

## High reflectivity high- $Q$ micromechanical Bragg mirror

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The authors report on the fabrication and characterization of a micromechanical oscillator consisting only of a freestanding dielectric Bragg mirror with high optical reflectivity and high mechanical quality. The fabrication technique is a hybrid approach involving laser ablation and dry etching. The mirror has a reflectivity of 99.6%, a mass of 400 ng, and a mechanical quality factor  $Q$  of approximately  $10^4$ . Using this micromirror in a Fabry-Pérot cavity, a finesse of 500 has been achieved. This is an important step towards designing tunable high- $Q$  high-finesse cavities on chip. © 2006 American Institute of Physics. [DOI: 10.1063/1.2393000]

Micromechanical oscillators are today widely used in applications from thermal, infrared, and chemical to biological sensing.<sup>1</sup> This huge success is due to the fact that sensors based on microcantilevers can detect extremely small stimuli such as temperature and mass changes as well as small external forces.<sup>2</sup> Available devices can be placed in two categories based on their readout scheme. Microelectromechanical systems (MEMSs) use a wide array of electronic coupling schemes to transduce mechanical energy into electronic signals, while micro-optomechanical systems (MOMSs) are usually read out using an optic lever or a Fabry-Pérot interferometer. For MOMS, the sensitivity or coupling strength is mainly dependent on both the mechanical quality and the reflectivity of the cantilever. By increasing the mechanical quality factor and using ultrahigh reflectivity materials one can thus considerably increase the performance of such sensors. Ultimately, when all technical noise sources have been eliminated, quantum mechanics poses a limit in the sensitivity of such devices.<sup>3</sup> Although in today's sensor applications this quantum limit has not yet been reached,<sup>4</sup> a very close approach has been demonstrated.<sup>5,6</sup>

While the reflectivity of a bulk dielectric or semiconductor material is, in general, quite low (typically around 50%), reflectivities of up to 98% can be achieved by depositing a thin metallic layer on top of predefined structures. If higher reflectivities are needed one has to use Bragg mirrors which consist of a stack of thin layers of materials with different refractive indices. Such mirror materials are widely used and can reach reflectivities larger than 99.999% or, when used as mirrors in an optical cavity, a cavity finesse of  $>10^6$ . High

reflectivities have been achieved in MEMS tunable Fabry-Pérot étalons, however, with a very low mechanical quality  $Q$ , typically well below  $10^7$ . In this letter we report the fabrication and characterization of a high-quality mechanical beam oscillator consisting of a freestanding Bragg mirror with  $(99.6 \pm 0.1)\%$  reflectivity and of high mechanical quality  $Q \approx 10^4$ . In contrast to previous approaches, where the reflectivity of Si microstructures is increased by coating them in a postprocessing step, we directly fabricate the microstructure out of a large-scale Bragg mirror (see Fig. 1). This avoids the unwanted side effects that typically arise during the coating procedure, such as bending due to thermal mismatch.<sup>8</sup> The fabrication technique is based on pulsed-laser ablation of the coating, followed by dry etching of the substrate underneath. Laser ablation is an interesting technique complementary to standard microfabrication methods, since, unlike wet etching or reactive ion etching, it does not depend on the chemical reactivity of the material being patterned.<sup>9,10</sup> Furthermore, the good spatial selectivity achieved with short laser pulses allows the local removal of material while it preserves the coating quality on the oscillator.

The low selectivity on material at high laser fluences allows ablation of thick dielectric stacks of materials with different chemical properties. The good control of the ablation depth permits well-defined removal of the coating. To free the structure from the substrate, a very selective dry-etching method was employed. It undercuts the patterned coating but does not etch it in any measurable manner. Following the description of the fabrication method we present the experimental setup to characterize the optical and mechanical quality of the resulting structure. Subsequently we give a short summary and discussion of the obtained results.

The fabrication of the micromirrors starts from a standard polished silicon wafer on which 16 layers of  $\text{TiO}_2$  and  $\text{SiO}_2$  have been deposited to form a highly reflective (HR) Bragg mirror. This process, which has been optimized to

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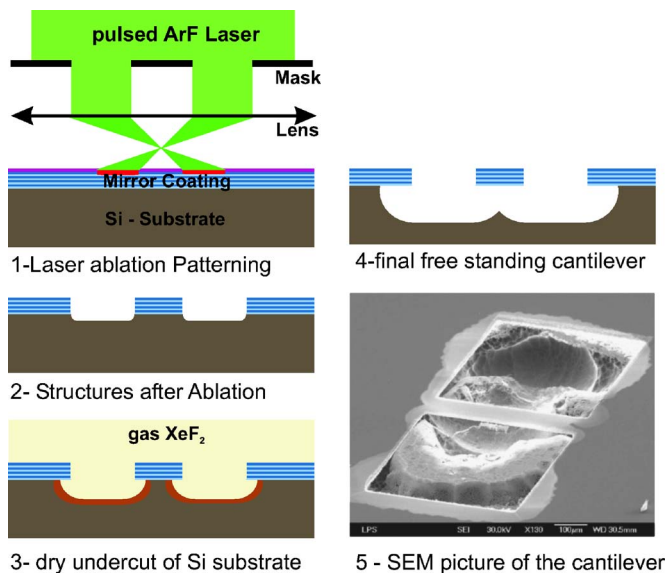


FIG. 1. (Color online) Steps of the fabrication process: (1) The Si substrate coated with a high reflectivity Bragg mirror is protected from debris of the ablation process with a thin layer of photoresist. Using a simple imaging system the light from a ArF laser ablates rectangular structures from the coating. The ablation is stopped as soon as the Si layer is reached. (2) The debris from ablation is removed together with the photoresist in a solvent bath. (3) Using  $\text{XeF}_2$  gas the silicon substrate is selectively etched, leading to an undercut of the beam. (4) The final structure consists only of a free-standing Bragg mirror. (5) The oscillator is the bridge in the center. It is about  $520 \mu\text{m}$  long,  $120 \mu\text{m}$  wide, and has a total thickness of about  $2.4 \mu\text{m}$ . The dark region of the surface corresponds to the region where the HR coating has not been undercut.

reduce tensile stress, was done by the coating company O.I.B.GmbH. The nominal reflectivity is 99.8% at a wavelength of 1064 nm.

Subsequently the coated wafer is patterned using laser ablation by projecting 193 nm ArF-laser radiation ( $1.3 \text{ J}/\text{cm}^2$ ,  $\tau_l=28 \text{ ns}$ , repetition rate of 1–10 pulses/s) via a mechanical mask (reduction optics 10:1). With the laser pulse length employed, the heat affected zone was about  $5 \mu\text{m}$ . This is in reasonable agreement with estimates of lateral heat diffusion in the silicon substrate.<sup>9</sup> To protect the mirror from debris generated during laser ablation, the surface is coated with a thin layer of a soft-baked photoresist (Shipley S1813). After ablation this layer is dissolved in an ultrasonic bath of acetone. By putting the sample in a  $\text{XeF}_2$  atmosphere the exposed Si substrate is etched rapidly<sup>11</sup> ( $1 \mu\text{m}/\text{min}$ ), isotropically, and very selectively in the ablated regions around and below the beam. The Si/SiO<sub>2</sub> selectivity of the etch is better than 1000:1,<sup>12</sup> and there is no measurable etch of TiO<sub>2</sub>, which is the top layer of the coating. The etching is optically monitored *in situ* and is stopped as soon as the beam is fully undercut. The final structure consists of a freestanding beam of approximately  $520 \mu\text{m}$  length and a width of  $120 \mu\text{m}$ , which is made only out of the original  $2.4 \mu\text{m}$  thick Bragg-mirror coating surrounded by a membrane of about half of its width. The total mass of the beam, as calculated from its dimensions, is about 400 ng. The uneven undercut of the structure depicted in Fig. 1 is most probably due to partial coverage of the silicon surface with other materials. Possible sources of contamination are incomplete ablation, redeposition of ablated material, or oxidation of the heated silicon surface in air, all of which can be avoided by ablating the coating in vacuum.

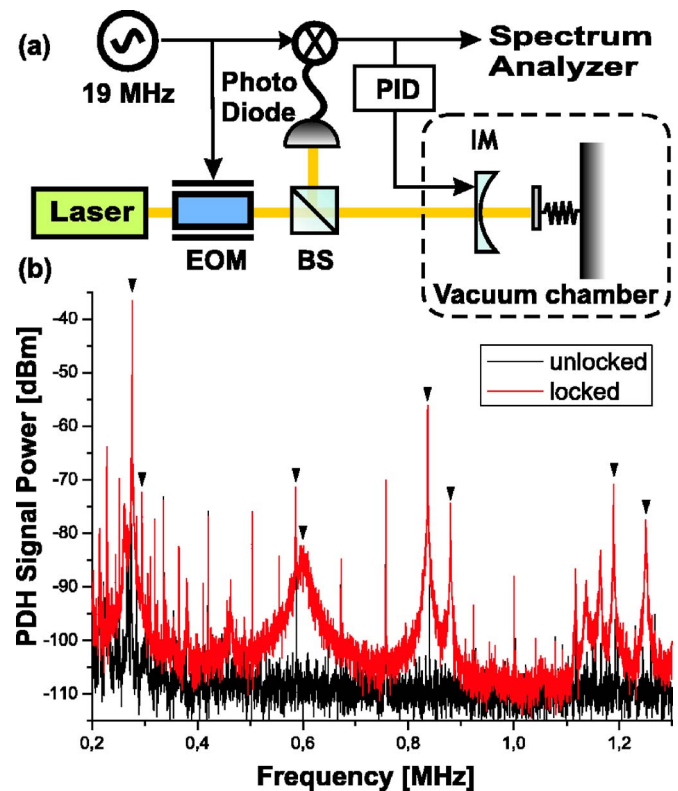


FIG. 2. (Color online) (a) Sketch of the measurement scheme. The laser is an ultrastable yttrium aluminium garnet laser which delivers up to 1 W continuous-wave laser light at 1064 nm with 1 kHz linewidth. The laser is phase modulated via an electro-optic modulator at 19 MHz. This frequency is chosen to be above the mechanical resonance frequencies, but within the cavity bandwidth. About 0.5 mW of this modulated light is used to pump the optical cavity. Using a Polarization beam splitter cube (PBS), we send part of the light reflected back from the cavity to a high-speed InGaAs photodiode. By mixing the photocurrent with the optical modulation frequency and subsequent low-pass filtering we derive the PDH (Ref. 13) error signal that is, to the first order, proportional to the cavity length. Feeding this signal to a PID controller that drives a piezoelectric actuator the length of the cavity is stabilized at resonance. Due to the limited bandwidth of the control loop, the cavity length is kept constant at acoustic frequencies, while above the cut-off frequency of the PID controller the vibrations of the beam are still present in the error signal. Therefore feeding the error signal to a spectrum analyzer allows us to monitor both cavity and mirror dynamics. (b) Frequency spectrum of the PDH signal when the cavity is locked (red) and not locked (black). The trace reflects the position rms noise of the cantilever. Markers indicate mechanical resonance peaks (see text). The noise floor corresponds to approximately  $10^{-16} \text{ m}/\sqrt{\text{Hz}}$ .

The micromirror was characterized via Fabry-Pérot interferometry. We built a linear Fabry-Pérot optical cavity with the beam as the highly reflecting end mirror on one side and a massive input coupler mirror on the other side (see Fig. 2). The input coupler is a concave mirror with radius of curvature  $R=25 \text{ mm}$  and a reflectivity of 99.4% for 1064 nm radiation. The cavity was slightly shorter than 25 mm. The chip containing the micromirror was placed on a three-axis translation stage for alignment and the optical beam was positioned on the oscillator. The size of the waist of the TEM<sub>00</sub> mode of the cavity is around  $20 \mu\text{m}$ , which is much smaller than the width of the beam. The input mirror is placed on a piezoelectric transducer (PZT) to scan the length of the cavity. The whole cavity is placed in a vacuum chamber with a pressure of  $p < 2 \times 10^{-5} \text{ mbar}$  to avoid damping of the oscillations of the beam due to air friction. All experiments were performed at room temperature.

For readout, the cavity is locked via the Pound-Drever-Hall (PDH) method.<sup>13</sup> The PDH locking signal is sent to a proportional-integrative-derivative (PID) controller, the output of which is sent to the PZT to control the fine length of the cavity at resonance (Fig. 2). It is known that the intensity of the PDH error signal around resonance is proportional to the change in length of the cavity. As a consequence, the vibrational noise of the beam can be monitored with high accuracy via the spectrum of the PDH error signal.<sup>14</sup> The optical quality is characterized by measuring the finesse  $F$  of the cavity, which is related to the round-trip intensity loss  $\gamma$  via  $F=2\pi/\gamma$  in the limit of a high-finesse cavity. We measured a finesse of 650 at nonundercut regions of the mirror and around 500 on the beam, corresponding to overall round-trip losses of 1% and 1.3%, respectively (this includes the 0.6% insertion losses on the input coupler). To determine the reflectivity of the coating, we built a cavity using a region of the coating that is spaced a few millimeters from the ablated structures. In this region we obtain a reflectivity of 99.6% (i.e., a minimal degradation from the nominal value). The additional losses of 0.3% on the beam can be explained both by diffraction losses and by imperfections introduced during laser ablation, in particular, near the edges of the beam.

The mechanical quality factor is obtained via the frequency spectrum of the PDH signal while the cavity is locked at resonance with the input laser frequency. Several mechanical resonance peaks can be detected within the range of 200 kHz to 5 MHz. Their frequencies match well with finite element simulations of transverse vibrational modes (i.e., oscillations occur normal to the surface) of a doubly clamped beam under tensile stress, specifically of a fundamental mode at 278 kHz and its harmonics. We observe an additional splitting of each transverse mode into two modes separated by a few kilohertz, which can be identified as modes with different torsional contributions.

A critical parameter for performing high-sensitivity measurements with movable micromirrors is their mechanical quality factor  $Q$ , which is a direct measure for the time scale of dissipation in an oscillating system.  $Q$  is defined as the ratio between the resonance frequency and the full width at half maximum (FWHM) corresponding to the resonance peak. It is a crucial parameter for sensors as it limits the sensitivity of all measurements. We isolated the lowest resonance at 278 kHz, which corresponds to the fundamental transverse mode of the beam. The measured  $Q$  factor of this mode was around 9000, with a FWHM of around 32 Hz. The  $Q$  factor of higher-order modes decreases monotonically to around 2000 for the fourth transverse mode at 1.2 MHz, which is indicative of the presence of clamping losses (see, for example, Ref. 2 and references therein). One should finally note that our method is not limited to the present parameter range but can in principle yield much higher reflectivity and  $Q$ . For example, the reflectivity can be increased by employing sophisticated state-of-the-art HR coatings as are typically used for gravitational wave detectors (yielding reflectivity of up to 99.9999%). Another possibility is to use silicon-on-insulator technology instead of plain silicon wa-

fers. The dry etch would then undercut only the device layer and stop on the buried oxide. This could lead to more kinetically controlled etching, i.e., to a better control of the membrane uniformity, and hence to a more controlled resonance frequency and higher  $Q$  factor.

In conclusion, we have demonstrated a promising method for the fabrication of micromechanical mirrors with high reflectivity, high mechanical quality, and low mass. Such a Bragg mirror is the lightest HR beam that one can design since the coating itself constitutes all the mass. We have characterized its mechanical and optical properties by using this micro-mirror in a Fabry-Pérot interferometer. The reflectivity of the mirror is in principle limited only by the intrinsic coating quality. The combination of high reflectivity, low mass, and high mechanical quality makes the fabricated micromechanical mirrors an excellent candidate for high-sensitivity measurements down to the quantum limit. In addition, such structures may provide the possibility to study genuine quantum effects involving mechanical systems.<sup>15-18</sup>

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