

PATENT SPECIFICATION

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(54) IMPROVEMENTS IN OR RELATING TO SEMICONDUCTOR DEVICES

(71) We, HEWLETT - PACKARD COMPANY of 1501 Page Mill Road, Palo Alto, California, United States of America, a corporation organised and existing under the laws of the State of California, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us and the method by which it is to be particularly described in and by the following statement:—

This invention is concerned with improvements in or relating to semiconductor devices.

Modern methods of producing miniaturized semiconductor devices involve many stages of layering and etching on a wafer of suitable material. As the lateral dimensions of the devices have decreased, severe difficulties have been encountered with the standard masking methods for defining the areas of the wafer to be etched. The usual method of defining these areas consists of superimposing a layer of photosensitive material, such as a positive or negative photo-resist material, on the wafer, and then exposing selected areas of the photo-resist material to light. In the case of commercially available negative photo-resist materials, such as KTRR, the exposed areas become insoluble in a developer while the unexposed areas dissolve. In the case of commercially available positive photo-resist materials, such as AZ-1350, the exposed areas will wash off in a developer, while the unexposed areas remain. In either case, the photo-resist remaining on the wafer forms a pattern for subsequent etching of an electrically-insulating layer, for instance an oxide, below the photo-resist layer. The pattern should be a faithful reproduction of an original pattern, the original having been transferred to the photo-resist from a mask on which the pattern was imprinted.

In one method for transferring the pattern, called contact mask printing, the mask and wafer are brought into intimate contact to align their adjacent surfaces in parallel planes relative to each other. The two are

then separated slightly and moved relative to each other to align the mask pattern to the pattern on the surface of the photo-resist material by viewing the mask and wafer through a microscope. The mask and wafer are then brought back into contact and illuminated by a light source to expose the photo-resist material. A major difficulty in using this method for producing devices whose smallest dimension is less than 1.0 micron is that the illuminating light diffracts through the pattern defining slits on the mask, so that the images of the slits on the photo-resist material are wider than the actual slits on the mask. Moreover, the width of the slit images is non-uniform since the amount of spreading of the beam depends on the thickness of the residual thin air film between the mask and the photo-resist material, which thickness may vary slightly from place to place on the wafer. Additional problems arise from the wear and tear on both the mask and the wafer as a result of the physical contact between them.

To surmount these problems, a more recent process called projection mask printing has been introduced, in which the mask does not come into contact with the wafer. Instead, the illuminating light first passes through the mask and then is directed through a lens system which functions as an inverse microscope projection system, reducing the image of the mask by a certain factor, for instance a factor of ten. The image is then projected onto the wafer, where the photo-resist is exposed and the pattern reproduced. Alignment is again effected optically, problems of lens resolution being mitigated by stepping the microscope so that sites of small dimension on the wafer are aligned and exposed sequentially. The field of view of each site is then small enough to ensure that the inverse microscope has adequate resolution.

But the use of this projection printing process introduces problems originating in a requirement that the exposing light be monochromatic, which in turn requires that the

photosensitive material exposed by the light be a positive photo-resist material.

These requirements come about because the lens system used to reduce the size of the image must be able to resolve one-micron widths in a large field. This can be done economically only if the system is designed for monochromatic light. Now, it is well known that although monochromatic light will expose positive photo-resist materials properly, it will not do as well for negative photo-resist materials. The projection mask printing process thus also requires the use of a positive photo-resist material such as AZ-1350.

An understanding of the problems of the prior art which result from the requirements mentioned above can best be had by reference to Figure 1 of the accompanying drawings, which shows a cross-section of a typical wafer on which semiconductor devices are to be fabricated. The layer 1 is a substrate of a semiconductor material such as silicon, on which is deposited a layer of an electrically-insulating material 2, for example an oxide. A layer of photosensitive material 3 is deposited onto the electrically-insulating layer 2.

The arrow labeled I represents monochromatic exposing light incident on the wafer after having passed through a mask and an inverse microscope projection system (not shown) that reduces the image in size, and focuses it on the wafer. The light wave I passes through the layer of photosensitive material 3 and into the electrically insulating layer 2, there being usually little reflection at their boundary since the index of refraction of the photo-sensitive material is very close to the index of refraction of the electrically insulating material. After passing through the electrically insulating layer, a fraction of the light, represented by I_1 , is reflected at the boundary between the electrically insulating layer 2 and the substrate 1, that fraction then being transmitted back through the electrically insulating layer into the photosensitive layer. In general these waves, I and I_1 , will undergo optical interference in the photosensitive layer producing a standing wave with nodes of minimum exposure and antinodes of maximum exposure distributed within the photosensitive material. If the intensity of the incident light is such as to give the correct exposure at the antinodes, then the regions of material in the vicinity of the nodes will be underexposed. The result will be that upon development the photosensitive layer will not be completely removed to permit the etching of the electrically insulating layer. On the other hand, if the intensity of the light is increased in order to completely expose the nodes and thus remove the photosensitive material on development, then the

areas in the vicinity of the antinodes will be overexposed, resulting in poor pattern definition on the wafer. Either of the above consequences of the optical interference in the photosensitive layer is unacceptable for one micron work.

An additional problem in the prior art discussed above with reference to Figure 1 is that the commercially available positive photo-resist material, which must be used to achieve good exposure from the monochromatic light used in the projection mask alignment process, adheres very poorly to the materials which are suitable for use in the electrically insulating layer.

It is an object of the present invention to provide an improved method of preparing a wafer use in the fabrication of semiconductor devices.

The present invention provides a method of preparing a wafer for use in the fabrication of semiconductor devices, said method comprising depositing an electrically insulating layer comprising one or more solid electrically insulating materials onto a substrate of a semiconductor material; depositing an antireflection layer comprising one or more solid materials onto said electrically insulating layer; and depositing a layer of positive photo-resist material on to said antireflection layer, the thickness of said antireflection layer and the thickness of said electrically insulating layer being chosen to achieve cancellation among light waves reflected back into said positive photo-resist layer from the other layers.

Preferably said substrate comprises a material selected from silicon, germanium, gallium arsenide, tantalum nitride, molybdenum, and epitaxially grown germanium on gallium arsenide; said electrically insulating layer comprises solid material selected from silicon dioxide (SiO_2), sputtered quartz, silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3), or silicon monoxide, and said antireflection layer comprises solid material selected from molybdenum, chromium, gold, aluminum, nickel, or tantalum nitride.

Preferably the thickness of said electrically insulating layer is chosen so that in the positive photo-resist layer a first light wave reflected from the boundary between said substrate and said electrically insulating layer will be 180° out of phase with a second light wave reflected from said antireflection layer back into said layer of positive photo-resist material, and the thickness of said antireflection layer is chosen so that the fraction of light transmitted through it is such that in the positive photo-resist layer the amplitude of said first wave will be equal to the combined amplitudes of said second wave and a third wave reflected a second time from the substrate-electrically insulating layer boundary after having been

reflected once from the boundary back to said antireflection layer and thence from said antireflection layer to the boundary.

The present invention further provides a wafer for use in the fabrication of semiconductor devices and comprising a substrate of a semiconductor material, a first layer of one or more solid electrically insulating material provided on the substrate, an antireflection layer of one or more solid materials provided on said first layer, and a layer of positive photo-resist material provided on said antireflection layer, the thickness of said antireflection layer and the thickness of said electrically insulating layer being chosen to achieve cancellation among light waves reflected back into said positive photo-resist layer from the other layers when the wafer is in use.

Preferably the thickness of said antireflection layer is chosen so that the fraction of light transmitted through it is such that in the positive photo-resist layer the amplitude of said first wave will be equal to the combined amplitudes of said second wave and a third wave reflected a second time from the substrate-electrically insulating layer boundary after having been reflected once from the substrate-electrically insulating layer boundary back to said antireflection layer and thence from said antireflection layer to the substrate-electrically insulating layer boundary.

Preferably the substrate comprises a material selected from silicon, germanium, gallium arsenide, tantalum nitride, molybdenum, and epitaxially grown germanium on gallium arsenide; the electrically insulating layer comprises solid material selected from silicon dioxide (SiO_2), sputtered quartz, silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3), or silicon monoxide (SiO); and the antireflection layer comprises solid material selected from molybdenum, chromium, gold, aluminum, nickel, or tantalum nitride.

There now follows a detailed description which is to be read with reference to Figure 2 of the accompanying drawings of a method and a wafer according to the invention; it is to be clearly understood that this method and this wafer have been selected for description to illustrate the invention by way of example and not by way of limitation.

Figure 2 is a cross-sectional view illustrating a preferred embodiment of the present invention, in which an antireflection layer is used to generate reflected light waves which cancel each other in the positive photo-resist layer.

Referring to Figure 2, a layer 1 is the substrate of a wafer and is formed of a suitable semiconductor material, such as silicon. Some other materials which might be used are germanium, gallium arsenide, tantalum nitride, molybdenum, or gallium arsenide

with epitaxially grown germanium on the surface. An electrically-insulating layer 2, of a solid material such as silicon dioxide (SiO_2), sputtered quartz, silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3) or silicon monoxide (SiO) is deposited onto the substrate. A region 4 which we call an antireflection layer consists of one or more solid materials, for example molybdenum, chromium, gold, nickel, or tantalum nitride. A layer of photosensitive (i.e. positive photo-resist) material 3 is deposited onto the antireflection layer 4. By suitably choosing the thickness of the antireflection layer 4 and also the thickness of the layer of the electrically-insulating material 2 lying below it, it is possible to prevent any light from being reflected back into the photosensitive layer 3, and hence to eliminate optical interference and the resulting standing wave in the photo-resist layer. At the same time it is possible to choose the material of this antireflecting layer so that the photo-resist material will adhere to it tenaciously.

The arrow labeled I in Figure 2 is a monochromatic light beam focused on the wafer by an inverse microscope projection system used in the projection mask printing process. The light has passed through a patterned mask and is used to transfer the pattern to the wafer by exposing the layer 3. I_1 is that part of the beam that is transmitted through the antireflection layer into the electrically insulating layer, while I_2 is that part of the incident beam that is reflected from the antireflection layer. (If the anti-reflection layer is thin relative to the wavelength of the light employed, then it is convenient to consider the waves reflected from the top and bottom surfaces of the antireflection layer as a single combined reflection labeled I_2 in Figure 2.) I_3 is that part of I_1 reflected from the boundary between the substrate 1 and the electrically insulating layer 2, and I_4 is that fraction of I_3 transmitted through the antireflection layer back into the layer 3 of the photosensitive material. The part of I_3 reflected back into the electrically insulating layer at the boundary between the insulating and antireflection layers is labeled I_5 , while I_6 represents that part of I_5 reflected from the substrate - electrically insulating layer boundary. Finally, I_7 is that part of I_6 transmitted back through the antireflection layer into the photosensitive layer. Only first and second order reflections are considered here, since higher order reflections have only negligible amplitudes relative to the first two. In the photo-resist layer then, there is an incident wave, I_7 travelling toward the antireflection layer, and a reflected wave which is the sum of I_2 , I_4 and I_5 travelling away from the substrate material of the wafer.

To eliminate the reflected wave in the positive photo-resist layer the amplitude and phase relations among the waves I_2 , I_4 and I_7 must be chosen so that the interference among these waves results in complete cancellation. This may be accomplished by choosing the thickness h_2 of the insulating layer to make I_4 180° out of phase with I_2 , thereby putting I_7 almost in phase with I_1 . The equations governing the phase changes of the reflected waves are known in the art and can be found in the *American Institute of Physics Handbook*, Second Edition, 1963, at pages 6-104, 6-105. More particularly, equations 6g-1 and 6g-2 of the aforesaid Handbook refer to intensity reflectance and phase change on reflection respectively of a wave reflected at the boundary between two different media (see particularly the description under case 1 on page 6-104). The description under case 2 on page 6-104 indicates that equations 6g-3 to 6g-6 govern intensity reflectance, phase change on reflection, and intensity transmittance by a thin absorbing medium such as the antireflection layer of a wafer according to the present invention. The thickness h_2 of the electrically insulating layer is chosen to make I_4 180° out of phase with I_2 . This may be accomplished by using the equation 6g-2 to determine the phase change from I_1 to I_7 upon reflection at the boundary between the electrically insulating layer and the substrate, in conjunction with equation 6g-4 to compute the phase change of the reflected wave I_2 from the antireflection layer. The thickness r_1 of the antireflection layer is then chosen so that the amplitude of the wave I_4 is equal to the sum of the amplitudes of the waves of I_2 and I_7 . These various amplitudes may all be computed from equation 6g-1, 6g-3, and 6g-5.

Since I_4 is 180° out of phase with I_2 and I_7 , complete cancellation will occur among these three waves, and no light will be reflected back into the layer 3. The photo-resist material will then be exposed uniformly by the incoming wave I only.

WHAT WE CLAIM IS:—

1. A method of preparing a wafer for use in the fabrication of semiconductor devices said method comprising depositing an electrically insulating layer comprising one or more solid electrically insulating materials onto a substrate of a semiconductor material; depositing an antireflection layer comprising one or more solid materials onto said electrically insulating layer; and depositing a layer of positive photo-resist material onto said antireflection layer, the thickness of said antireflection layer and the thickness of said electrically insulating layer being chosen to achieve cancellation among light waves re-

flected back into said positive photo-resist layer from the other layers.

2. A method according to claim 1 wherein said substrate comprises a material selected from silicon, germanium, gallium arsenide, tantalum nitride, molybdenum, and epitaxially grown germanium on gallium arsenide; said electrically insulating layer comprises solid material selected from silicon dioxide (SiO_2), sputtered quartz, silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3), or silicon monoxide (SiO); and said antireflection layer comprises solid material selected from molybdenum, chromium, gold, aluminum, nickel, or tantalum nitride.

3. A method according to either one of claims 1 and 2 wherein the thickness of said electrically insulating layer is chosen so that in the positive photo-resist layer a first light wave reflected from the boundary between said substrate and said electrically insulating layer will be 180° out of phase with a second light wave reflected from said antireflection layer back into said layer of positive photo-resist material, and the thickness of said antireflection layer is chosen so that the fraction of light transmitted through it is such that in the positive photo-resist layer the amplitude of said first wave will be equal to the combined amplitudes of said second wave and a third wave reflected a second time from the substrate-electrically insulating layer boundary after having been reflected once from the boundary back to said antireflection layer and thence from said antireflection layer to the boundary.

4. A method according to claim 1 substantially as hereinbefore described with reference to Figure 2 of the accompanying drawings.

5. A wafer for use in fabrication of semiconductor devices and comprising a substrate of a semiconductor material, a first layer of one or more solid electrically insulating materials provided on the substrate, an antireflection layer of one or more solid materials provided on said first layer, and a layer of positive photo-resist material provided on said antireflection layer, the thickness of said antireflection layer and the thickness of said electrically insulating layer being chosen to achieve cancellation among light waves reflected back into said positive photo-resist layer from the other layers when the wafer is in use.

6. A wafer according to claim 5 wherein the thickness of said antireflection layer is chosen so that the fraction of light transmitted through it is such that in the positive photo-resist layer the amplitude of said first wave will be equal to the combined amplitudes of said second wave and a third wave reflected a second time from the substrate-electrically insulating layer boundary after having been reflected once from the sub-



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To eliminate the reflected wave in the positive photo-resist layer the amplitude and phase relations among the waves I_2 , I_4 and I_1 must be chosen so that the interference among these waves results in complete cancellation. This may be accomplished by choosing the thickness h_2 of the insulating layer to make I_4 180° out of phase with I_2 , thereby putting I_1 almost in phase with I_2 . The equations governing the phase changes of the reflected waves are known in the art and can be found in the *American Institute of Physics Handbook*, Second Edition, 1963, at pages 6-104, 6-105. More particularly, equations 6g-1 and 6g-2 of the aforesaid Handbook refer to intensity reflectance and phase change on reflection respectively of a wave reflected at the boundary between two different media (see particularly the description under case 1 on page 6-104). The description under case 2 on page 6-104 indicates that equations 6g-3 to 6g-6 govern intensity reflectance, phase change on reflection, and intensity transmittance by a thin absorbing medium such as the antireflection layer of a wafer according to the present invention. The thickness h_2 of the electrically insulating layer is chosen to make I_4 180° out of phase with I_2 . This may be accomplished by using the equation 6g-2 to determine the phase change from I_1 to I_3 upon reflection at the boundary between the electrically insulating layer and the substrate, in conjunction with equation 6g-4 to compute the phase change of the reflected wave I_2 from the antireflection layer. The thickness r_1 of the antireflection layer is then chosen so that the amplitude of the wave I_4 is equal to the sum of the amplitudes of the waves of I_2 and I_1 . These various amplitudes may all be computed from equation 6g-1, 6g-3, and 6g-5.

Since I_4 is 180° out of phase with I_2 and I_1 , complete cancellation will occur among these three waves, and no light will be reflected back into the layer 3. The photo-resist material will then be exposed uniformly by the incoming wave I only.

WHAT WE CLAIM IS:—

1. A method of preparing a wafer for use in the fabrication of semiconductor devices said method comprising depositing an electrically insulating layer comprising one or more solid electrically insulating materials onto a substrate of a semiconductor material; depositing an antireflection layer comprising one or more solid materials onto said electrically insulating layer; and depositing a layer of positive photo-resist material onto said antireflection layer, the thickness of said antireflection layer and the thickness of said electrically insulating layer being chosen to achieve cancellation among light waves re-

flected back into said positive photo-resist layer from the other layers.

2. A method according to claim 1 wherein said substrate comprises a material selected from silicon, germanium, gallium arsenide, tantalum nitride, molybdenum, and epitaxially grown germanium on gallium arsenide; said electrically insulating layer comprises solid material selected from silicon dioxide (SiO_2), sputtered quartz, silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3), or silicon monoxide (SiO); and said antireflection layer comprises solid material selected from molybdenum, chromium, gold, aluminum, nickel, or tantalum nitride.

3. A method according to either one of claims 1 and 2 wherein the thickness of said electrically insulating layer is chosen so that in the positive photo-resist layer a first light wave reflected from the boundary between said substrate and said electrically insulating layer will be 180° out of phase with a second light wave reflected from said antireflection layer back into said layer of positive photo-resist material, and the thickness of said antireflection layer is chosen so that the fraction of light transmitted through it is such that in the positive photo-resist layer the amplitude of said first wave will be equal to the combined amplitudes of said second wave and a third wave reflected a second time from the substrate-electrically insulating layer boundary after having been reflected once from the boundary back to said antireflection layer and thence from said antireflection layer to the boundary.

4. A method according to claim 1 substantially as hereinbefore described with reference to Figure 2 of the accompanying drawings.

5. A wafer for use in fabrication of semiconductor devices and comprising a substrate of a semiconductor material, a first layer of one or more solid electrically insulating materials provided on the substrate, an antireflection layer of one or more solid materials provided on said first layer, and a layer of positive photo-resist material provided on said antireflection layer, the thickness of said antireflection layer and the thickness of said electrically insulating layer being chosen to achieve cancellation among light waves reflected back into said positive photo-resist layer from the other layers when the wafer is in use.

6. A wafer according to claim 5 wherein the thickness of said antireflection layer is chosen so that the fraction of light transmitted through it is such that in the positive photo-resist layer the amplitude of said first wave will be equal to the combined amplitudes of said second wave and a third wave reflected a second time from the substrate-electrically insulating layer boundary after having been reflected once from the sub-

strate-electrically insulating layer boundary back to said antireflection layer and thence from said antireflection layer to the substrate-electrically insulating layer boundary.

- 5 7. A wafer according to either one of claims 5 and 6 wherein the substrate comprises a material selected from silicon, germanium, gallium arsenide, tantalum nitride, molybdenum, and epitaxially grown germanium on gallium arsenide; the electrically insulating layer comprises a material selected from silicon dioxide (SiO_2), sputtered quartz, silicon nitride (Si_3N_4), aluminum oxide (Al_2O_3), or silicon monoxide (SiO);

and the antireflection layer comprises a material selected from molybdenum, chromium, gold, aluminum, nickel, or tantalum nitride. 15

8. A wafer according to claim 5 substantially as hereinbefore described with reference to Figure 2 of the accompanying drawings. 20

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