

DIFFERENTIAL STRESS REDUCTION IN THIN FILMS

FIELD OF THE INVENTION

5 The present invention relates to a method of manufacture of crystalline thin film structures having reduced differential stress build up, and to the crystalline thin film structures that result from the application of this method.

 The invention has been developed primarily for use in the manufacture of micro-electro mechanical systems (MEMS) formed using CMOS semiconductor chip technology
10 from materials suited to this particular manufacturing process, and will be described hereinafter with reference to this preferred application. However, it will be appreciated by those skilled in the art, that the invention may be applied to other thin film structures where it is similarly desirable to reduce differential stress levels within the thin film structure.

15 BACKGROUND OF THE INVENTION

 Processes for the construction of micro-electro mechanical systems (MEMS) are characterised by the formation of micro actuator devices and mechanisms in multi layered wafer structures. Often these layers comprise thin films of different materials having different properties. For example, some of the layers may be required to be conductive,
20 such as where the mechanism includes a heating element as may be used with a thermal bend actuator or the like.

 Thin film structures of this kind are typically formed as a wafer using a molecular deposition process such as "sputtering" which causes the requisite material to be deposited at a molecular level until the desired layer thickness has been attained. With these
25 deposition processes, the first layer of material typically forms small seed crystals which adhere to and align themselves with the supporting substrate. However, subsequent deposited material tends to self align on top of these seed crystals and because of the restraint placed on the development of the growing crystals by the substrate and adjacent crystals, further deposition of the same material tends to thus form columnar crystals.
30 Unfortunately, the columnar crystals and the underlayer of small seed crystals have quite different thermal expansion properties and other physical characteristics. With many materials, the growing layer also exhibits progressively expanding crystals during

deposition due to the dominant growth of some columnar crystals over others. As a result, certain crystal boundaries exist through the entire thickness of the film, these particular boundaries not only weaken the overall structure, but also representing potential locations for the onset of crack propagation.

5 As a result of this natural film building process, residual stress is induced into the material during wafer cooling. This can have several undesirable effects. Firstly, the residual stress gradient maybe sufficient to cause a flap beam actuator formed by this process to curl, even though its design is such that it is effectively a clamped or free beam. This may necessitate a re-design of the structure to include additional stiffening elements to
10 counteract any inclination to curl and as a result is highly likely during operation to require additional power to operate the actuator to overcome either the residual stress or the additional resistance caused by the need to stiffen the structural design.

 A common method of reducing stress in thin films is annealing. However, for many crystalline thin films, this requires high temperatures which may be incompatible with the
15 device structure or previous processing steps. For example, if a crystalline thin film is deposited on an integrated circuit with aluminium wiring, then the temperature must remain below the melting point of aluminium, which is too low to anneal many crystalline materials typically used in integrated circuits made using CMOS techniques.

 It is an object of the invention to provide a method and structure to reduce the
20 differential stress formed in thin film structures of this kind so as to overcome or at least ameliorate these disadvantages of the prior art, or at least offer a useful alternative.

SUMMARY OF THE INVENTION

 According to a first aspect of the invention there is provided a method of manufacture
25 of a crystalline thin film structure from a predominant first crystalline material, said method including the steps of:

 depositing said predominant first crystalline material as two or more sub-layers; and
 depositing between said first crystalline material sub-layers, a layer of second
crystalline material, said second material possessing a lattice constant that is different from
30 that of the first crystalline material, so as to disrupt columnar crystal growth in said
underlying first crystalline material and thereby form a composite thin film structure having

a differential stress profile that is less than the differential stress profile of a comparative film formed solely from said predominant first crystalline material.

While the final total internal stress present in a thin film structure manufactured in accordance with the invention may be higher than may be achieved when annealing can be used, the differential stress is much reduced and the curl tendency of a released layer can be reduced by orders of magnitude.

Preferably, the crystalline thin film structure is a layer of a MEMS structure and more preferably an operational or active layer of a MEMS structure.

Desirably, the second material is selected to have appropriately compatible physical properties relevant to the intended application, as well as possessing a lattice constant that is different from that of the predominant first layer. Where the relevant physical properties of the two materials are similar, such as electrical or thermal conductivity, the thickness of the second material layer relative to the first material sub-layers is less significant. However, where the differences are more pronounced, it is preferable to have a very thin intermediate second material layer so as to minimise the impact of the property difference between the two materials on the final composite structure. Naturally, the pairing of the first and second materials must enable production of a thin film structure having relevant key properties or characteristics that are close to that of the selected predominant first crystalline material.

Preferred combinations of first and second crystalline materials, particularly suited for use in MEMS structures incorporating thermal bend actuators are:

titanium nitride as a predominant first material with intermediate layers of tantalum nitride; and

silicon as a predominant first material with intermediate layers of germanium.

The combinations are particularly suitable for MEMS constructions formed on top of CMOS circuitry.

BRIEF DESCRIPTION OF THE DRAWINGS

A preferred embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 shows an enlarged partial cross-section of a thin film formed in accordance with the prior art techniques;

Figure 2 shows a length of the thin film of Figure 1 deforming under the residual differential stress;

Figure 3 shows a series of clamped/free thin film strips formed in accordance with the prior art techniques;

5 Figure 4 shows a partial cross-section through a thin film formed in accordance with the present invention;

Figure 5 shows the crystal boundaries between the primary and secondary layers of the film shown in Figure 4;

10 Figure 6 shows a thin film formed in accordance with the present invention where the deposition of the primary material has been re-seeded three times; and

Figure 7 shows clamped/free end strips of thin film formed in accordance with the present invention.

DESCRIPTION OF PREFERRED AND OTHER EMBODIMENTS

15 Referring first to figure 1, there is shown a partial cross-section of a titanium nitride layer showing the grain morphology. The layer has been built up from a first side 1 on a substrate composed of silicon with a thin silicon nitrate coating (not shown). As can be seen, the titanium nitride builds up gradually on the silicon nitrate surface commencing with a thin layer 2 of small seed crystals which gradually evolve into larger columnar crystals
20 shown generally at 3. These columnar crystals tend to become progressively larger during deposition due to the dominant growth of some columnar crystals over others. Thus, certain crystal boundaries exist through the entire thickness of the titanium nitride layer. These particular boundaries weaken the titanium nitride layer and would be the likely location for the onset of crack propagation.

25 The differing thermal conductivity and expansion characteristics of the different portions of the titanium nitride layer induce residual stress in the wafer during cooling. As shown in Figure 2, this residual stress gradient through the layer thickness tends to cause the layer to curl. This can adversely affect the function of MEMS devices formed from the wafer. In particular, thermoelastic actuators in the form of clamped/free end strips are
30 susceptible to a relatively high degree of curl. As shown in Figure 3, a series of clamped/free end beam thin titanium nitride strips are shown. The longer and thinner strips deflect the most however because of the residual compression on the underside of the strips

and residual tension on the upper side each strip will tend to curl about it's longitudinal axis as well as lateral axis. Wider strips will curl about the longitudinal axis to produce a deeper lateral cross-section which gives the strip a greater bending stiffness about the lateral axis.

A proposed solution for alleviating this differential stress problem, is shown in

5 Figures 4 to 7. An extremely thin layer (e.g. 100 Angstroms) of tantalum nitride is deposited on top of the titanium nitride at certain levels during the deposition of the titanium nitride layer. The tantalum nitride disrupts any predominant titanium nitride columnar crystal growth and provides a new re-seeding layer. The tantalum nitride effectively acts as a crack inhibitor because the maximum titanium nitride grain boundary
10 can only exist between any two tantalum nitride layers.

The presence of the tantalum nitride layers also effectively moderates the range of grain sizes present. Thus, the magnitude of any induced stress gradient related to the grain size is also moderated. This effectively reduces post fabrication curl.

In this particular preferred embodiment, it is important to note that the tantalum layer
15 is thin enough not to affect the mechanical or resistive properties of the actuator. Tantalum nitride has a decomposition temperature of 750 degrees Centigrade which is above that of titanium nitride.

Examples

A finite element model of a simple beam suitable for use in a thermal bend actuator
20 was constructed to investigate residual curl of the tantalum nitride/titanium nitride layer structure. The intent of the analysis was to ascertain the relative effect that different morphologies have on residual curl rather than the calculation of absolute values. The beam model has identical dimensions to the heater section of a centreline prototype thermal actuator and was constructed with ten elements through the thickness. A stress gradient
25 was indirectly included by applying a linearly varying temperature field through the entire thickness. The presence of a tantalum nitride layer is modelled by reapplying the gradient from the initial value.

Four different layer combinations were analysed including no tantalum nitride re-seeding layer, and one, two and four layers of tantalum nitride. The solutions resulted in
30 deflections at the beam tip of 0.543, 0.0611, 0.0172 and 0.001 micrometres respectively. It should be noted that these values are relative and not absolute.

The results of the tests show that the inclusion of tantalum nitride layers can significantly reduce the amount of post-fabrication curl by progressive orders of magnitude depending on the desired overall thickness, number of intermediate layers and the thickness of those intermediate layers.

5 The above described examples relate to a specific conductor layer having titanium nitride as the predominant material with intermediate layers of tantalum nitride. However, the processes can also be applied to other conductor layer combinations and to non-conductor materials such as silicon which can be compared with intermediate layers of germanium.

10 Accordingly, while the invention has been described with reference to only one use and two preferred combinations, it will be appreciated by those skilled in the art that the invention can be embodied in many other forms.

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I CLAIM:

1. A method of manufacture of a crystalline thin film structure from a predominant first crystalline material, said method including the steps of:

depositing said predominant first crystalline material as two or more sub-layers; and

5 depositing between said first crystalline material sub-layers, a layer of second crystalline material, said second material possessing a lattice constant that is different from that of the first crystalline material, so as to disrupt columnar crystal growth in said underlying first crystalline material and thereby form a composite thin film structure having a differential stress profile that is less than the differential stress profile of a comparative
10 film formed solely from said predominant first crystalline material.

2. A method according to claim 1 wherein the crystalline thin film structure is a layer of a MEMS structure.

3. A method according to claim 2 wherein the crystalline thin film structure is an operational or active layer of a MEMS structure.

15 4. A method according to any one of the preceding claims wherein the second material is selected to have appropriately compatible physical properties relevant to the intended application.

5. A method according to any one of claims 1 to 4 wherein the predominant first material is titanium nitride and the second material is tantalum nitride.

20 6. A method according to any one of claims 1 to 4 wherein the predominant first material is silicon and the second material is germanium.

7. A method according to any one of the preceding claims wherein the intermediate second layer has a thickness of approximately 100 Angstroms.

8. A crystalline thin film structure including a first and second layer of a predominant
25 first crystalline material; and

a second crystalline material between the first and second layers wherein,

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the lattice constant of the second crystalline material differs from the lattice constant of the predominant first crystalline material so that columnar crystals in the first layer terminate at the layer of the second crystalline material so that the initiation of crystal growth in the second layer of the first predominant material reduces the differential stress profile relative to a comparative crystalline thin film formed solely from the first predominant crystalline material.

9. A crystalline thin film structure according to claim 8 wherein the structure is a layer of a MEMS structure.

10. A crystalline thin film structure according to claim 9 wherein the structure is an operational arm in a thermo elastic actuator.

11. A crystalline thin film structure according to claim 10 wherein the predominant first material is titanium nitride and the second material is tantalum nitride.

12. A crystalline thin film structure according to claim 10 wherein the predominant first material silicon and the second crystalline material is germanium.

13. A crystalline thin film structure according to claim 8 wherein the film thickness is less than 500 nanometres.

14. A crystalline thin film structure according to claim 8 having more than two layers of predominant first crystalline material wherein a layer of the second crystalline material is interleaved between each adjacent layer of the first predominant crystalline material.

15. A crystalline thin film structure according to claim 14 having four layers of the predominant first crystalline material and three layers of the second crystalline material interleaved between each adjacent layer of the predominant first crystalline material.

16. A crystalline thin film structure according to claim 15 wherein the thickness of the structure is approximately 300 nanometres and the thickness of each of the layers of predominant first crystalline material is approximately 70 nanometres and the thickness of the second crystalline material is approximately 10 nanometres each.