Nanometer-Scale Flatness and Reliability Investigation of Stress-Compensated Symmetrically-Metallized Monocrystalline-Silicon Multi-Layer Membranes

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Abstract—This paper demonstrates a very robust and fabrication-parameter insensitive concept of full stress compensation in metallized monocrystalline silicon membranes, by symmetrical metal deposition on both sides of a transfer-bonded silicon membrane, resulting in previously unmatched near-perfectly flat and high-reliability metal-coated membranes. Application examples are high-performance optical mirror devices and quasi-optical tuneable microwave surfaces. The influence of the thickness ratio between the metal films on the two membrane sides are investigated, demonstrating a controllable curvature range from $0.3 \text{ mm}^{-1}$ to $0.1 \text{ mm}^{-1}$ by varying the top to bottom metal thickness ratio from 0.38 to 3.5, using metal thicknesses from 200 nm to 800 nm, and achieving near-zero curvature down to $0.004 \text{ mm}^{-1}$. Extensive reliability tests, up to 100 million cycles, showed no detectable change in curvature, no plastic deformation and good repeatability in analog-mode deflection (within 2.5 %), proving the robustness of this concept of metallized monocrystalline membranes.

I. INTRODUCTION

Many MEMS applications, especially optical, require coated, typically metallized, membranes of high flatness maintained over the whole device lifetime. Purely metallic membranes, for instance aluminum mirrors, exhibit poor flatness and are susceptible to plastic deformation, especially at slightly elevated temperatures [1]. Monocrystalline silicon membranes, as employed by our research group for micromirrors [2] and for RF MEMS metamaterial surfaces [3], offer almost perfectly elastic mechanical properties and high flatness, but metallization layers, as required for reflective-surface applications, induce a stress gradient resulting in membranes bending and buckling. [4] Additional stress-compensating layers [5], [6], typically deposited on the same side as the reflective coating, or finely tuned deposition methods [7] are difficult to manage because they require accurate control of tolerances in the process parameters, and can only be optimized for a small operation temperature range.

This paper presents a very robust stress-compensation concept for metallized monocrystalline silicon membranes, featuring symmetrical deposition of the metal on both sides of the membrane to balance the stresses induced by the metallization. The resulting multi-layer membrane retains the near-ideal mechanical properties of the monocrystalline silicon core, proven by life-cycle measurements over 100 million actuation cycles showing virtually no degradation or plastic deformation. In contrast to conventional stress compensation methods, where the coating layers must be thin compared to the structural layer, the presented concept is shown up to 800 nm of gold on a 1000 nm core.

II. STRESS-COMPENSATED SYMMETRICAL METALLIZATION OF MONOCRystALLINE-SILICON MEMBRANES

The stress-compensation concept of this paper (Fig. 1) is based on depositing the metal layers before and after the transfer of the membrane to a target substrate, achieving metal layers that are deposited under exactly the same conditions, and from antipodal directions (i.e. on both sides of the silicon core the metal is deposited towards the surface).

The fabrication process is outlined in Fig. 2. The thin device layer of a silicon-on-insulator (SOI) wafer is transferred to the final substrate by adhesive transfer-bonding at 200 °C with MR-I 9150XP sacrificial bond polymer allowing for subsequent release of the membrane in oxygen plasma. [8] The transferred monocrystalline-silicon device layer becomes the core of the multi-layer-metallized membrane, which is then patterned and supported by electroplated posts before the final release etch.

The direction of the symmetrical metallization of the membrane is indicated by the arrows in Figs. 1 and 2. The first
metal layer is deposited on the device layer directly before the transfer-bonding. The second metal layer is deposited on the other side of the device layer directly after it has been exposed by etching away the handle and the BOX layer of the SOI wafer. Since the metal layers are deposited under the same conditions, the stresses induced by the metallization will be balanced out by symmetry. This also makes the process very insensitive to machine parameter variations in the metallization step, such as stress and deposition rate, as long as the parameters are stable between the two runs on the same membrane. The final bending is independent on absolute deposition time, since only the ratio between the metal layer thicknesses affects the result.

Fig. 3 shows SEM pictures of fabricated test devices, in this embodiment tuneable RF MEMS quasi-optical metamaterial surfaces [3], featuring 1000 nm thick silicon membranes covered by 500 nm of gold on both sides.

III. INFLUENCE OF THE THICKNESS RATIO OF THE METAL LAYERS

The matching of the thicknesses of the top and bottom metal layers is important for controlling the final bending of the membranes. In theory, if the deposition conditions are the same for the two metal layers, the ideal flatness should result from having the same metal thickness on top and bottom of the membrane. However, in our observations, the best flatness is achieved by having slightly less metal on the bottom. This could be explained by the internal state of the thin monocrystalline silicon device layer being different during the two metal depositions, for example caused by pre-stress from the SOI wafer or from the transfer-bonding. The final bending can, however, still be controlled to near-zero by tuning the thickness ratio of the metal layers.

To investigate the influence of asymmetric thickness variations on the flatness of the membrane, test membranes were fabricated where the metal thickness on the top and bottom side were independently varied from 200 nm to 800 nm. All
test membranes could be fabricated on the same wafer by employing a moving shadow-mask to create two stair-case patterns orthogonal to each other on the top and bottom side, as shown in Fig. 4.

Fig. 5 shows the curvature distribution obtained by the independent parameter variation. The curvature is extracted from white-light profilometer measurements of 16 test membranes for each combination of top and bottom thickness. The isoline of thickness combinations resulting in zero bending is indicated in the figure, and it is clearly seen that this ideal line is offset from the symmetric case. However, the data can be used to select a deposition ratio of top to bottom metal thickness that gives a low curvature, which will then be independent of the exact processing conditions as long as the metal thickness is proportional to the deposition time.

IV. MECHANICAL RELIABILITY OF THE MULTI-LAYER MEMBRANES

The excellent mechanical properties of monocrystalline-silicon membranes are retained by the multi-layer membranes, since the highly elastic and stiff silicon core dominates over the softer metal layers. Fig. 6 shows white-light interferometric measurements of a stress-compensated test membrane, with a low and fairly uniform flatness of 20 nm to 40 nm over the 200 µm membrane, corresponding to roughly 0.01 mm\(^{-1}\).

The test membranes are electrostatically actuated with roughly 30 % tuning range from the initial distance of 3.6 µm. In Fig. 7 the curvature and deflection is plotted for a symmetrically metallized membrane over the full analog tuning range, showing almost invariant curvature over the whole range (−0.165 mm\(^{-1}\) to −0.154 mm\(^{-1}\)).

Furthermore, the reliability of the membranes has been investigated by studying both the membrane shape and absolute deflection during life-cycle measurements over 100 million cycles (Fig. 8), demonstrating the excellent long-term stability with virtually no degradation neither in curvature nor in repeatability of the actuated deflection. The curvature varies by only 0.005 mm\(^{-1}\) and the deflection is within 2.5 % variation in both states. The actuation cycles were performed at 10 kHz unipolar frequency, and stopped at power-of-ten
intervals to make a white-light interferometric measurement of the actuated and unactuated states. No charging was observed, since there is no dielectric isolation layer in the all-metal actuator. After 100 million cycles the measurement was stopped without observing any failure. This good reliability was achieved even though the experiment was performed with an unpackaged device in a general cleanroom area with no additional atmospheric control over temperature and humidity.

V. CONCLUSION

A robust stress-compensation concept for metallized monocrystalline silicon membranes, featuring symmetrical metal deposition to balance stresses induced by the metal layers, has been shown to result in multi-layer membranes with near-zero curvature down to 0.004 mm\(^{-1}\) with up to 800 nm thick metal layers on a 1000 nm monocrystalline-silicon core, and near-ideal mechanical properties, proven by life-cycle measurements over 100 million actuation cycles showing virtually no degradation or plastic deformation.

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REFERENCES


