored method for depositing silicon dioxide is known as plasma enhanced chemical vapor deposition (PECVD) in which a radio-frequency plasma contains a silicon component and an oxygen component. The plasma provides
20 energy for enhancing the reaction required for silicon dioxide formation at temperatures below the melting point of the first level of conductors over which the deposition is made. It should be noted that other oxides such as silicon monoxide may be deposited by this process, but the predominant deposited material is silicon dioxide, which is the term that will be used herein. Also, deposition is on a
25 "substrate," which may be part of the semiconductor, the metal conductors, or previously deposited or grown silicon dioxide.

As circuit density increases, the ratio of the height of adjacent conductors to their separation distance, known as the aspect ratio of the structure, also increases. If the thickness of the deposited silicon dioxide is greater than half
30 the separation between adjacent conductors, the silicon dioxide deposited on adjacent vertical walls of adjacent conductors is likely to meet and cause a discontinuity in the deposited silicon dioxide. If the top corner coverage is slightly greater than the coverage on the remainder of the vertical sidewalls, the corners may meet first, thus producing a void within the deposited silicon dioxide between
35 adjacent conductors. This problem becomes more pressing as the aspect ratio

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increases.

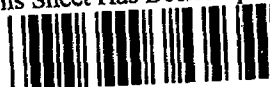
One solution to the problem is the use of electron cyclotron resonance (ECR) as described, for example, in the paper, "SiO₂ Planarization Technology with Biasing and Electron Cyclotron Resonance Plasma Deposition for Submicron Interconnections," Katsuyuki Machida et al., *Journal of Vacuum Science Technology B4* (4), July/August 1986, pp. 818-821. In a chamber connected to the deposition chamber, the combination of an applied microwave frequency and magnetic field sets up a cyclotron resonance of ions which are directed into the deposition chamber and cause silicon dioxide to deposit. The addition of a wafer rf bias in the deposition chamber causes the silicon dioxide to sputter etch, resulting in deposition at different angles on the substrate, thereby to reduce the problem of voids caused by merging vertical walls. One problem with this approach is that it requires the design of new equipment, it is more difficult to maintain the standards of ultracleanliness required in chip manufacture, and the need for microwaves and a separate ECR chamber complicate and increase the cost of the apparatus for manufacture.

The paper, "Sidewall-Tapered Oxide by Plasma-Enhanced Chemical Vapor Deposition," G. C. Smith et al., *Journal of Electrochemical Society: Solid-State Science and Technology*, Vol. 132, No. 11, November 1985, pp. 2721-2725, describes another approach in which sputtering is induced concurrently with silicon dioxide deposition. This leads to V-shaped sidewalls of the deposited silicon dioxide, rather than vertical sidewalls that merge to create voids. A problem with this approach is the relatively long time period required for depositing a useful layer of silicon dioxide over a conductor pattern having a relatively high aspect ratio.

There is therefore a continuing need in industry for a method for depositing dependable layers of silicon dioxide over conductor patterns having high aspect ratios in a manner that is amenable to mass production, is consistent with cleanliness requirements, and which does not greatly increase the cost of manufacture.

Summary of the Invention

Equipment is available on the market for sputter etching a wafer in one chamber and then moving it to another chamber for silicon dioxide deposition. I have found that, with practical modifications, such equipment can expediently be used to deposit silicon dioxide over conductors having high aspect ratios. In the modified sputter etch chamber, an rf plasma is formed for depositing a layer of silicon dioxide. A magnetic field extends through the wafer and plasma, in a direction generally transverse to the rf field. Simultaneous sputter etching and



deposition occurs which inhibits net deposition on the corners of the first level conductors; this results in a generally V-shaped surface to the deposited silicon dioxide between adjacent conductors. This could constitute the entire deposition, but preferably the substrate is removed and transferred to the conventional deposition chamber. Here, a generally conformal second layer of silicon dioxide is formed over the previously deposited layer but, because of the configuration of the first silicon dioxide layer, there can be no problems of voids or other discontinuities. Thereafter, the upper surface is planarized and the second level of conductors is deposited.

The method which has been briefly described yields a reliable silicon dioxide insulation layer in a manner which is consistent with mass production and operation by workers of moderate skill. No problems of cleanliness are introduced because the equipment that is used is, for the most part, commercially available equipment that has been designed to meet modern standards of cleanliness. As will become clear from the detailed description, there is little added cost to the apparatus or method which is used in obtaining the silicon dioxide dielectric layers. These and other objects, features and benefits of the invention will be better understood from a consideration of the following detailed description taken in conjunction with the accompanying drawing.

Brief Description of the Drawing

FIG. 1 is a schematic view of silicon dioxide deposited over metal conductors in accordance with the prior art;

FIGs. 2, 3 and 4 are schematic views illustrating successive steps of silicon dioxide dielectric formation in accordance with an illustrative embodiment of the invention;

FIG. 5 is a schematic view of certain commercially available equipment that can be modified to be used in accordance with the invention;

FIG. 6 is a schematic view of one modified reactor chamber in the apparatus of FIG. 5;

FIG. 7 is a view taken along line 7-7 of FIG. 6; and

FIG. 8 is a schematic view of another reactor chamber of the apparatus of FIG. 5.

Detailed Description

Referring now to FIG. 1, there is illustrated schematically the prior art deposition of silicon dioxide 11 on a substrate 12, which creates the problem with which the invention is concerned. Located on the top surface of the substrate 12 are



conductors 13, which illustratively constitute the first conductor level of an integrated circuit. The aspect ratio of the conductors is defined as the ratio of the height of the vertical sidewalls 14 of the conductors to the separation distance of adjacent vertical sidewalls of adjacent conductors. With conventional conformal deposition, a high aspect ratio results in the silicon dioxide on adjacent vertical walls growing together. The corners of the deposited silicon dioxide are likely to meet first, which results in voids 15 in the deposited oxide layer. Even if voids are not formed, discontinuities 16 are created, which adversely affect the etch characteristics and insulation characteristics of the silicon dioxide layer. One can appreciate that as the aspect ratio increases, the problems accompanying conformal silicon dioxide deposition generally increase.

Referring to FIG. 2, in accordance with the invention, the silicon dioxide is formed in two steps. First, a first silicon dioxide layer 18 is formed, which has generally a V-shaped configuration between adjacent conductors 13 as shown. Then, as shown in FIG. 3, a second silicon dioxide layer 19 is formed over the first silicon dioxide layer, which is generally conformal and therefore has a succession of V-shapes in its upper surface as shown. FIG. 4 shows the silicon dioxide layer planarized so as to permit the formation of conductors 20 on its upper surface, which constitutes the second conductor level of the integrated circuit device being made.

An important aspect of the inventive method is that it can be practiced through the use of commercially available chemical vapor deposition (CVD) equipment. Specifically, FIG. 5 illustrates schematically apparatus known as the "Precision 5000 System," commercially available from the Applied Materials Company of Santa Clara, California, which may be used for the practice of the invention. This system includes separate chambers 22-25 interconnected by a central transfer chamber 27. Wafers are introduced into a load lock chamber 26 and are transferred among various chambers by a robot arm contained in a transfer chamber 27. These individual chambers can be used for different operations on semiconductor wafers while maintaining high standards of cleanliness and avoiding cross contamination from one chamber to the other. By using separate chambers to deposit layers 18 and 19 (of FIG. 3), one can optimize the parameters to obtain the highest possible overall deposition rate, or, in other words, to reduce as much as possible the overall time required for the entire process.

FIG. 6 is a schematic sectional view of the chamber 22 of FIG. 5 used for depositing the first silicon dioxide layer 18 of FIG. 2. A wafer 30 is mounted on an electrode 31 connected through a matching network 32 to a radio-frequency source 33. A grounded electrode 35 opposite the wafer 30 constitutes a source of gas



for forming an rf plasma between electrodes 35 and 31. The grounded electrode 35 is hollow and contains a plurality of apertures that permit the flow of injected gas as shown by the arrows. The gas is taken from a source of argon 36, a source of nitrogen oxide 37 and a source of silane 38. Appropriate valves and transmission
5 lines permit a mixture of these gases to be directed into the region between the electrodes 35 and 31.

As can be seen in FIG. 7, four coils 40 through 43 are located in quadrature around the chamber 22. The intended purpose of the chamber 22, as part of the "Precision 5000 System," is to sputter etch material from wafers, rather than
10 deposit the material on wafers. To this end, the coils produce a magnetic field through the wafer generally parallel with the upper surface of the wafer 30 and they promote sputter etching by increasing the density of impinging ions on the wafer surface. Coils 42 and 43 are connected together and, when current through them is at a maximum, they produce a magnetic field B_1 shown in FIGs. 6 and 7.
15 Interconnected coils 40 and 41 produce a magnetic field B_2 when they carry current to the maximum. By directing current at a low alternation frequency through the coils, with the current through coils 42 and 43 being displaced ninety degrees from the current through coils 40 and 41, one can create a magnetic field of uniform strength B which rotates in a plane parallel to the upper surface of the wafer 30.
20 Preferably, the current is varied through the coils such that the magnetic field B remains of constant total strength and rotates with a frequency of one rotation for each two seconds although a frequency as high as one hundred rotations per second could be used.

Prior to deposition, argon is introduced into the system and the rf power
25 is applied so as to heat the wafer 30. Thereafter, gas from sources 37 and 38 are introduced. Nitrogen oxide, N_2O , constitutes a source of oxygen, and silane, SiH_4 , constitutes a source of silicon which are reacted to deposit silicon dioxide on the upper surface of the wafer in accordance with the principles of PECVD. As will be explained later, these gases are chosen so as to enhance sputtering from the surface
30 of wafer 30 as well as to constitute sources for deposition of silicon dioxide onto wafer 30. The wafer 30 is supported on an electrode 31 which is rf driven and is smaller in area than electrode 35. The total pressure within the chamber 22 is low and the rate of silicon dioxide deposition is relatively low. Together with the magnetic field, these choices of parameters tend to enhance sputtering.

35 Referring again to FIG. 2, it is desired in the apparatus of FIGs. 6 and 7 to deposit silicon dioxide 18 having an upper surface 45 that is generally V-shaped between successive conductors 13. This is accomplished because sputtering occurs



predominantly at the corners of conductors 13, which results in a net thickness of deposition that is lowest at the corners. Thus, in effect, we deposit at a rate that is balanced with respect to the rate of removal by sputtering so as to give a minimum net deposition at the corners of conductors 13. I have found that using parameters
5 designed to give a sputtering rate of three hundred angstroms per minute and a silicon dioxide deposition rate of one thousand angstroms per minute will yield a net deposition rate of seven hundred angstroms per minute and will yield the upper surface 45 shown in FIG. 2. The rotation of the magnetic field B enhances uniformity of deposition.

10 Referring again to FIG. 5, after completion of the silicon dioxide deposition in chamber 22, the wafer is removed to transfer chamber 27 and then to chamber 23, which is shown schematically in FIG. 8. In chamber 23, the upper electrode 47, rather than the lower electrode is driven by an rf source 48 (the matching network is not shown for purposes of brevity). The wafer 30 rests on a
15 grounded electrode 49. As before, gases are directed through electrode 47 toward the wafer 30, but different gas compositions are used. The silicon component of the silicon dioxide is obtained from gaseous tetraethoxysilane (TEOS) derived from a heated liquid source 51. Typically, TEOS is commercially available as a liquid and a vaporized form is obtained by bubbling helium from a source 52 through the liquid
20 TEOS and deriving vaporized molecules from the TEOS container as indicated schematically. Also included in the plasma atmosphere is pure oxygen gas from source 53. Various known valves and metering equipment are not shown for brevity.

The lower electrode 49 is heated by a plurality of lamps 55 that direct light through a quartz window 56 so as to impinge on an aluminum oxide layer 57 of
25 electrode 49. This heats the wafer to a temperature below the melting point of the metal conductors contained on its surface.

In the configuration of chamber 23, the gas composition of the plasma atmosphere and the various other parameters are chosen so as to maximize the silicon dioxide deposition rate. Referring to FIG. 3, this process yields a conformal
30 coating 19 having an upper surface 59 that corresponds generally to the upper surface 45 of the silicon dioxide layer 18 of FIG. 2. One can appreciate that with the silicon dioxide depositing at a generally equal rate on all surfaces, there is not likely to be a problem of adjacent sidewalls growing together with consequent formation of voids as was described with reference to FIG. 1. The upper surface of silicon
35 dioxide layer 19 is then planarized in a known manner to yield the silicon dioxide layer 19 of FIG. 4 upon which one may then deposit the second level of conductors 20. Alternatively, the silicon dioxide 19 may be ground to a horizontal level equal to



the top level of conductors 13 using the top surface of the conductors as a "stop" to the grinding operation. Thereafter, another silicon dioxide layer is deposited in the chamber 22 of FIG. 6 to yield a silicon dioxide layer having a flat upper surface. As still another option, etching may be used to planarize the upper surface of deposited layer 19.

Referring again to FIG. 2, it can be appreciated that the crux of the invention lies in depositing a first silicon dioxide layer 18 having the upper surface 45 generally as shown. The vertical walls are prevented from growing together by depositing the silicon dioxide 18 so as to have V-shaped upper surfaces between successive conductors which, in turn, requires a balance between removal of material by sputtering and deposition of silicon dioxide by PECVD. Table I below shows the parameters that were used in both chambers 22 and 23 for covering conductors having aspect ratios up to 1.7. The table also shows the parameters used in chamber 23 for increasing the deposition rate of the silicon dioxide.

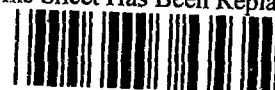
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Table I

Parameter	Chamber 22	Chamber 23
RF Power	500 watts	450 watts
Pressure	30 millitorr	9 torr
Magnetic Field	130 gauss	0
Argon	180 sccm	0
N ₂ O	20 sccm	0
SiH ₄	8 sccm	0
SiO ₂ Deposition Rate	700 A/min	125 A/sec
TEOS	0	500 sccm
O ₂	0	500 sccm
Electrode Spacing	6-8 inches	200 mils

Table I demonstrates the radically different conditions for silicon dioxide deposition in chamber 22 with respect to that in chamber 23. In the table, A means angstrom units and sccm means standard cubic centimeters per minute. Many experiments have demonstrated to me that the desirable objective of depositing in chamber 22 is to maximize the sputtering rate, because the rate at which the silicon dioxide can be deposited is limited by the rate at which it must be sputtered away from the corners of the conductors; the time taken for the overall process is reduced by increasing both the sputtering and deposition rates in chamber 22. Thus, to maximize sputtering rate, argon is used to increase the mass of impinging ions on the surface of the wafer. A much lower pressure is used in chamber 22 (between one and one hundred millitorr) than in chamber 23 (between about one and twenty torr). The electrode 31 of chamber 22 is made smaller than electrode 35 and is driven by the rf source 33 in order to maximize the energy of ion impingement on the wafer surface. The magnetic field greatly increases sputtering rate and therefore greatly improves the efficiency of chamber 22. One hundred thirty gauss was the highest magnetic field that could be obtained in the system used; it appears that this value should be significantly increased to speed up the overall process. Silane as the silicon source and N₂O as the oxygen source further enhance the sputtering component. A high rf power in chamber 22 (i.e., power in excess of at least one



hundred watts) is preferred to maximize sputtering and, in fact, the rf power and the magnetic field are perhaps the two most important parameters for increasing the sputtering component. Of course, TEOS, O_2 , and other alternative gases could be used in chamber 22, but the process window for good quality films is much narrower
5 with these gases in chamber 22. In chamber 23, one wishes to maximize the deposition rate and so TEOS and O_2 are appropriate choices. By maximizing the sputtering rate in chamber 22, one minimizes the time needed to establish the configuration of FIG. 2. Thus, in the embodiment described, the deposition rate in chamber 23 is 125 angstroms per second and in chamber 22 the rate is only 700
10 angstroms per minute. In the chamber 23, no effort is made to make the electrode 49 that supports wafer 30 smaller than the electrode 47 and the electrode spacing is only 200 mils because there is no need for any sputtering component.

In the "Precision 5000 System" that was used, a pair of quartz rings and a graphite ring that surrounded electrode 31 of chamber 22 were removed. Other
15 minor structural changes were made, but essentially full advantage was taken of the commercially available system for processing semiconductor wafers with a high throughput. The diameter of electrode 31 was adjusted to be approximately equal to that of the wafer 30 (six inches). The purpose of these changes was to make as uniform as possible the plasma distribution over the upper surface of the wafer, and
20 as mentioned before it appears that substitute coils should be used to give a higher rotating magnetic field.

The various parameters which are described merely illustrate in one embodiment the optimum choices for balance sputtering with deposition. Various other gases could be used in which case the parameters should be adjusted
25 accordingly. Only a single chamber could be used for making both depositions, but in that case more compromises in apparatus structure would have to be made. It is not essential that the magnetic field rotate if one can tolerate non-uniform deposition and density. Various other embodiments and modifications may be made by those skilled in the art without departing from the spirit and scope of the invention.

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Claims:

1. A method for making an integrated circuit device comprising the steps of depositing a first layer (18) of silicon dioxide on a substrate (12) surface by exposing the substrate surface to an rf plasma in an atmosphere including silicon and oxygen components, characterized by:
 - 5 forming a magnetic field (B) that extends through the substrate and through the plasma contiguous to the surface in a direction substantially parallel to the surface;
the rf plasma is formed by subjecting the atmosphere to rf power in excess of one hundred watts;
 - 10 and the plasma contains an inert gas component, the magnetic field, rf power and inert gas cooperating to cause sputtering preferentially at discontinuities of the substrate..
2. The method of claim 1 further characterized in that:
 - 15 during deposition, the magnetic field is caused to rotate in a plane substantially parallel to the substrate surface.
3. The method of claim 1 or 2 further characterized in that:
 - the substrate has a generally planar configuration and is supported such
 - 20 that its exposed surface is a relatively large-area surface of the substrate and is located in a substantially horizontal plane;
 - and the substrate surface contains a plurality of relatively closely spaced conductive elements (13) having adjacent vertical wall portions (14), whereby the electric and magnetic fields cause a sputtering phenomenon primarily at exposed
 - 25 corners of the conductive elements.
4. The method of claim 3 further characterized in that:
 - the magnetic field has a value at the substrate surface of more than about one hundred gauss.
 - 30
5. The method of claim 1, 2 or 4 further characterized in that:
 - the magnetic field is defined by a magnetic field vector of substantially constant value that rotates at a frequency of between about 0.5 and one hundred rotations per second.
 - 35
6. The method of claim 1, 2 or 5 further characterized in that:



a second layer (19) of silicon dioxide is deposited on the first layer by exposing the substrate surface to an rf plasma in an atmosphere containing silicon and oxygen components, but without a magnetic field.

5 7. The method of claim 6 further characterized in that:

during formation of the first layer, the substrate is supported on an rf excited electrode, and during formation of the second layer, the substrate is supported on a grounded electrode.

10 8. The method of claim 6 or 7 further characterized in that:

during formation of the first layer, the atmosphere contains an inert gas component, and during formation of the second layer, the atmosphere contains substantially no inert gas component and the total gas pressure of the atmosphere is much higher during formation of the second layer than during formation of the first
15 layer.

9. The method of claim 6, 7 or 8 further characterized in that:

during formation of the first layer, the silicon component in the atmosphere comprises silane and the oxygen component comprises nitrogen oxide,
20 and, during formation of the second layer, the silicon component comprises tetraethoxysilane and the oxygen component comprises pure oxygen.

10. The method of claim 6, 8 or 9 further comprising the step of:

planarizing an upper surface of the deposited second silicon dioxide;
25 and forming a second conductive pattern on the planarized second silicon dioxide surface.

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