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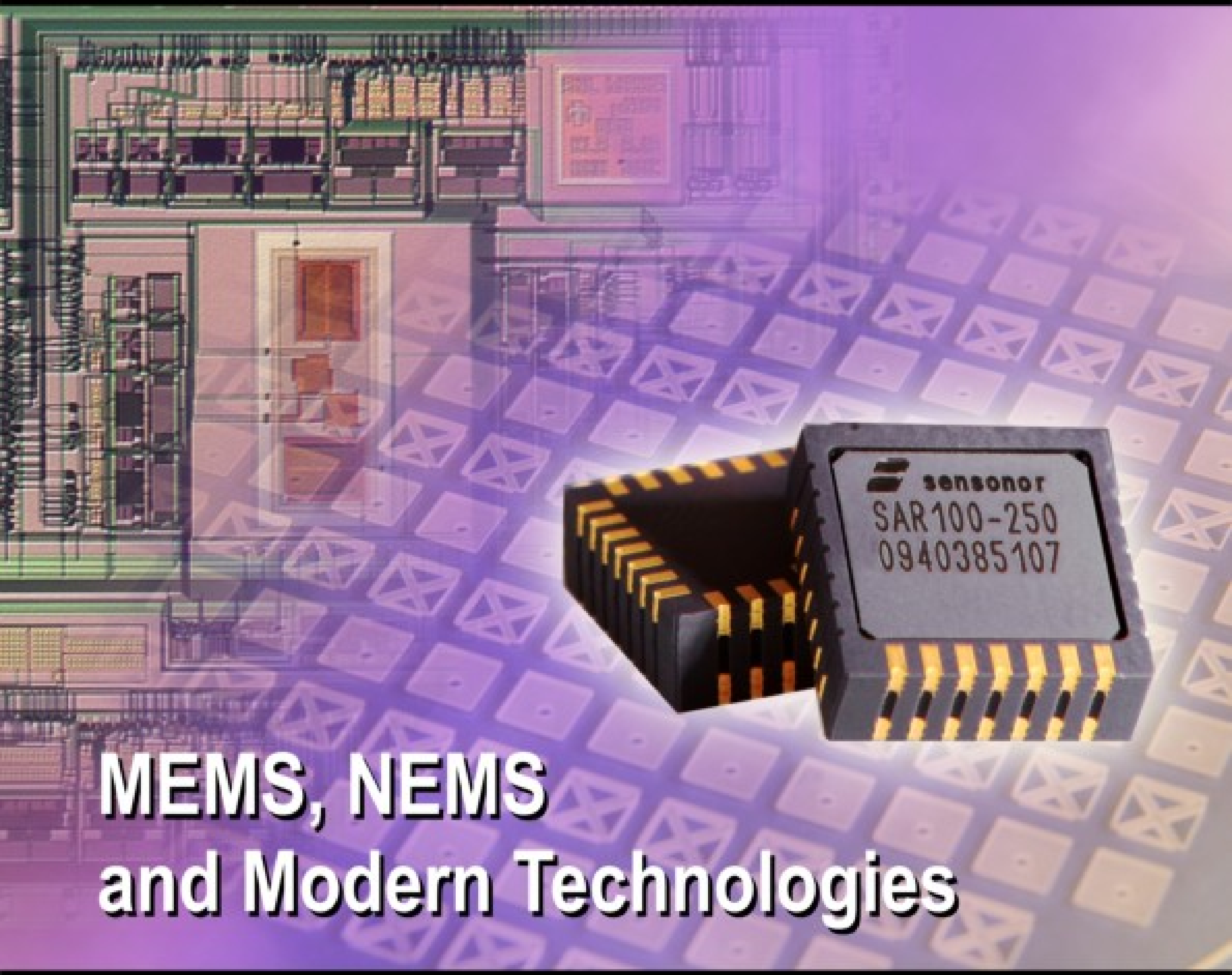

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Electroplated Nickel Micromirror Array

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Abstract: This paper presents the design, fabrication and testing of metallic micromirror array for use in Metal-Organic Molecular Beam Epitaxy system (MOMBE) to define the device structure and hence eliminate the need for etching and lithography. The micromirror is structurally composed of primarily electroplated nickel, a mechanically durable material with controllable residual stress. The high glass transition temperature of nickel allows it to be used without causing any contamination to the epitaxial systems or to the deposited materials. Each mirror is designed with hexagonal shape with a diameter of 0.5 mm to provide high fill factor. The torsion beams were designed with a straight bar and serpentine shape in order to optimize the voltage necessary to tilt the micromirror by 10^o. The fabricated micromirrors with a plate thickness of 2.5 μm and torsion beam length of 80 μm, were rotated 6.84^o by applying 65 V. *Copyright © 2010 IFSA.*

Keywords: Micromirror, Electroplated nickel, Metallic micromirror

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1. Introduction

Several groups have successfully demonstrated scanning micromirror arrays using various actuation mechanisms, including electrostatic [1-4], piezoelectric [6, 7], magnetic [8] and thermal [9, 10]. Electrostatic actuation was selected for use here due to its fast switching time, low power consumptions, low production cost, simple electronics, and simple fabrication and integration. Micromachined electrostatic micromirrors have also been used in many applications which include projection display [11, 12], maskless lithography [13, 14], optical scanner [15], laser printer [16], microconfocal microscopy, [4], switches and optical cross-connects, variable optical attenuator and optical/add drop multiplexer for telecommunication networks [1, 17, 18]. On the other hand, the piezoelectric actuation requires high voltage to rotate the micromirror with large angle. The magnetic actuation can achieve large rotation angle, e.x., 16.1^o. However, the device occupies a large area; therefore, it cannot be used for large array format [8]. The micromirror arrays have been fabricated using bulk and surface micromachining of single crystal silicon (SCS) [19, 20], bulk micromachining of silicon [21], deep reactive ion etching (DRIE) of silicon on insulator (SOI) [1, 22-24] and surface micromachining of polycrystalline silicon [25].

Several groups have successfully demonstrated micromirror array with high fill factor using the electrostatic actuation mechanism. The digital micromirror device (DMD), the core of DLP, is an array of aluminum micromirrors, each with an area of 16×16 μm^2, monolithically fabricated over an array of SRAM cells. Each mirror can rotate up to $\pm 10^o$. Although this technology has shown superiority over other micromirror structures, its complicated design reduces the yield which results in an expensive array [11, 28]. Other groups have fabricated micromirror arrays (16×16 μm^2) with high fill factor using membrane transfer bonding technology. In this case a thin mono-crystalline silicon layer is transferred from silicon on insulator (SOI) wafer to a target wafer using low temperature adhesive bonding. In the first group (Niklaus and colleagues), the micromirror lost a large portion of its area due to the torsion beam design; no testing results were reported [29]. Bakke and colleagues fabricated the micromirror to fit a specific application. In this case, the displacement is only 62 nm, which correspond to a rotation angle less than 1o [30]. A third group (Jeon and colleagues) developed micromirror with high fill factor of 91 %. In this case, the micromirror is supported by three anchors located underneath the mirror plate and the voltage required to rotate the mirror by 6^o is 57 V [31]. Tsai and colleagues developed a two axis optical scanner linear array with a fill factor as high as 96 %. The torsion beams are fabricated underneath the mirror plate. The achieved rotation angle is 4.4^o [32]. In this paper, micromirror arrays are fabricated using electroplated nickel and surface micromachining. The micromirror array will be used to project the desired image onto a GaAs wafer surface inside a MOMBE system. It will reflect the deep ultra-violet (DUV) light through the deposition gases to the GaAs wafer. The DUV is used to preferentially break GaN bonds allowing Ga to desorb from the surface, thus adjusting composition via selective photodesorption and hence partially eliminating ex-situ etching and lithography. Other examples can be constructed for the oxide, nitride, arsenide, phosphide, and antimonide material systems among others showing the versatility of the approach.

2. Design and Modeling

The micromirror consists of a nickel electroplated membrane that is connected to the address lines on a silicon substrate via two nickel electroplated posts. Fig. 1 shows schematics of the electrostatic micromirrors with two torsion beam design, straight bar and serpentine shape. The micromirrors are designed with several arrays, 5×5, 16×16, and 1×16 pixels. Metal addressing lines and bottom electrodes are formed on the silicon substrate below the mirror plate. The 16×16 micromirror array is individually addressed by rows and columns fabricated from two metal layers (gold) separated by oxide layer while the 5×5 and 1×16 micromirror arrays are individually addressed by a single metal layer (gold). To actuate the mirror, a voltage is applied between the mirror membrane and the bottom electrode. Each micromirror is designed with a hexagonal shape and has a diameter of 500 µm. The hexagonal shape will allow the mirror array to have high fill factor in comparison to a circular shape array. Each mirror is also designed with circular dimples in order to control the maximum tilt angle and prevent an electrical short circuit between the mirror and the bottom electrode (Fig. 1).

Finite element analysis using ANSYS/Multiphysics simulation package has been employed to determine the micromirror geometries and to provide accurate prediction of their static and dynamic performance. A reduced order modeling (ROM element type 144) method is used in order to efficiently solve coupled-field problems involving flexible (micromirror) structures. Both the static and dynamic behavior of the torsional micromirror have been investigated using the proposed model. The structural and electrical domains were modeled using solid45 and solid122 elements. In this model, an input text file is used where the design parameters can be easily changed. The torsion beams are designed with either a serpentine and straight bar geometry. The serpentine beam has longer length and is less sensitive to the beam width than the straight bar beams. Therefore, a lower actuation voltage is achieved with the serpentine type. The two models show that a voltage of 130 V and 210 V, respectively, are required to rotate the mirror by 10^o.

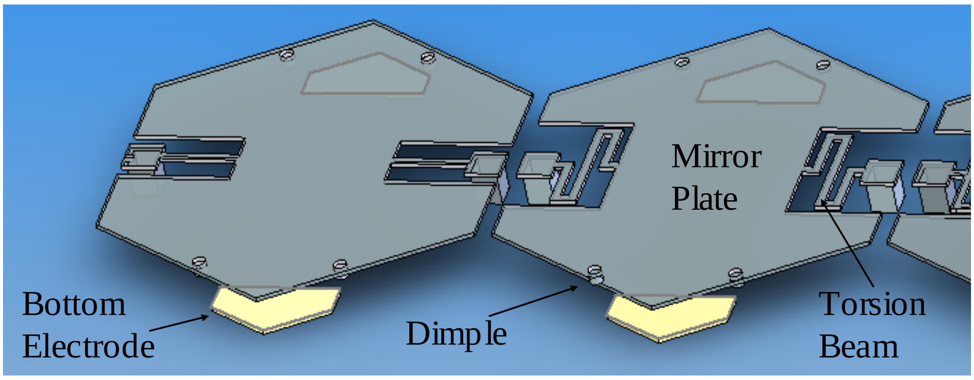

Fig. 1. The 3-D view of torsional micromirror geometries with straight bar and serpentine shape beams. The micromirror consists of a nickel electroplated surface, torsion beams, dimple and anchors. The bottom electrode is fabricated from sputtered gold.

The micromirror becomes unstable at certain tilting angle commonly referred to as “snap-down” angle where the electrostatic force (in case of serpentine beam is 130 V) overcomes the mechanical force and the movable mirror snaps abruptly to the fixed electrode plate, when the applied voltage is increased above a 130 V. The snap down behavior can be prevented if the mirror rotation is limited to one-third to one-half of the mirror touch-down angle [27]. Therefore, the air gap underneath the mirror must be at least 3 times thicker than the air gap needed to achieve the desired physical -swing angle. The results are plotted in Fig. 2. The structural displacements in the Z-direction for the two models are shown in Fig. 3. The length, width and thickness of the torsion beams for the 500 μm diameter mirror are shown in Table 1. The micromirror with the serpentine torsion beam is operated at a resonant frequency of 2.2 kHz as shown in Fig. 4.

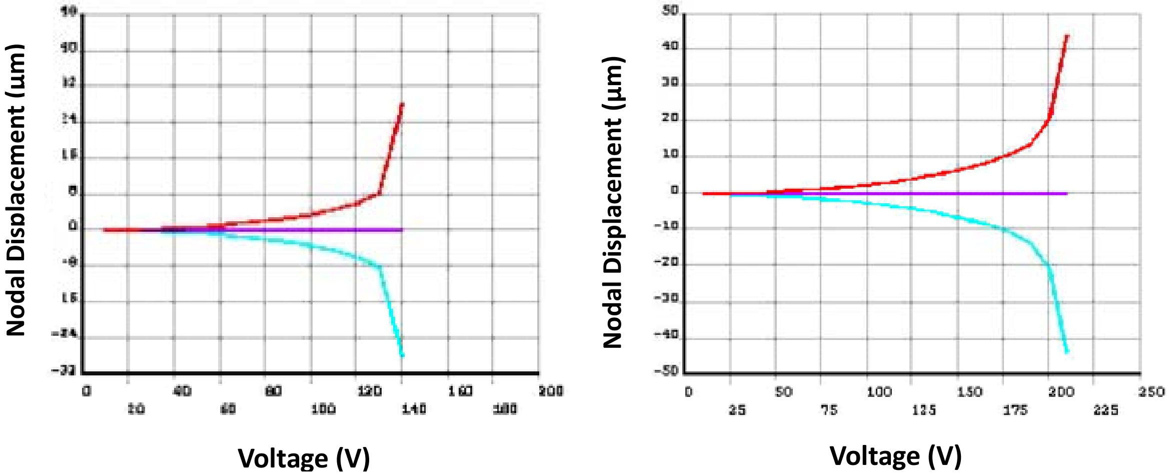

Fig. 2. Characteristics of the micromirror with a) a serpentine and b) straight bar beam.

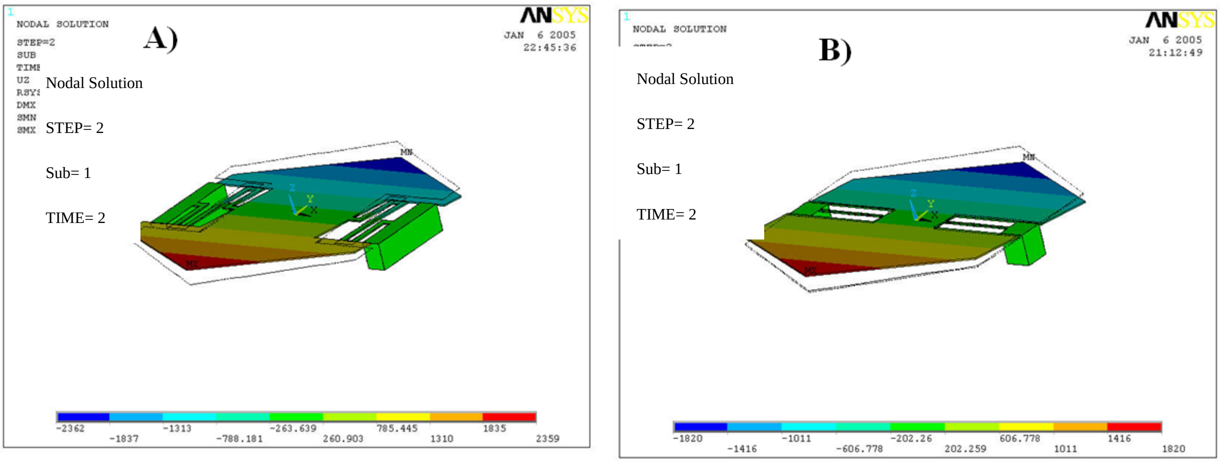

Fig. 3. The structural displacements in the Z-direction of the micromirror with (a) a serpentine shape; and (b) straight bar torsion beam.

Table 1. The serpentine and straight bar torsion beam geometries and the simulation results.

	Length (μm)	**Width (μm)**	**Thickness (μm)**	**Voltage (V)**	**Res. Frequency (Hz)**
Serpentine	300	10	2	140	2200
Straight	120	4	2	210	2200

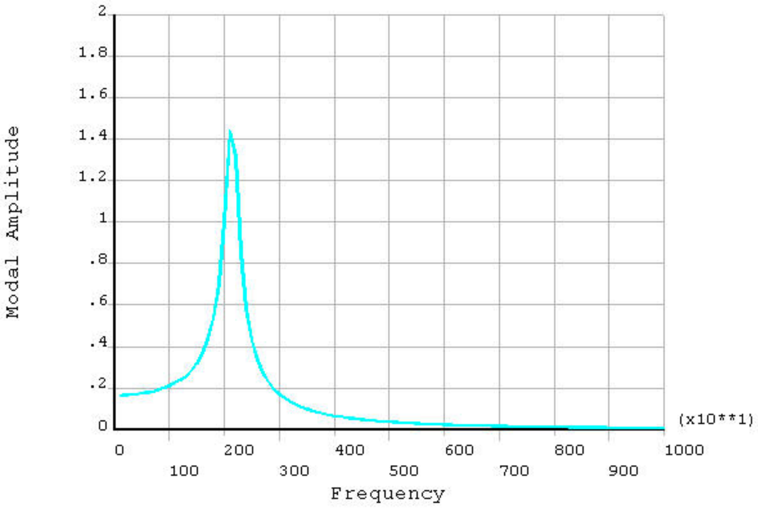

Fig. 4. Resonant frequency as a function of modal amplitude of the micromirror with a serpentine shape torsion beam.

3. Fabrication

The micromirrors are fabricated with hexagonal shape and with a diameter of 0.50 mm using metal sputtering, nickel electroplating, photoresist sacrificial layer, surface micromachining, and photolithography. In this paper, the fabricated micromirrors can rotate up to 6.84^{o}, which is smaller than the designed ones (rotation angle 10^{o}). In future fabrication, the photoresist sacrificial layer will be increased to allow the mirror to rotate up to 10^o. This will require changing the serpentine torsion beam dimensions in order to keep the actuation voltage low. Fig. 5 shows the micromirror array fabrication sequence. The device fabrication steps are described as follows. Initially, conventional ICP silicon etching is used to etch 5 µm deep trenches, 40×40 μm^2, into a silicon wafer at locations corresponding to the micromirror anchors (Fig. 5a). This step enables fabrication of nickel anchors with excellent adhesion to the substrate (seed layer) because of increasing the adhesion surface area. To make this process CMOS compatible, this step can be eliminated. The wafer is then cleaned with acetone, methanol and DI water followed by pirhana etch for 5 min. The wafer is thermally oxidized at 1100 ^oC to grow a 300 nm thick SiO_2 for insulation. Next, four layers of titanium (Ti), Copper (Cu), chromium (Cr) and gold (Au) thin films were sputter deposited to serve as seed layer for the mirror-anchors as well as the bottom electrode. The measured thicknesses of each layer were 5 nm, 60 nm, 10 nm, and 150 nm, respectively. Initially, the bottom electrode traces and bonding pad are patterned by etching Au using KI/ I_2 solution. The Cr layer is used as an adhesion layer for gold and to protect the copper layer from gold etch. The Cr layer is etched in diluted hydrochloric acid (HCl) (Fig. 5b). The Cu layer is used in order to provide uniform current across the wafer during electroplating nickel anchors. The Ti is used as an adhesion layer for Cu. The mask set is designed to build both 5×5 and 16×16 arrays where the micromirror arrays are addressed individually or via rows and columns, respectively. However, in this paper the fabrication process is developed to address the micromirrors that are addressed individually. Therefore, the fabrication process is adjusted to accommodate the mask set. e.x., we have used four metallic layers instead of two. Next, a thick AZ4620 (Clariant) photoresist layer is spun on and patterned to form an electroplating mold using the anchor mask. The photoresist is subsequently cured at 100 ^oC for 5 min to obtain a film, nominally 30 µm thick. The anchors are created by electroplating nickel inside the mold with a thickness between 35 µm (Fig. 5c). Next, the wafer was cleaned with DI water and baked at 100^oC using oven for 90 min to obtain a durable film. The second seed layer which consists of Ti and Cu is similarly sputter deposited (Fig. 5d). The nominal thicknesses are 5 nm and 120 nm, respectively. The deposition is divided into several runs with 10 min of cool time in between in order to avoid inducing cracks in the sacrificial layer as a result of overheating. A second photoresist mold is patterned and filled with electroplated nickel to form the top mirror and torsion beams (Fig. 5e).

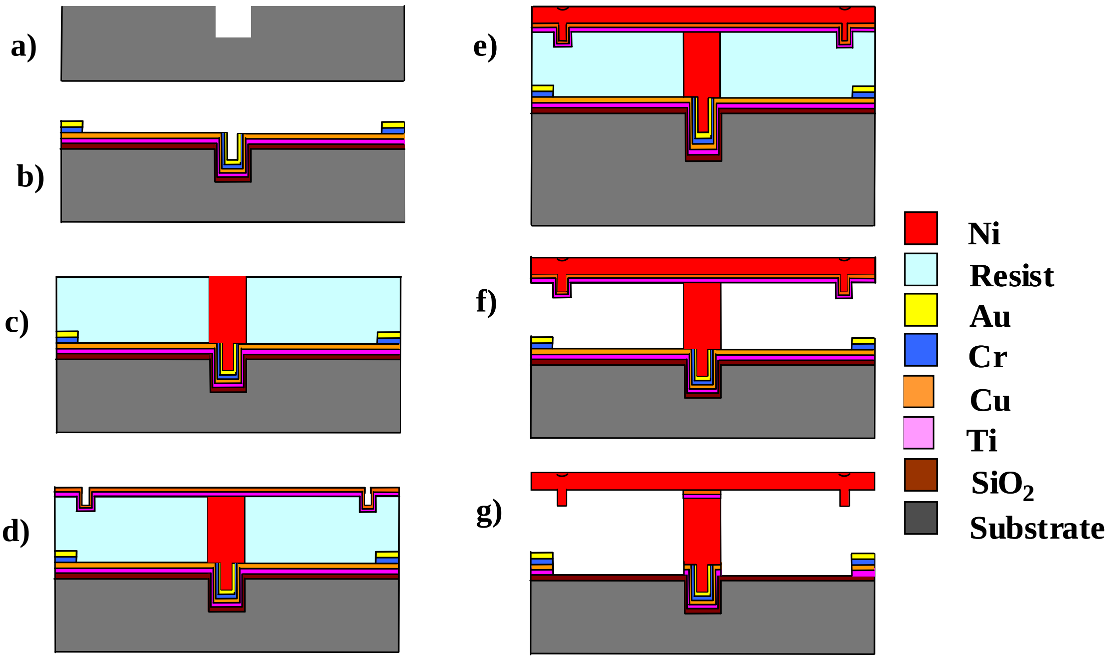

Fig. 5. Micromirror process flow. The dimples were not fabricated at this stage of the project for simplicity.

Several wafers are processed. The thickness of the top plate is ranged between 2 µm to 5 µm. Next, the photoresist layer is removed with acetone, methanol and DI-water. The second seed layer is removed, the Cu is etched in potassium hydroxide solution at 70^{o}C and the Ti is etched using diluted HF. The wafer is then diced and the bottom sacrificial layer is dissolved in resist stripper (AZ400T) at 90^{o}C (Fig. 5f). Next, the bottom seed layer (Cu/Ti) is etched using the same etching solution (Fig. 5g). In this step the Cu/Ti layer are also etched from underneath the top mirror plate. Finally, the processed samples are placed inside critical point dryer to make sure that all micromirrors are suspending without stiction.

4. Results and Discussion

Nickel electroplated micromirror arrays are fabricated with two thicknesses of 2.5 µm and 5 µm. The torsion beams have length ranged from 50-90 m and width is 20 m for all micromirrors. The air gap depth is 30 m which correspond to a rotation of 6.84^{o}. SEM micrographs of the resulting micromirror arrays, 16×16 and 1×16 are shown in Fig. 6, and Fig. 7, respectively. The micrographs display the micromirrors with flat surface. The micromirrors are mounted on a vertical homemade probe station and are actuated by signal generator and AC power supply with a sinusoidal voltage.

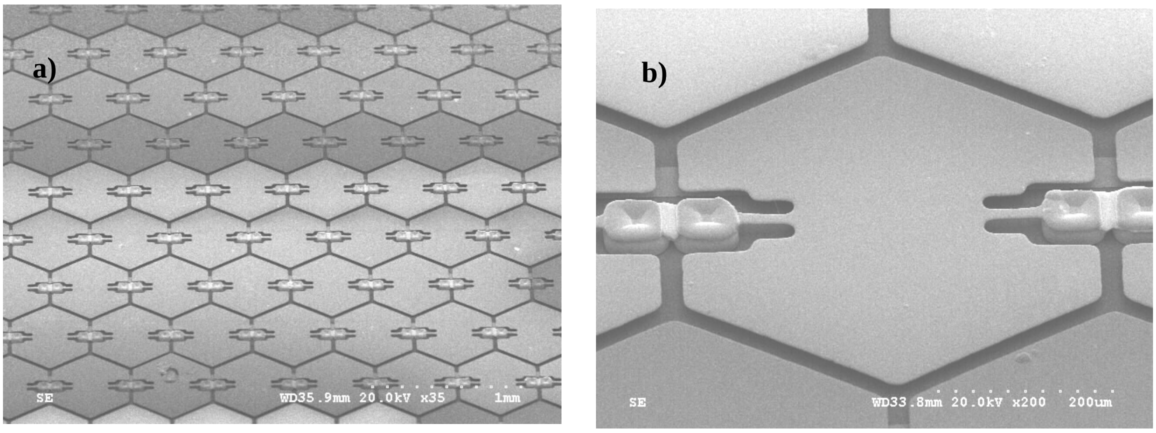

Fig. 6. SEM micrographs of a 16×16 array of nickel micromirrors with straight bar torsion beam (a), a close-up of a single metallic micromirror (b).

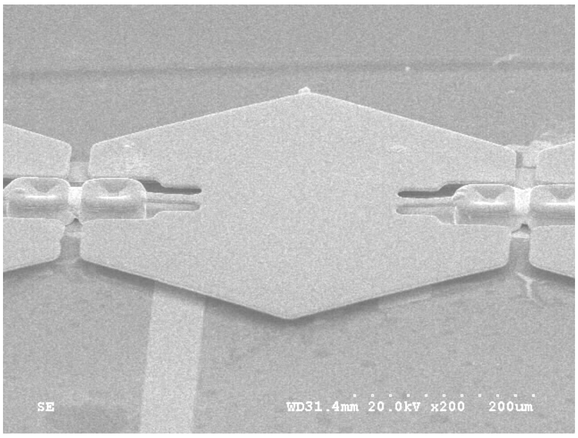

Fig. 7. SEM micrograph of a 1×16 array of nickel micromirrors with straight bar torsion beam.

A laser Vibrometer (standing several feet far from the device) is used to measure the micromirror displacement. However, we are not able to measure the displacement with our current setup since the laser beam was reflected far from the detector and no signal can be recorded. In order to measure the maximum rotation, several tests are performed on the micromirrors with a plate thickness of 2.5 µm and length of 80 µm. In one test, a 65 V (peak-peak voltage) is applied and the micromirror rotation is observed with microscope and recorded with CCD camera. The micromirror appears to rotate with large displacement with approximately 30 µm which correspond to 6.84^{o} as designed (air gap height). We have also applied a series of voltages up to 65 V and we can observe the mirror rotating via an optical microscope but we have no means to measure it at this stage of the project. The torsion beams are also designed with serpentine shape and with narrower width in order to achieve 10^{o} rotation angle with a smaller voltage.

The micromirror array is controlled by a graphical user interface (GUI) created using LabView. The GUI allows the user to choose mirrors to be actuated via text box where the user can enter an alphanumeric character (letters and numbers). The data will be displayed on a virtual on-screen array. Once the micromirrors to be rotated are selected, an ASCII output is sent via the asynchronous serial port to a microcontroller to turn on the appropriate pins. The data is then decoded and the indices of the mirrors are determined. The microcontroller outputs electrical signals (+5 V) on each selected micromirror of 25 pins. The output voltage of each pin is amplified by DC-DC voltage converter to a value as high as 150 V which is applied to the micromirror arrays. A GUI representing 5×5 a micromirror array and the microcontroller used in the experiment are shown in Fig. 8.

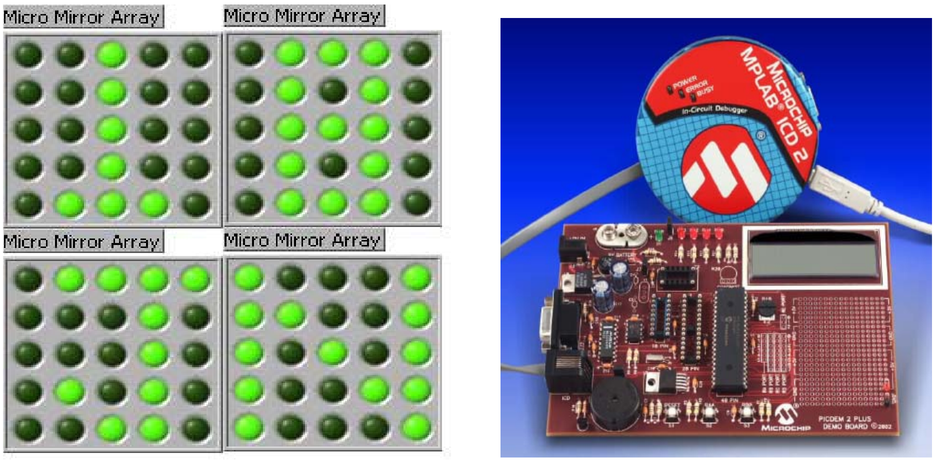

Fig. 8. a) LabView graphical user interface (GUI) of 5×5 micromirror array displaying numbers (1, 8) and letters (J, N); b) the microcontroller is a Microchip Programmable Interface.

5. Conclusion

The micromirror fabrication process, actuation method, and spring designs are presented. New approach is used to create electrostatic micromirror arrays with high fill factor using surface micromachining, electroplated nickel and photoresist sacrificial layer. The fabricated micromirrors have flat surface. The electroplated nickel enables the use of the micromirror array inside MOMBE system. Finite element models are created using ANSYS to determine the micromirror geometries and to provide accurate prediction of their performance.

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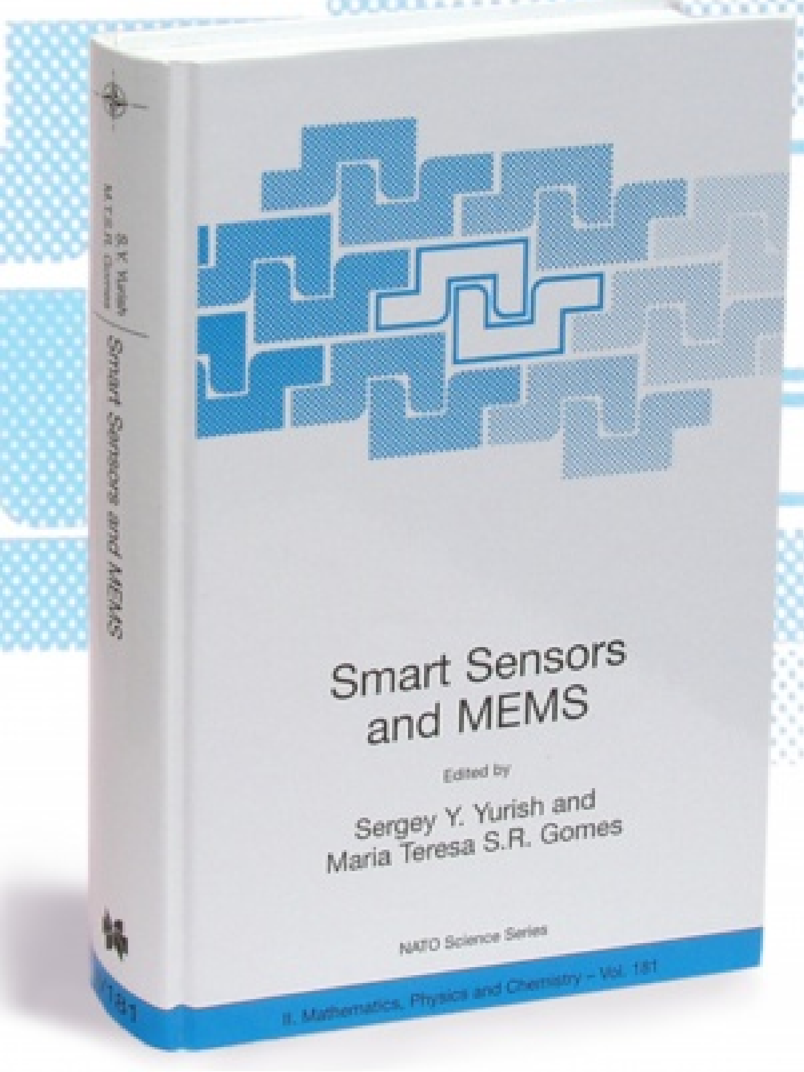
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