APPARATUS AND METHOD FOR INTEGRATED SURFACE TREATMENT AND DEPOSITION FOR COPPER INTERCONNECT

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BACKGROUND

[1] In the fabrication of semiconductor devices such as integrated circuits, memory cells, and the like, a series of manufacturing operations are performed to define features on semiconductor wafers. The semiconductor wafers include integrated circuit devices in the form of multi-level structures defined on a silicon substrate. At a substrate level, transistor devices with diffusion regions are formed. In subsequent levels, interconnect metallization lines are patterned and electrically connected to the transistor devices to define a desired integrated circuit device. Also, patterned conductive layers are insulated from other conductive layers by dielectric materials.

[2] Reliably producing sub-micron and smaller features is one of the key technologies for the next generation of very large scale integration (VLSI) and ultra large scale integration (ULSI) of semiconductor devices. However, the shrinking dimensions of interconnect in VLSI and ULSI technologies have placed additional demands on the processing capabilities. As circuit densities increase, the widths of vias, contacts and other features, as well as the dielectric materials between them, decrease to sub-micron dimensions (e.g., less than 0.20 micrometers or less), whereas the thickness of the dielectric layers remains substantially constant, with the result that the aspect ratios for the features, i.e., their height divided by width, increase. Many traditional deposition processes have difficulty achieving substantially void-free and seam-free filling of sub-micron structures where the aspect ratio exceeds 4:1.

[3] Currently, copper and its alloys have become the metals of choice for sub-micron interconnect technology due to its lower resistivity. One problem with the use of copper is that copper diffuses into silicon, silicon dioxide, and other dielectric materials, which may compromise the integrity of devices. Therefore, conformal barrier layers become increasingly important to prevent copper diffusion. Copper might not adhere well to the

barrier layer; therefore, a liner layer might need to be deposited between the barrier layer and copper. Conformal deposition of the liner layer is also important to provide good step coverage to assist copper adhesion and/or deposition.

[4] Conformal deposition of the barrier layer on interconnect features by deposition methods, such as atomic layer deposition (ALD), needs to occur on clean surfaces to ensure good adhesion between the barrier layer and/or liner layer, and the material(s) the barrier layer deposited upon. Surface impurity can become a source of defects during the heating cycles of the substrate processing. Pre-treatment can be used to remove unwanted compounds from the substrate surface prior to barrier deposition. In addition, deposition by ALD might need surface pre-treatment to make the substrate surface easier to bond with the deposition precursor to improve the quality of barrier layer deposition.

[5] Electro-migration (EM) is a well-known reliability problem for metal interconnects, caused by electrons pushing and moving metal atoms in the direction of current flow at a rate determined by the current density. EM in copper lines is a surface phenomenon. It can occur wherever the copper is free to move, typically at an interface where there is poor adhesion between the copper and another material, such as at the copper/barrier or copper/liner interface. The quality and conformality of the barrier layer and/or liner layer can certainly affect the EM performance of copper interconnect. It is desirable to perform the ALD barrier and liner layer deposition right after the surface pre-treatment, since the pre-treated surface might be altered if the surface is exposed to oxygen or other contaminants for a period of time.

[6] A post-treatment after barrier and/or liner layer deposition prior to the deposition of copper can improve the adhesion between the barrier or liner layer with copper by removing impurities from the substrate surface. In addition, a post-treatment after barrier or liner layer deposition prior the deposition of a copper seed layer by electroless method can increase nucleation sites for copper seed layer deposition, which can improve the film quality of the copper seed layer.

[7] In view of the foregoing, there is a need for integrated systems and methods that perform substrate surface treatment and film deposition for copper interconnect with improved metal migration performance and reduced void propagation.

SUMMARY

[8] Broadly speaking, the embodiments fill the needs for integrated apparatus and methods that perform substrate surface treatment and film deposition for copper interconnect with improved metal migration performance and reduced void propagation. It should be appreciated that the present invention can be implemented in numerous ways, including as a solution, a method, a process, an apparatus, or a system. Several inventive embodiments of the present invention are described below.

[9] In one embodiment, an apparatus for treating a surface of a substrate is provided. The apparatus includes a substrate support configured to support the substrate. The apparatus also includes a proximity head configured to dispense a treatment gas to treat an active process region of a substrate surface under the proximity head. The proximity head covers the action process region of the substrate surface and the proximity head includes at least one vacuum channel to pull excess treatment gas from a reaction volume between the proximity head and the substrate. The proximity head has an excitation chamber to excite the treatment gas before the treatment gas being dispensed on the active process region portion of the substrate surface.

[10] In another embodiment, a method of treatment a substrate surface is provided. The method includes moving a proximity head for surface treatment above a substrate. The proximity head has at least one gas channel configured to dispense a treatment gas on a region of the substrate surface. The proximity head has at least one vacuum channel used to vacuum excess treatment gas from a reaction volume underneath the proximity head, and the proximity head for surface treatment covers the region of the substrate surface. The method also includes exciting the treatment gas in an excitation chamber of the proximity head before the treatment gas is dispensed on the region of the substrate surface. The method further includes dispensing the excited treatment gas on the region of the substrate surface to treat the substrate surface.

[11] In another embodiment, a chamber for performing surface treatment and film deposition is provided. The chamber includes a first proximity head for substrate surface treatment configured to dispense a first treatment gas to treat a portion of a surface of a substrate under the first proximity head for substrate surface treatment. The chamber also includes a first proximity head for atomic layer deposition (ALD) configured to sequentially

dispensing a first reactant gas and a first purging gas to deposit a first ALD film under the second proximity head for ALD.

[12] In another embodiment, a method of performing surface treatment and film deposition on a substrate in a processing chamber is provided. The method includes placing the substrate in the processing chamber with a plurality of proximity heads for surface treatment and film deposition. Each of the plurality of proximity head covers a portion of a substrate surface. The method also includes moving a pre-treatment proximity head above a region on the substrate surface. The method further includes performing a surface pre-treatment with the pre-treatment proximity head at the region on the substrate surface. In addition, the method includes moving an atomic layer deposition 1 (ALD1) proximity head above the region on the substrate surface. Additionally, the method includes depositing a barrier layer for copper with the ALD 1 proximity head at the region on the substrate surface.

[13] In another embodiment, a method of depositing films on a substrate for copper interconnect in an integrated system is provided. The method includes moving the substrate into a processing chamber having a plurality of proximity heads. Selected ones of the proximity heads is configured to perform at least one of surface treatments and atomic layer depositions (ALDs). The processing chamber is part of the integrated system. Within the processing chamber, barrier layer deposition is performed over a surface of the substrate using one of the plurality of proximity heads functioning to perform barrier layer ALD. In addition, the method includes moving the substrate from the processing chamber, through a transfer module of the integrated system and into a processing module for performing copper seed layer deposition. The processing module for performing copper seed layer deposition is part of the integrated system. Within the processing module for performing copper seed layer deposition, copper seed layer deposition is performed over the surface of the substrate. The integrated system enables controlled-ambient transitions within the integrated system to limit exposure of the substrate to uncontrolled ambient conditions outside of the integrated system.

[14] In another embodiment, an integrated system for depositing films on a substrate for copper interconnect is provided. The integrated system includes a processing chamber having a plurality of proximity heads. Selected ones of the proximity heads are used for surface treatments and atomic layer depositions (ALDs). The integrated system also

includes a vacuum transfer module coupled to the processing chamber. The vacuum transfer module is used to transfer the substrate in the integrated system. The integrated system further includes a processing module for copper seed layer deposition. In addition, the integrated system includes controlled-ambient transfer module coupled to the processing module for copper seed layer deposition. Additionally, the integrated system includes a loadlock coupled to the vacuum transfer module and to the controlled-ambient transfer module. The loadlock is used to assist transferring the substrate between the vacuum transfer module and to the controlled-ambient transfer module. The integrated system enables controlled-ambient transitions within the integrated system to limit exposure of the substrate to uncontrolled ambient conditions outside of the integrated system.

[15] Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[16] The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings, and like reference numerals designate like structural elements.

[17] Figure 1A show an exemplary cross section of an interconnect structure prior to barrier layer deposition, in accordance of an embodiment of the current invention.

[18] Figure 1B show an exemplary cross section of an interconnect structure after deposition of barrier layer deposition and copper, in accordance of an embodiment of the current invention.

[19] Figure 2 shows an exemplary ALD deposition cycle.

[20] Figure 3 shows a cross-sectional diagram of an ALD film grown with limited growth sites in the beginning of ALD deposition.

[21] Figure 4A shows a schematic diagram of a proximity head ALD chamber, in accordance with an embodiment of the current invention.

[22] Figure 4B shows a schematic diagram of a proximity head for ALD, in accordance with an embodiment of the current invention.

[23] Figure 5A shows a schematic diagram of a chamber with a surface treatment proximity head, in accordance with an embodiment of the current invention.

[24] Figure 5B shows a schematic diagram of a proximity head for surface treatment, in accordance with an embodiment of the current invention.

[25] Figure 6A shows a top view of a proximity head for surface treatment or ALD over a substrate, in accordance with an embodiment of the current invention.

[26] Figure 6B shows a top view of a proximity head for surface treatment or ALD over a substrate, in accordance with another embodiment of the current invention.

[27] Figure 6C shows a top view of a proximity head for surface treatment or ALD over a substrate, in accordance with yet another embodiment of the current invention.

[28] Figure 6D shows a bottom view of a proximity head for surface treatment or ALD, in accordance with an embodiment of the current invention.

[29] Figure 6E shows a bottom view of a proximity head for surface treatment or ALD, in accordance with another embodiment of the current invention.

[30] Figure 6F shows a schematic cross-sectional view of a proximity head for surface treatment or ALD below a substrate, in accordance with one embodiment of the current invention.

[31] Figure 7A shows a schematic diagram of a proximity head for surface treatment, in accordance with an embodiment of the current invention.

[32] Figure 7B shows a schematic diagram of a proximity head for surface treatment, in accordance with another embodiment of the current invention.

[33] Figure 7C shows a schematic diagram of a proximity head for surface treatment coupled to an RF power source over a substrate and a grounded substrate support, in accordance with an embodiment of the current invention.

[34] Figure 7D shows a schematic diagram of a grounded proximity head for surface treatment over a substrate and a substrate support coupled to an RF power source, in accordance with an embodiment of the current invention.

[35] Figure 8 shows a schematic diagram of a thin film deposited by proximity head ALD, in accordance with an embodiment of the current invention.

[36] Figure 9A show s plurality of proximity heads for surface treatment and deposition over a substrate, in accordance with an embodiment of the current invention.

[37] Figure 9B show s plurality of proximity heads for surface treatment and deposition over a substrate, in accordance with another embodiment of the current invention.

[38] Figure 9C shows a proximity head for CVD over a substrate, in accordance with one embodiment of the current invention.

[39] Figure 9D show s plurality of proximity heads for surface treatment and deposition over a substrate, in accordance with yet another embodiment of the current invention.

[40] Figure 10A shows a interconnect feature deposited with an ALD barrier layer, an ALD liner layer, and a CVD layer, in accordance with one embodiment of the current invention.

[41] Figure 10B show s plurality of proximity heads for surface treatment and deposition over a substrate, in accordance with yet another embodiment of the current invention.

[42] Figure11A shows a process flow of surface treatment using a proximity head, in accordance with an embodiment of the current invention.

[43] Figure 11B shows a process flow of surface treatment and deposition using a plurality of proximity heads in a process chamber, in accordance with an embodiment of the current invention.

[44] Figure 11C shows a process flow of surface treatment and deposition using a plurality of proximity heads in a process chamber, in accordance with another embodiment of the current invention.

[45] Figure 12A shows a process flow for surface treatment and film deposition for copper interconnect using the integrated system of Figure 12B, in accordance with one embodiment of the current invention.

[46] Figure 12B shows an integrated system for surface treatment and film deposition for copper interconnect, in accordance with one embodiment of the current invention.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

[47] Several exemplary embodiments of integrated apparatus (or systems) and methods for substrate surface treatment and film deposition for copper interconnect are detailed. Substrate pre-treatment prior to barrier layer deposition can either remove surface contaminants or can activate surface for barrier layer atomic layer deposition (ALD). Substrate post-treatment after film deposition can either remove surface contaminants or prepare the substrate surface for deposition of another film, such as a copper seed layer. Pre-treatment and post-treatment proximity heads can be integrated with an atomic layer deposition (ALD) proximity head to complete the film deposition and surface treatment in one chamber. Afterwards, the substrate can be moved into a copper seed layer deposition chamber in the same integrated system for copper seed layer deposition. The substrate is either transferred under vacuum or in a controlled ambient to limit the exposure to oxygen or other contaminants. ALD barrier layer, ALD liner layer, and copper seed layer deposited on clean or activated surfaces yield good electro-migration (EM) performance, and avoid delamination and void propagation.

[48] It should be appreciated that the present invention can be implemented in numerous ways, including a process, a method, an apparatus, or a system. Several inventive embodiments of the present invention are described below. It will be apparent to those skilled in the art that the present invention may be practiced without some or all of the specific details set forth herein.

[49] Figure 1A shows an exemplary cross-section of an interconnect structure(s) after being patterned by using a dual damascene process sequence. The interconnect structure(s) is on a substrate 50 and has a dielectric layer 100, which was previously fabricated to form a metallization line 101 therein. The metallization line is typically fabricated by etching a trench into the dielectric 100 and then filling the trench with a conductive material, such as copper.

[50] In the trench, there is a barrier layer 120, used to prevent the copper material 122, from diffusing into the dielectric 100. The barrier layer 120 can be made of PVD tantalum nitride (TaN), PVD tantalum (Ta), ALD TaN, or a combination of these films. Other barrier layer materials can also be used. Alternatively, a liner layer can be deposited between the barrier layer 120 and the copper material 122 to increase the adhesion between the copper

material 122 and the barrier layer 120. Another barrier layer 102 is deposited over the planarized copper material 122 to protect the copper material 122 from premature oxidation when via holes 114 are etched through overlying dielectric materials 104, 106 to the barrier layer 102. The barrier layer 102 is also configured to function as a selective etch stop and a copper diffusion barrier. Exemplary barrier layer 102 materials include silicon nitride (SiN) or silicon carbide (SiC).

[51] A via dielectric layer 104 is deposited over the barrier layer 102. The via dielectric layer 104 can be made of a material with a low dielectric constant. Over the via dielectric layer 104 is a trench dielectric layer 106. The trench dielectric layer 106 may be a low K dielectric material, which can be a material same as or different from layer 104. In one embodiment, both the via and trench dielectric layers are made of the same material, and deposited at the same time to form a continuous film. After the trench dielectric layer 106 is deposited, the substrate 50 that holds the structure(s) undergoes patterning and etching processes to form the via holes 114 and trenches 116 by known art.

[52] Figure 1B shows that after the formation of via holes 114 and trenches 116, a barrier layer 130, an optional liner layer 131, and a copper layer 132 are deposited to line and fill the via holes 114 and the trenches 116. The barrier layer 130 can be made materials, such as tantalum nitride (TaN), tantalum (Ta), Ruthenium (Ru), or a hybrid combination of these films. Barrier layer materials may be other refractory metal compound including but not limited to titanium (Ti), titanium nitride (TiN), tungsten (W), zirconium (Zr), hafnium (Hf), molybdenum (Mo), niobium (Nb), vanadium (V), and chromium (Cr), among others.

[53] The optional liner layer 131 can be made materials, such as tantalum (Ta), and Ruthenium (Ru). Liner layer materials may be other refractory metal compound including but not limited to titanium (Ti), titanium nitride (TiN), tungsten (W), zirconium (Zr), hafnium (Hf), molybdenum (Mo), niobium (Nb), vanadium (V), and chromium (Cr), among others. While these are the commonly considered materials, other barrier layer and liner layer materials can also be used. A copper film 132 is then deposited to fill the via holes 114 and the trenches 116. A copper seed layer 133 can be deposited prior to the gap-filling copper film 132 is deposited.

[54] As discussed above, before depositing a metallic barrier layer 130, the substrate surface can have residual contaminants left from etching the dielectric layers 104, 106 and

the barrier layer 102 to allow the metallic barrier layer 130 to be in contact with the copper material 122. A cleaning process, such as Ar sputtering, can be used to remove surface contaminant. Also as discussed above, conformal deposition of metallic barrier layer 130 by ALD might need surface pre-treatment to make the substrate surface easier to bond with the deposition precursor. The reason is described below.

[55] Atomic layer deposition (ALD) is known to produce thin film with good step coverage. ALD is typically accomplished by using multiple pulses, such as two pulses, of reactants with gas purge in between, as shown in Figure 2. For metallic barrier deposition, a pulse of barrier-metal-containing reactant (M) 201 is delivered to the substrate surface, followed by a pulse of purging gas (P) 202. The pulse of barrier-metal-containing reactant 201 delivered to the substrate surface to form a monolayer of barrier metal, such as Ta, on the substrate surface. In one embodiment, the pulse of purging gas is a plasma-enhanced (or plasma-assisted) gas. The barrier metal, such as Ta, bonds to the substrate surface, which can be made of a dielectric material, such as low-k materials 104, 106 of Figure 1A, and/or a conductive material, such as copper material 122 of Figure 1A . The purge gas 202 removes the excess barrier-metal-containing reactant 201 from the substrate surface.

[56] Following the pulse of the purging gas 202, a pulse of reactant (B) 203 is delivered to the substrate surface. If the barrier material contains nitrogen, such as TaN, the reactant (B) 203 is likely to contain nitrogen. The reactant (B) 203 can be nitrogen-containing gas to form TaN with the Ta on the substrate. Examples of reactant (B) 203 include ammonia (NH_3), N_2, and NO. Other N-containing precursors gases may be used including but not limited to N_xH_y for x and y integers (e.g., N_2H_4), N_2 plasma source, $NH_2N(CH_3)_2$, among others. If the barrier material contains little or no nitrogen, the reactant (B) 203 can be a hydrogen-containing reducing gas, such as H_2. H_2 is a reducing gas that reacts with the ligand bounding with the barrier-metal in reactant M 201 to terminate the film deposition. Following pulse 203 is a pulse of purging gas 204. Reactants M, B, and purge gas P can be plasma enhanced or thermally excited. In one embodiment, the pulse of reactant (B) 203 is a plasma-enhanced (or plasma-assisted).

[57] However, in some situations, the substrate surface does not possess ample bonding sites for all the potential locations on the surface. Accordingly, the barrier-metal-containing reactant M (or precursor) bonding to the surface can result in the formation of islands and

grains which are sufficiently far apart to form poor quality ALD film. Figure 3 shows an ALD film with islands 301 that are grown with limited growth sites in the beginning of ALD deposition. Between the islands 301, there are voids 303 along the surface of the substrate. Substrate surface, such as SiO2 or low-k material, can be quite inert and not easy to bond with for barrier metal in the barrier-metal-containing reactant M. Surface treatment by OH, O, or O radical exposure can efficiently insert HOH into the SiOSi to generate 2 Si-OH surface species that are highly reactive with the barrier-metal-containing reactant M. The introduction of the pre-treatment plasma into the processing chamber containing the substrate can result in the formation of surface species at various desired bonding sites. In order to grow continuous interfaces and films, one embodiment of the present invention is to pre-treat the surface of the substrate prior to ALD in order to make the surface more susceptible to ALD, due to more deposition sites.

[58] Due to the relatively long deposition cycle of conventional ALD process, the deposition rate (or throughput) for some barrier or liner layers, such as Ru, is considered too low from manufacturing standpoint. In order to improve the deposition rate, new systems and methods of using a proximity head for ALD of barrier layer and/or liner layer are invented. Figure 4A shows a schematic diagram of an ALD reactor 400 with a proximity head 440. In reactor 400, there is a substrate 410 disposed on a substrate support 420. The proximity head 440 is supported above substrate 410 and covers only a portion of substrate surface. Between the proximity head 430 and the substrate 410, there is a reaction volume 450.

[59] A gas inlet 440 and a vacuum line 465 are coupled to the proximity head 430. The gas inlet 440 supplies reactants and purging gas to process chamber 400. The gas inlet 440 can be coupled to a plurality of containers that store reactants and purging gas. The gas inlet 440 can be coupled to a container 441 that stores a first reactant, such as reactant M described in Figure 2. The gas inlet 440 can also be coupled to a container 443 that supplies a second reactant, such as reactant B described in Figure 2. As described above, reactant B can be plasma assisted. Reactant B can be supplied by a reactor 443' that generate plasmarized reactant B. Alternatively, the substrate support 420 can be coupled to a radio frequency (RF) generator to generate a plasma of reactant B when reactant B is dispensed into the reaction volume 450, instead of supplying plasmarized reactant B from reactor 443'. Another alternative is to couple an RF generator 473 to the proximity head 430 to generate

plasma. In one embodiment, one electrode is coupled to the RF generator and the other electrode is grounded, during plasma generation.

[60] The gas inlet 440 is coupled to a container 445 that stores a purging gas. Reactant M, purging gas and reactant B can be diluted by a carrier gas, which can be an inert gas. During ALD deposition cycles, one of reactants M, B and purging gas P is supplied to the gas inlet 440. The on and off of gas supplies of these gas are controlled by valves 451, 453, and 455. The other end of the vacuum line 465 is a vacuum pump 460. The reaction volume 450 in Figure 4a is much smaller than the reaction volume in a conventional ALD chamber. The deposition rate of proximity head ALD of barrier layer can be 10 times or higher than the deposition rate of conventional ALD.

[61] Figure 4B shows one embodiment of a proximity head 410 disposed above substrate 410, with a reaction volume 450 between the proximity head 410 and substrate 410. The substrate surface under the reaction volume 450 is an active process region 455. The proximity head 410 has one or more gas channels 411 that supplies reactant M, B, or purging gas P. On both sides of the gas channel 411, there are vacuum channels 413, 415 pumping excessive reactant M, B, purging gas, and/or reactant byproducts from the reaction volume 450. Reactant M, B, and purging gas P is passed through the gas channel 411 sequentially, such as the sequence shown in Figure 2. Gas channel 411 is coupled to the gas inlet 440. When a pulse of gas, either reactant M, B, or P, is injected form the gas channel 411 to the substrate surface, the excess amount of gas is pumped away from the substrate surface by the vacuum channels 413, 415, which keeps the reaction volume small and reduces the purging or pumping time. Since the reaction volume is small, only small amount of reactant is needed to cover the small reaction volume. Similarly only small amount of purging gas is needed to purge the excess reactant from the reaction volume 450. In addition, the vacuum channels are right near the small reaction volume 450, which assists the pumping and purging of the excess reactants, purging gas, and reaction byproducts from the substrate surface. As a consequence, the pulse times ΔT_M, ΔT_B, ΔT_{P1}, and ΔT_{P2} for reactants M, B, and purging gas respectively, can be greatly reduced. As a consequence, the ALD cycle time can be reduced and the throughput can be increased.

[62] The proximity head for ALD can also have multiple sides with different sides dispensing different types of processing gases. Rotating the proximity head from side to side allows the ALD cycle to be completed and a thin film being deposited.

[63] As discussed above, in order to grow continuous interfaces and films, one embodiment of the present invention is to pre-treat the surface of the substrate prior to ALD in order to have the surface more susceptible to ALD. In addition, after barrier layer and/or liner layer is deposited on the substrate surface, the surface can be post-treated to remove any surface contaminant or to reduce impurities in the film, or to density the film. Post-treatment can also enhance nucleation of copper seed layer deposited by an electroless process in a similar mechanism described above for pre-treatment prior to barrier layer deposition. Copper seed layer with enhanced nucleation has better film quality and results in better reliability (such as EM performance) and avoids delamination and void propagation. Surface pre-treatment and post-treatment can be performed by proximity heads.

[64] Figure 5A shows a schematic diagram of a chamber 500 for substrate surface treatment with a proximity head 530. In chamber 500, there is a substrate 510 disposed on a substrate support 520. The proximity head 530 is supported above substrate 510. Between the proximity head 530 and the substrate 510, there is a reaction volume 550. Since the proximity head 530 only covers a portion of the substrate surface, the reaction volume 550 is much smaller than conventional surface treatment that applies to the entire substrate surface.

[65] A gas inlet 540 and a vacuum line 565 are coupled to the proximity head 530. The other end of the vacuum line 565 is a pump 560. The gas inlet 540 supplies reactant gas to process chamber 500. The excess treatment gas is pumped away from the from the reaction volume 550 by the vacuum line 565. The gas inlet 540 can be coupled to a container 541 that stores a treatment gas, such as H_2. The treatment gas can be diluted with an inert gas. As described above, the treatment gas can be plasma assisted. In one embodiment, the plasmarized treatment gas is supplied by a reactor 541' that plasmarizes the treatment gas. Alternatively, the substrate support 520 can be coupled to a radio frequency (RF) generator to generate plasma to plasmarize treatment gas when treatment gas is dispensed into the reaction volume 550, instead of supplying plasmarized treatment from reactor 541'. Another alternative is to couple an RF generator 573 to the proximity head 530 to generate plasma. The inert gas can be used to sustain chamber pressure or to sustain plasma.

[66] Figure 5B shows one embodiment of a proximity head 510 disposed above substrate 510, with a reaction volume 450 between the proximity head 510 and substrate 510. The proximity head 530 has one or more gas channels 511 that supply treatment gas. On both sides of the gas channel 511, there are vacuum channels 513, 515 pumping excess treatment gas(es) from the reaction volume 550. Gas channel 511 is coupled the container of the treatment gas. When treatment gas is injected form the gas channel 511 to the substrate surface, the excess amount of gas is pumped away from the substrate surface by the vacuum channels 513, 515, which limits the reaction volume to be substantially below the proximity head 530.

[67] Figure 6A shows a schematic top view of an embodiment of surface treatment proximity head 530 of Figures 5A and 5B on top of a substrate 510. The description of various embodiments of proximity heads for surface treatment can also apply to ALD proximity head 430 of Figures 4A and 4B on a substrate 410. Proximity head 530 moves across the substrate surface. In this embodiment, the length of the proximity head L_{PH} is equal to or greater than the diameter of the substrate. The reaction volume under the proximity covers the substrate surface underneath. By moving the proximity head across the substrate once, the entire substrate surface is treated with the treatment gas, which can be excited by plasma, thermally, by UV, or by laser. In another embodiment, the substrate 510 is moved under the proximity head 530. In yet another embodiment, both the proximity head 530 and the substrate 510 move, but in opposite directions to cross each other. The amount of surface treatment the substrate receives can be controlled by the speed the proximity head 530 move across the substrate 510.

[68] Alternatively, the length of the proximity head L_{PH} can be shorter than the diameter of the substrate. Multiple passes of the proximity head 530' across the substrate is needed to deposit a thin barrier or liner layer on the substrate surface. Figure 6B shows a proximity head 530' with the length of the proximity head $L_{PH'}$ shorter than the diameter of the substrate. After the proximity head 530' move across the substrate surface in pass 1, the proximity head 530' can move downward to move across the substrate in pass 2 and pass 3. At the end of pass 3, the entire substrate surface is deposited with a thin layer of the barrier or liner film.

[69] Figure 6C shows another embodiment with a proximity head 530" rotating around the surface of substrate 510. In this embodiment, the treatment gas is supplied to a gas inlet 540' that is attached to the end of the proximity head 530. The vacuum line 565' is also coupled to the end of the proximity head 530".

[70] Figure 6D show an embodiment of a bottom view of the proximity head 530 of Figure 5A. The proximity head 530 has a gas injection head 501, coupled to gas channel 511 with a plurality of gas injection holes 521. The arrangement and shapes of gas injection holes 521 shown in Figure 6D are merely examples. Other arrangement of injection holes and shapes of injection holes can also be used. In one embodiment, the injection head 510 has only one narrow slit (not shown), not injection holes. Alternatively, For example, there could be two or more rows of injection holes, instead of one. The injection holes can be staggered or can be side by side. The shapes of the injection holes can be round, square, hexagonal, or other shapes. The proximity head 530 also has vacuum heads 503, 505, coupled to the vacuum channels 513, 515 on both sides of the gas injection head 501. In this embodiment, vacuum heads, 503, 505 are two slits. Other shapes of geometries of vacuum heads can also be used. Alternatively, the slits of vacuum heads 503 and 505 are connected to become one single slit 503' surrounding the gas injection head 501, as shown in the proximity head 530"' in Figure 6E. The description above for various embodiments of proximity heads for surface treatment can also be applied to proximity heads for ALD.

[71] In addition to placing a substrate under a proximity head, a substrate can also be placed above a proximity head to treat the substrate surface. Figure 6F shows a schematic drawing of a proximity head 530 placed below a substrate 510, with an active surface 570 of the substrate 510 facing the proximity head 530. Devices are manufactured on the active surface 570. The substrate 510 is suspended above the proximity head 530 by a device (not shown). The proximity head 530 is also supported by a mechanical device (not shown).

[72] As discussed above, the treatment gas can be thermally excited. Treatment gas can be thermally excited by a hot filament. Figure 7A shows a proximity head 530* with a hot filament 561 in an excitation chamber 566 in the gas channel 511 to heat up the treatment gas before the treatment gas reaches the substrate surface. It was also discussed above that surface treatment can also performed with a laser or ultra-violet (UV) excited gas. Figure 7B

shows a proximity head 530** with a light source 563, which can be a laser or a UV light source, in an excitation chamber 564 to excite the treatment gas.

[73] As discussed above, the treatment gas can be plasmarized. Figure 7C shows a proximity head 530 with an excitation chamber 568 to plasmarize the treatment gas supplied by gas line 540. The proximity head is coupled to an RF generator 573, as described in Figure 5A. The substrate support 520 is grounded. Figure 7D shows another embodiment with the proximity head 530 grounded and the substrate support coupled to an RF power supply 570, as described in Figure 5A.

[74] Figure 8 shows a schematic cross-sectional diagram of a thin barrier or liner layer 820 deposited on a substrate 810. At the edge of substrate 810, a small section 821 of thin barrier or liner layer 820 is deposited under the proximity head. After section 821 is deposited, the proximity is moved towards left to deposit another section 822, which overlaps section 821 slightly. Section 823 follows section 822, and section 824 follows section 823, and so on. At the other edge of the substrate, the deposition process stops and a complete thin film 810 is formed. In one embodiment, substrate 810 has been pre-treated to increase to growth sites on the substrate surface.

[75] As discussed above, a substrate to be deposited with a barrier layer and/or a liner layer might need to be pre-treated to clean the substrate surface or to prepare the substrate surface for depositing an ALD with better film quality. ALD proximity head(s), pre-treatment proximity head(s), and/or post-treatment proximity head(s) can be integrated in one single process chamber to complete the deposition and treatment processes. For a substrate to be deposited with a thin barrier layer, such as TaN, and a liner layer, such as Ru, the substrate can be pre-treated to clean the substrate surface or the substrate surface can be pre-treated to prepare the surface for ALD deposition, as discussed above. After the deposition, the liner layer deposition, the substrate surface can be posted-treated to prepare the surface for copper seed layer deposition. In a single and integrated deposition/treatment chamber, the substrate is pre-treated, deposited with a barrier layer and a liner layer, and post-treated. Figure 9A shows a substrate 610 with a plurality of proximity treatment and deposition heads over the substrate 610. Pre-treatment proximity head 620 is used to pre-treat the substrate surface either to remove impurities or to prepare the substrate surface for ALD. Between the proximity head 620 and the surface of substrate 610, there is a reaction

volume 660. The substrate surface below the reaction volume 660 is an active process region 670. Next to pre-treatment proximity head 620 is an ALD1 proximity head 630 used to deposit a barrier layer on the substrate. After the ALD1 proximity head 630 is an ALD2 proximity head 640 used to deposit a liner layer on the substrate. After the liner layer is deposited, the substrate is post-treated either to remove impurities or to prepare the substrate surface for copper seed layer deposition following. The post-treatment is performed by a post-treatment proximity head 650. The various proximity head moves sequentially across the substrate surface to complete treatment and deposition surface. The treatment and deposition processes can occur simultaneously or in sequence.

[76] Many types of materials can be used to make the proximity head. The examples of these materials include, but not limited to, stainless steel, alumina (Al_2O_3), quartz, SiC, and Silicon. For treatment gases, such as H_2 and NH_3, that have short radical lifetime, quartz would be a suitable material.

[77] The embodiment shown in Figure 9A is only an example of integrating treatment proximity head with deposition proximity head. Other combinations are possible. For example, there could be a surface treatment after the barrier layer is deposited and before the deposition of the liner layer. Figure 9B shows an embodiment with a surface treatment between two deposition steps. Inter-treatment proximity head 635 is inserted between ALD1 proximity head 630 and ALD2 proximity head 640.

[78] Proximity head surface treatment chamber can be integrated with other deposition, substrate cleaning, or treatment system(s) to complete copper interconnect deposition. Proximity head for ALD also can be integrated with another proximity head for ALD or CVD, and proximity heads for pre-treatment and post-treatment in the same ALD deposition chamber to complete the barrier/liner layer deposition.

[79] The gap distance between the proximity head and the substrate for surface treatment is small is between about 5 mm to about 10 mm. The gap distance between the proximity head and the substrate during ALD changes from side to side and is less than 5 mm, such as 1 mm. The gap distance between the different proximity head and substrate surface can be different for different proximity heads in the chamber.

[80] Proximity head can also be used to deposit thin film by methods other than ALD. For example, proximity head can be used to deposit a chemical vapor deposition (CVD) film.

For copper plating, the thickness of barrier layer and/or seed layer on the substrate surface needs to be thick enough to have the sheet resistivity low enough for to copper plating. A CVD proximity head can be integrated in the chamber with ALD proximity head(s). After the conformal barrier/liner layer(s) is deposited, a less conformal CVD liner layer can be deposited to increase the thickness of the total barrier layer and liner layer(s) to lower the sheet resistivity to enable copper plating.

[81] Figure 9C shows a proximity head 655 that can be used to deposit a CVD (or plasma-enhanced CVD) film with reactant A and B on a substrate 610. Such a CVD proximity head can also be integrated pre-treatment proximity head, ALD proximity head, or post-treatment proximity head. Many types of combinations are possible. For example, post-treatment might not be needed after an ALD. Therefore, only pre-treatment, ALD1 proximity head, and/or ALD2 are needed. Or the combination can be pre-treatment, ALD1, CVD, and post-treatment, as shown in Figure 9D.

[82] Figure 10A shows a schematic cross section of an interconnect structure 700 on a substrate 710. The interconnect structure 700 has an opening 705, and is lined with a barrier layer 720, an optional liner layer 730. The barrier layer 720 and liner layer 730 in Figure 7A are used as examples. Alternatively, it is possible that there is only one single barrier layer 720 for copper interconnect. Both the barrier layer 720 and the liner layer 730 are deposited by ALD. Since both the barrier layer 720, and the liner 730 are deposited by ALD processes, the film thicknesses of layers 720 and 730 are quite uniform around the structure feature. The thickness of each layer is between about 10 Å to about 50 Å. The total thickness (T_{BL}) of barrier layer and liner layer is between about 20 Å to about 100 Å.

[83] For example, the barrier layer 710 is about 20 Å of TaN barrier layer. The liner layer 730 is about 20 Å of Ru liner layer. The T_{BL} is about 40 Å with a sheet resistivity at between about 100-1000 Ω/ , which is too high for copper plating. A sheet resistivity of between about 1 Ω/ to about 10 Ω/ is needed for copper plating process. By adding another about 60 Å of Ru on the liner layer, the total sheet resistivity of the barrier/liner layers would be about 1 Ω/ to about 1.5 Ω/ , and would be low enough for copper plating, without an Electroless copper seed layer. Please note that the initial step of the direct copper plating on the liner layer (or barrier layer) is referring to copper seed layer by plating. Therefore, there is a need to deposit another layer 740 over the feature to increase the total barrier/liner layer

thickness T_{BL}' over the substrate surface to lower the sheet resistivity to be between about 1 Ω/ to about 10 Ω/ for copper plating. In one embodiment, the total thickness T_{BL}' is between about 60 Å to about 200 Å. Various methods can be used to deposit a barrier layer or liner layer to increase the thickness. The methods include, but not limited to, CVD and physical vapor deposition (PVD).

[84] As described above in Figure 9C, proximity head can also be used to deposit a chemical vapor deposition (CVD) film. CVD film deposited by using a proximity in a fashion similar to the proximity ALD deposition allow the CVD proximity head to be integrated with surface treatment and film deposition tools using proximity heads. CVD processes using the proximity head can be conducted over a wide range of process conditions. In one embodiment, the process temperature range between about 250°C to about 400°C. In another embodiment, the temperature range is between about 300°C to about 350°C. In one embodiment, the process pressure is between about 1 Torr to about 10 Torr. The vacuuming of treatment gas can be performed by turbo pump capable of achieving 10^{-6} Torr. The gap between the substrate surface and the surface of proximity head facing the substrate is between about 1 mm to about 10 mm, in one embodiment. In another embodiment, the gap is between about 3 mm to about 7 mm.

[85] Such a CVD proximity head can also be integrated pre-treatment proximity head(s), ALD proximity head(s), or post-treatment proximity head(s) to perform substrate surface treatment and film deposition in one single chamber. Many types of combinations are possible. Using the example in shown in Figure 10A, a process chamber can include a pre-treatment proximity head 750, an ALD1 proximity head 760 for depositing a barrier layer, an ALD2 proximity head 770 for depositing a liner over the barrier layer, a CVD proximity head 780 for depositing another liner layer, followed by a post-treatment proximity head 790 for post-treatment, as shown in Figure 10B.

[86] There is a wafer area pressure (P_{wap}) in the reaction volume. For surface treatment, such as pre-clean, P_{wap} is in the range of about 100 mTorr to about 10 Torr. In another embodiment of ALD, P_{wap} is in the range between about 100 mTorr to about 2 Torr. Wafer area pressure P_{wap} in the reaction volume needs to be greater than chamber pressure ($P_{chamber}$) to control P_{wap}. Chamber pressure ($P_{chamber}$) needs to be at least slightly higher than the pressure of the vacuum pump that is used to control the chamber pressure.

[87] Figure 11A shows an embodiment of a process flow 1100 for treating the substrate surface. The process flow can be used to treat any type of substrate surface, and is not limited to barrier/liner layer deposition pre-treatment or post-treatment. At step 1101, a proximity head for surface treatment is placed above a substrate. The proximity head is placed over a region of substrate surface that needs surface treatment. The region refers to the action process region 670 of Figure 9A and Figure 9B, which is under a reaction volume once the treatment gas is dispensed on the substrate surface. At step 1103, the treatment gas that is used to treat the substrate surface is excited before the treatment gas is dispensed on the substrate surface to activate the treatment gas. The treatment gas can be excited thermally by a hot-filament in an excitation chamber described above. The treatment gas can also be excited by UV or by laser. In addition, the treatment gas can also be excited to be a plasma. After the treatment gas is excited, the treatment gas is dispensed on the region of the substrate surface at step 1105. Afterwards, a question of whether the end of surface treatment has been reached or not is asked at step 1107. If the answer is "yes", the treatment process is finished. If the answer is "no", the next treatment location is identifies at step 1109. The process then returns to process step 1101.

[88] The surface treatment process using the proximity head can be conducted over a wide range of process conditions. In one embodiment, the process temperature range between about room temperature to about 400°C. When the surface proximity head is integrated with ALD proximity head in the same process chamber, the temperature range is between 150°C to about 400°C. In another embodiment, the temperature range is between 250°C to about 350°C. In one embodiment, the process pressure is between about 10 mTorr to about 10 Torr. The vacuuming of treatment gas can be performed by turbo pump capable of achieving 10^{-6} Torr.

[89] Figure 11B shows an embodiment of a process flow 1120 for pre-treating a substrate surface, depositing a barrier layer and a liner layer on the substrate surface, followed by post-treating the substrate surface in a process chamber with multiple proximity heads for treatment and deposition. At step 1121, a substrate is placed in a chamber with a plurality of proximity heads for surface treatment and deposition. The plurality of proximity heads are placed in a sequence of pre-treatment proximity head, ALD1 proximity head, ALD2 proximity head, and followed by a post-treatment proximity head. At step 1123, a pre-treatment proximity head is moved above a region on the substrate surface and a surface pre-

treatment is performed at the region on the substrate surface. At step 1125, an ALD1 proximity head is moved above a region on the substrate surface and a barrier layer is deposited at the region on the substrate surface. At step 1127, an ALD2 proximity head is moved above a region on the substrate surface and a liner layer is deposited at the region on the substrate surface. At step 1129, a post-treatment proximity head is moved above a region on the substrate surface and a surface post-treatment is performed at the region on the substrate surface. At step 1131, a question of whether the end of deposition and surface treatment has been reached is asked. If the answer is "yes", the deposition and surface treatment in the chamber is completed. If the answer is "no", next region for treatment/deposition cycle is identified at step 1133. Afterwards, the process cycle returns to step 803 to undergoes the pre-treatment/ALD1/ALD2/post-treatment cycle.

[90] Figure 11C shows an embodiment of a process flow 1150 for pre-treating a substrate surface, depositing a barrier layer, a liner layer, and another liner layer on the substrate surface, followed by post-treating the substrate surface in a process chamber with multiple proximity heads for treatment and deposition, as shown in Figure 10B. At step 1151, a substrate is placed in a chamber with a plurality of proximity heads for surface treatment and deposition. The plurality of proximity heads are placed in a sequence of pre-treatment proximity head, ALD1 proximity head, ALD2 proximity head, and followed by a post-treatment proximity head. At step 1153, a pre- treatment proximity head is moved above a region on the substrate surface and a surface pre-treatment is performed at the region on the substrate surface. At step 1155, an ALD1 proximity head is moved above the region on the substrate surface and a barrier layer is deposited at the region on the substrate surface. At step 1157, an ALD2 proximity head is moved above a region on the substrate surface and a liner layer is deposited at the region on the substrate surface.

[91] At step 1159, a CVD proximity head is moved above the region on the substrate surface and another liner layer is deposited at the region on the substrate surface. At step 1161, a post-treatment proximity head is moved above the region on the substrate surface and a surface post-treatment is performed at the region on the substrate surface. At step 1163, a question of whether the end of deposition and surface treatment has been reached is asked. If the answer is "yes", the deposition and surface treatment in the chamber is completed. If the answer is "no", next region for treatment/deposition cycle is identified at

step 1165. Afterwards, the process cycle returns to step 1153 to undergoes the pre-treatment/ALD1/ALD2/post-treatment cycle.

[92] The surface pre-treatment and the barrier layer deposition being performed in the same chamber reduces process time and protecting the pre-treated substrate surface from being contaminated or being non-active before the barrier layer is deposited. Surface post-treatment and the liner layer deposition being performed in the same chamber also reduces process time.

[93] In addition, not every proximity heads in the process chamber needs to be used for processing. For example, if pre-treatment is not needed for some types of substrates, the pre-treatment proximity head can move across the substrate with ALD1 proximity head, ALD2 proximity head, and post-treatment proximity, but no treatment gas is dispensed form the pre-treatment proximity head.

[94] Once the substrate completes processing in the integrated surface treatment and deposition system, such as the ones in Figures 9A and 9B, the substrate is ready for electroless deposition (ELD) of copper seed layer. The substrate should not be exposed to oxygen or other contaminants to ensure the surface is ready for depositing high-quality electroless copper seed layer. To achieve controlled and limited exposure to oxygen or to protect the surface from contaminants, the substrate should be transferred or processed in controlled environment, such as an environment under vacuum or an environment filled with an inert gas.

[95] Figure 12A shows an embodiment of a process flow 1200 of depositing a barrier layer, an optional liner layer, an electroless copper seed layer, and a copper gap-fill layer to fill an interconnect structure. The barrier layer and the optional liner layer are deposited in an integrated chamber that has the process capability of surface treatment. At step 1201, the substrate is moved into a process chamber with integrated surface treatment and ALD deposition. As described above, the integrated surface treatment and ALD deposition chamber uses proximity heads for surface treatment and ALD deposition, since proximity heads allow integration of multiple processing heads in one processing chamber.

[96] At step 1203, the substrate surface is processed in the process chamber with integrated surface treatment and ALD deposition to deposit a barrier layer and an optional liner layer with surface treatment before and/or after film deposition. In one embodiment,

the substrate surface before film deposition, such as the one shown in Figure 1A, is pre-treated to prepare the surface for barrier layer deposition. The surface is either cleaned to remove surface contaminants or treated with a treatment gas to increase deposition grown sites, as described above. In one embodiment, substrate surface of the interconnect feature, such as surface 122a of Figure 1A, could have been oxidized to have formed a metal oxide. The metal oxide can be removed by an Ar sputtering process, a plasma process using a fluorine-containing gas, such as NF_3, CF_4, or a combination of both. Alternatively, the dielectric surfaces of openings 114, 116 might need to be plasma treated to increase deposition sites to improve film quality, as described above. For some barrier layer, such as TaN, a liner layer, such as Ru, might be needed before copper deposition. For other barrier layer, such as Ru, the liner layer might not be needed. In one embodiment, the barrier layer is TaN and the thickness of the barrier layer is between about 20 Å to about 200 Å. The liner layer is Ru and the thickness of the liner layer is between about 20 Å to about 200 Å.

[97] After the barrier layer and the optional liner layer are deposited, the substrate can be post-treated, as described above, to remove surface contaminants or to prepare the substrate surface copper seed layer deposition. Therefore, the integrated chamber can include a proximity head for post-treatment. In one embodiment, the barrier layer is hydrogen-plasma treated to produce a metal-rich surface on the Ta, TaN, or Ru layer to provide a catalytic surface for the subsequent copper seed deposition step.

[98] At step 1205, the substrate is moved into a copper seed layer deposition chamber. At step 1207, a copper seed layer is deposited. In one embodiment, the thickness of the copper seed layer is between about 25 Å to about 200 Å. In another embodiment, the thickness of the copper seed layer is between about 50 Å to about 100 Å. In one embodiment, the copper seed layer is deposited by an electroless process. The thick copper bulk fill process can be deposited by an electroless deposition (ELD) process or by an electrochemical plating (ECP) process. At step 1209, the substrate is moved to a copper-plating chamber. However, if the copper gap-fill layer is deposited by ELD, this step can be skipped (optional step), since the gap-fill layer deposition will be done in the same processing chamber as the seed layer. At step 1211, a copper gap fill layer is deposited.

[99] Electroless copper deposition and ECP are well-known wet process. For a wet process to be integrated in a system with controlled processing and transporting

environment, the reactor needs to be integrated with a rinse/dryer to enable dry-in/dry-out process capability. In addition, the system needs to be filled with inert gas to ensure minimal exposure of the substrate to oxygen. Recently, a dry-in/dry-out electroless copper process has been developed. Further, all fluids used in the process are de-gassed, i.e. dissolved oxygen is removed by commercially available degassing systems.

[100] The electroless deposition process can be carried out in a number of ways, such as puddle-plating, where fluid is dispensed onto a substrate and is allowed to react in a static mode, after which the reactants are removed and discarded, or reclaimed. In another embodiment, the process uses a proximity process head to limit the electroless process liquid is only in contact with the substrate surface on a limited region. The substrate surface not under the proximity process head is dry.

[101] After copper deposition at steps 1207 and 1211, the substrate can be optionally moved into a substrate cleaning chamber to undergo an optional substrate cleaning at step 1213. Post-copper-deposition clean can be accomplished by using a brush scrub clean with a chemical solution, such as a solution containing CP72B supplied by Air Products and Chemical, Inc. of Allentown, Pennsylvania. Other substrate surface cleaning processes can also be used.

[102] Figure 12B shows an embodiment of a schematic diagram of an integrated system 750 that allows minimal exposure of substrate surface to oxygen or other contaminants after barrier surface preparation. In addition, since it is an integrated system, the substrate is transferred from one process station immediately to the next process station, limiting the duration that the clean or treated barrier layer or liner layer surface is exposed to oxygen. The integrated system 1250 can be used to process substrate(s) through the process sequence of flow 1200 of Figure 12A.

[103] As described above, the pre-treatment and post-treatment for barrier/liner layer deposition, ALD of barrier and liner layers, and electroless deposition of copper seed layer, copper gap-fill layer deposition, and the optional post copper gap-fill deposition involve a mixture of dry and wet processes. The wet processes are typically operated near atmosphere, while the dry plasma processes are operated at less than 1 Torr. Therefore, the integrated system needs to be able to handle a mixture of dry and wet processes.

[104] The integrated system 1250 has 2 substrate transfer modules 1255, and 1257. Transfer modules 1255 and 1257 are equipped with robots to move substrate 1251 from one process area to another process area. The process area could be a substrate cassette, a reactor, or a loadlock. Substrate transfer module 1255 is operated under vacuum, at a pressure less than about 1 Torr. Substrate transfer module 1255 is coupled to a process chamber 1256 for integrated surface treatment and ALD, which is also operated under vacuum, at a pressure less than 1 Torr. In one embodiment, vacuum transfer module 1255 interfaces with a substrate loader (or substrate cassette) 1252 to bring the substrate 1251 into the integrated system or to return the substrate to the cassette 1252. Between the vacuum transfer module 1255 and the cassette 1252, there is a loadlock 1253 to assist transferring the substrate between the atmospheric cassette 1252 and the vacuum transfer module 1255, which is operated under vacuum at a pressure compatible with processing chamber(s), such as processing chamber 1256, attached. For example, if the substrate 1251 is to be transferred from the atmospheric cassette 1252 to the vacuum transfer module 1255, the pressure of the loadlock 1253 is first being brought to be atmospheric to allow the substrate 1251 to be transferred from the atmospheric cassette 1252 to the loadlock 1253. After the substrate 1251 is in the loadlock 1253 and the loadlock door(s) is closed, the loadlock 1253 is pumped to be in vacuum to allow the substrate 1251 to be transferred from the loadlock 1253 to the vacuum transfer module 1255.

[105] As described above in process flow 1200, the substrate 1251 is brought to the integrated system 1250 to deposit barrier/liner layer(s) and copper seed layer, and a copper gap-fill layer. As described in step 1201 of process flow 1200, substrate 1251 is moved to process module 1256 with a chamber 1256 for integrated surface treatment and ALD barrier/liner deposition. The surface treatment and ALD barrier/liner deposition are performed with proximity heads, such as the ones in Figure 9A. The surface treatment processes, ALD barrier deposition, and ALD liner deposition described in Figure 9A are all dry processes and are all operated below 1 Torr.

[106] After substrate 1251 is processed in process chamber 1256 at step 1202, the substrate is ready for ELD copper seed layer deposition. Electroless copper deposition and electro-chemical plating (ECP) are well-known wet processes. As discussed above, for a wet process to be integrated in a system with controlled processing and transporting environment, which has been described above, the reactor needs to be integrated with a

rinse/dryer to enable dry-in/dry-out process capability. In addition, the system needs to be filled with inert gas to ensure minimal exposure of the substrate to oxygen. Recently, a dry-in/dry-out electroless copper process has been developed. Further, all fluids used in the process are de-gassed, i.e. dissolved oxygen is removed by commercially available degassing systems.

[107] Both ELD copper and ECP copper processing modules need to be integrated with a transfer module with controlled ambient; therefore, the substrate transport module 1257 is operating under controlled-ambient to limit the exposure of substrate to oxygen or contaminants. In one embodiment, the substrate transport module 1257 is filled with an inert gas and operated at atmospheric pressure. Substrate 1251 is moved from processing chamber 1256 to ELD copper processing module 1258 for copper seed layer deposition, as described in steps 1205 and 1207. Afterwards, the substrate 1251 is moved to ECP copper module 1259 for copper gap-fill deposition, as described in step 1209 and 1211. After ECP gap-fill, the substrate 1251 could be moved into a cleaning module 1261 and undergoes a substrate cleaning, as described in step 1213. However, the cleaning after ECP copper deposition is optional. The ECP processing module has an integrated rinse/dry, which might have sufficiently cleaned the substrate.

[108] While this invention has been described in terms of several embodiments, it will be appreciated that those skilled in the art upon reading the preceding specifications and studying the drawings will realize various alterations, additions, permutations and equivalents thereof. Therefore, it is intended that the present invention includes all such alterations, additions, permutations, and equivalents as fall within the true spirit and scope of the invention. In the claims, elements and/or steps do not imply any particular order of operation, unless explicitly stated in the claims.

CLAIMS

1. An apparatus for treating a surface of a substrate, comprising:

a substrate support configured to support the substrate;

a proximity head configured to dispense a treatment gas to treat an active process region of a substrate surface under the proximity head, wherein the proximity head covers the action process region of the substrate surface and the proximity head includes at least one vacuum channel to pull excess treatment gas from a reaction volume between the proximity head and the substrate, the proximity head having an excitation chamber to excite the treatment gas before the treatment gas being dispensed on the active process region portion of the substrate surface.

2. The apparatus of claim 1, wherein there are two vacuum channels, one on each side of at least one gas channel to dispense the treatment gas.

3. The apparatus of claim 1, wherein there is one vacuum channel surrounding at least one gas channel to dispense the treatment gas.

4. The apparatus of claim 1, wherein the treatment gas is selected form a group consisting of H_2, NH_3, NF_3, NH_4F, O_2, and N_2.

5. The apparatus of claim 4, wherein the treatment gas is diluted by an inert gas.

6. The apparatus of claim 1, wherein the treatment gas is excited by a hot-filament, by laser, by ultra-violent (UV), or by plasma.

7. A method of treatment a substrate surface, comprising:

moving a proximity head for surface treatment above a substrate, wherein the proximity head has at least one gas channel configured to dispense a treatment gas on a region of the substrate surface, the proximity head having at least one vacuum channel used to vacuum excess treatment gas from a reaction volume underneath the proximity head, and the proximity head for surface treatment covering the region of the substrate surface;

exciting the treatment gas in an excitation chamber of the proximity head before the treatment gas is dispensed on the region of the substrate surface; and

dispensing the excited treatment gas on the region of the substrate surface to treat the substrate surface.

8. The method of claim 7, wherein the surface treatment is used to remove surface impurities prior to the deposition of a film on the substrate.

9. The method of claim 7, wherein the surface treatment is used to increase initial deposition sites for an ALD of a barrier layer for copper.

10. The method of claim 7, wherein the surface treatment is performed on a deposited liner layer to enhance nucleation for an electroless copper seed layer to be deposited, or to remove contaminants on the deposited liner layer prior to the deposition of a copper seed layer.

11. A chamber for performing surface treatment and film deposition, comprising:

a first proximity head for substrate surface treatment configured to dispense a first treatment gas to treat a portion of a surface of a substrate under the first proximity head for substrate surface treatment; and

a first proximity head for atomic layer deposition (ALD) configured to sequentially dispensing a first reactant gas and a first purging gas to deposit a first ALD film under the second proximity head for ALD.

12. The apparatus of claim 11, further comprising:

a second proximity head for substrate surface treatment configured to dispense a second treatment gas to treat a portion of the surface of the substrate under the first proximity head for substrate surface treatment; and

a second proximity head for ALD configured to sequentially dispensing a second reactant gas and a second purging gas to deposit a second ALD film under the second proximity head for ALD.

13. The apparatus of claim 11, wherein the first proximity head for substrate surface treatment is used to perform a surface treatment before or after the substrate is deposited with the first ALD film.

14. The apparatus of claim 11, wherein the first ALD film is a barrier layer for copper.

15. The apparatus of claim 12, wherein the second ALD film is a liner layer for copper.

16. The apparatus of claim 12, wherein the second proximity head for substrate surface treatment is used to perform a surface treatment after the substrate is deposited with the second ALD film.

17. The apparatus of claim 12, wherein the first proximity head for ALD is placed next to the first proximity head for substrate surface treatment, the second proximity head for ALD being placed next to the first proximity head for ALD, and the second proximity head for substrate surface treatment being placed next to the second proximity head for ALD.

18. The apparatus for claim 17, wherein the first proximity head for substrate surface treatment is used to perform a pre-treatment before film deposition on the substrate, the first proximity head for ALD being used to deposit a barrier layer for copper, the second proximity head for ALD being used to deposit a liner layer for copper, and the second proximity head for substrate surface treatment being used to perform a post-treatment after the barrier layer and the liner layer being deposited.

19. The apparatus of claim 11, wherein the first reactant gas is a barrier-metal-containing reactant or a reactant gas that form a barrier layer with the barrier-metal-containing reactant.

20. The apparatus of claim 12, wherein the second reactant gas is a liner-metal-containing reactant or a reactant gas that form a liner layer with the liner-metal-containing reactant.

21. A method of performing surface treatment and film deposition on a substrate in a processing chamber, comprising:

placing the substrate in the processing chamber with a plurality of proximity heads for surface treatment and film deposition, wherein each of the plurality of proximity head covers a portion of a substrate surface;

moving a pre-treatment proximity head above a region on the substrate surface;

performing a surface pre-treatment with the pre-treatment proximity head at the region on the substrate surface;

moving an atomic layer deposition 1 (ALD1) proximity head above the region on the substrate surface; and

depositing a barrier layer for copper with the ALD 1 proximity head at the region on the substrate surface.

22. The method of claim 21, further comprising:

moving an atomic layer deposition 2 (ALD2) proximity head above the region on the substrate surface;

depositing a liner layer for copper with the ALD2 proximity head at the region on the substrate surface;

moving a post-treatment proximity head above a region on the substrate surface; and

performing a surface post-treatment with the post-treatment proximity head at the region on the substrate surface.

23. The method of claim 21, wherein the surface pre-treatment is used to remove surface impurities prior to the deposition of the barrier layer or to increase initial deposition sites for the barrier layer deposited with ALD1 proximity head.

24. The method of claim 22, wherein the surface post-treatment is performed on the liner layer for copper to enhance nucleation for an electroless copper seed layer to be deposited.

25. The method of claim 21, wherein the surface pre-treatment and the barrier layer deposition are performed in the same chamber to reduce process time and to protect the pre-treated substrate surface from being contaminated or being non-active before the barrier layer is deposited.

26. A method of depositing films on a substrate for copper interconnect in an integrated system, comprising:

moving the substrate into a processing chamber having a plurality of proximity heads, selected ones of the proximity heads being configured to perform at least one of surface treatments and atomic layer depositions (ALDs), the processing chamber being part of the integrated system, and within the processing chamber, performing,

barrier layer deposition over a surface of the substrate using one of the plurality of proximity heads functioning to perform barrier layer ALD; and

moving the substrate from the processing chamber, through a transfer module of the integrated system and into a processing module for performing copper seed layer deposition, the processing module for performing copper seed layer deposition being part of the integrated system, and within the processing module for performing copper seed layer deposition, performing,

copper seed layer deposition over the surface of the substrate,

wherein the integrated system enables controlled-ambient transitions within the integrated system to limit exposure of the substrate to uncontrolled ambient conditions outside of the integrated system.

27. The method of claim 26, further comprising:

moving the substrate from the processing module for performing copper seed layer deposition, through the transfer module of the integrated system and into a processing module for performing copper gap-fill layer deposition, the processing module for performing copper gap-fill layer deposition being part of the integrated system, and within the processing module for performing copper gap-fill layer deposition, performing,

copper gap-fill layer deposition over the copper seed layer of the substrate; and

moving the substrate from the processing module for performing copper gap-fill layer deposition, through the transfer module of the integrated system and into a processing module for performing substrate cleaning, the processing module for performing substrate cleaning being part of the integrated system, and within the processing module for substrate cleaning, performing,

cleaning of the substrate after the copper gap-fill layer deposition has been performed.

28. The method of claim 26, further comprising:

performing surface pre-treatment over the surface of the substrate using one of the plurality of proximity heads functioning to perform surface pre-treatment in the processing chamber before the barrier layer deposition.

29. The method of claim 28, wherein the surface pre-treatment is performed over the surface of the substrate to remove contaminants or to activate the surface of the substrate for the barrier layer deposition.

30. The method of claim 28, further comprising:

performing liner layer deposition over the barrier layer of the substrate using one of the plurality of proximity heads functioning to perform liner layer ALD in the processing chamber, and

performing surface post-treatment over the surface of the substrate using one of the plurality of proximity heads functioning to perform surface post-treatment in the processing chamber after the liner layer deposition.

31. The method of claim 30, wherein the surface post-treatment is performed over the surface of the substrate to remove contaminants or to activate the surface of the substrate in preparation for the copper seed layer deposition.

32. The method of claim 26, wherein the films deposited on the substrate for copper interconnect in the integrated system with limited exposure to uncontrolled ambient conditions outside the integrated system improve electro-migration (EM) performance for copper interconnect.

33. An integrated system for depositing films on a substrate for copper interconnect, comprising:

a processing chamber having a plurality of proximity heads, selected ones of the proximity heads being used for surface treatments and atomic layer depositions (ALDs);

a vacuum transfer module coupled to the processing chamber, the vacuum transfer module being used to transfer the substrate in the integrated system;

a processing module for copper seed layer deposition;

a controlled-ambient transfer module coupled to the processing module for copper seed layer deposition; and

a loadlock coupled to the vacuum transfer module and to the controlled-ambient transfer module, the loadlock being used to assist transferring the substrate between the vacuum transfer module and to the controlled-ambient transfer module, wherein the integrated system enables controlled-ambient transitions within the integrated system to limit exposure of the substrate to uncontrolled ambient conditions outside of the integrated system.

34. The integrated system of claim 33, further comprising:

a processing module for copper gap-fill layer deposition, which is coupled to the controlled-ambient transfer module; and

a processing module for substrate cleaning, which is coupled to the controlled-ambient transfer module.

35. The integrated system of claim 33, further comprising:

a cassette for holding the substrate before and after the substrate being processed in the integrated system; and

a loadlock coupled to the cassette and to the vacuum transfer module, the loadlock being used to assist transferring the substrate between the cassette and the vacuum transfer module.

36. The integrated system of claim 33, wherein one of the proximity heads is used to deposit an ALD barrier layer for copper interconnect.

37. The integrated system of claim 33, wherein one of the proximity heads is used to deposit an ALD liner layer for copper interconnect.

38. The integrated system of claim 33, wherein one of the proximity heads is used to perform surface pre-treatment before ALDs, and another one of the proximity heads is used to perform surface post-treatment after ALDs.

39. The integrated system of claim 33, wherein the selected ones of the proximity heads includes a proximity head for surface pre-treatment, a proximity head for barrier layer ALD, a proximity head for liner layer ALD, and a proximity head for surface post-treatment.

40. The method of claim 33, wherein the controlled-ambient transfer module and the processing module for performing copper seed layer deposition are filled with an inert gas to limit the exposure of the substrate to oxygen.