

HIGH SPEED COPPER PLATING BATH

BACKGROUND OF THE INVENTION

The present invention relates to the field of electroplating of metals and more particularly to novel electroplating baths, electroplating aqueous solutions and methods of electroplating copper onto a substrate.

Copper based materials are frequently used as low resistivity interconnects in the microelectronics industry. In addition to its use for IC interconnects, the use of copper electro-deposition to produce high aspect ratio structures such as vias, pillars, and bumps on semiconductor chips is one of the key technologies for 3D packaging. It is important that an electroplating process for copper be sufficiently fast to allow the processing of a large number of substrates and have an acceptable yield. This is particularly important for the production of the high aspect ratio structures that are needed for 3D packaging, since larger amounts of copper need to be plated for this purpose. However, current electroplating processes for copper are not sufficiently fast because the copper plating speed is normally limited by the mass transport of copper ions in the aqueous plating solution in the diffusion layer area. Only high copper ion concentrations are able to accommodate high speed plating under mass transport controlled conditions. However the copper concentration is limited by the solubility of copper salts at ambient temperature to allow the transportation of electrolytic solutions from material suppliers to manufacturers. Therefore, the maximum copper concentration is limited by the copper salt solubility in any selected electrolytic solution at normal transportation temperatures.

SUMMARY OF THE INVENTION

Electroplating baths for the high speed electroplating of copper and methods of electroplating copper on semiconductor chips are disclosed. In particular, copper electroplating baths that includes an aqueous solution that comprises a copper salt and at least one acid and a container that comprises a copper salt in solid form, is disclosed. The container supplies copper ions to the aqueous solution to maintain the copper ion concentration of the aqueous solution at saturation levels while retaining the copper salt in solid form within the container. This makes possible high electroplating speeds that

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are particularly useful for plating high aspect ratio structures such as vias, pillars, and bumps on semiconductor chips without using more costly and toxic high solubility copper salts.

In one embodiment, the present invention provides copper electroplating baths comprising: an aqueous solution that comprises a copper salt and at least one acid; at least one additive to accelerate the copper deposition rate of the copper electroplating bath; and a container that comprises a copper salt in solid form, wherein the container is immersed in the aqueous solution and supplies copper ions to the aqueous solution to maintain the copper ion concentration of the aqueous solution at about saturation levels while retaining the copper salt in solid form within the container.

In certain embodiments, the container of the copper electroplating bath comprises a sealed box having a plurality of openings that are covered with a porous membrane that allows dissolved copper ions to leave the container while retaining the copper salt in solid form within the container.

In additional embodiments, the present invention provides methods of electroplating copper on substrates comprising: providing a substrate; placing the substrate in contact with a copper electroplating bath, wherein the copper electroplating bath comprises an aqueous solution that comprises a copper salt and at least one acid and a container that comprises a copper salt in solid form, wherein the container is immersed in the aqueous solution and supplies copper ions to the aqueous solution to maintain the copper ion concentration of the aqueous solution at about saturation levels while retaining the copper salt in solid form within the container; and electroplating copper on the substrate.

In other aspects, a method of electroplating copper on a substrate is provided and can include immersing a substrate in a copper electroplating bath and disposing a copper salt in solid form within a container located in the copper electroplating bath. A chamber of the container can be in fluid communication with the copper electroplating bath. The method can further include electroplating copper on the substrate and solubilizing the copper salt to supply copper ions to the copper electroplating bath, and optionally maintaining a copper ion concentration of the copper electroplating bath at about saturation levels.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred and alternative embodiments of the present invention are described in detail below with reference to the following drawings:

FIGURE 1A is a schematic view of an exemplary copper electroplating bath, in accordance with an embodiment of the present invention;

FIGURE 1B is a schematic, magnified view of a portion of a container used in an exemplary copper electroplating bath, in accordance with an embodiment of the present invention;

FIGURE 2, is a block diagram illustrating an exemplary method of electroplating copper on a substrate, in accordance with an embodiment of the present invention;

FIGURE 3 is a scanning electron microscope image of copper pillars having a thickness of 70 microns that have been plated on a semiconductor wafer, wherein the sample I.D. (003203), the electron beam energy (2.0 kV), the image magnification (x449) and a dashed line corresponding to a distance of 66.8 microns are shown, in accordance with an embodiment of the present invention; and

FIGURE 4 is a scanning electron microscope image of copper pillars having a thickness of 120 microns that have been plated on a semiconductor wafer, wherein the sample I.D. (003246), the electron beam energy (2.0 kV), the image magnification (x147) and a dashed line corresponding to a distance of 204 microns are shown, in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS OF THE INVENTION

Referring now to FIGURE 1A, a schematic view of an exemplary copper electroplating bath 10, in accordance with an embodiment of the present invention, is shown. The copper electroplating bath 10 includes an aqueous solution 20 that comprises a copper salt and at least one acid and a container 30 that comprises a copper salt in solid form. Optionally, the copper electroplating bath 10 can include various

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other materials, including chloride ions and one or more additives to accelerate the copper deposition rate of the copper electroplating bath 10. The container 30 is immersed in the aqueous solution 20 and supplies copper ions to the aqueous solution 20 to maintain the copper ion concentration of the aqueous solution 20 at about saturation levels while retaining the copper salt in solid form within the container 30. The term "copper ions" as used herein includes both the Cu^{2+} and the Cu^+ species. The phrase "at about saturation level" refers to a concentration of an ion which is within about 80% of its saturation value at the environmental conditions that the system is subjected to. In other embodiments, the concentration of an ion can be within about 85%, 90%, 95%, 96%, 97%, 98%, 99%, or greater or less values relative to its saturation value at the environmental conditions the system is subject to.

In the illustrated embodiment, the container 30 is a sealed box 32 having a plurality of openings 34 that are covered with a porous membrane 36 (FIGURE 1B) that allows dissolved copper ions to leave the container 30 while retaining the copper salt in solid form within the container 30. However, it should be understood that the container 30 can be any structure that supplies copper ions to the aqueous solution 20 to maintain the copper ion concentration of the aqueous solution 20 at about saturation levels while retaining the copper salt in solid form within the container 30. For example, in some embodiments, the container 30 can have a single opening that is covered with a porous membrane, and/or the entire container 30 can be formed of a porous membrane that allows dissolved copper ions to leave the container 30 while retaining the copper salt in solid form within the container 30. Also shown in FIGURE 1A is a tank 40 for holding the copper electroplating bath 10.

Various copper salts can be used in the copper electroplating bath 10 of the present invention. Suitable copper salts for use in the aqueous solution 20 and in solid form in the container 30 include, for example, copper sulfate, copper pyrophosphate, copper sulfamate, copper chloride, copper formate, copper fluoride, copper nitrate, copper oxide, copper tetrafluoroborate, copper trifluoromethanesulfonate, copper trifluoroacetate and copper methane sulfonate, or hydrates of any of the foregoing compounds. In one embodiment, the copper salt used in the aqueous solution 20 and in solid form in the container 30 is copper sulfate. The concentration of the copper salt used in the aqueous solution 20 will vary depending on the particular copper salt used

and can range from about 10 grams/liter to about 400 grams/liter. In the case of copper sulfate, the concentration used in the aqueous solution 20 can range from about 50 grams/liter to about 250 grams/liter. The amount of the copper salt used in solid form in the container 30 will vary depending on the particular copper salt used and can range from about 10 grams to about 1000 grams per liter of the aqueous solution 20. In the case of copper sulfate, the amount used in the container 30 can range from about 100 grams to about 600 grams per liter of the aqueous solution 20.

Various acids can be used in the copper electroplating bath 10 of the present invention. Suitable acids include, for example, sulfuric acid, methanesulfonic acid, fluoroboric acid, hydrochloric acid, hydroiodic acid, hydroboric acid, nitric acid, phosphoric acid and other suitable acids. In one embodiment, the acid used in the copper electroplating bath 10 is sulfuric acid. The concentration of the acid used in the copper electroplating bath 10 will vary depending on the particular acid used and can range from about 10 grams/liter to about 300 grams/liter. In the case of sulfuric acid, the concentration used in the copper electroplating bath 10 can range from about 20 grams/liter to about 200 grams/liter.

Optionally, chloride ions can be included in the copper electroplating bath 10 of the present invention. Suitable sources of chloride ions include, for example, hydrochloric acid, sodium chloride, potassium chloride and any bath soluble chloride salts. The concentration of chloride ions used in the copper electroplating bath 10 can range from about 10 ppm to about 100 ppm.

If desired, one or more optional additives that accelerate the copper deposition rate can be used in the copper electroplating bath 10 of the present invention. Suitable additives include, for example, brighteners, for example, organic sulfide compound, such as bis (sodium-sulfopropyl) disulfide, 3-mercapto-1-propanesulfonic acid sodium salt, N,N-dimethyl-dithiocarbamyl propylsulfonic acid sodium salt and 3-S-isothiuronium propyl sulfonate, or mixtures of any of the foregoing compounds. Additional suitable accelerator agents include, but are not limited to, thiourea, allylthiourea, acetylthiourea, pyridine, mixtures of any of the foregoing compounds, or other suitable accelerator agents.

The electroplating solution may also include additives, such as a carriers, leveler agents, or both that improve certain electroplating characteristics of the electroplating solution. Carriers may be a surfactant, a suppressor or a wetting agent. Levelers may be a chelating agent, a dye, or an additive that exhibits a combination of any of the foregoing functionalities. The carrier and leveler agents may be selected from the following agents: a polyether surfactant, a non-ionic surfactant, a cationic surfactant, an anionic surfactant, a block copolymer surfactant, a polyethylene glycol surfactant, polyacrylic acid, a polyamine, aminocarboxylic acid, hydrocarboxylic acid, citric acid, entrol, edetic acid, tartaric acid, a quaternized polyamine, a polyacrylamide, a cross-linked polyamide, a phenazine azo-dye (*e.g.*, Janus Green B), an alkoxyated amine surfactant, polymer pyridine derivatives, polyethyleneimine, polyethyleneimine ethanol, a polymer of imidazoline and epichlorohydrine, benzylated polyamine polymer, mixtures of any of the preceding suppressor agents, or other suitable suppressor agents. In a more specific embodiment of the invention, a combination of one accelerator, one carrier and one leveler is added to the electroplating bath to improve certain electroplating characteristics.

Various materials can be used to construct the container 30, used in the copper electroplating bath 10 of the present invention. For example, in the embodiment illustrated in FIGURE 1A in which the container 30 is a sealed box 32 having a plurality of openings 34 that are covered with a porous membrane 36, the sealed box 32 can be constructed from a plastic such as high density polyethylene, and the porous membrane 36 can be a fiber or filter membrane. 36 made from a material such as PFA, PTFE, PVDF or similar materials. Other suitable materials for construction of the sealed box 32 include, for example, a fabric bag, while other suitable materials for the porous membrane 36 include, for example, PFA or PTFE. In general, the number of openings 34 must be high enough and the pores of the porous membrane 36 must be large enough to allow the aqueous solution 20 containing copper ions to pass through the porous membrane 36 while retaining the copper salt in solid form within the container 30. In one embodiment, the plurality of openings 34 constitute about 50% to about 90% of the surface area of the sealed box 32 and the pore size of the porous membrane 36 ranges from about 1 micron to about 10 microns or from about 1 micron to about 100 microns. While the sealed box 32 in the embodiment illustrated in FIGURE 1A has a rectangular

shape, it should be understood that the sealed box can have any desired shape without departing from the scope of the present invention.

In another embodiment, a container for use in the copper electroplating bath 10 of the present invention can have one or more openings, which can optionally be covered with a porous membrane. The one or more openings can have any size and shape suitable for allowing the aqueous solution 20 containing copper ions to pass through the porous membrane while a chamber within the container retains a copper salt in solid form. Alternatively, or in addition, the container can be formed entirely from a porous membrane (e.g., a mesh-like frame or flexible bag enveloping the copper salt). In such an embodiment, the porous membrane can have a rigidity suitable for retaining a particular shape, such as a rectangle or box shape. In other embodiments, the porous membrane can be flexible enough such that it does not retain a particular shape while within the aqueous solution 20.

Also contemplated hereunder are methods for electroplating copper on a substrate using the copper electroplating bath of the present invention that is described in detail above. In describing this method, reference will be made to FIGURE 2, which shows a block diagram illustrating an exemplary method of electroplating copper on a substrate using the copper electroplating bath of the present invention.

Block 100 of FIGURE 2 represents provision of the copper electroplating of the present invention that is described in detail above. The pH and temperature of the copper electroplating bath are selected and maintained to promote efficient plating of copper on a substrate. With respect to pH, in one embodiment, the pH of the copper electroplating bath is below 7. If necessary, the pH of the copper electroplating bath may be adjusted with an acid such as sulfuric acid or a base such as sodium hydroxide. With respect to temperature, in one embodiment, the temperature of the copper electroplating bath ranges from about 24°C to about 60°C. In another embodiment, the temperature of the copper electroplating bath is about 45°C.

Block 110 of FIGURE 2 represents providing a substrate to be electroplated. Various substrates can be electroplated with copper in accordance with the present invention. In general, the term "substrate" as used herein means any material on which copper is to be electroplated. Typically, the substrate is a semiconductor material such as a silicon wafer. Other suitable substrates include, for example, circuit boards with

large and small diameters, high aspect ratio microvias, through silicon-vias, or circuit boards with large and small diameters, high aspect ratio pillars, bumps and other apertures.

Blocks 120 and 130 of FIGURE 2 represent placing the substrate in contact with the copper electroplating bath and electroplating copper on the substrate, respectively. In order for the electroplating of copper to take place, an electric current is applied to the copper electroplating bath using a set of electrodes (i.e., an anode and a cathode). For the electroplating of copper, the anode is typically made of copper plates or phosphorus doped copper plates and the cathode is typically the substrate. The amount of current applied to the copper electroplating bath can vary widely, with typical current densities ranging from about 10mA/cm² to about 600mA/cm². The substrate is removed from the electroplating path after the desired amount of copper is electroplated on the substrate. In one embodiment, the substrate remains in the copper electroplating bath for a time period ranging from about 1 min to about 90 min. In other embodiments, the substrate remains in the copper electroplating bath for a time period ranging from about 5 minute to about 25 minutes.

In another embodiment, a method of electroplating copper on a substrate is provided and can include, for example, immersing a substrate in a copper electroplating bath. The substrate can be a silicon wafer or another appropriate substrate as noted above. A copper salt in solid form can be disposed within a container that is located in the copper electroplating bath. A chamber within the container can be in fluid communication with the copper electroplating bath such that copper ions from the copper salt are in fluid communication with the copper electroplating bath while the copper salt in solid form is retained within the chamber in the container. The substrate can be electroplated with copper, as described above, and the copper salt can be solublized to supply copper ions to the copper electroplating bath such that a copper ion concentration of the copper electroplating bath is maintained at about saturation levels.

The copper electroplating baths of the present invention and related methods make possible high copper electroplating speeds. In one embodiment, the electroplating speed is about 6 microns per minute or greater. These high electroplating speeds are particular useful for electroplating high aspect ratio structures (i.e., structures having a height:diameter ratio greater than 1:1) on substrates. Such high aspect ratio structures

include, for example copper pillars, copper bumps, copper through-silicon vias, copper micro vias and trenches and the like.

The following examples illustrate certain embodiments of the present invention, and are not to be construed as limiting the present disclosure.

Examples

Example 1

A plating bath containing 240g/L copper sulfate, 60g/L sulfuric acid, 50ppm chloride and a basket containing solid copper sulfate (180g per liter of plating bath) was used to plate test wafers with copper pillars having a thickness of 70um, and aspect ratios of 0.78:1 (height : diameter). Additives included 40 ppm of the accelerator bis (sodium-sulfopropyl) disulfide, 100 ppm of the carrier polyethylene glycol:polypropylene glycol monobutyl ether block copolymer (molecular weight=750) and 100 ppm of the leveler RALU®PLATE CL 1000 (Raschig GmbH, Ludwigshafen, Germany). Plating speeds of 6um/min, and 7um/min were obtained at a plating bath temperature of 45°C. FIGURE 3 is a SEM image of plating results that were obtained using a 6um/min plating speed (plating time was 11 minutes).

Example 2

The same plating electrolyte bath conditions as used in Example 1 but with different additives were used to plate test wafers with copper pillars having a thickness of 120um and aspect ratios of 1.2:1 (height : diameter). Additives included 40 ppm of the accelerator bis (sodium-sulfopropyl) disulfide, 100 ppm of the carrier polyethylene glycol and 100 ppm of the leveler Ralu®Mer 11 (Raschig GmbH, Ludwigshafen, Germany). FIGURE 4 is a SEM image of plating results that were obtained using a plating bath temperature of 45°C and a 6um/min plating speed (plating time was 20 minutes).

It is to be understood that this invention is not limited to the particular methods, apparatus and materials disclosed herein as such methods, apparatus and materials may vary somewhat. For instance, these copper plating baths can be implemented with plating of other metals, in which other metal ions can be delivered from a soluble metal salt in a container of the bath as described herein. It is also to be understood that the

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terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting since the scope of the present invention will be limited only by the appended claims and equivalents thereof.

What is claimed is:

CLAIMS

1. A method of changing a copper concentration in an electroplating bath, comprising:
placing a substrate in a copper electroplating bath comprising an acidic, aqueous solution exhibiting a copper ion concentration;
disposing a copper salt in solid form within a container located in the copper electroplating bath, a chamber of the container being in fluid communication with an the aqueous solution of the copper electroplating bath;
dissolving at least some of the copper salt in solid form to raise the copper ion concentration in the aqueous solution and maintain the copper ion concentration in the aqueous solution at about saturation to achieve high copper ion concentrations for accommodating high speed plating; and
electroplating copper on the substrate using a copper containing anode.
 2. The method of claim 1, wherein the aqueous solution comprises at least one of copper sulfate, copper methane sulfonate, copper fluoroborate, copper acetate, copper nitrate, copper oxide, copper hydroxide and copper chloride.
 3. The method of claim 1, wherein a concentration of the copper salt in the aqueous solution ranges from about 10 grams/liter to about 400 gram/liter.
 4. The method of claim 1, wherein the aqueous solution comprises at least one of sulfuric acid, methanesulfonic acid, fluoroboric acid, hydroboric acid, hydrochloric acid, hydroiodic acid, phosphoric acid and boric acid.
 5. The method of claim 1, wherein a concentration of acid in the aqueous solution ranges from about 10 grams/liter to about 250 grams/liter.
 6. The method of claim 1, wherein the aqueous solution comprises at least one additive to accelerate the copper deposition rate of the copper electroplating bath.
 7. The method of claim 1, wherein the aqueous solution comprises at least one suppressor additive.
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8. The method of claim 1, wherein the copper salt in solid form is selected from the group consisting of copper sulfate, copper methane sulfonate, copper fluoroborate, copper acetate, copper nitrate, copper oxide, copper hydroxide and copper chloride.
 9. The method of claim 1, wherein the container comprises a membrane that allows dissolved copper salt to leave the container while retaining the copper salt in solid form within the container.
 10. The method of claim 9, wherein an area of the membrane comprises about 50% to about 90% of a surface area of the container.
 11. The method of claim 1, wherein the container comprises an enclosure containing a porous membrane material having pore sizes ranging from about 1 μm to about 100 μm .
 12. The method of claim 1, wherein the copper salt comprises copper sulfate.
 13. The method of claim 12, wherein a copper sulfate concentration of the aqueous solution ranges from about 50 grams/liter to about 250 grams/liter.
 14. The method of claim 12, wherein a concentration of copper sulfate in the aqueous solution ranges from about 100 grams to about 300 grams per liter.
 15. The method of claim 1, wherein the aqueous solution comprises sulfuric acid.
 16. The method of claim 15, wherein a sulfuric acid concentration of the aqueous solution ranges from about 20 grams/liter to about 100 grams/liter.
 17. The method of claim 1, wherein the aqueous solution comprises chloride ions.
 18. The method of claim 17, wherein a chloride ion concentration of the aqueous solution ranges from about 10 ppm to about 100 ppm.
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19. The method of claim 1, wherein a temperature of the aqueous solution ranges from about 30° C. to about 60° C.
 20. The method of claim 1, wherein electroplating copper comprises an electroplating speed of about 4 microns per minute or greater.
 21. The method of claim 1, wherein electroplating copper comprises electroplating one or more high aspect ratio copper structures on the substrate.
 22. The method of claim 21, wherein the high aspect ratio structures are selected from the group consisting of pillars, bumps and through-silicon vias.
 23. The method of claim 1, further comprising:
retaining at least a portion of the copper salt in solid form within the container.
 24. The method of claim 1, wherein the container is immersed in the aqueous solution.
 25. The method of claim 1, wherein said step of placing the substrate in the copper electroplating bath is performed after said step of dissolving at least some of the copper salt.
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