Concave silicon micromirrors for stable hemispherical optical microcavities

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Abstract
A detailed study of the fabrication of silicon concave micromirrors for hemispherical microcavities is presented that includes fabrication yield, surface quality, surface roughness, cavity depth, radius of curvature, and the aspect ratio between the cavity depth and radius of curvature. Most importantly, it is shown that much larger cavity depths are possible than previously reported while achieving desirable aspect ratios and nanometer-level roughness. This should result in greater frequency stability and improved insensitivity to fabrication variations for the mode coupling optics. Spectral results for an assembled hemispherical microcavity are presented, demonstrating that high finesse and quality factor are achieved with these micromirrors, \( F = 1524 \) and \( Q = 3.78 \times 10^5 \), respectively.

OCIS codes
(140.3945) Microcavities; (220.4000) Microstructure fabrication; (350.3950) Micro-optics

1. Introduction
Fabry-Pérot hemispherical cavities composed of a microscale concave mirror and a flat mirror have been shown to have high sensitivity and low uncertainty for measuring cavity length changes, making them a good option for physical sensing [1–10]. These microcavities have been used in a number of precision measurement applications, including cavity quantum electrodynamics [3,4,8], quantum information [5], atom trapping [1], and displacement sensing for microcantilevers [8]. The hemispherical microcavities reported to date can generally be divided into two approaches. The first is to use an optical fiber with a concave end as one of the mirrors in the cavity, where the concave surface is typically laser micromachined [3,4,9,10]. The other mirror can be an optical fiber or any other type of mirror. The second approach is to microfabricate a concave micromirror in a flat substrate, such as silicon [1,2,5,7,8] or glass [6]. While both approaches have advantages, the latter is of particular interest for optomechanical sensors because the wafer-scale fabrication processes facilitate direct integration with microelectromechanical systems and nanophotonics. The optical cavities can then be combined with micromechanical structures, lasers, and photodetectors in a multi-chip package. Additionally, the optical cavity can be formed by bonding multiple silicon or glass chips together, thereby simplifying alignment of...
the two mirrors and improving the stability of the cavity since the two mirrors are directly connected. Due to these advantages, this paper focuses on optimizing concave silicon micromirrors for hemispherical cavities.

The biggest challenge in the development of microscale hemispherical cavities is the precise fabrication of concave mirrors with the required roughness, depth, and radius of curvature for stable and sensitive operation. Silicon concave micromirrors with adequate surface shape and quality have been fabricated by several groups [1,2,5,7,8] and have been used to demonstrate microscale hemispherical cavities with a finesse of up to 64,000 [5]. In this paper, we explore the optimization of the geometric parameters of concave micromirrors to achieve stable silicon hemispherical microcavities for sensing applications. First, the geometric requirements for a stable hemispherical microcavity are discussed in the next section. Based on these requirements, a set of fabrication experiments were developed to determine the process parameters for achieving specific cavity geometry, which are presented in Section 3. This is followed by a detailed analysis of the results of these fabrication experiments in Section 4, including micromirror yield, shape, roughness, depth, and radius of curvature. Finally, optical coupling into an assembled hemispherical microcavity with near-optimal geometry is demonstrated and the optical properties of the cavity are presented in Section 5.

2. Hemispherical microcavities

The hemispherical microcavity of interest in this paper is shown in Fig. 1(a). It is composed of a concave micromirror and a flat mirror that have been assembled together to form a solid structure, where both mirrors have high-reflectivity (HR) coatings and anti-reflection (AR) coatings are applied to the backside of the mirrors. A mode coupling lens is used to couple light into the cavity, which can be done from either side, and a photodetector is used to measure the transmitted light. Measurement in reflection is also possible with this cavity. By bonding the concave and flat mirrors together, the cavity can be very compact and highly stable since relative motion between the mirrors is nearly eliminated. This configuration is particularly advantageous for developing reference cavities and optomechanical sensors. With respect to the latter, if the flat mirror is replaced with a mechanical transducer such as a flexure mechanism, as shown in Fig. 1(b), the cavity can be used to measure a number of different physical stimuli along the optical axis. These include force, pressure, and acceleration, where the flexure mechanism would be designed for optimal sensitivity to the given stimulus. These applications in optomechanical sensing and reference cavities motivate the research presented here.

The critical geometric parameters of the cavity are the depth, \( L \), the radius of curvature at the bottom of the spherical mirror, \( R \), and the aspect ratio between \( L \) and \( R \), \( \alpha = L/R \). These parameters must be selected to maximize the performance and stability of the cavity for sensing length changes, as required for optomechanical sensors for example. For the design described here, the depth of the mirror determines the cavity length, so the terms mirror depth and cavity length will be used interchangeably, although they may differ slightly due to the mirror bonding technique used.
Looking at the previous research on hemispherical microcavities [1–10], a wide range of values for $\alpha$ has been achieved, including going well below 0.1 [5]. However, there has been little research on tuning $\alpha$ to a specific value, with the exception of a polishing method that uses an inductively coupled plasma etch to increase the radius of curvature of micromirrors after they are wet etched [7]. In terms of the cavity depth, the largest value of $L$ reported for a hemispherical microcavity is 50 μm [7]. Short cavities have largely been pursued previously due to interest in using hemispherical cavities for experiments in cavity quantum electrodynamics, where a small mode volume is desirable. However, a small mode volume does not provide any obvious benefits for reference cavities and optomechanical sensors so the geometric optimization of hemispherical microcavities requires further analysis for these applications.

The most important stability criterion for the hemispherical cavity is that $L$ must be smaller than $R$ ($L < R$ or $\alpha < 1$) for light to be confined within the cavity [11]. Assuming that $L < R$, the cavity geometry should be optimized to provide stable mode coupling and cavity length stability, as required for sensing and reference cavity applications. Light entering the cavity must be matched to the fundamental mode beam waist of the cavity for efficient coupling using a lens selected based on $R$ and $L$. Since $R$ and $L$ will vary across a wafer of micromirrors and between fabrication runs, it is desirable to select nominal $R$ and $L$ design values that will make mode coupling relatively insensitive to these fabrication variations. This insensitivity will allow a single set of input coupling optics to be used with a range of cavities, which is particularly important for sensors and reference cavities since they will be produced at large volume and individual tuning of coupling optics is not possible. The beam waists on the flat and concave mirrors, $w_f$ and $w_c$, respectively, for the light confined in the cavity are defined as:

$$w_f = (\lambda/\pi)^{1/2} L^{1/2} \left( \frac{1 - \alpha \lambda}{\alpha} \right)^{1/4} \quad (1)$$

$$w_c = (\lambda/\pi)^{1/2} L^{1/2} \left( \frac{1 - \alpha \lambda}{\alpha - \alpha^2} \right)^{1/4} \quad (2)$$

where $\lambda$ is the optical wavelength [2]. Using Eqs. (1) and (2), $w_f$ and $w_c$ are shown as a function of $L$ and $\alpha$ in Figs. 2(a) and 2(b), respectively. It can be shown that the gradients in these contour maps for $w_f$ and $w_c$ are least sensitive to changes in $\alpha$ when $\alpha = 0.625$ for $w_f$ and $\alpha = 0.5$ for $w_c$. Therefore, a semi-confocal geometry (i.e., $\alpha \approx 0.5$) is advantageous for mode coupling. Additionally, $w_f$ and $w_c$ become less sensitive to changes in $L$ as $L$ increases since $\partial w/\partial L$ decreases for increasing $L$.

Temperature variations result in cavity length changes that in turn change the optical resonance frequencies. This is problematic for reference cavities and when absolute cavity length is used for physical measurements, such as when measuring the acceleration of or pressure on one of the mirrors. External heat sources are typically addressed through
isolation or ovenization and will not be addressed here. The primary internal source of heat is the light in the cavity, where optical power densities can easily exceed 1 MW/cm$^2$ for moderate input power due to the high finesse typically sought in microcavity applications. The best way to mitigate the power density on the mirrors without negatively affecting the finesse is to design the cavity to maximize the beam waist on each mirror, thereby minimizing the power density for a given finesse. It can easily be shown that $w_f < w_c$ for $0 < \alpha < 1$, making $w_f$ the limiting beam waist in terms of heating. Based on Eq. (1) and Fig. 2(a), it is clear that $w_f$ is maximized by increasing $L$, which also means increasing $R$ if $\alpha$ is held constant near 0.5. In addition, the free spectral range (FSR), where FSR = $0.5c/L$, and the linewidth of the optical resonances will also be reduced by increasing $L$, thereby reducing the wavelength tuning range requirements for the laser used to interrogate the cavity. This is important for optomechanical sensors since they must be reasonably inexpensive and therefore, cannot rely on the widely-tunable external cavity diode lasers typically used for cavity optomechanics. In summary, using the largest achievable $L$ and $\alpha$ in the range of 0.5 and 0.625 provides optimal geometry that will achieve the best mode coupling insensitivity to fabrication variations while yielding a reasonable reduction in the power density on the mirrors, thereby mitigating stability issues related to laser heating. Regarding $L$, there is a clear limit on how much it can be increased since the focus is on microcavities and the substrate, a silicon wafer in this case, has a finite thickness. Therefore, the objective is to maximize $L$ as much as possible within those constraints.

3. Concave micromirror fabrication

Concave structures for microscale optics have been fabricated using several methods, including isotropic etching in a mixture of hydrofluoric, nitric, and acetic acids (HNA) [1,2,7,12–15], etching in fluorine gas [5], inductively coupled plasma etching using fluorine-based chemistry [8,16], a combination of irradiation and wet etching [17,18], laser ablation [3,4,9,10], and focused ion beam milling [6]. Among these methods, etching silicon features through apertures in a hard mask using HNA results in low surface roughness and can achieve high throughput, making it an excellent choice for wafer-level fabrication of hemispherical microcavities. As a result, this work investigates using HNA etching to achieve greater cavity depths and better tuning of $\alpha$.

The micromirror fabrication process is shown in Fig. 3. The micromirrors are fabricated on $<100>$ silicon wafers with a 350 nm thick layer of stoichiometric $\text{Si}_3\text{N}_4$ that has been deposited using low pressure chemical vapor deposition. An array of circular apertures is etched through the $\text{Si}_3\text{N}_4$ layer using conventional optical lithography and reactive ion etching. The wafer is then etched in a mixture of hydrofluoric acid, nitric acid, and acetic acid (HNA) with a ratio of H:N:A = 9:75:30 at room temperature, as previously used in [1]. The setup for wet etching is described in Fig. 3(b). The wafer is placed into the etchant with the patterned side down and is supported at multiple points along its edge. A magnetic stirrer bar is used to stir the HNA to minimize the formation of bubbles on the surface and to provide continuous flow of fresh acid to the etch sites. After the etch is complete, the wafer is rinsed, the $\text{Si}_3\text{N}_4$ layer is removed in hot phosphoric acid, and the wafer goes through a final RCA cleaning process.
In previous research, the aperture diameter has ranged from 1 μm to 100 μm. To explore the possibility of etching deeper micromirrors, the aperture diameter, $D$, ranged from 100 μm to 700 μm in this work. The etch time was varied between 1 hr and 4 hr. The mask layout has an even distribution of aperture diameters across the wafer to provide better statistical analysis. Figure 4 shows two typical silicon micromirrors etched with HNA, demonstrating smooth, spherical structures. The results of the etch studies are discussed in the next section.

4. Micromirror results

In this section, the micromirror fabrication yield, mirror shape and roughness, and achievable depth, radius of curvature, and aspect ratio are presented as a function of the aperture diameter.

4.1 Fabrication yield

After removal of the Si$_3$N$_4$ hard mask, the etched wafers were inspected with an optical microscope. The resulting micromirrors were classified into three groups: 1) defect-free (Fig. 5(a)), 2) acceptable with minor defects (Fig. 5(b)), and 3) unacceptable due to significant defects (Fig. 5(c)). For verification, an optical profilometer was used to measure the morphology of many of the silicon mirrors, as shown in the right-side column in Fig. 5. Groups 1 and 2 are considered acceptable for use in optical microcavities. Although Group 2 has some defects, these mirrors are generally defect-free at their center where the laser spot is positioned. Group 3 mirrors are randomly rough and without a well-defined shape, which cannot be corrected by further processing.

Optical inspection was used to determine the fabrication yield as a function of aperture diameter and etch time, where yield is defined as the percentage of mirrors in Groups 1 and 2. As shown in Fig. 6, the yield decreases linearly with increasing aperture diameter. The yield drops below 20% for diameters greater than 600 μm, making use of the larger apertures impractical for most applications. Interestingly, the yield does not appear to be affected by etch time, indicating that the mirror quality does not improve as they are etched. The results for the 450 μm aperture show greater variation than for other diameters because there were fewer samples for this diameter. The reduction in yield as $D$ increases is likely because the etch process through small apertures is controlled by diffusion of the reactants through the aperture (e.g., see [13]). One possible explanation is that as the aperture increases in diameter, forced convection of the reactants due to stirring has a larger effect, thereby increasing the etch rate and resulting in more defective mirrors.

4.2 Mirror shape and roughness

Mirror shape was measured using topographical images from an optical profilometer, such as those shown in Fig. 5. Surface quality is defined here as the peak-to-valley deviation of the residual after fitting the bottom of the mirror to a sphere. As an example, the difference between a spherical fit and the measured topography is shown for the primary axes in Fig. 7(a). The peak-to-valley deviation across a 45 μm diameter area at the bottom of the mirror, which is much larger than the beam waist for the optical cavity, was found to be less than 11.3 nm.
The measured surface roughness is the residual for a polynomial fit of the surface quality data, as shown in Fig. 7(b), and was found to be 0.7 nm RMS over the 45 μm area. The optical profilometer (Wyko NT1100, Veeco [19]) has a vertical resolution of 0.1 nm and a spatial resolution of 550 nm that is set by the diffraction limit. The roughness could be improved further by growing a thermal oxide on the wafer and removing it with hydrofluoric acid. Biedermann et al. [5] have shown that this process can reduce the roughness of concave silicon micromirrors from approximately 0.74 nm RMS to 0.22 nm RMS. This level of roughness is similar to that demonstrated for laser micromachined fiber cavities (e.g., see [3,4]). However, it was found that improving the roughness was unnecessary for achieving the finesse targeted in the research reported here. Several mirrors with different aperture diameters and etching times were measured with the optical profilometer, yielding surface quality and roughness results similar to that presented in Fig. 7.

4.3 Micromirror depth and radius of curvature

The depth, \( L \), and radius of curvature, \( R \), were measured using an optical profilometer for 100 μm ≤ \( D \) ≤ 550 μm and all etch times. Mirrors with larger \( D \) had low yield, making them unsuitable for this analysis. As expected, \( L \) increases with etch time (see Fig. 8(a)) and the maximum value is \( L = 350 \) μm for \( D = 550 \) μm and an etch time of 4 hr. This range for \( L \) is approximately seven times larger than previously reported for silicon hemispherical microcavities [1,2,5,7,8]. It was also found that \( L \) increases as \( D \) increases for a set etch time, where there is at least a 105% increase in \( L \) going from \( D = 100 \) μm to \( D = 550 \) μm.

As shown in Fig. 8(b), \( R \) increases with increasing \( D \), where the range of \( R \) is 135 μm ≤ \( R \) ≤ 840 μm. The etch time has a significantly smaller effect on \( R \) than the aperture diameter, \( D \). By combining the data for \( L \) and \( R \), the ratio \( \alpha \) is shown in Fig. 8(c). A shorter etch time results in a lower value of \( \alpha \) and \( L \) approaches \( R \) (and the limit of stable optical cavity geometry) as the etch time increases. The etch time required for \( L = R \) increases as \( D \) increases, although the condition of \( L = R \) was only observed for the smallest values of \( D \). Based on the data, it is clear that values of \( \alpha \) between 0.5 and 0.625 can be achieved for 200 μm < \( D \) < 550 μm. Larger apertures result in \( \alpha \) values in this range at longer etch times, making them more desirable since \( L \) will be larger and the linewidth, free spectral range, and optical power density will be lower. In summary, it is possible to achieve \( \alpha \approx 0.5 \) over a wide range of aperture diameters, \( L \) can be seven times larger than reported in previous work, and the optimal value of \( D \) is around 550 μm, although the yield will only be around 30%.

4.4 Stirring effect

A magnetic stirrer bar is used during the etch process of the micromirrors to promote a constant exchange of reactants, to release bubbles from the silicon surface, and provide uniform etching. The constant circular stirring has been found to have a clear effect on the symmetry of the mirrors, as shown in Fig. 9. The figure shows multiple mirrors from the same wafer after etching but before removal of the Si₃N₄ layer as imaged with an optical microscope. The center of each mirror has a bright spot due to the microscope illumination and it is clear that this spot is not at the center of the aperture for all of the mirrors except the one at the center of the wafer. The red arrows represent the vector between the aperture and mirror centers, showing that the shift in the mirror centers correlates with a vortex around
the center of the wafer, similar to the stirring motion. While the shift in the mirror centers is not problematic in this current work, improvements in the stirring that reduce the net directionality of the flow should be used when accurate mirror location is critical.

5. Microcavity results

A hemispherical microcavity was assembled using a concave silicon micromirror and a polished silicon flat mirror. Each mirror was coated on the back side with an anti-reflective coating and on the front side with a high reflectivity coating, where the coatings were deposited using a commercial ion beam sputtering process. The coatings were optimized for a nominal wavelength of 1550 nm and the high reflectivity coating is specified as 99.8% at this wavelength. The 1 cm² chips were bonded together using a thin layer (< 10 μm) of UV curable adhesive. The micromirror used in this experiment has a radius of curvature of \( R = 310 \mu m \) and a cavity depth of \( L = 196 \mu m \) based on optical profilometer measurements, resulting in \( \alpha = 0.63 \).

A fiber-coupled tunable diode laser with a center wavelength of 1575 nm and a tuning range of +/- 45 nm was used to interrogate the assembled microcavity. A custom aspheric coupling lens designed for efficient coupling to this specific cavity was attached to the fiber and the assembled cavity was aligned to the output beam to maximize coupling into the cavity. The transmitted light was monitored on the other side of the cavity using a photodetector. Optical resonances were measured as the wavelength was scanned over a full free spectral range (FSR) of the cavity, as shown in Fig. 10. Adjacent fundamental modes and higher modes are present with excellent contrast. The FSR was measured to be 779.456 GHz yielding a cavity depth of 192.3 μm \( (L = 0.5c/\text{FSR}) \). The 1.9% difference between the cavity length obtained from the optical profilometer and the FSR is likely due to the high reflectivity coating thickness and the phase shift on reflection introduced by this coating.

The fundamental mode at \( \lambda = 1547.97 \) nm was fit to a Lorentzian function and the finesse was found to be \( F = 1524 \), which is only 2.9% smaller than the calculated value for a reflectivity of 99.8%. The resulting quality factor \( (Q = 2FL/\lambda) \) is \( Q = 3.78 \times 10^5 \). The highest finesse reported for a concave silicon micromirror with a dielectric mirror coating is \( F = 64,000 \), where the uncoated mirror had a roughness of 0.22 nm [5]. It is plausible that the mirrors presented here can achieve a similar finesse if the roughness is improved using the oxidation process previously discussed. However, surface quality also plays a role in the achievable finesse, as shown by the analysis in [9,21]. Further modeling [9,21] and experiments with higher reflectivity coatings are required to determine the limits of finesse for the presented mirror geometries.

6. Conclusion

It has been shown that the fabrication of silicon concave micromirrors for hemispherical microcavities can be optimized to achieve a wide range of cavity depths, \( L \), and aspect ratios, \( \alpha \), by changing the masking aperture diameter and etch time. Specifically, values for \( L \) that are 7 times larger than previously reported for hemispherical microcavities have been achieved and the tuning of the process to attain \( \alpha \approx 0.5 \) with a single etch step has been
demonstrated. Larger $L$ and $\alpha \approx 0.5$ will result in cavities that are more stable due to reduced power densities from the laser on the two cavity mirrors and greater insensitivity to fabrication variations in terms of mode coupling. A hemispherical microcavity was assembled and its optical spectrum was characterized to assess its resonances. The cavity was shown to have a finesse, $F$, of 1524 and a quality factor, $Q$, of $3.78 \times 10^5$. These cavities will be useful in precision optomechanical sensors for physical measurements, including acceleration, force, and pressure, and have potential as reference cavities for laser stabilization. Additionally, they may be useful in extending the fabrication capabilities for microlenses [14,16,18] and other complex optical components such as microscale objectives [20]. Our current efforts are focused on pushing the limits of $F$ and $Q$ for the presented mirrors, and testing the frequency stability of the hemispherical microcavities as a function of environmental conditions.

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19. Certain commercial equipment, instruments, or materials are identified in this article in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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Fig. 1.
The hemispherical optical microcavity. (a) Cross-sectional diagram of the microcavity and optical readout method. (b) Cross-sectional diagram showing the application of the microcavity to optomechanical sensing.
Fig. 2.
Calculated cavity beam waists, $w_f$ and $w_c$, (a) and (b) respectively, as a function of cavity length, $L$, and aspect ratio, $\alpha$, for $\lambda = 1550$ nm.
Fig. 3.
Micromirror fabrication process. (a) Process steps, and (b) experimental setup for the HNA etch.
Fig. 4.
Scanning electron micrographs of two concave silicon micromirrors. (a) Top view, $D = 300$ μm, etch time = 2 h. (b) Cross-sectional view, $D = 200$ μm, etch time = 2 h, $\alpha = 0.73$. 
Fig. 5.
Optical characterization of the micromirror surface. (a) A defect-free mirror surface, (b) a mirror surface with minor defects, and (c) a rough mirror surface with significant defects. Images on the left were taken with an optical microscope focused on the bottom of the mirror and the topographical images on the right were taken with an optical profilometer.
Fig. 6.
Fabrication yield as a function of aperture diameter and etch time.
Fig. 7.
Surface quality and roughness of a silicon micromirror measured with an optical profilometer. (a) Surface quality with polynomial fit, (b) surface roughness.
Fig. 8.
Micromirror depth, radius of curvature, and aspect ratio. (a) Depth, $L$, as a function of $D$, (b) radius of curvature, $R$, as function of $D$, and (c) aspect ratio, $\alpha$, as a function of $D$ where the two dashed lines represent the optimal aspect ratios for the flat and concave mirrors, $\alpha = 0.625$ and $\alpha = 0.5$, respectively.
Fig. 9.
Optical microscope images of etched silicon mirrors before Si$_3$N$_4$ aperture removal. Each image is from a different location on the etched wafer. Red arrows are vectors from the mirror center to the aperture center, indicating flow dependent formation of the mirrors.
Fig. 10.
Optical resonances for one FSR of an assembled hemispherical microcavity, where two fundamental modes and multiple higher modes are shown. Inset: A single fundamental resonance and a fit to a Lorentzian function.