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(54) Title: PROCESS FOR RECONDITIONING SEMICONDUCTOR SURFACE TO FACILITATE BONDING

(57) Abstract: A non-abrading method to facilitate bonding of semiconductor components, such as silicon wafers, that have micro structural defects in a bonding interface surface. In a preferred method, micro structural defects are removed by forming an oxide layer on the bonding interface surface to a depth below the level of the defect, and then removing the oxide layer to expose a satisfactory surface for bonding, thereby increasing line yield and reducing scrap triggers in fabrication facilities.



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TITLE

PROCESS FOR RECONDITIONING SEMICONDUCTOR SURFACE TO
FACILITATE BONDING

BACKGROUND OF THE INVENTION

[0001] This invention relates in general to valves and to semiconductor electromechanical devices, and in particular, to micromachined components formed from layers of a semiconductor material, such as silicon, bonded together.

[0002] MEMS (micro electro mechanical systems) are a class of systems that are physically small, having features or clearances with sizes in the micrometer range or smaller (i.e., smaller than about 10 microns). These systems have both electrical and mechanical components. The term "micro machining" is commonly understood to mean the production of three-dimensional structures and moving parts of MEMS devices. MEMS originally used modified integrated circuit (e.g., computer chip) fabrication techniques (such as chemical etching) and materials (such as silicon semiconductor material) to micro machine these very small mechanical devices. Today there are many more micro machining techniques and materials available. The term "MEMS device" as may be used in this application means a device that includes a micro machined component having features or clearances with sizes in the micrometer range, or smaller (i.e., smaller than about 10 microns). It should be noted that if components other than the micro machined component are included in the MEMS device, these other components may be micro machined components or standard sized (i.e., larger) components. Similarly, the term "microvalve" as may be used in this application means a valve having features or clearances with sizes in the micrometer range, or smaller (i.e., smaller than about 10 microns) and thus by definition is at least partially formed by micro machining. The term "microvalve device" as may be used in this application means a device that includes a microvalve, and that may include other components. It should be noted that if components other

than a microvalve are included in the microvalve device, these other components may be micro machined components or standard sized (i.e., larger) components.

[0003] Many MEMS devices may be made of multiple layers (or substrates) of material, which may be micromachined to form components of the MEMS device prior to assembly of the multiple layers into a completed MEMS device. For example, such a MEMS device may be manufactured using suitable MEMS fabrication techniques, such as the fabrication techniques disclosed in United States Patent No. 6,761,420, the disclosures of which are incorporated herein by reference; United States Patent No. 7,367,359, the disclosures of which are incorporated herein by reference; Klassen, E. H. et al. (1995). "Silicon Fusion Bonding and Deep Reactive Ion Etching: A New Technology for Microstructures," Proc. Transducers 95 Stockholm Sweden pp. 556-559, the disclosures of which are incorporated herein by reference; and Petersen, K. E. et al. (Jun. 1991). "Surface Micromachined Structures Fabricated with Silicon Fusion Bonding," Proceedings, Transducers' 91 pp. 397-399, the disclosures of which are incorporated herein by reference.

SUMMARY OF THE INVENTION

[0004] The invention relates to a method to facilitate bonding of semiconductor components, such as silicon wafers, that have micro structural defects on a bonding interface surface, for example due to exposure to wet or dry chemical micromachining processes while creating structures on or in the semiconductor material. Many bonding processes require that a substrate bonding interface surface be substantially free of defects to facilitate the bonding of the surface to the surface of another substrate with highly reliable bonding strength. Fusion bonding is a process that is particularly susceptible to bond failure due to poor surface quality. Semiconductor wafers that have undergone extensive micromachining processes may have bonding interface surfaces that have micro structural defects caused by these micromachining processes. In a novel method, wafers which have such defects in interface surfaces, and which otherwise might have to be discarded as scrap, may be reconditioned to remove these defects using a non-abrading process. One example of such a non-abrading process in a method which includes forming an oxide layer (such as a silicon dioxide layer) on the bonding interface surface to a depth below the level of the defect, and then removing the oxide or silicon dioxide layer to expose a satisfactory surface for bonding, thereby increasing line yield and reducing scrap triggers in fabrication facilities.

[0005] Various aspects of this invention will become apparent to those skilled in the art from the following detailed description of the preferred embodiment, when read in light of the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Fig. 1 is a non-scale cross-sectional view of a MEMS device component formed of a semiconductor material, and having a micro structural defect in a bonding interface surface thereof.

[0007] Fig. 2 is a flow chart illustrating a method for reconditioning the bonding interface surface to remove the surface defect and facilitate bonding of the surface with another surface.

[0008] Fig. 3 is a view similar to Fig. 1, showing an oxide layer grown on the bonding interface surface to a depth below the surface defect, according to the method illustrated in Fig. 2.

[0009] Fig. 4 is a view similar to Figs. 1 and 3, showing the oxide layer and surface defect removed.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0010] Referring now to the drawings, there is illustrated in Fig. 1 a portion of a first component, indicated generally at 10. The component 10 is formed of a semiconductor material, such as single crystal silicon or other suitable semiconductor material. The component 10 includes a bonding interface surface 12. A second component (not shown) is to be bonded to the bonding interface surface 12 of the component 10 during manufacture of a composite device. The component 10 could be, for example, a substrate or layer of a multi-layer MEMS device, or a surface mounted component to be bonded to a larger substrate.

[0011] A micro structural defect 14 exists on the bonding interface surface 12. A micro structural defect is defined in this application as being a surface defect, such as a surface pit, or scratch extending into the bonding interface surface. Micro structural defects will typically be on the order of about 2 microns or less deep; note that the depth of a defect which may be treated according to the non-abrading methods described herein may vary according to a variety of factors such as the particular material from which the component 10 is composed, the thickness of the component 10 and the required thickness of the component 10, the economics of scrapping parts versus refurbishing bonding interface surface 12 of the component 10; accordingly, the definition of a micro structural defect is not tied to a precise numerical value of the depth. Various ways this micro structural defect 14 might have been created include, for example, scratching of the bonding interface surface 12 during handling of the component 10, or as a result of exposure of the bonding interface surface 12 to wet or dry chemical micromachining processes while creating micromachined features 16 on or in the semiconductor material of the component 10.

[0012] Many bonding processes require that a bonding interface surface be substantially free of defects to facilitate the bonding of the bonding interface surface 12 to a bonding interface surface of another component with highly reliable bonding strength. Fusion bonding is a process that is particularly susceptible to bond failure due to poor surface quality. If the micro structural defect 14 in the bonding interface

surface 12 were, for example, on an otherwise featureless semiconductor wafer, then perhaps the wafer could be reconditioned utilizing a known abrading method, that is, a method mechanically removing material from the wafer such as by cutting, grinding, or polishing the bonding interface surface 12 to uniformly remove material from the bonding interface surface 12 to a depth below the micro structural defect 14. One such abrading method is the Chemical Mechanical Polishing (CMP) method disclosed in *Fusion Bonding of Rough Surfaces With Polishing Technique for Silicon Micromachining*, C. Gui et al., *Microsystem Technologies* (1997), pp. 122-128 (copyright 1997 Springer-Verlag), the disclosures of which are incorporated herein by reference. However, instead of utilizing conventional abrading methods to smooth the component 10, or scrapping the component 10 in the alternative, it is contemplated that inventive non-abrading methods (i.e., methods of removing material from the component 10 other than mechanical removal) may be utilized to remove the micro structural defect 13. The inventive methods described below are especially useful when the component 10 has already been micromachined to create structures 16 in the component 10, where abrading methods of removing defects, such as polishing of the bonding interface surface 12, would damage such micromachined structures 16. Such abrading methods may damage the micromachined structures 16, for example, by mechanically overstressing such micromachined structures 16.

[0013] Referring now to Fig. 2, a non-abrading method of resurfacing the bonding interface surface 12 is described. The preferred method may be most broadly described as including a step 101, wherein an oxide layer 18 (seen in Fig. 3) is formed on the bonding interface surface 12. The oxide layer 18 may be a layer formed of any suitable oxide (for example, a silicon dioxide layer) formed by oxidizing the semiconductor material of the component 10. The oxide layer 18 will penetrate into the semiconductor material to form an oxide/semiconductor interface 20 below the original level of the bonding interface surface 12. The oxide layer 18 may be thicker than the depth of penetration into the semiconductor material, so that an exterior surface 22 of the oxide layer 18 may be above the original level of the bonding interface surface 12.

[0014] In a step 102, the oxide layer 18 is removed, exposing a new bonding interface surface 12'. If the oxide/semiconductor interface 20 was sufficiently below the depth of the micro structural defect 14, then the micro structural defect 14 will have been removed. This completes the basic steps of the method.

[0015] However, preferably, the method includes a step 100 (before the step 101) of cleaning the bonding interface surface 12. Cleaning the bonding interface surface 12 helps ensure that the oxide layer 18 grows uniformly on the bonding interface surface 12.

[0016] The method may also be considered to include a preliminary evaluation step 99, before step 100, wherein the bonding interface surface 12 is inspected, the micro structural defect 14 is identified, and a decision is made to refurbish the component 10 rather than to scrap the component 10.

[0017] The method also may be considered to include a reevaluation step 103, wherein the new bonding interface surface 12' is inspected to verify that the bonding interface surface 12' is substantially defect free. If it is not, then steps 100, 101, and 102 can be repeated, growing and removing additional oxide layers until the bonding interface surface 12' is substantially defect free.

[0018] Once the refurbished bonding interface surface 12' is substantially defect free, the surface 12' is preferably cleaned in a step 104 to completely remove remnants from the previous oxide layer removal step 102.

[0019] The processes utilized to accomplish the method illustrated in Fig. 2 may be varied according to a variety of factors. Generally, these can be broken into two classes: Surface reconditioning methods conducted at relatively high temperatures (for semiconductor components 10 with no features which may be damaged at such relatively high temperatures, such as metal plated, bonded, or adhered to the component, or polymer coatings), and surface reconditioning methods conducted at relatively low temperatures.

[0020] A non-abrading process for reconditioning the bonding interface surface 12 of the component 10 at relatively high temperatures will now be described, elaborating on the steps illustrated in Fig. 2. Note that if the semiconductor material

from which the component 10 is made is silicon, thermal oxidation of silicon is usually performed at a temperature between about 800°C and 1200°C, resulting in so called High Temperature Oxide layer (HTO). It may use either water vapor (steam) or molecular oxygen as the oxidant; it is consequently called either wet or dry oxidation.

[0021] According to this high temperature method, the step 100 includes cleaning the bonding interface surface 12 with the micro structural defect 14 utilizing standard wafers cleaning methods, for example (without limitation) "SC1/SC2". SC1 is an abbreviation for Standard Clean Solution #1; SC2 is an abbreviation for Standard Clean Solution #2. Their names are derived from the original wafer cleaning process developed at RCA Laboratories circa 1970. This process included a sequence of cleaning steps using "standard" solutions SC1 and SC2 to clean a wafer. SC1 consists of a mixture of ammonium hydroxide (NH₄OH), hydrogen peroxide (H₂O₂), and DI water (deionized H₂O). Once suitable concentration ratio for the SC1 mix is 1:4:20 NH₄OH:H₂O₂:H₂O, although other ratios have been used. SC2 consists of a mixture of hydrochloric acid (HCl), hydrogen peroxide (H₂O₂), and DI water (H₂O). A typical concentration ratio for the SC2 mix is 1:1:5 HCl:H₂O₂:H₂O (that is, 1 part HCl, 1 part H₂O₂, with 5 parts H₂O). SC1 and SC2 are utilized to remove different types of contamination from the components being cleaned. Use of the SC2 solution usually follows the use of the SC1 solution in the RCA sequence.

[0022] The step 101 includes placing the component 10 in a wet/dry thermal oxidation chamber and growing the oxide layer 18 to a thickness of anywhere between a sub-micron thickness to an about 2 micron thickness. During the oxidation process the surface damage (micro structural defect 14) is consumed by the oxide growth process).

[0023] The step 102 includes removing the component 10 from the furnace (thermal oxidation chamber) once the desired oxide thickness is achieved, and utilizing a suitable method, such as a wet oxide strip method, to remove the oxide layer 18. Depending upon the material from which the semiconductor component 10 is formed, such a suitable method may include the application of a suitable oxide

removal etchant, such as dilute hydrofluoric acid, buffered oxide etch, vapor hydrofluoric acid, or oxide removing chemical agents.

[0024] The step 103 includes inspecting the bonding interface surface 12 to determine if the micro structural defect 14 was completely consumed by the oxide growth process in Step 101. If surface damage (such as a remaining portion of the micro structural defect 14) still exists, repeat steps 100, 101, and 102 as necessary; however, large surface damage may mean that the component 10 is not able to be economically salvaged regardless of the number of repetitions of steps 100, 101, and 102. For example, in some applications, it is believed that the use of this procedure may be limited to micro structural defects up to 2 microns in depth for cost considerations, however it is anticipated that larger defects could be removed if required.

[0025] The step 104 includes cleaning the reconditioned component 10 with standard wafer cleaning methods, for example "SC1/SC2" described above. The component 10 can then be further processed as desired. For example, the bonding interface surface 12 can be bonded to the bonding interface surface of another component; if desired, before bonding the bonding interface surface 12 can be exposed to a desired bonding interface surface chemistry to facilitate the desired bonding process.

[0026] As discussed above, a non-abrading low temperature method for reconditioning the bonding interface surface 12 of the semiconductor component 10 may alternatively be utilized, which process will now be described, again elaborating on the steps illustrated in Fig. 2.

[0027] The step 100 includes first cleaning the bonding interface surface 12 of the component 10 with the micro structural defect 14 utilizing standard wafer cleaning methods, for example (without limitation) "SC1/SC2". If suitable (for example, if oxides are present or suspected on the bonding interface surface 12), the step 100 may include a second subsequent sub-step of exposing the component 10 to a suitable oxide removal agent. For example, if the component 10 is formed of silicon, the second sub-step of the step 100 may include exposing the component 10 to vapor

hydrofluoric acid or dilute buffered oxide etch. The step 100 may then further include third and fourth sub-steps of, respectively, washing the component 10 in deionized water and drying the component 10.

[0028] In the step 101, the component 10 is exposed to a suitable oxidizing agent to grow an oxide layer 18 on the bonding interface surface 12. For example, if the component 10 were made of silicon, the bonding interface surface 12 of the component 10 could be exposed to nitric acid (which might be, for example, at a temperature ranging from a comfortable room temperature to the vaporizing temperature of the nitric acid) (and thus the nitric acid could be either in vapor or liquid form) to promote the growth of a silicon oxide monolayer on the bonding interface surface 12. Note that with this low temperature method, the silicon oxide layer is a monolayer, and may not grow into a relatively thicker (micron range) silicon dioxide layer. Once the area of the silicon exposed to nitric acid forms the silicon oxide monolayer, the oxidation process stops. For non silicon semiconductor material, utilize a suitable oxidizing agent.

[0029] The step 102 provides for exposing the oxidized component 10 to a suitable oxide removal agent. This may actually require preparatory sub-steps. For example, if the oxidized component 10 is a silicon semiconductor, as part of such preparatory sub-steps, one may wash the oxidized component 10 in deionized water, dry the oxidized component 10, and then expose the oxidized component 10 to vapor hydrofluoric acid or dilute buffered oxide etch for the removal of the silicon oxide monolayer. For non-silicon components 10, a suitable oxide removal agent may be utilized.

[0030] The step 103 is the inspection step to determine if the micro structural defect 14 has been removed. Again this may actually require preparatory sub-steps, such as cleaning the oxidized component 10 in deionized water and drying the oxidized component 10, and then inspecting the bonding interface surface 12 for surface damage. If any of the micro structural defect 14 (or other surface damage) is observed, the process to this point may be repeated as required to completely remove the micro structural defect 14 or other surface damage. Note that due to the relative

small thickness of the silicon oxide monolayer 18 achieved in the low temperature process (compared to the thickness of the silicon dioxide type oxide layer 18 that may be generated in the high temperature process described above), normally many more repetitions of forming an oxide layer 18 and removing it may be required compared to the high temperature method. Removing the silicon oxide monolayer 18 re-exposes the silicon layer, and the oxidation and removal process will normally be repeated several times (depending on the dimensions of the micro structural defect 14), until the micro structural defect 14 is removed. It may not be required to perform the cleaning step 100 again, and instead jump straight (as indicated by the dashed flow path on Fig. 2) to repeating the steps 101 and 103 as desired until the surface damage (the micro structural defect 14) is removed.

[0031] Once the micro structural defect 14 has been removed (and the component 10 is still usable) the next step is the step 104, clean the reconditioned component 10 with standard wafer cleaning methods, such as (without limitation) "SC1/SC2". The component 10 can then be further processed as desired. For example, the bonding interface surface 12 may be bonded to the bonding interface surface of another component; if desired, before bonding the bonding interface surface 12 can be exposed to a desired bonding interface surface chemistry to facilitate the desired bonding process.

[0032] It is noted that although the steps of oxide formation and removal may be required to be performed several times before enough material is removed to eliminate the micro structural defect 14, the low temperature method for reconditioning the bonding interface surface 12 of the semiconductor component 10 can be highly automated utilizing a wet tank dedicated for this process.

[0033] It is contemplated that a mixture of non-abrading methods of surface reconditioning may be utilized. For example, in the case of a relatively deep micro structural defect 14, the surface reconditioning method conducted at relatively high temperatures (described above) may be utilized to form and then remove one or more relatively thick oxide layers 18. Then the surface reconditioning method conducted at relatively low temperatures (described above) may be utilized to form and then

remove one or more relatively thin oxide layers 18, thereby helping to avoid removing more material than required to remove the micro structural defect 14.

[0034] The principles and modes of operation of this invention have been explained and illustrated in its preferred embodiments. However, it must be understood that this invention may be practiced otherwise than as specifically explained and illustrated without departing from its spirit or scope.

CLAIMS

What is claimed is:

1. A method of reconditioning a surface of a semiconductor device having a micro structural defect, comprising:
 - a) identifying a micro structural defect in a surface; and
 - b) utilizing a non-abrading method to remove material from the surface to a depth below the maximum depth of the micro structural defect.
2. The method of Claim 1, wherein step b) includes the sub-steps:
 - b1) growing an oxide layer on the surface below the depth of the micro structural defect; and
 - b2) removing the oxide layer to reveal a surface substantially free of micro structural defects.
3. The method of Claim 2, wherein the oxide layer is grown at a temperature between about 800°C and 1200°C.
4. The method of Claim 2 wherein the oxide layer is grown at a temperature below 800°C.
5. The method of Claim 1, further comprising an intermediate step x) after step a) and before step b) of utilizing a non-abrading method to remove material from the surface to a depth less than the maximum depth of the micro structural defect.
6. The method of Claim 5, wherein the non-abrading method of step x is a different method than the non-abrading method of step b).

7. The method of Claim 6, wherein the non-abrading method of step x) is a surface reconditioning method conducted at relatively high temperatures, and the non-abrading method of step b) is a surface reconditioning method conducted at relatively low temperatures.

8. The method of Claim 1, further comprising an intermediate step y) after step a) and before step b) of cleaning the surface.

9. The method of Claim 2, wherein step b1) includes exposing the surface to a suitable oxidizing agent to grow an oxide layer on the surface.

10. The method of Claim 9, where the semiconductor device is made of silicon, and step b1) includes exposing the surface to nitric acid.

11. The method of Claim 2, wherein step b2) includes exposing the surface to a suitable oxide removal agent.

12. The method of Claim 11, where the semiconductor device is made of silicon, and step b2) includes exposing the oxide layer to vapor hydrofluoric acid.

13. The method of Claim 11, where the semiconductor device is made of silicon, and step b2) includes exposing the oxide layer to dilute buffered oxide etch for the removal of the oxide layer.

14. The method of Claim 11, where the semiconductor device is made of silicon, and step b2) includes exposing the oxide layer to dilute hydrofluoric acid for the removal of the oxide layer.

15. The method of Claim 9, wherein step b1) includes placing the semiconductor device in a wet/dry thermal oxidation chamber growing an oxide layer on the surface.

16. The method of Claim 15, wherein the oxide layer is grown to a depth of up to about two microns.

17. The method of Claim 15, wherein step b2) includes using a wet oxide strip method to remove the oxide layer.

18. The method of Claim 17, wherein the wet oxide strip method includes utilizing dilute hydrofluoric acid as an oxide removal etchant.

19. The method of Claim 2 wherein the oxide layer is comprised of silicon dioxide.

20. The method of Claim 2 wherein the oxide layer is a silicon oxide monolayer.

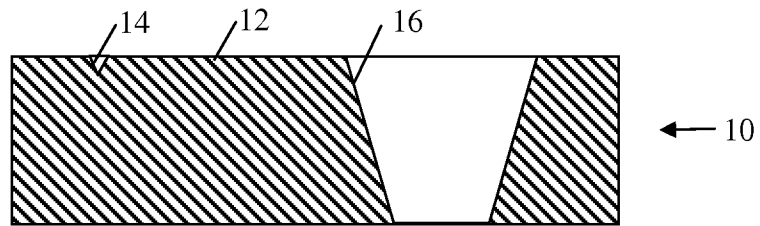


Fig. 1

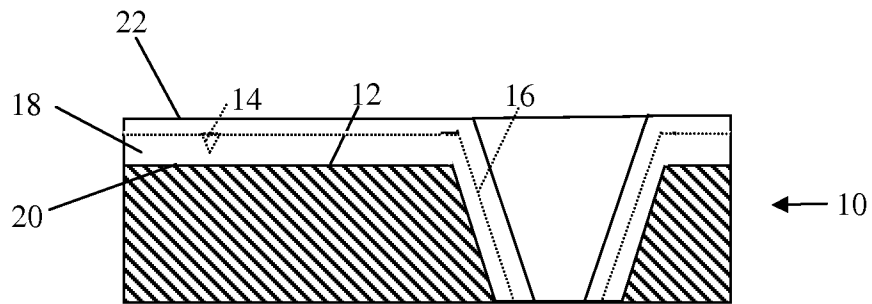


Fig. 3

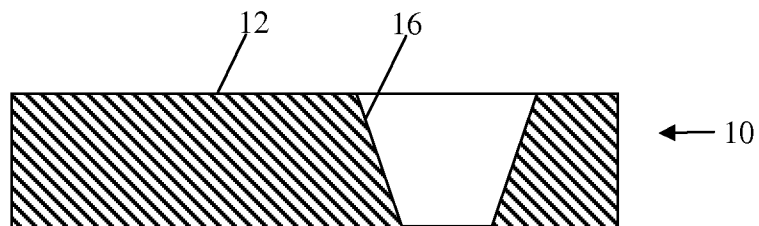


Fig. 4

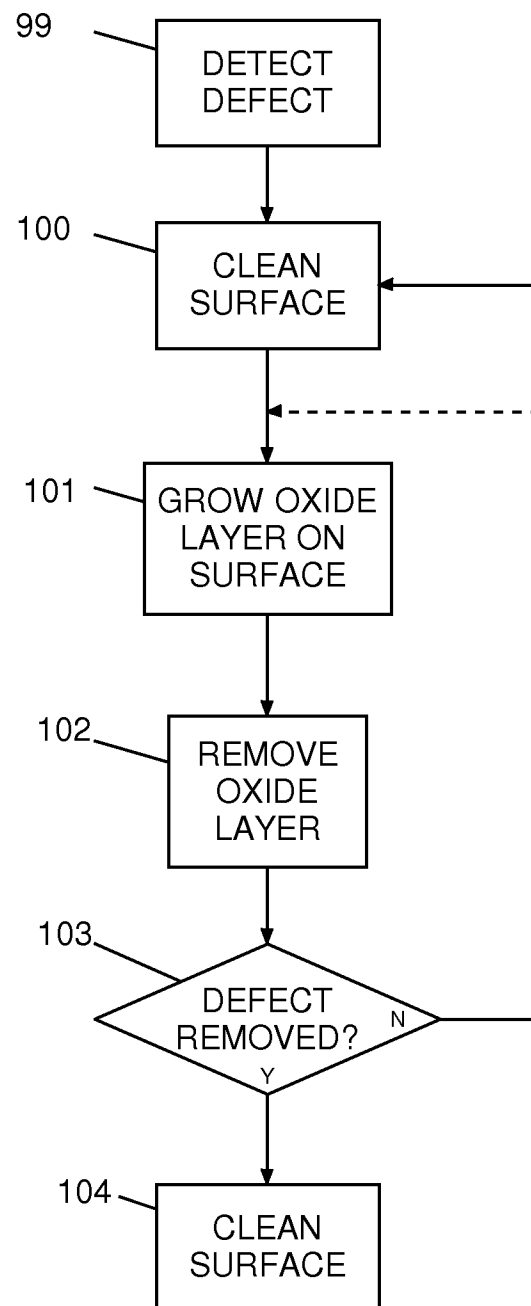


FIG. 2