

Method of coating a surface of a substrate with a metal by electroplating

The present invention relates in general to a method of coating a surface of a substrate with a metal, and more particularly copper, by electroplating, in particular a surface consisting of an electrically resistive material.

The invention is especially applicable in the field of microelectronics for the fabrication of interconnects in integrated circuits. It is also applicable in other fields of electronics, for the fabrication of interconnects in printed circuits (called printed circuit boards or printed wire boards) or for the fabrication of passive elements, such as inductors, or in the electromechanical field in integrated circuits or in microsystems (called microelectromechanical systems).

The term "electroplating" is understood here to mean a method of covering a surface of a substrate with a metallic or organometallic coating, in which the substrate is electrically biased and brought into contact with a liquid that contains precursors of the said metallic or organometallic coating, so as to form the said coating. When the substrate is an electrical conductor, the electroplating is for example carried out by passing a current between the substrate to be coated which constitutes an electrode (the cathode in the case of a metallic or organometallic coating) and a second electrode (the anode) in a bath containing a source of precursors of the coating material (for example metal ions in the case of a metallic coating) and optionally various agents intended to improve the properties of the coating formed (uniformity and fineness of the deposit, resistivity, etc.), optionally with a reference electrode being present. By international convention, the current flowing through and the voltage applied to the substrate of interest, that is to say the cathode of the electrochemical circuit,

are negative. Throughout this text, when these currents and voltages are mentioned with a positive value, it is implicit that this value represents the absolute value of the said current or the said voltage.

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Copper electroplating is used in particular in the microelectronics field for the fabrication of interconnects in integrated circuits. The good electrical conductivity of copper and its high resistance to the phenomenon of electromigration, that is to say the low migration of copper atoms under the effect of the electric current density that can be responsible to significantly deform the conductor and be a major cause of failure, makes it in particular a material of choice for the fabrication of metal interconnects for integrated circuits of increasingly smaller etched features.

Integrated circuits are generally fabricated by forming active semiconductor devices, especially transistors, on the surface of silicon wafers, the said semiconductor devices being connected together by a system of metal interconnects consisting of "lines" and "contacts", also called "vias" placed in superimposed levels and obtained by respectively filling "trenches" and "wells" also called "interconnection holes", made in the dielectric layers.

Since copper is difficult to etch and has a high diffusivity in many materials, the interconnects are generally produced by a sequence of steps comprising:

- deposition of an insulating dielectric layer;
- etching of the interconnect features in the said dielectric layer;
- deposition of a barrier layer (generally made of tantalum, titanium nitride, tantalum nitride, tungsten nitride or tungsten carbide, for example) used to prevent copper migration;
- filling of the lines and interconnection holes

with copper; and

- removal of the excess copper by chemical mechanical polishing.

- 5 This sequence of steps is known by the name "Damascene process", which has been described for example by C.Y. Chang and S.M. Sze "ULSI Technology", McGraw-Hill, New York, (1996), pages 444-445.
- 10 The barrier layer generally has too high a resistance for copper to be electrochemically deposited homogeneously or uniformly at the wafer scale, an effect known to those skilled in the art by the term "ohmic drop". The high resistance of the barrier layer
- 15 results both from the high resistivity of its constituent materials (generally metal nitrides) and from its small thickness (generally from a few nm to a few tens of nm, depending on the integrated circuit generation), which thickness is imposed by the small
- 20 size of the interconnect features.

Consequently, it is generally necessary, prior to the copper electroplating step, to cover the barrier layer - using a non-electrochemical method - with a thin

25 layer of metallic copper, called a seed layer. This seed layer, like the barrier layer, is currently produced by vapor phase deposition techniques such as PVD (physical vapor deposition) or CVD (chemical vapor deposition) deposition processes.

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Owing to the critical dimensions of the lines and interconnection holes of current integrated circuits, and their trend towards ever smaller dimensions, the thickness of the copper seed layers at the present time

35 is around 30 nm and should rapidly move towards 10 nm or less.

CVD deposition produces a conformal copper layer, that is to say one that accurately matches the topography of

the surface to be coated, and does so for a wide range of aspect ratios. However, the adhesion to the diffusion barriers of the copper layers formed by chemical deposition is poor. This limits in practice
5 the benefit of this type of process since as strong adhesion between the copper and the barrier is required in order to ensure reliability of the structures constituting the interconnects.

10 In addition, processes using chemical vapor deposition are relatively expensive because of the high cost of the consumables (the precursors), of the equipment needed to implement them and their low efficiency.

15 PVD deposition is presently preferred from the industrial standpoint because it allows surfaces having a high resistance to be coated with better adhesion of the copper to the barrier than obtained with CVD processes.

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The thickness of the coating deposited by PVD is directly proportional to the solid angle seen from the surface to be coated. Consequently, those portions of the surface having salient angles are covered with a
25 thicker layer than those portions of the surface having re-entrant angles. As a result, the copper seed layers formed by physical vapor deposition are not conformal, and therefore do not have a uniform thickness at every point on the surface of the substrate. In particular,
30 shadow or overhang effects are observed at the sharp edges of trenches or vias, up to the point of obstructing their apertures and then making it impossible to fill them. Moreover, the sidewalls of the trenches and vias may be covered with an insufficient
35 thickness of the seed layer, which then results in imperfect subsequent filling, missing material or voids. In addition, the seed layer produced on the sidewalls of the features exhibits by nature an adhesion that differs from that deposited on the flat

surface of the substrate (at the top and bottom of the trenches and vias). This may lead to inferior reliability properties, such as resistance to electromigration. In other words, the non-conformal coverage does not solely result in differences in thickness as lack of continuity and poor adhesion of the layer on the sidewalls of the trenches and vias may also arise therefrom.

These limitations make it very tricky to use PVD technology in advanced generation integrated circuits with very small dimensions of the trenches and vias (of the order of a few tens of nanometers) and very high aspect ratios.

In this context, the electroplating technique presented here constitutes an advantageous alternative to chemical vapor deposition or physical vapor deposition processes, and to the more conventional metal electroplating techniques, which cannot be implemented on resistive substrates.

This is because conventional electroplating, which consists in applying in general a DC current to the substrate immersed in a bath containing metal ions, can be applied only to surfaces that are sufficiently conducting, that is to say typically having a sheet resistance of less than about a few ohms/square, which is not the case for the layers forming a copper diffusion barrier in the most advanced technologies, the sheet resistance of which is commonly a few tens of ohms/square to several hundred ohms/square and may be several tens of thousands of ohms/square.

Sheet resistance is a quantity used by those skilled in the art for measuring electrical resistance of thin films or layers. It is expressed in ohms/square and is equivalent to the resistivity for a two-dimensional system, that is to say one in which the current flows

in the plane of the layer and not in a plane perpendicular to this layer. Mathematically, the value of the sheet resistance is obtained by dividing the resistivity (expressed in ohms.m or microohms.cm) of the constituent material of the layer by the thickness (expressed in m or nm) of this layer.

At the present time, conventional copper electroplating is mainly used for filling the trenches and wells in the damascene process by applying a DC current to a wafer covered beforehand with a seed layer and immersed in an acid copper sulphate bath containing additives. This process for filling the trenches and wells with metallic copper is described for example by Rosenberg et al., in "Copper metallization for high performance silicon technology", Ann. Rev. Mater. Sci (2000), 30, 229-62.

The use of copper electroplating on a copper seed layer for filling trenches and wells has also been described in Patent US 6 893 550 incorporated herein by reference.

The electroplating method described in document US 6 893 550 is essentially characterized:

- on the one hand, in that it makes use of an electroplating bath whose specific chemical composition comprises at least one acid, preferably sulphuric acid, at least one halide ion, preferably chloride, and a combination of chemical agents capable of accelerating or suppressing formation of the coating; and

- on the other hand, in that it consists in modifying the density of the current applied in predetermined sequences.

Copper electroplating has also been recommended, for example in Patent US 6 811 675, for filling any voids in the seed layer (seed enhancement) or for repairing this layer (seed repair).

In a preferred embodiment described in this prior document, a first step is carried out, preferably by a physical vapor deposition process, in which a non-uniform "ultrathin" (thickness of about 20 nm) copper seed layer is deposited and then in a second step the conformality of the layer is improved by electroplating using an alkaline electroplating solution (the pH of which is greater than 9) containing copper sulphate, a copper complexing agent, preferably citric acid, and optionally boric acid in order to improve the brightness of the coating and/or ammonium sulphate for reducing the resistivity of the coating. The DC current density applied during electroplating is between 1 mA/cm² and 5 mA/cm².

It is indicated in the above prior document that this electroplating process may also be used to produce a copper seed layer directly, but this possibility is not illustrated by any example and it appears not to be easily achievable owing to the high current densities mentioned in that document.

In this situation, the object of the present invention is to solve a new technical problem, namely of how to provide a method of coating a surface of a substrate by electroplating with a metal which makes it possible in particular to produce continuous and conformal copper seed layers having a thickness of the order of 10 nm or less and exhibiting excellent adhesion to diffusion barrier surfaces that may have a high surface resistance of up to a few megohms/square.

It has been discovered, and it is this that constitutes the basis of the present invention, that it is possible to solve this technical problem in a relatively simple manner, which can be used on an industrial scale, by using a specific electroplating bath and by controlling the conditions under which the surface to be coated is

brought into contact with the electroplating bath prior to the formation of the coating and the conditions under which this surface is separated from the said bath after the coating has been formed.

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Thus, the object of the present invention is in general a method of coating a surface of a substrate with copper by electroplating, characterized in that it comprises:

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- a step referred to as "cold entry" during which the said surface to be coated is brought into contact with an electroplating bath while the said surface is not under electrical bias;

15

- a step of forming the coating during which the said surface is biased for a time long enough to form the said coating;

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- a step referred to as "hot exit" during which the said surface is separated from the electroplating bath while it is still under electrical bias;

and in that the aforementioned electroplating bath comprises, in solution in a solvent:

25

- a source of copper ions, with a concentration of between 0.4 and 40mM, preferably of between 0.4 and 18 mM and more preferably of between 0.4 and 15 mM; and

- at least one copper complexing agent chosen from the group comprising primary aliphatic amines, secondary aliphatic amines, tertiary aliphatic amines, aromatic amines, nitrogen heterocycles, and oximes.

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It has been observed, quite unexpectedly, that it is possible, with the aforementioned electroplating baths, to improve the adherence between the copper coating layer produced by electroplating and the barrier layer by bringing the surface to be coated into contact with the electroplating bath without being under electrical bias, that is to say without imposing an electric current or electric potential relative to a counterelectrode or relative to a reference electrode on this surface, prior to the electroplating step.

35

An even more substantial improvement in this adherence has been observed when the surface of the substrate to be coated is kept in contact with the electroplating bath for a period of at least 5 seconds after this
5 contacting step and still prior to the electroplating step.

It has also been observed, surprisingly, that it is possible to obtain a seed layer having a conductivity
10 compatible with electroplating filling methods, while keeping the coated surface under electrical bias, preferably for a time of between 1 and 10 seconds, after its removal from the electroplating bath.

15 It is therefore the "cold entry" and "hot exit" steps that constitute the essential characteristic steps of the method according to the present invention.

The step of forming the copper coating is carried out
20 in a relatively conventional manner, but it has been observed that, unlike the processes described in the prior art and especially in Patent US 6 811 675, the level of current needed to form the coating is much lower (at least five times lower than the mean value
25 mentioned in this prior patent, and in any case outside the process windows mentioned therein).

"Hot entry", that is to say entry under bias, is the standard practice in processes for electrochemically
30 depositing copper for filling trenches and wells. This is because, since the electroplating solution is generally acidic, it is likely to cause etching of the seed layer and consequently electroplating is prevented, something which must be avoided.

35 During the "cold entry" step of the method according to the invention, the surface of the substrate to be coated is preferably kept in contact with the electroplating bath for a period of at least 5 seconds.

It has been observed that by adjusting this parameter during the fabrication of just the seed layer it is possible, surprisingly, to improve the adhesion of the "seed layer/fill layer or thick copper or thick layer" assembly, that is to say the "operational" adhesion of the assembly for which the seed layer is produced. Specifically, even though it is in general difficult for the adhesion of a single seed layer to be measured directly, especially owing to its small thickness, it is observed that the adhesion of the seed layers produced according to the present invention is obviously very high. However, it is after production of a thick copper layer (with a thickness of about 500 nm to 1 micron, or more) that it is easier and more useful to determine the energy of adhesion of the "seed layer/fill layer or thick copper or thick layer" assembly to the barrier layer, which energy is the operational property of interest that is actually to be optimized. For example, this adhesion may be determined by peeling an adhesive tape bonded to the upper surface of the assembly, for example by using a pulling test system. The adhesion measured in this way, or interfacial energy expressed in J/m^2 , characterizes overall both the adherence of the seed layer to the barrier and that of the thick copper layer to the seed layer. It does not given precise information about one or the other interface, but it does allow the desired operational property to be quantified, namely the strength of the copper/barrier interface. In what follows, the expressions "adhesion of the seed layer", "adhesion of the thick copper layer to the seed layer" and "the strength of the copper/barrier interface after filling" will thus be used interchangeably.

It has also been observed that if the duration of the "cold" entry step is less than 5 seconds, the adhesion of the copper layer to the substrate, although improved compared with entry under bias, may remain insufficient in certain cases, especially those requiring the

deposition of a copper seed layer in direct contact with a barrier layer of an integrated circuit interconnect.

- 5 On the other hand, if the duration of this step is 5 seconds or longer, preferably between 10 and 60 seconds and more preferably about 10 to 30 seconds, the interfacial energy measured by the peel force is substantially equal to, or even greater than that
10 obtained by sputtering processes (greater than 10 J/m^2).

There is no particular limit regarding the maximum duration of this step, but under the experimental
15 conditions employed, no significant improvement in the adhesion is observed for a time of longer than about 60 seconds.

During the "hot exit" step of the method according to
20 the invention, the substrate surface coated with the copper is removed from the electroplating bath while under electrical bias preferably for a period of between 1 and 10 seconds, more preferably for a period of about 1 to 5 seconds.

25 It has been observed in this case that a "cold exit", that is to say exit while not under bias (that is to say again when the electrical bias of the substrate is interrupted before the said substrate is removed from
30 the electroplating bath), the resistance of the copper coating remains very close to that of the barrier layer, even though it is sometimes possible to deposit a thick filling copper on such a coating with conventional electrochemical means.

35 In contrast, it has been observed, unexpectedly, that a "hot exit" results in an extremely thin (10 nm) seed layer having an electrical conductivity sufficient to allow the next step of filling with copper by

electrochemical deposition using processes known to those skilled in the art.

Advantageously, the "hot exit" step is carried out in
5 potentiostatic mode, that is to say by keeping the
electric potential of the wafer at a fixed value, this
potential being measured either relative to the
counterelectrode of the circuit or relative to a
10 reference electrode, preferably at the same voltage
level as during the coating deposition step when this
is also carried out in potentiostatic mode.

The combination of "cold entry" and "hot exit" steps in
the method according to the invention makes it possible
15 to achieve better adhesion of the "seed layer/copper
filling" assembly more easily and reproducibly.

The step of forming the coating by electroplating is
carried out for a duration sufficient to form the
20 desired coating. This duration may be easily determined
by a person skilled in the art, the growth of the film
being a function of the charge, which is equal to the
time integral of the electric current flowing in the
circuit over the deposition time (Faraday's law).

25 During the step of forming the coating, the surface to
be coated is biased, either in galvanostatic mode (with
a fixed set current) or in potentiostatic mode (with a
fixed set potential, optionally relative to a reference
30 electrode) or else in pulsed mode (either the current
or the voltage being pulsed).

It is also possible to combine these steps, for example
a step in potentiostatic mode followed by a step in
35 galvanostatic mode.

In general, a satisfactory coating can be obtained by
biasing in galvanostatic mode preferably within the
current range from 0.1 mA/cm^2 (milliamps per square

centimetre) to 5 mA/cm², and more particularly from 0.1 mA/cm² to 1 mA/cm².

5 A satisfactory coating may also be obtained by biasing in potentiostatic mode, by imposing a cell voltage in such a way that the resulting cell current lies within the same current range as indicated previously. Although the cell voltage depends in particular on cell design parameters, such as the distance from the
10 counterelectrode or the presence of a membrane, it will be easy for a person skilled in the art to determine the cell voltage by measuring and adjusting the current obtained for a given potential and a given configuration.

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A satisfactory coating may also be obtained by biasing in pulsed mode, preferably so as to impose voltage pulses.

20 In general, this step may be carried out so as to impose voltage pulses corresponding to a maximum current per unit area within the range from 0.1 mA/cm² to 5 mA/cm², and more particularly from 0.1 mA/cm² to 1 mA/cm², and to a minimum current per unit area within
25 the range from 0 mA/cm² to 0.5 mA/cm², and more particularly from 0 mA/cm² to 0.1 mA/cm².

According to one particular feature, the duration of bias at the maximum voltage may be between 0.15 and 5
30 seconds, for example around 2 seconds for a voltage corresponding to a maximum current per unit area of around 0.5 mA/cm², whereas the duration of bias at the minimum voltage may be between 0.15 and 7 seconds, for example around 3 seconds, for a voltage corresponding
35 to a minimum current per unit area of around 0.05 mA/cm².

The number of cycles to be performed during this step depends on the desired thickness of the coating.

In general, a person skilled in the art will readily determine the number of cycles to be performed knowing that, under the aforementioned general conditions, illustrated by the examples below, it has been observed
5 that the deposition rate is about 0.1 nm per cycle.

The latter method of implementing the invention has been used in particular to produce copper seed layers on highly resistive substrates, the sheet resistance of
10 which may be up to 100 000 ohms/square, or even a few megohms/square.

The electroplating bath (or composition) used in the method according to the present invention comprises, in
15 solution in a solvent, a source of copper ions and at least one specific copper complexing agent, preferably in a particular copper/complexing agent(s) molar ratio, and more preferably this bath must have a pH of less than 7.

20 In particular, excellent results have been obtained when, in the electroplating bath:

- the copper/complexing agent(s) molar ratio is between 0.1 and 2.5, preferably between 0.3 and 1.3;
25 and

- the pH of the said composition is less than 7, preferably between 3.5 and 6.5.

Although in principle there is no restriction on the
30 nature of the solvent (provided that it dissolves the active species of the solution sufficiently and does not interfere with the electroplating), water or a hydroalcoholic solution will be preferred.

35 The copper complexing agents that can be used within the context of the present invention may be chosen from:

- primary aliphatic amines, in particular ethylamine, cyclohexylamine, ethylenediamine and

cyclohexanediamine;

- secondary aliphatic amines, in particular pyrrolidine;

- tertiary aliphatic amines, in particular
5 hydroxyethyldiethylamine and tetraethylenepentamine;

- aromatic amines, in particular 1,2-diaminobenzene and 3,5-dimethylaniline;

- nitrogen heterocycles, in particular pyridine, 2,2'-bipyridine, 8-hydroxyquinoline sulphonate, 1,10-
10 phenanthroline, 3,5-dimethylpyridine and 2,2'-bipyrimidine; and

- oximes, in particular dimethylglyoxime.

In general, the nitrogen heterocycles that constitute
15 one of the preferred classes of complexing agents that can be used within the context of the present invention may be defined as monocyclic or polycyclic compounds, whether fused or not, having 1 to 8 nitrogen atoms, each ring of which contains 5 to 6 members and may or
20 may not be substituted with 1 to 8 atoms or groups of atoms chosen from halogens, hydroxyl and alkyl groups having from 1 to 6 carbon atoms.

The electroplating composition may include one or more
25 complexing agents.

It has been found that excellent results can be obtained with complexing agents capable of being adsorbed on a metal surface, resulting in ordered
30 layers. Such agents, which constitute the copper complexing agents currently preferred according to the invention, are especially pyridine, 2,2'-bipyridine and the mixtures thereof, in particular mixtures in which the molar ratio between pyridine and 2,2'-bipyridine
35 lies between 5:1 and 1:5, preferably between 3:1 and 1:1 and more preferably about 2:1.

In general, the electroplating composition includes a source of copper ions, in particular cupric (Cu^{2+}) ions.

Advantageously, the aforementioned source of copper ions is a copper salt such as in particular copper sulphate, copper chloride, copper nitrate or copper acetate, preferably copper sulphate.

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According to one particular feature, the source of copper ions is present within the electroplating composition with a concentration of between 0.4 and 40 mM, preferably of between 0.4 and 18 mM and more
10 preferably of between 0.4 and 15 mM.

Excellent results have been obtained with compositions in which the source of copper ions is present with a concentration of between 0.5 and 4 mM.

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According to a preferred method of implementation, the copper ion source/copper complexing agent(s) molar ratio in the electroplating composition used in the method according to the invention is between 0.1 and
20 2.5, preferably between 0.3 and 1.3.

In general, this electroplating composition advantageously has a pH of less than 7, preferably between 3.5 and 6.5.

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The pH of the composition may optionally be adjusted within the aforementioned pH by means of a buffer, such as one of those described in "Handbook of Chemistry and Physics", 84th edition, David R. Lide, CRC Press.

30

A currently preferred electroplating composition comprises, in aqueous solution:

- copper sulphate, with a concentration of between 0.4 and 40 mM, preferably of between 0.4 and
35 18 mM and more preferably of between 0.4 and 15 mM;
- a mixture of pyridine and 2,2'-bipyridine as copper complexing agents;
- the copper/copper complexing agents molar ratio being between 0.3 and 1.3; and

- the pH of the said composition being less than 7, preferably between 3.5 and 6.5.

5 The process according to the present invention is particularly useful for preparing a copper seed layer having a very low thickness, for instance of the order of 10 nm or less, on a surface forming a barrier layer preventing copper diffusion.

10 According to a particular embodiment, the barrier layer preventing copper diffusion comprises at least one material chosen among tantalum nitride, tantalum, ruthenium, cobalt, tungsten, titanium nitride, examples of specific barrier surfaces being ones consisting of a
15 tantalum nitride/tantalum bilayer or a ruthenium layer.

The present invention will now be illustrated by the following non-limiting examples in which the method according to the invention is used to deposit a copper
20 seed layer on silicon substrates coated with a copper diffusion barrier layer. This method is especially applicable in the fabrication of copper interconnect structures for integrated circuits.

25 **EXAMPLE 1: Deposition of a copper seed layer on a TaN/Ta barrier layer according to a first method of implementing the invention**

A. Apparatus and equipment

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Substrate:

The substrate used in this example consisted of a 200 mm diameter silicon wafer covered with a silica
35 layer having a thickness of 400 nm, itself coated with a tantalum nitride (TaN) layer having a thickness of 15 nm deposited by reactive sputtering and with a tantalum (Ta) layer having a thickness of 10 nm, also deposited by sputtering.

This TaN/Ta "bilayer" constitutes a copper diffusion barrier as used in "double damascene" structures in the fabrication of copper interconnects for integrated circuits.

5

Electroplating solution:

The electroplating solution used in this example was an aqueous solution containing: 0.3 g/l (or 1.7mM) of
10 2,2'-bipyridine; 0.6 g/l (or 2.4mM) of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$; and
0.3 ml/l (or 3.3mM) of pyridine, the pH of the solution
being around 6.

Equipment:

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In this example, an electroplating deposition
equipment representative of that employed in the
microelectronics industry, model Equinox™ from
Semitool®, capable of processing 200 mm wafers was
20 used.

This equipment comprised an electroplating deposition
cell in which the seed layer was deposited and a
rinse/dry station was used after deposition.

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The electroplating deposition cell comprised an anode,
made either of an inert metal (for example platinum-
coated titanium) or of a metal identical to that
constituting the seed layer, in this case copper, the
30 silicon wafer coated with the TaN/Ta barrier layer
constituting the cathode of this cell.

This cell also included a stabilized power supply for
delivering up to 30 V and 4 A and a device for
35 electrically contacting the cathode, physically
isolated from the solution by a seal. This electrical
contacting device generally had a ring shape and
allowed the substrate to be biased at various contact
points placed uniformly around the said substrate.

It also included a device for supporting the wafer to be coated, including means for rotating the said wafer at a predetermined speed.

5 **B. Experimental protocol**

The method according to the invention comprised the following various consecutive steps.

10 **Step 1: "Cold entry"**

This step was divided into two substeps:

15 1.1. The aforementioned substrate was introduced into the electroplating deposition cell so that the face having the TaN/Ta barrier layer came into contact with the electrical contacting device, the latter not yet being electrically powered.

20 1.2. The assembly formed by the electrical contacting device and the substrate, which hereafter will be referred as the "cathode assembly", was brought into contact, for example by immersion, with the electroplating solution. This contacting step, generally lasting 5 seconds or less (for example 2
25 seconds), was carried out while the device was still not electrically powered. According to one particular feature of the method according to the invention, the cathode assembly was then kept in the electroplating solution without being biased for a period of at least
30 5 seconds (for example around 30 seconds).

Step 2: Formation of the copper coating

35 The cathode assembly was then biased in potentiostatic mode by imposing a cell voltage corresponding to a current per unit area of generally between 0.4 mA/cm² and 0.8 mA/cm² (for example 0.6 mA/cm²) and at the same time rotated at a speed of 20 to 60 rounds per minute (for example 40 rounds per

minute).

The duration of this step depended, as will have been understood, on the targeted thickness of the seed
5 layer. This duration can be easily determined by a person skilled in the art, the growth of the film depending on the charge passed in the circuit.

Under the aforementioned conditions, the deposition
10 rate was about 1 nm per coulomb of charge passed in the circuit.

In this example, the duration of the electroplating step was around 50 seconds for obtaining a coating
15 having a thickness of 10 nm, and around 200 seconds for obtaining a coating having a thickness of 40 nm.

Step 3: "Hot exit"

20 This step may be divided into two substeps:

3.1. After the electroplating step, the copper-coated cathode assembly was withdrawn from the electroplating solution with a zero speed of rotation,
25 while being maintained under voltage bias. The duration of this phase was about 2 seconds.

The speed of rotation was then increased to 500 rounds per minute for 10 seconds, the cathode assembly bias
30 being cut off during this final phase.

A pre-rinse with deionized water was carried out in the cell.

35 3.2. The substrate coated with the seed layer was then transferred into the rinsing/drying module in order to be rinsed with deionized water.

The rinsing water was then removed, and then a drying

operation under a stream of nitrogen was carried out.

The rotation was then stopped so as to allow the dried coated substrate to be removed.

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In this example, the exit step, and in particular the removal of the cathode assembly from the electroplating solution, was carried out under voltage bias at the same level as during the step of forming the coating.

10

C. Results obtained

By applying the experimental protocol described above, copper layers of 10 nm, 20 nm and 40 nm in thickness exhibiting excellent conformality, adhesion and resistance characteristics were obtained.

Conformality was assessed by observing scanning electron microscope cross sections and comparing the thickness of the seed layer on the horizontal surfaces with that on the vertical surfaces.

The sheet resistance was measured using a "4-point" measurement instrument well known to those skilled in the art.

The adhesion or interfacial energy was measured after electrochemical deposition of a 500 nm thick copper layer (plating layer or fill layer or thick copper or thick layer) on the seed layer. This measurement was carried out using an apparatus (pulling test system) that applied an increasing vertical pulling force on the surface via a strong adhesive tape until the copper layer (seed layer and plating layer) separates from the substrate. The work of this force (force multiplied by length of the layer that has delaminated) is equivalent to the energy that had to be supplied in order to separate the copper layer from its substrate. By dividing this energy by the area that has delaminated,

the energy per unit area is obtained.

Some of the results of the measurements taken are given in Table 1 below.

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EXAMPLE 2: Deposition of a copper seed layer on a TaN barrier layer according to a second method of implementing the invention

10 In this example, the method according to the present invention is used for depositing a copper seed layer on diffusion barriers having a high resistance.

A. Apparatus and equipment

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Substrate:

20 The substrate used in this example consisted of a 200 mm diameter silicon wafer coated with a silica layer having a thickness of 400 nm, itself coated with a tantalum nitride (TaN) layer having a thickness of 5 nm deposited by the ALD (atomic layer deposition) technique.

25 This TaN layer constituting a copper diffusion barrier as used in "double damascene" structures for the copper interconnects of integrated circuits had a surface resistance of around 3500 ohms/square.

30 This wafer was then cut into rectangular pieces 1.5 cm in width and 6 cm in length, called hereafter "samples".

Electroplating solution:

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The solution used in this example was an aqueous solution containing: 0.3 g/l (or 1.7mM) of 2,2'-bipyridine; 0.6 g/l (or 2.4mM) of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$; and 0.3 ml/l (or 3.3mM) of pyridine, the pH of which was around

6.

Equipment:

5 For this example, a glass cell was used in which 100 ml of the aforementioned electroplating solution were introduced.

10 This cell was provided with a cover having two openings, opening into two enclosures in which, on the one hand, a sample holder and its electrical contacting device and, on the other hand, the anode formed from a platinum coated titanium part were fastened.

15 The electrical contacting device and the anode were connected to a potentiostat capable of delivering 20 V/2 A.

B. Experimental protocol

20

The method according to the invention comprised the following various consecutive steps.

Step 1: "Cold entry"

25

This step may be divided into two substeps:

30 1.1. Each specimen was introduced into the electroplating deposition cell so that the face having the TaN barrier layer came into contact with the electrical contacting device, the latter not yet being electrically powered.

35 1.2. The assembly formed by the electrical contacting device and the substrate, which hereafter will be referred as the "cathode assembly", was brought into contact, for example by immersion, with the electroplating solution. This contacting step, generally lasting 5 seconds or less (for example 2

seconds), was carried out while the device was still not electrically powered. According to one particular feature of the method according to the invention, the cathode assembly was then kept in the electroplating solution without being biased for a period of greater than 5 seconds (for example around 30 seconds).

Step 2: Formation of the copper coating

10 The cathode assembly was then voltage biased so as to impose voltage pulses on the cell, having a maximum of 8 V to 12 V (for example 10 V) and a maximum between 0 V and 2 V (for example 1 V).

15 The duration of biasing at 10 V was between 0.1 and 5 seconds (for example 2 seconds).

The duration of biasing at 1 V was between 0.15 and 7 seconds (for example 3 seconds).

20

In one specific example, each voltage application cycle therefore consisted of biasing for 2 seconds at 10 V followed by biasing for 3 seconds at 1 V.

25 Under these experimental conditions, the deposition rate was about 0.32 nm per cycle and 200 cycles were thus carried out in order to obtain a copper coating having a thickness of 65 nm.

30 Step 3: "Hot exit"

The cathode assembly was then withdrawn vertically from the solution while still being under voltage bias of 10 V.

35

Each specimen was then rinsed by hand with deionized water for 30 seconds and dried with an argon gun for 30 seconds.

C. Results obtained

In the specific example defined above, a copper seed layer having a sheet resistance of 0.5 ohm/square was
5 obtained.

A copper fill layer was electrochemically deposited on this layer.

10 The seed layer/fill layer assembly had an interfacial energy of around 6 J/m² measured by the technique described in example 1.

The aforementioned protocol was also employed with
15 coupons obtained from silicon wafers coated with barrier layers having high resistivities varying between 200 microhms.cm and 50 000 microhms.cm (i.e. between 400 and 100 000 ohms/square).

20 Good results were obtained in terms of conformality, adhesion and resistance.

EXAMPLE 3: Deposition of a copper seed layer on an Ru barrier layer according to a third method of
25 **implementing the invention**

In this example, the method according to the present invention was used to deposit a copper seed layer on a ruthenium-based diffusion barrier.
30

Substrate:

The substrate used in this example consisted of a silicon coupon 6 cm in length by 2 cm in width, coated
35 with a silica layer having a thickness of 400 nm, itself coated with a ruthenium (Ru) layer having a thickness of 30 nm deposited by sputtering. The sheet resistance of this substrate was 7.5 ohms/square.

This Ru layer may constitute a copper diffusion barrier as used in "double damascene" structures in the fabrication of copper interconnects for advanced integrated circuits.

5

Solution:

The solution used in this example was identical to that of Example 1.

10

Equipment:

In this example, a glass electrolytic deposition cell made up of two parts was used, namely the cell intended to contain the electroplating solution, and a "cover" for maintaining the various electrodes in operative position.

The electrolytic deposition cell had three electrodes:

- 20
- an inert metal (platinum) anode;
 - the silicon coupon coated with the TaN/Ta layer, constituting the cathode; and
 - an Ag/AgClO₄ reference electrode.

25 Connectors enabled the electrical contacting of the electrodes which were connected via electrical wires to a potentiostat delivering up to 10 V/2 A.

B. Experimental protocol

30

The electroplating method used in this example was made up of the following various consecutive steps.

Step 1: "Cold entry"

35

The electroplating solution was poured into the cell.

The various electrodes were placed on the cover of the electrolytic cell.

The electrodes were brought into contact with the electroplating solution. At this stage, the assembly thus formed was still not electrically biased (it was at its open-circuit potential).

5

The assembly was maintained in this state (i.e. under no electrical bias) for a period of 10 to 60 seconds (for example 30 seconds).

10

Step 2: Formation of the copper coating

The cathode was biased in galvanostatic mode within a current range from 2 mA (or 0.25 mA/cm²) to 8 mA (or 1 mA/cm²) (for example 6 mA (or 0.75 mA/cm²)).

15

Degassing with argon may be employed - it allows some hydrodynamic regime to be established in the cell.

20 The duration of this step depended on the targeted thickness of the seed layer and could easily be determined by a person skilled in the art, the growth of the film being a function of the charge passed in the circuit.

25 Under the aforementioned conditions, the deposition rate was about 33 nm per coulomb of charge passed in the circuit.

30 In this example, the duration of the electroplating step was about 200 seconds in order to obtain a coating having a thickness of about 40 nm.

Step 3: "Hot exit"

35 The cathode was then removed from the solution, the bias still being applied.

The cathode was then disconnected, and thoroughly rinsed with 18 MΩ deionized water, then dried using an

argon gun with a gas pressure of around 2 bar.

C. Results obtained

- 5 By applying the experimental protocol described above, a continuous conformal copper layer 40 nm in thickness was obtained (this being observed in a scanning electron microscope).
- 10 This copper seed layer had a sheet resistance of 2.5 ohms/square measured by the method described in Example 1.

EXAMPLE 4: Deposition of a copper seed layer on a TaN/Ta barrier layer according to a fourth method of implementing the invention

A. Apparatus and equipment

Substrate:

The substrate used in this example is identical to the one used in example 1.

Electroplating solution:

The electroplating solution used in this example was an aqueous (de-ionized water 18.2 Mohm.cm) solution prepared in a cleanroom environment (class 10,000 or ISO 7) containing: 0.4 g/l (or 2.56 mM) of 2,2'-bipyridine (purity 99.7%) supplied by Oxkem; 0.8 g/l (or 3.2 mM) of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (purity 99.995%) supplied by Alfa Aesar; and 0.367 ml/l (or 4mM) of pyridine (purity 99.9%) supplied by Aldrich.

35 After preparation, the solution was filtered at 0.2 μm . The pH of the solution was between 5.94.

Equipment:

The equipment used in this example is identical to the one used in example 1.

B. Experimental protocol

5

The electroplating method used in this example is identical to the one used in example 1.

C. Results obtained

10

By applying the above experimental protocol, copper layers of 10 nm and 20 nm in thickness exhibiting excellent conformality, adhesion and resistance characteristics were obtained.

15

The excellent conformality characteristics of this layer are illustrated in figures 1a and 1b which represent cross-sectional view in backscattered electrons mode enhancing chemical contrast.

20

Conformality over trenches was also characterized on a large scale (0.01mm^2) using scatterometry. These measurements showed a copper layer thickness of 7nm at the top, bottom and sidewalls of trenches and they are in good agreement with actual thicknesses observed by SEM cross-sections.

25

Except for scatterometry, all characterization methods are identical to the ones used in example 1.

30

Table 1 below gives some of the results obtained by implementing Examples 1 to 4 described above. More precisely, this table reports the sheet resistance and adhesion values (measured according to the protocols indicated in Example 1) obtained for copper seed layers of variable thicknesses. Similar trends were also observed for the sheet resistance before treatment of a few hundred ohms/square, or several tens of thousands of ohms/square or even up to a few megohms/square.

35

For comparison, this table also reports the sheet resistance and adhesion values obtained from the compositions specifically used within the context of the invention by applying a standard electroplating method comprising a "hot" entry and a "cold" exit.

TABLE 1

Copper seed layer obtained according to:	Thickness (nm)	Sheet resistance (ohms/square)		Adhesion (J/m ²)
		Before treatment	After treatment	
Comparative Example	20	23	18	5
Example 1	20	23	8	11-13
Example 1	10	23	18	11-13
Example 2	65	3 500	0.5	6
Example 3	40	7.5	2.5	> 20
Example 4	20	22	5.3	> 20
Example 4	10	21	15	> 20

The observations made on scanning electron microscope cross sectional views showed that the copper seed layers obtained by implementing the method according to the invention are uniform and continuous and fully meet conformality requirements.

The results thus obtained also show that the method according to the invention makes it possible in particular to produce continuous conformal copper seed layers that may have a thickness of around 10 nm or less and exhibit excellent adhesion to diffusion barrier surfaces.

Table 1 shows in particular that the copper seed films have a sheet resistance very much lower than that of the surface of the substrate, this sheet resistance being lower the thicker the seed layer.

The copper seed layers obtained are sufficiently conducting (of sufficiently low sheet resistance) to allow subsequent filling by conventional electroplating, including when the thickness of the
5 copper seed layer is very small, such as for example around 10 nm or less.

The measured adhesion values are at least equivalent if not better than those that would be expected by a
10 person skilled in the art within the context of the implementation of a sputtering process.

These results therefore show that the method according to the invention clearly solves the technical problem
15 posed.

CLAIMS

1. Method of coating a surface of a substrate with copper by electroplating, characterized in that it
5 comprises:

- a step referred to as "cold entry" during which the said surface to be coated is brought into contact with an electroplating bath while the said surface is not under electrical bias;

10 - a step of forming the coating during which the said surface is biased for a time long enough to form the said coating;

- a step referred to as "hot exit" during which the said surface is separated from the electroplating bath under electrical bias; and in that the
15 aforementioned electroplating bath comprises, in solution in a solvent:

- a source of copper ions, with a concentration of between 0.4 and 40mM, preferably of between 0.4 and
20 18 mM and more preferably of between 0.4 and 15 mM; and

- at least one copper complexing agent chosen from the group comprising primary aliphatic amines, secondary aliphatic amines, tertiary aliphatic amines, aromatic amines, nitrogen heterocycles, and oximes.

25

2. Method according to Claim 1, characterized in that, during the aforementioned "cold" entry step, the surface to be coated is kept in contact with the electroplating bath for a period of at least 5 seconds.

30

3. Method according to Claim 1 or 2, characterized in that the aforementioned step of forming the coating is carried out by biasing in galvanostatic mode, preferably within the current range from 0.1 mA/cm²
35 (milliamps per square centimetre) to 5 mA/cm², and more particularly from 0.1 mA/cm² to 1 mA/cm².

4. Method according to Claim 1 or 2, characterized in that the aforementioned step of forming the coating is

carried out by biasing in potentiostatic mode, preferably imposing a cell voltage so that the resulting cell current lies within the 0.1 mA/cm² to 5 mA/cm² range, and more particularly the 0.1 mA/cm² to 1 mA/cm² range.

5. Method according to Claim 1 or 2, characterized in that the aforementioned step of forming the coating is carried out by biasing in pulsed mode, preferably so as to impose voltage pulses corresponding to a maximum cathode current per unit area within the range from 0.1 mA/cm² to 5 mA/cm², and more particularly from 0.1 mA/cm² to 1 mA/cm², and to a minimum cathode current per unit area within the range from 0 mA/cm² to 0.5 mA/cm², and more particularly from 0 mA/cm² to 0.1 mA/cm².

6. Method according to one of Claims 1 to 5, characterized in that, during the "cold entry" step, the surface to be coated is maintained in contact with the electroplating bath for a period of between 10 and 60 seconds, preferably for a period of about 10 to 30 seconds.

7. Method according to one of Claims 1 to 6, characterized in that the aforementioned substrate is a silicon wafer in the course of fabricating integrated circuits, the surface of which, to be coated, is that of a copper diffusion barrier layer, such as a bilayer based on tantalum nitride/tantalum (TaN/Ta) or just a tantalum nitride (TaN) layer.

8. Method according to one of Claims 1 to 7, characterized in that, during the "hot exit" step, the coated surface is withdrawn from the electroplating bath while under bias for a period of between 1 and 10 seconds, preferably for a period of about 1 to 5 seconds.

9. Method according to one of Claims 1 to 8,

characterized in that, in the aforementioned electroplating bath:

- the copper/complexing agent(s) molar ratio is between 0.1 and 2.5, preferably between 0.3 and 1.3;
5 and

- the pH of the said composition is less than 7, preferably between 3.5 and 6.5.

10. Method according to one of Claims 1 to 9,
10 characterized in that, in the aforementioned electroplating bath, the aforementioned solvent is chosen from water and hydroalcoholic mixtures and the source of copper ions is a copper salt, such as in particular copper sulphate, copper chloride, copper
15 nitrate or copper acetate, preferably copper sulphate.

11. Method according to one of Claims 1 to 10,
characterized in that, in the aforementioned electroplating bath, the aforementioned copper complexing
20 agent is a nitrogen heterocycle chosen from pyridine, 2,2'-bipyridine, 8-hydroxyquinoline sulphonate, 1,10-phenanthroline, 3,5-dimethylpyridine and 2,2'-bipyrimidine.

25 12. Method according to one of Claims 1 to 11, characterized in that the aforementioned electroplating bath includes a mixture of pyridine and 2,2'-bipyridine as copper complexing agents.

30 13. Method according to one of Claims 1 to 12, characterized in that the aforementioned electroplating bath comprises, in aqueous solution:

- copper sulphate, with a concentration of between 0.4 and 40mM, preferably of between 0.4 and
35 18 mM and more preferably of between 0.4 and 15 mM;

- a mixture of pyridine and 2,2'-bipyridine as copper complexing agents;

- the copper/complexing agents molar ratio being between 0.2 and 0.6; and

- 35 -

- the pH of the said composition being less than 7, preferably between 3.5 and 6.5.