

**CONTROLLING ELECTROMECHANICAL BEHAVIOR OF
STRUCTURES WITHIN A MICROELECTROMECHANICAL SYSTEMS
DEVICE**

FIELD OF THE INVENTION

[0001] This invention relates to microelectromechanical systems devices. In particular it relates to thin film structures in microelectromechanical systems devices and to electromechanical and optical responses of such thin film structures.

BACKGROUND OF THE INVENTION

[0002] Today a wide variety of microelectromechanical systems (MEMS) devices may be fabricated using microfabrication techniques. Examples of these MEMS devices include motors, pumps, valves, switches, sensors, pixels, etc.

[0003] Often these MEMS devices harness principles and phenomena from different domains such as the optical, electrical and mechanical domains. Such principles and phenomena, while seemingly difficult to harness in the macroscopic world, can become extremely useful in the microscopic world of MEMS devices, where such phenomena become magnified. For example, electrostatic forces which are generally considered to be too weak in the macroscopic world to be harnessed, are strong enough in the microscopic world of MEMS devices to activate these devices, often at high speeds and with low power consumption.

[0004] Materials used in MEMS devices are generally selected based on their inherent properties in the optical, electrical, and mechanical domains and the characteristic response to input, such as for example, a driving or actuation voltage.

[0005] One problem affecting the fabrication of MEMS devices is that in some cases, a material having a highly desirable response to input, for example an optical response to incident light, may also have an undesirable response to input, for example, an electromechanical response to an actuation or driving voltage. To overcome, or at least reduce, the undesirable response, new materials have to be found or developed often at great expense.

[0006] Another problem with the fabrication of MEMS devices is that sometimes, a material selected for its characteristic response may become damaged due to exposure to chemical agents used during a particular microfabrication process. This causes the material to demonstrate less of the characteristic response to the input.

SUMMARY OF THE INVENTION

In one embodiment, the invention provides a method for fabricating a microelectromechanical systems device. The method comprises fabricating a first layer comprising a film or structured film having a characteristic electromechanical response, and a characteristic optical response, wherein the characteristic optical response is desirable and the characteristic electromechanical response is undesirable; and modifying the characteristic electromechanical response of the first layer by manipulating charge build up thereon during activation of the microelectromechanical systems device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figures 1 and 2 show a block diagram of a MEMS device in an unactuated, and an actuated state respectively;

[0008] Figure 3 shows a chart of the actuation and release voltages for the MEMS device of Figures 1 and 2;

[0009] Figure 4 shows one embodiment of a thin film stack for a MEMS device, in accordance with one embodiment of the invention;

[0010] Figure 5 shows a hysteresis curve for a MEMS device including the thin film stack shown in Figure 4 of the drawings;

[0011] Figure 6 shows another embodiment of a thin film stack for a MEMS device;

[0012] Figure 7 shows a hysteresis curve for a MEMS device including the thin film stack of Figure 6 of the drawings;

[0013] Figure 8a shows a block diagram of an electrostatic fluid flow system within a MEMS device in accordance with one embodiment of the invention;

[0014] Figure 8b shows a schematic drawing of the fluid flow system of Figure 8a illustrating its principle of operation; and

[0015] Figure 9 shows another embodiment of a MEMS device in accordance with the invention.

DETAILED DESCRIPTION

[0016] A particular structure or layer within a microelectromechanical systems (MEMS) device may be desirable for its optical response to input in the form of incident light, but may at the same time have an undesirable electromechanical response to input in the form of an actuation or driving voltage. The present invention discloses techniques to manipulate or control the electromechanical response of the structure or layer, thus at least reducing the undesirable electromechanical response.

[0017] As an illustrative, but a non-limiting example of a MEMS device, consider the interference modulator (IMOD) device 10 shown in Figure 1 of the drawings. Referring to Figure 1, it will be seen that IMOD device 10 has been greatly simplified for illustrative purposes so as not to obscure aspects of the present invention.

[0018] The IMOD device 10 includes a transparent layer 12 and a reflective layer 14 which is spaced from the transparent layer 12 by an air gap 16. The transparent layer 14 is supported on posts 18 and is electrostatically displaceable towards the transparent layer 12 thereby to close the air gap 16. An electrode 20 which is connected to a driving mechanism 22 is used to cause the electrostatic displacement of reflective layer 14. Figure 1 shows the reflective layer 14 in an undriven or undisplaced condition, whereas Figure 2 shows the reflective layer 14 in a driven or displaced condition. The reflective layer 14 is generally selected to produce a desired optical response to incident light when it is brought into contact with the transparent layer 12. In one IMOD design, the transparent layer 12 may comprise SiO_2 . The electrode 20 and the transparent layer 12 are formed on a substrate 24. The substrate 24, the electrode 20, and the transparent layer 12 thereon will be referred to as a "thin film stack."

[0019] Typically, a plurality of IMOD devices 10 are fabricated in a large array so as to form pixels within a reflective display. Within such a reflective display, each IMOD device 10 essentially defines a pixel which has a characteristic optical response when in the undriven state, and a characteristic optical response when in the driven state. The transparent layer 12 and the size of the air gap 16 may be selected so that an IMOD within the reflective display may reflect red, blue, or green light when in the undriven state and may absorb light when in the driven state.

[0020] It will be appreciated that during operation of the reflective display, the IMOD devices 10 are rapidly energized, and de-energized in order to convey information. When energized, the reflective layer 14 of an IMOD 10 device is electrostatically driven towards the transparent layer 12, and when the IMOD 10 is de-energized, the reflective layer 14 is allowed to return to its undriven state. In order to keep the reflective layer 14 in its driven condition, a bias voltage is applied to each IMOD device 10.

[0021] If an actuation voltage, $V_{\text{actuation}}$, defined as a voltage required to electrostatically drive the reflective layer 14 of an IMOD device to its driven condition, as showed in Figure 2 of the drawings, is equal to a release voltage, V_{release} , defined as the voltage at which the reflective layer 14 returns to its undisplaced condition, as is shown in Figure 1 of the drawings, then it becomes extremely difficult to select an appropriate bias voltage, V_{bias} , that can be applied to all of the IMOD's 10 within the reflective display to keep the reflective layers 14 of each respective IMOD device 10 within the reflective display in its driven condition. The reason for this is that each IMOD 10 within the reflective display may have slight variations, for example, variations in a thickness of the layers 12, 14, etc., which, in practice, result in a different release voltage, V_{release} , for each IMOD 10. Further, due to line resistance, there will be variations in the actual voltage applied to each IMOD 10, based on its position within the display. This makes it very difficult, if not impossible, to select a value for V_{bias} that will keep the reflective layer 14 of each respective IMOD 10 within the reflective display in its driven condition. This is explained with reference to Figure 3 of the drawings, which shows the observed hysteresis behavior of the reflective layer 14 of an IMOD 10, in which the transparent layer 12 comprised SiO_2 .

[0022] Referring to Figure 3, a curve, 30 is shown, which plots applied voltage (in volts) on the X-axis, against optical response measured in the volts on the Y-axis for an IMOD 10 comprising a transparent layer of SiO_2 . As can be seen, actuation of the reflective layer 14 occurs at about 12.5 volts, i.e., $V_{\text{actuation}}$ equals 12.5 volts, and the reflective layer 14 returns to its undriven condition when the applied voltage falls to below 12.5 volts, i.e., V_{release} , equals 12.5 volts. Thus, the reflective layer 14 in an IMOD device 10 in which the transparent layer comprises only SiO_2 demonstrates no hysteresis. Therefore, if the reflective display is fabricated using IMOD devices 10, each comprising a transparent layer 12 having only SiO_2 , it would be impossible to select a value for V_{bias} . For example, if V_{bias} is selected to be 12.5 volts, because of variations within the IMOD devices 10 in the reflective display, for at least some of the IMOD devices 10, a V_{bias} of 12.5 volts would fail to keep the reflective layer 14 of those IMOD devices 10 in the driven condition.

[0023] In order to select a V_{bias} that is sufficient to keep the reflective layer 14 of a respective IMOD device 10 within a reflective display in its driven condition, it is necessary for each reflective layer 14 of a respective IMOD device 10 within the reflective display to demonstrate some degree of hysteresis, defined as a non-zero difference between the $V_{\text{actuation}}$ and V_{release} .

[0024] It will be appreciated that the electromechanical response of the reflective layer 14 of each IMOD device 10 is determined by the electromechanical properties of the reflective layer 14 as well as the electrical properties of the transparent layer 12. In one particular IMOD device design, the transparent layer 12 comprises SiO_2 which gives a desired optical response when the reflective layer 14 is brought into contact therewith. However, the transparent layer 12 comprising SiO_2 has a certain electrical characteristic or property (the SiO_2 traps negative charge) that affects the hysteresis behavior of the reflective layer 14. Thus, the transparent layer 12 has a desired optical response but an undesirable electromechanical response to a driving or actuation voltage which affects the hysteresis behavior of the reflective layer 14.

[0025] In accordance with embodiments of the present invention, the electromechanical behavior of the transparent layer 12 is altered by adding a further layer

to the thin film stack. This further layer at least minimizes or compensates for the effect of transparent layer 12 on the hysteresis behavior of the reflective layer 14.

[0026] In one embodiment of the invention, the further layer comprises Al_2O_2 which is deposited, in accordance with known deposition techniques, over the transparent layer 12. This results in a thin film stack 40 as shown in Figure 4 of the drawings, comprising a substrate 42, an electrode 44, an SiO_2 reflective layer 46 and an Al_2O_3 layer 48 which functions as a charge trapping layer.

[0027] Figure 5 of the drawings shows a hysteresis curve 50 for an IMOD device 10 comprising the thin film stack 40. As with the hysteresis curve 30, the X-axis plots applied voltage in Volts, whereas the Y-axis plots optical response in Volts. The hysteresis curve 50 shows a hysteresis window of 2.8 volts defined as the difference between $V_{\text{actuation}}$ (7.8 volts) and V_{release} (5.0 volts). When the individual IMOD's 10 within a reflective display each have a respective reflective layer 14 which demonstrates hysteresis in accordance with the hysteresis curve 50, it will be seen that it is possible to choose a value for the V_{bias} between 5 volts and 7.8 volts which will effectively perform the function of keeping the reflective layer 14 of each respective IMOD device 10 within the reflective display in its driven condition. In a further embodiment of the invention, the thin film stack may be further modified to include an Al_2O_3 layer above, as well as below, the reflective layer 12. This embodiment is shown in Figure 6 of the drawings, where it will be seen that the thin film stack 60 includes a substrate 62, an electrode 64, a first Al_2O_3 layer 66, an SiO_2 transparent layer 68 and a second Al_2O_3 layer 70.

[0028] Figure 7 of the drawings shows a hysteresis curve 80 for a transparent layer 14 of an IMOD device 10 having the thin film stack 60 shown in Figure 6 of the drawings. As will be seen, the hysteresis window is now wider, i.e., 4.5 volts, being the difference between $V_{\text{actuation}}$ (9 volts) and V_{release} (4.5 volts).

[0029] However, other materials that have a high charge trapping density may be used. These materials include AlO_x , which is the off-stoichiometric version of Al_2O_3 , silicon nitride (Si_3N_4), its off-stoichiometric version (SiN_x), and tantalum pentoxide (Ta_2O_5) and its off-stoichiometric version (TaO_x). All of these materials have several orders of magnitude higher charge trapping densities than SiO_2 and tend to trap charge of

either polarity. Because these materials have a high charge trapping density, it is relatively easy to get charge into and out of these materials, as compared to SiO_2 , which has a low charge trapping density and has an affinity for trapping negative charge only.

[0030] Other examples of materials that have a high charge trapping density include the rare earth metal oxides (e.g., hafnium oxide), and polymeric materials. Further, semiconductor materials doped to trap either negative or positive charge may be used to form the further layer above, and optionally below the SiO_2 transparent layer 12.

[0031] Thus far, a technique for manipulating the electromechanical behavior of a MEMS device has been described, wherein charge buildup within the MEMS device is controlled by the use of a charge trapping layer which has a high charge trapping density. However, it is to be understood that the invention covers the use of any charge trapping layer to alter or control the electromechanical behavior of a MEMS device regardless of the charge trapping density thereof. Naturally, the choice of a charge trapping layer whether it be of a high, low, or medium charge trapping density will be dictated by what electromechanical behavior for a MEMS device is being sought.

[0032] In some embodiments the incorporation of metals, in the form of thin layers or aggregates, provide yet another mechanism for manipulating the charge trapping density of a host film in a MEMS device. Structuring the host film by producing voids or creating a variation or periodicity in its material characteristics may also be used to alter the charge trapping characteristics..

[0033] According to another embodiment of the invention, an IMOD device 10 includes a chemical barrier layer deposited over the reflective layer 12 in order to protect the reflective layer 12 from damage or degradation due to exposure to chemical etchants in the microfabrication process. For example, in one embodiment, the transparent layer 12 which comprises SiO_2 , is protected by an overlying layer comprising Al_2O_3 , which acts as a chemical barrier to etchants, for example, XeF_2 . In such embodiments, it has been found that when the transparent SiO_2 layer 12 is protected from the etchants, nonuniformities in the SiO_2 are eliminated along with attendant nonuniformities in electromechanical behavior, thus causing the transparent layer 14 within each IMOD device 10 to display hysteresis.

[0034] Figures 8a and 8b show another application within a MEMS device wherein a charged trapping layer is used to control the electromagnetic behavior of a structure within the MEMS device.

[0035] Referring to Figure 8a, reference numeral 90 generally indicates a portion of an electrostatic fluid flow system. The electrostatic fluid flow system includes a substrate 92 within which is formed a generally U-shaped channel 94. The channel 94 includes an inner layer 96 of a first material which is selected, for example, because of its chemical and mechanical properties, for example, the material may be particularly wear-resistant, and may demonstrate little degradation due to the flow of a fluid within the channel. The channel 94 also includes an outer layer 98 which is selected for its charge-trapping properties, as will be explained in greater detail below.

[0036] The electrostatic fluid flow system 90 also includes pairs of electrodes 100 and 102 which are selectively energized to cause displacement of charge particles within a fluid in the channel 94 in the direction indicated by the arrow 104 in Figure 8b of the drawings. In one embodiment, the outer layer 98 traps charge in the fluid thereby to provide greater control of fluid flow within the system 101. In another embodiment, the layer 98 may trap charge in order to eliminate or to reduce hysteresis effects.

[0037] Referring now to Figure 9 of the drawings, another application of using a charge-trapping layer to alter the electromechanical behavior of a structure within a MEMS device is shown. In Figure 9, reference numeral 120 generally indicates a motor comprising a rotor 122 which is axially aligned and spaced from a stator of 124. As can be seen, the stator 124 is formed on a substrate 126 and includes electrodes 128, which, in use, are energized by a driving mechanism (not shown). The rotor 122 includes a cylindrical portion 130 which is fast with a spindle 132. The rotor 122 may be of a material that may be selected for its mechanical properties, including resistance to wear, but may have undesirable electrical properties in response to input, such as when the electrodes 128 are energized in order to cause rotation of the rotor 122. In order to compensate for these undesirable electrical properties, layers 134 and 136 are deposited on the rotor 122 in order to effectively act as a charge trapping layer to alter the electromechanical behavior of the rotor 122.

[0038] Although the present invention has been described with reference to specific exemplary embodiments, it will be evident that the various modification and changes can be made to these embodiments without departing from the broader spirit of the invention as set forth in the claims. Accordingly, the specification and drawings are to be regarded in an illustrative sense rather than in a restrictive sense.

IN THE CLAIMS:

It is claimed:

1. An apparatus, comprising:
 - a substrate;
 - an electrode, wherein the electrode is located over the substrate;
 - an additional layer, wherein the additional layer is located over the electrode;
 - an etch barrier layer, wherein the etch barrier layer is located over the additional layer;
 - an air gap, wherein the air gap is located adjacent the etch barrier layer; and
 - a displaceable layer, wherein the displaceable layer is reflective to incident light.
2. The apparatus of claim 1, wherein the additional layer comprises SiO_2 .
3. The apparatus of claim 1, wherein the etch barrier layer is resistant to XeF_2 .
4. The apparatus of claim 1, wherein the etch barrier layer comprises Al_2O_3 .
5. The apparatus of claim 1, wherein the additional layer is transparent.
6. The apparatus of claim 1, wherein the apparatus is an interferometric modulator.
7. A method of making a MEMS device, comprising:
 - forming an electrode layer over a substrate;
 - forming an additional layer over the electrode layer;
 - forming an etch barrier layer over the additional layer; and
 - exposing the etch barrier layer to a chemical etchant, wherein the etch barrier layer is resistant to the chemical etchant.
8. The method of claim 7, wherein the additional layer comprises SiO_2 .
9. The method of claim 7, wherein the additional layer is transparent.

10. The method of claim 7, wherein the etch barrier layer comprises Al_2O_3 .
11. The method of claim 7, wherein the chemical etchant comprises XeF_2 .
12. The method of claim 7, additionally comprising forming a displaceable layer, wherein the displaceable layer is separated from the etch barrier layer by an air gap.
13. The method of claim 7, wherein the MEMS device is an interferometric modulator.
14. A microelectromechanical systems device comprising:
 - a substrate;
 - a displaceable layer;
 - an electrode, wherein the electrode is located over the substrate;
 - an air gap, wherein said air gap is located between the electrode and the displaceable layer;
 - a charge-trapping layer formed over the electrode, wherein the charge-trapping layer comprises a material capable of trapping both positive and negative charge; and
 - a transparent layer formed between the charge-trapping layer and the electrode.
15. The device of claim 14, wherein the charge-trapping layer comprises a material selected from the group of: AlO_x (non-stoichiometric), Si_3N_4 , SiN_x (non-stoichiometric), Ta_2O_5 , and TaO_x (non-stoichiometric).
16. The device of claim 14, wherein the transparent layer comprises SiO_2 .
17. The device of claim 14, additionally comprising a second charge-trapping layer formed between the transparent layer and the electrode.

18. The device of claim 14, additionally comprising a layer comprising Al_2O_3 located between the transparent layer and the electrode.
19. The device of claim 14, wherein the device is an interferometric modulator.
20. A method of making a MEMS device, comprising:
 - forming an electrode layer over a substrate;
 - forming a transparent layer over the electrode layer;
 - forming a charge-trapping layer over the transparent layer, wherein the charge-trapping layer comprises a material capable of trapping both positive and negative charge; and
 - forming a displaceable layer, wherein the displaceable layer is separated from the charge-trapping layer by an air gap.
21. The method of claim 20, wherein the charge-trapping layer comprises a material selected from the group of: AlO_x (non-stoichiometric), Si_3N_4 , SiN_x (non-stoichiometric), Ta_2O_5 , and TaO_x (non-stoichiometric).
22. The method of claim 20, wherein the transparent layer comprises SiO_2 .
23. The method of claim 20, additionally comprising forming a second charge trapping layer between the transparent layer and the electrode.
24. The method of claim 20, additionally comprising forming a layer comprising Al_2O_3 between the transparent layer and the electrode.
25. The method of claim 20, wherein the displaceable layer is reflective.
26. A microelectromechanical systems device comprising:
 - a substrate;

an electrode, wherein the electrode is located on the substrate;

an air gap;

a layer including SiO_2 , wherein the layer including SiO_2 is located between the electrode and the air gap; and

at least one layer comprising Al_2O_3 on or adjacent the layer comprising SiO_2 , wherein the layer comprising Al_2O_3 is located between the air gap and the layer comprising SiO_2 .

27. The device of claim 26, further comprising an electrostatically displaceable layer located on the opposite side of the air gap from the electrode.

28. The apparatus of claim 26, additionally comprising a layer comprising Al_2O_3 located between the layer comprising SiO_2 and the electrode.

29. The device of claim 26, wherein the device is an interferometric modulator.