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Self-terminating electrochemical etching of stainless steel for the fabrication of micro-mirrors

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Abstract
A novel, self-terminating electrochemical etch process is proposed for the fabrication of scanning steel micro-mirrors. The process uses single mask photolithography, and the etching step is terminated automatically, which at the same time enables the depth profile shaping of the fabricated structure. The proposed process is characterized and then used to fabricate two versions of one-dimensional (1D) steel micro-scanners: one with selective thinning of the predefined parts and one without thinning. The fabricated devices are characterized and compared with respect to their resonance frequencies and mechanical quality factors. The thickness of the starting substrate is selectively thinned down by approximately 150 μm in order to decrease the mass of the mirror and eventually to increase the resonance frequency of the fundamental mode. The resonance frequency of the structure is increased from 4210 Hz to 6060 Hz resulting in a normalized frequency shift of 15%.

1. Introduction
Many different MEMS applications including optical micro-scanners require structures with varying thicknesses to improve their performances. Conventional micromachining technologies such as surface micromachining [1], bulk micromachining [2] and LIGA [3] are not always sufficient to shape the profile of micro structures and to fabricate curved three-dimensional (3D) surfaces. A number of attempts have been reported to make out-of-plane curved surfaces on substrates like silicon, polymers and glass using methods such as inclined/rotated UV lithography [4], micro-stereo lithography [5], image mirroring to create etch-enhanced areas [6], femtosecond laser microfabrication using direct laser writing and holographic recording [7] and electroplating fabrication [8]. However, these methods do not have the full ability to build complete and real 3D structures on metal substrates in a simple and cheap way.

The main focus of this work is to shape a stainless steel substrate to different depths using a simple and quick process in order to enhance the performance of optical MEMS devices. A fabrication method that benefits from conventional lithography and electrochemical metal etching to produce a micromachined steel scanner was presented earlier [9]. Electrochemical etching is an effective method for the micromachining of metals, which are hard to etch. The fundamental aspects of electrochemical microfabrication were previously given in the literature [10]. Moreover, the basic characteristics of the electrochemical etching of various compositional Ni–Fe corrosion-resistant alloys such as stainless steel have been reported [11]. In this paper, we present a novel fabrication process which is self-terminating and uses stainless steel as the structural material. The proposed method also enables having structures with different thicknesses on the same substrate using a single mask lithography step and utilizing electrochemical etch lag. The depth of etch is changing for different widths of mask openings due to etch lag [12]. An etch mask is designed such that the openings defining the frame boundary of the mirror die have the fastest etch rate, whereas the openings for the areas where thinning is desired have slower rates. The etch stops automatically as soon as the frame of the device is etched.
through, thinning of desired areas is obtained as well. In order to obtain a correct set of process parameters to acquire spring beams and masses with the desired thicknesses, first, the electrochemical etch lag of steel is characterized. Based on these results, a photomask is designed to realize devices with selective thinned areas. Such devices can be used as micro-mirrors in resonant mode and also as inertial sensors.

This paper is organized as follows. Section 2 explains the proposed electrochemical etching process and shares its characteristics. Moreover, it gives details on the fabrication of the targeted 1D steel scanner structure. Section 3 describes the device operation of a 1D steel scanner along with its design and actuation principles. Section 4 characterizes the devices by giving experimental results and discusses the performance of the proposed system. Finally, concluding remarks and outlook are provided in section 5.

2. Fabrication process

In order to characterize the etch process, and to supply experimental data to device designs, a series of etch tests are performed. The etch rate and anisotropy of the process for various current density values and electrode gaps are the important parameters of the process to control the depth profile of the device. Test substrates (stainless steel type 301) shown in figure 1 are prepared by first spin coating 15 μm of the SPR 220-7.0 positive photoresist on them and then patterning the photoresist layer using photolithography. Square openings of various dimensions ranging from 30 μm × 30 μm to 3 mm × 3 mm are formed on this test wafer to investigate the feature size-dependent etch rate.

The electrochemical etch setup that is employed to etch the stainless steel substrate is depicted in figure 2. In the first set of experiments, a 1:7 HCl:DI water solution is used in the setup as the electrolyte. The sample to be etched and the counter electrode are both immersed into the solution as shown in the figure. The backside of the sample is protected against electrochemical etching using duct tape. Initially, the etch rate and the anisotropy of the process are characterized using different values of current densities for a constant electrode gap of 6 mm. A current density ranging from 1.5 A cm⁻² to 7.5 A cm⁻² is applied to the test setup. The etch duration for each current density is adjusted such that the total amounts of charges delivered to the electrochemical etch cell during the tests are equal to each other. The etch depth and the related undercut values of the square openings are carefully measured by using a measurement microscope (Nikon MM400 L).

The photoresist mask can stay stable for approximately 15 min in this HCl solution. The etch rate of stainless steel in this solution for a 3 A cm⁻² current density is around 39 μm min⁻¹ for a square opening of 500 μm × 500 μm and for an electrode gap of 3 cm. With this etch rate, it takes around 5 min to etch through a 200 μm thick steel substrate, which can be tolerated by the photoresist mask. Therefore, 3 A cm⁻² can be considered as an optimum value of current density to minimize the etch-mask erosion. In the second set of experiments, 20% (by weight) NaCl:DI water solution is used as a neutral electrolyte in the electrochemical etch setup to investigate the tolerance of the photoresist while immersed in the solution and to compare the anisotropy and etch rate values of the setups. It is found that the etch rate of SS301 in this solution for a 3 A cm⁻² current density is around 41 μm min⁻¹ for a square opening of 750 μm × 750 μm and for an electrode gap of 3 cm. Moreover, the photoresist mask stays stable for a much longer time in the solution compared to the HCl solution.

Etch tests reveal that the average roughness goes down from a top value of 16 μm to 1 μm as the widths of the square openings decrease in the HCl electrolyte. Similarly, the roughness is reduced from a top value of approximately 8 μm for a square opening of 750 μm × 750 μm to 0.5 μm as the widths of the openings decrease in the NaCl neutral electrolyte. The improvement of the roughness with the decrease of opening size can be explained by the enhancement of the electrolytic polishing effect inside smaller openings as discussed in [11].

One disadvantage of using the NaCl solution in electrochemical etching compared to the HCl solution is the formation of byproducts that do not dissolve during the etch process. This contamination becomes more pronounced if a smaller electrode gap and a small current density are used, since it becomes more difficult to remove the byproducts from the locations where they are generated.
Following this experiment, a constant current density of 3 A cm$^{-2}$ is applied to the samples for 5 min with a dc current source in the rest of the process characterization tests. Different values of the electrode gap ranging from 3 cm to about 22 cm between the steel sample and the counter electrode are also characterized in these tests. The data acquired from these experiments can be seen in figure 3.

As can be seen from this plot, there is an optimum opening size of approximately 500 μm × 500 μm for the HCl solution and 750 μm × 750 μm for the NaCl solution that results in the maximum etch rate in electrochemical etching. Almost the same behavior is noticed in the experiments with different electrode gaps. Larger or smaller square dimensions than this optimum value result in significant reduction in the etch rate. For dimensions smaller than 500 μm in the HCl solution or 750 μm in the NaCl solution, etch rates start to decrease since etching becomes mass transport limited. The transport of chemical reactants and byproducts is getting increasingly difficult for smaller dimensions. Consequently, the etch rate decreases for smaller dimensions. On the other hand, for dimensions larger than the optimum value, the edge effect, which provides higher etch rates at the edges of the square openings due to higher electric field densities, becomes negligible compared to the etch rates in the rest of the opening area. Current crowding at the edges is a well-known concept that states that the electrical field at the edges is stronger than that toward the center of the opening. In other words, the etch rate at the edges is higher than that at the rest of the etched areas. As the square dimensions get larger, this effect eventually becomes negligible. The ratio of edge surfaces to the overall area of the openings gets smaller and the etch rate of the center becomes dominant. Consequently, the overall etch rate decreases as the dimension increases from the optimum point.

Figures 4(a) and (b) show the etch depth and etch anisotropy, respectively, in the NaCl solution as a function of the current density for different opening widths with an electrode gap of 6 mm.

These results support the fact that the shaping of the wafer in the third dimension is possible by choosing the dimensions of the etch openings according to the etch rate data acquired. Figure 5 depicts the profile of a sample when it is etched using a mask with two different opening sizes; one of them represents the optimum opening size and the other a smaller opening size to thin the thickness of the device.
This way, a substrate can be thinned down, or curved surfaces can be formed by simply tailoring the etch openings accordingly. Figure 5(b) illustrates the resulting cross-sectional profile, where a substrate is etched through at the locations of optimum openings, and thinning is performed in the same etch interval by forming much smaller etch openings in the resist mask. In order to utilize this fact, a new masking scheme as shown in figure 6(b) is proposed. The areas that are to be protected against standard electrochemical etching are covered with a resist mask (figure 6(a)) whereas in the proposed method shown in figure 6(b), in addition to the conventional masking, most of the open-to-etch area is also protected to increase current density.

The gap \( W_2 \), shown in figure 6(b), defines the mirror, and it is designed to be approximately 500 \( \mu \)m to ensure an etch rate greater than at any other area of the sample. The gap \( W_1 \), which defines the frame of the mirror, is designed to be slightly smaller than \( W_2 \) to ensure that the inner gap between the flexures/mirror and the frame etched through first compared to the frame itself. Since electrical connection to the etching setup is made at the edge of the wafer, the complete etch of the gap \( W_1 \) cuts the electrical connection of the sample to the setup and automatically terminates the electrochemical etch process. It is important to note that while the etch process at \( W_1 \) and \( W_2 \) regions progresses with a larger etch rate, the mirror mass is thinned down due to the smaller etch rate of 50 \( \mu \)m wide openings. Small holes on the mirror mass are connected to each other during the etch due to undercuts as shown in figure 5(b).

### 3. Device operation

Two versions of micro-scanners are designed to exploit the capability of the present technology, as shown in figure 7. The device that is depicted in figure 7(a) has a uniform thickness of \( t \), consisting of two narrow beams, with a length of \( L_f \) and a width of \( W_f \), supporting a rectangular mirror mass with a size of \( W_m \times L_m \). The beams are clamped at both ends and tailored to have a mechanical torsion motion about the rotation axis at the fundamental resonance mode \( (f_R) \). The device shown in figure 7(b) has the same planar geometry as the device shown in figure 7(a), but both the starting substrate thickness and the local topography of the mirror are different.

Table 1 summarizes the dimensions of the devices as well as the finite element simulation results for the fundamental mode frequencies.

The scanner works on the principle that the mirror deflects according to Hooke’s law, when there is an electromagnetic actuation force acting on the device. The deflection of the mirror is increased substantially at the resonance frequency due to the high mechanical quality factor. If a light beam is shined on the reflecting mirror, a 1D scan line which is orthogonal to the torsion movement can be projected on a desired target.

The mechanical computations to design such a micro-scanner are reported in the literature [13, 14]. Following a similar design procedure, the dimensions of the device are determined for the targeted operation. The structural mechanics and frequency response behavior of the device are checked by finite element simulations as shown in figure 8, where the torsional rotation at 4380 Hz is observed. In the inset of figure 8, the mode shape of the device operating at 4380 Hz can be seen.

Increasing the resonance frequency of a 1D mirror is a major issue to attain a high number of resolvable pixels along the scan line. The resonance frequency of the torsional mode can be given as [13]

\[
f_R = \frac{1}{2\pi} \sqrt{\frac{K_\theta}{J_{\text{eff}}}},
\]

where the torsional stiffness of the device \( (K_\theta) \) and the effective moment of inertia \( J_{\text{eff}} \), which consists of mirror inertia \( (J_m) \) and flexure inertia \( (J_f) \) according to \( J_{\text{eff}} = J_m + \frac{3}{2} J_f \), play an
finite element simulations of the designed micro-scanner showing the mode shape (inset) and the resonance peak of the torsional movement (fundamental mode) that occurs at 4380 Hz.

Figure 9. Close-up view of the thinned micro-mirror.

important role [13]. The resonance frequency can be increased by either increasing the stiffness or reducing the effective moment of inertia. However, when stiffness is increased, the mechanical torque required to actuate the mirror also increases, leading to either higher power consumption or reduced scan angle. Therefore, it is preferred to reduce the mirror inertia to obtain a higher scan frequency as shown in figure 7(b).

The moment of inertia of a generic 1D micro-mirror seen in figure 7(a) is given as [14]

\[ J_{m,u} = \frac{M_m}{12} (W_b^2 + t^2). \]  

The moment of inertia of the thinned device can be computed as

\[ J_{m,t} = J_{m,u} - \frac{4}{3} M_{m,t} (W_b^2 + W_a^2 + W_b W_a), \]

where \( W_c \) is the width of the one of the thinned rectangular masses, \( W_a \) and \( W_b \) are the distances from the edges of the thinned region to the rotation axis of the scanner as depicted in figure 9 and having \( \rho \) as the density, \( M_{m,t} = \rho t (W_b - W_a)W_c \) is the excluded mass of one thinned region. Therefore, with the help of the proposed fabrication method, shaping the device in the third axis and eventually increasing its resonance frequency by changing its moment of inertia become possible. In order to increase the integrity of the mirror and to reduce the dynamic deformation, a cross-shaped rib and rims around the scanning mirror are used.

4. Experimental results

The proposed fabrication method is tested by implementing two steel micro-scanners: the device with a thinned mirror mass on a 200 \( \mu \)m thick steel starting substrate is processed by using the design explained above (device-2). In order to make a comparison, the same design is also fabricated without thinning the mirror mass on a 170 \( \mu \)m thick steel substrate (device-1). The electrode gap and the current density values of 3.25 cm and 3 A cm\(^{-2}\), respectively, are employed through electrochemical etching. Fabricated steel micro-scanners can be seen in figure 10.

The mirror mass of the scanner shown in figure 10(a) is thinned down by approximately 150 \( \mu \)m. As can be realized, a rim is deliberately formed around the mirror mass along with cross-ribs inside to minimize the dynamic mirror deformation.

The bulk fabrication material (stainless steel 301) is a soft magnetic material. Thus, electromagnetic actuation can be directly used to exert torque on the mirror. The scanners are actuated by a stationary off-chip coil that provides a frequency-dependent magnetic flux. The flux created by the coil produces a magnetic moment that acts against the spring force resulting in the deflection of the mirror. The devices are characterized using a laser Doppler vibrometer (Polytec OFV-534 sensor with OFV-5000 controller) by varying the frequency of the actuation signal [15]. The frequency responses of the fabricated devices are plotted in figure 11. The fundamental resonant mode of the unthinned steel mirror occurs at approximately 4210 Hz, which is very close to the finite element analysis result shown in figure 8. This device has a quality factor of 420 in the ambient air. The torsional resonance frequency of the thinned version of the same device experiences a shift to 6060 Hz, and it has a quality factor of 606. This indicates 43% of absolute frequency shift. However, to make a fair comparison, if we consider the thickness difference between these two devices and set both of them to have an equal starting substrate thickness, we acquire a normalized frequency shift of 15%.
Since the resonance frequency is inversely proportional to the square root of the moment of inertia, there is agreement between the theory and the experimental results shown in figure 11. Although the dynamics of the mechanical quality factor is heavily dependent on the damping and the vibration frequency, a first-order approximation, assuming a mass-spring-damper model, estimates an increase in the quality (Q) factor as the inertia is reduced for a fixed spring constant. Assuming a constant damping factor with respect to the frequency shift from 4210 Hz to 6060 Hz, experimental results show that the quality factor is increased by a factor of 1.45 for the thinned mass device. The ratio of the quality factors of device-1 and device-2 can be related to the ratio of the resonance frequencies.

5. Conclusion

An alternative, simple fabrication method which uses a single lithography step that is followed by electrochemical etching is presented in this paper. The proposed method enables patterning steel devices in the third axis and forms curved structures on the surface using the feature size-dependent etch rates. The process is carefully tested and characterized by actually producing different micro-scanners. The scanner fabricated using the proposed method has reasonable etch uniformity with an etch rate of approximately 39 \( \mu \text{m} \text{min}^{-1} \) for the HCl electrolyte and 41 \( \mu \text{m} \text{min}^{-1} \) for the NaCl electrolyte, both measured at the same electrode gap of 3 cm. The resonance frequency of the fundamental mode is increased approximately from 4210 Hz to 6060 Hz indicating a 43% of absolute frequency shift. Taking the thickness difference between device-1 and device-2 into account, both devices are set to have equal starting substrate thicknesses, and a normalized frequency shift of 15% is calculated from experimental data. Additionally, the proposed method is batch fabrication compatible unlike traditional steel process methods such as electric discharge machining (EDM) or steel micromilling. Such a fabrication process is especially useful for high-resolution one-dimensional and two-dimensional micro-mirrors, where a thinned mirror mass and a set of thinned slow-scan suspensions result in a high fast-scan frequency and a low slow-scan frequency, respectively.

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