Optimization of the batch production of silicon fiber-top MEMS devices

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Abstract

We present a fabrication procedure for batch production of MEMS devices directly on top of an optical fiber. The procedure relies on the approach introduced earlier by our group (Gavan et al 2011 Opt. Lett. 36 2898–900), which has been optimized here to obtain higher yield and increased reliability. We describe in details the eight steps of the procedure and we show its application to the fabrication of several cantilever-based structures. Overall, we report a process yield of 80% functioning MEMS devices in our final batch.

Keywords: fiber-top MEMS, align-and-shine photolithography, reactive ion etching, silicon, sputter deposition, cantilever

(Some figures may appear in colour only in the online journal)

1. Introduction

Micro-electro-mechanical systems (MEMS) generally consist of miniaturized (electro)mechanical elements that are usually fabricated by growing and patterning alternate layers of sacrificial and structural materials on a flat surface. MEMS devices can vary from relatively simple structures, having no moving elements, to extremely complex electromechanical systems with multiple functional elements under the control of integrated microelectronics [1, 2]. The quality of MEMS has seen a remarkable development over the last decades, resulting in a wide variety of applications such as accelerators, gyroscopes, inkjet printers, pressure sensors and optical switches [3–5], to name a few. Functionalized MEMS devices further enable physical, chemical and bio-sensing, and can even be embedded into biomedical instrumentation [6–8].

For utilization in liquids and harsh environments, where electronics is prone to failure, the movement of the mechanical parts of a MEMS device has to be monitored optically. For this kind of applications, one may resort to the use of optical fiber interfaces, which adapt well to the development of all-optical remote sensing readouts [9]. For instance, MEMS devices can be produced with traditional semiconductor technology in flat wafers and then glued onto the end of an optical fiber [10, 11]. Alternatively, one can use the cleaved end of the optical fiber as the very same building block from which a MEMS device can be obtained [12–19]—an approach that has been dubbed fiber-top technology. Unfortunately, both approaches have considerable disadvantages, such as cumbersome manufacturing, high cost of production, and lack of versatility.

As a solution to this problem, a few years ago our group proposed to fabricate MEMS devices on the cleaved end of a fiber via a top-down process similar to that used in semiconductor technology [20, 21]. This approach does not require any gluing procedure, making the fabrication process simpler, more cost effective, and more reliable. Furthermore, it relies on a series of steps that, in principle, can be used to parallelize production. Due to a series of technical obstacles, however, the method was never tuned to a point where series, low cost production could be achieved.

To overcome this impasse, we have spent a dedicated engineering effort to develop and fine-tune all the equipment needed to optimize our top-down fabrication process. In this paper, we present the results of this effort, demonstrating that we can indeed fabricate fiber-top sensors via a parallel process with an 80% effective fabrication yield in our final batch.
Fabrication procedure

The direct fabrication of a MEMS device on top of an optical fiber consists of four major processes (sputter deposition, align-and-shine (AS) photolithography, reactive ion etching (RIE), and chemical wet etching) divided into the eight steps illustrated in figure 1 and discussed here below.

2.1 Step 1: fiber preparation

The MEMS device is built on the cleaved end of a standard single-mode optical fiber (SMF 28e+, Corning Inc). This fiber has a cladding diameter of 125 μm and a core diameter of 8 μm. The fiber is protected on the outside by a dual acrylate coating with a diameter of 250 μm to prevent fractures of the glass fiber. Before cleaving the fiber, this coating is stripped away such that only 3 mm of cladding is exposed after cleaving.

In our top-down fabrication method the cleaved end of the optical fiber is the substrate on which the consecutive layers are deposited. The quality of the cleave defines the growth conditions and surface morphology of the deposited layers and, ultimately, the quality of the MEMS device. To produce our devices in a reliable manner, it is thus imperative to start with a flat and well defined smooth surface morphology. Upon cleaving, hand-held cleaving machines, like those developed for the telecom industry, leave a fish-shell surface morphology behind (see figure 2(A)), which is not suitable for our purpose.

To obtain a flat and perpendicular end plane of the fiber, one must therefore rely on laboratory cleaving machines that offer a better control on the cleaving process (see figure 2(B)).

2.2. Step 2: layer deposition

2.2.1 Deposition equipment. The fiber-top MEMS devices fabricated in our facility are machined on a 1 μm thick structural silicon layer anchored on a 3 μm thick sacrificial gold layer. Both layers are deposited on the fibers by means of sputtering deposition.

Sputtering deposition can produce pure and uniform films even when the substrate is not heated up at high temperatures—a major advantage for our fabrication process, in which we aim to prevent damage to the dual acrylate coating of the fibers. Unfortunately, the rate of deposition that one can obtain with our method is notoriously low, forcing us to rely on long sputtering sessions. Long periods of sputtering, however, may lead to cross-contamination of the source materials. This can be prevented by mounting long tubular chimneys.
on the sputter sources. Ductile metals like gold form a thick, stable layer on the inside of the chimneys and, thus, enable use of the source for many (long) runs without any further maintenance on the machine. For the silicon source, however, the same solution is actually counterproductive. Due to the high intensity of the plasma and the high deposition rate inside the chimney, the compressive stress of the deposited layer of silicon in the chimney increases rapidly, leading to delamination of the silicon layer into a fine silicon powder. This powder becomes ionized in the sputter plasma and gets drawn into the gap between the grounding ring and the target material, causing electrical short-cuts that prematurely stop the deposition process. To limit cross-contamination and reduce the probability of source shortcuts, we have equipped the system with a series of shutters mounted in close proximity of the target material. Furthermore, the silicon source is unmounted and cleaned after every deposition.

Our machine is equipped with four sputter sources (A320 UHV, AJA Company), containing 2 inch diameter high purity targets of titanium, chromium, gold and silicon, mounted in a custom built ultra-high vacuum (UHV) system (Demaco Vacuum N.V.). The vacuum system is evacuated using a turbo molecular drag pump (TMU 450 UHV, Balzer), resulting in a base pressure of the UHV system of $2 \times 10^{-9}$ mbar after a 48 hrs bake out (100 °C). The four sputter sources are connected to an RF power supply of 300W (R301, Seren) in combination with a Seren MC automatic matching box and a DC power supply of 500W (MDX 500, advanced energy). We use an RF power supply (RFG-300-A, Yima Co.), electrically connected to the fiber holder, for plasma cleaning of the fibers. During deposition, argon gas of 6N purity is used as sputter gas. The flow of argon gas is controlled by a MKS flow controller type 247. A rest gas analyzer (LM502, Spectra Vacscan) is included to measure the quality of the rest gas in the system. A load-lock system (CF64, MKS) is connected to the deposition chamber to facilitate the introduction of the fibers. The load-lock system is pumped down to $2 \times 10^{-9}$ mbar (HiCube 80, Pfeiffer) before the fibers are introduced into the deposition chamber.

2.2.2. Titanium sublimation. Before introducing the fibers into the deposition system, the titanium source is run for 15 min using 150W RF power and a flow of 50ml min$^{-1}$ argon gas at $7 \times 10^{-3}$ mbar to cover the inside of the vacuum system with a 100nm titanium layer. This layer acts as a titanium sublimation pump that captures oxygen, hydrogen, and water of the rest gas, thus enabling the production of an oxygen- and hydrogen-free silicon film. The argon gas settings are the same for all the successive steps and depositions unless stated otherwise.

2.2.3. Plasma cleaning. Next, the fibers are introduced into the chamber via the load-lock system, where carbon hydrides and water on the fiber surface are removed by means of an RF plasma cleaning procedure (3 min, 30W). While mounted in the deposition machine, the back ends of the fibers are protected by a ceramic tube mounted on the holder.

2.2.4. Chromium adhesion layer. A 10nm chromium adhesion layer is deposited at 80W RF sputter source power, resulting in a deposition rate of 0.1 nm s$^{-1}$. To prevent contamination of the cleaved fiber surface the chromium deposition is started during the last 30s of the plasma cleaning. The total chromium deposition time is set to 100 s. This adhesion layer is of paramount importance since noble metals do not adhere well on glass.

2.2.5. Gold sacrificial layer. To facilitate a gradual transition towards gold deposition, the gold sputter source is started during the last 30s of the chromium deposition. In this way an intermixed layer between the chromium and the gold is created (of about 20nm) to further enhance the gold adhesion. After 30s of mixed deposition, the chromium source is turned off and a layer of 3 μm gold is deposited using 20W DC power and an effective deposition rate of 0.55 nm s$^{-1}$. The total gold deposition time is set to 91 min.

2.2.6. Silicon structural layer. After gold deposition, an intermixed layer of gold and silicon (of about 20nm) is created by simultaneous sputtering of gold and silicon for 30s, after which 1 μm silicon is produced using 150W RF power and an effective deposition rate of 0.19 nm s$^{-1}$ (figure 1(B)). The total silicon deposition time is set to 88 min.

2.3. Step 3: application of the photoresist

In our process, the silicon layer is patterned via a selective RIE etching step, which is preceded by a photolithography step that defines which parts of the layer have to be removed and which parts have to remain. The photolithography step is achieved via AS photolithography, which is described in [20, 21] and later in the text. To achieve good reproducibility in the fabrication process, it is important that the photoresist (PR) layer is uniform and flat. In our previous experiments.
Figure 4. Light microscope images of silicon wafers ((A)–(C)) and an optical fiber (D) after photoresist spray coating. (A) Open photoresist coverage after 1 spray cycle of the spray coater (layer thickness = 0.9 μm). (B) Closed coverage after two spray cycles (layer thickness = 1.6 μm). (C) Coverage after three spray cycles (layer thickness = 2.3 μm). (D) Spray coated photoresist applied on an optical fiber (with deposited layers) using two spray cycles.

[20, 21], this detail was somewhat neglected. In earlier AS photolithographic experiments, in fact, the PR layer was applied by dipping the fibers in a solution of PR and acetone [20]. This approach resulted in a highly curved PR layer that would be too thin at the edges to withstand the RIE etching step.

To avoid this problem and obtain a more evenly distributed PR layer on top of the fibers, we have thus decided to switch to a spray coating machine (Altaspray AS8, Suss Tec GmbH). The spray coating is based on micro gear pumps that, in combination with a nitrogen gas jet, are able to produce sub-micrometer PR droplets. For optimal coating, we use low-viscosity PR (AZ4999, Microchemicals GmbH), which is designed for micro-droplet formation [22], diluted with methyl ethyl ketone (MEK) as fast evaporating thinner, and 1-methoxy-2-propyl-acetate (PGMEA) as a slower evaporating solvent. During the flight between the spray nozzle and the substrate the MEK evaporates quickly, increasing the viscosity of the droplets to an intermediate value. When the PR has reached the substrate, the viscosity has increased to such an extent that flowing on the substrate is minimal. The diffusion of the PR on the sample surface is further reduced by maintaining a substrate temperature of 75°C during spray coating, resulting in further evaporation of the solvent and an increase of the PR viscosity. A viscosity which is too low causes macroscopic PR flowing, thereby reducing the coverage of the PR film on the rounded edge of the fiber [23].

A homogeneous PR film requires, nevertheless, flowing of the PR on the substrate for at least 1-2 μm, thus defining an upper limit for the resist viscosity or, in other words, a certain minimum for the remaining solvent concentration. We have performed several experiments with the Altaspray AS8 manual system to optimize PR film coverage and layer thickness. The standard process for spray coating on a 10 cm diameter substrate consists of four cycles of the nozzle in a zig-zag movement scanning over the whole substrate surface area. After each cycle the substrate is rotated 90°. Tests have been done on standard silicon wafers analyzing the PR coverage, thickness and morphology after each consecutive cycle using a profilometer (Dektak 8, Veeco).

Figure 4(A) shows the film produced after one spray cycle. Although the film thickness is found to be approximately 1 μm, the film shows open spots with a diameter of 20 μm. After two spray cycles a film thickness of 1.6 μm is obtained (figure 4(B)). This film is completely closed with the exception of a few minor irregularities. After applying three spray cycles a film thickness of 2.3 μm is realized and no open spots can be discerned (figure 4(C)).

To achieve the thinnest closed layer, PR is spray coated on the fibers in two spray cycles. To apply the PR on the optical fibers, the batch fiber holder (figure 3(C))—holding the cleaved fibers with deposited layers of gold and silicon— is mounted vertically on an aluminum disk of 10 cm diameter that served as a dummy wafer to run through the spray coating process as described above. The PR coverage on the fiber top, the sidewalls, and the rounded edge was found to be uniformly 1.5 μm thick and, therefore, sufficient to withstand the RIE process (figure 4(D)).

2.4. Step 4: align-and-shine photolithography

Upon completion of the PR prebake (95°C, 1 min), the fibers are serially patterned via our in-house developed AS photolithography technique (figure 1(D)) [20, 21]. The AS photolithography approach relies on standard contact-mask lithography, where, however, the mask is written on the facet of a multimode fiber (figure 5). The facet of the mask fiber is then brought to perfect contact with the facet of the PR coated fiber (the target fiber). Shining light from the other end of the mask fiber, one can then transfer the pattern to the PR layer. We refer the reader to our earlier work for further details [20, 21].

To align the two facets, the mask fiber is mounted on a manual stage (nanomax TS XYZ, Thorlabs GmbH), while the target fiber is mounted on a motorized platform (Nanomax 343/m XYZ, Thorlabs GmbH) with stepper motor controller (SSC103, Thorlabs GmbH) with a step resolution of 0.1 μm. Automated fine positioning of the target fiber is performed by a LabView program that, via a shape recognition algorithm, recognizes the position of both fibers and moves the target fiber into contact with the mask fiber. The input for the feedback on the controller is the image of two webcams, each in front of a 40 × microscope objective and operating in orthogonal directions. Illumination is achieved by low intensity red LEDs, which were found to have no influence on the quality of the lithographic process. After alignment, light (420nm, 30 μW) is coupled through the mask fiber for 5 s. During this step the fibers are processed one-by-one to guarantee a good alignment for each fiber.
2.5. Step 5: development of the photoresist

After exposure of the target fiber, the PR is developed in a standard TMHA developer for 1 min (figure 1(E)). No hard bake is applied to prevent deterioration of the pattern.

2.6. Step 6: reactive ion etching

RIE (figure 1(F)) has become the standard dry etching technique in MEMS production and is often used to remove materials that are laborious to etch chemically such as silicon, silicon nitride and silicon carbide [24–28]. Our RIE process is based on a two-step approach. First, an SF$_6$ plasma is created, enabling fluoride species to dissociate according to the following reaction: 

$$\text{SF}_6 + e^- \rightarrow \text{SF}_{6-x}^{-} + F^* \quad (3 \leq x \leq 6).$$

Afterwards, the dissociated fluoride can react chemically with silicon (Si + 4F* $\rightarrow$ SiF$_4$). The volatile product of this reaction is sputtered in a strongly anisotropic etch process [29, 30].

Since all the equipment in the semiconductor industry is designed for utilization in flat wafers, we implemented our own RIE chamber, in which we increased the distance between the two capacitor plates to 20 cm (figure 6(A)). Furthermore, we designed a customized RIE stub, taking into account the maximum permitted bending radius of SMF28 optical fibers (figures 6(B) and (C)). This RIE stub contains the batch fiber holder and can be transported into the main reaction chamber via a loadlock system. After transfer to the reaction chamber, the RIE stub is clamped onto the RF electrode by a horseshoe like clamp to insure good thermal contact with the water-cooled RF electrode.

The reaction chamber (custom built by Demaco vacuum systems) is pumped down to $1 \times 10^{-7}$ mbar by a Pfeiffer Hi Pace 300C molecular drag chemical resistant turbo molecular pump. To prevent degradation of the TM pump by the aggressive reaction products of the RIE process, the pump is purged with N$_2$ gas to dilute the reaction gas. The TM pump is backed by an oil free pre-vacuum pump (Adixen ACP 15G, Pfeiffer). During RIE processing the pump outlet gas of the reaction chamber is diluted with a high flow of compressed air and lead through a water container to capture hazardous byproducts of the RIE reaction such as HF. A pH indicator is added to the container to monitor the acidity of the water filter. The SF$_6$ gas is flow controlled (Model 5878, Brooks) and the pressure is maintained by an adaptive pressure controller (PM-3, VAT). An AJA 100/300 power supply of 300 W in combination with an AJA MC2 automatic matching box is used for the creation of the RIE plasma.

In order to optimize our RIE process, experiments have been conducted on flat silicon wafers glued to the surface of the RIE stub. Either silicon nitride, silicon oxide or silicon was deposited on the wafer to compare the etching rate of various structural layers. Standard photolithographic processing was used to pattern a grid of squares of 50 $\times$ 50 $\mu$m$^2$ in PR (maP1205, Micro Resist Technology GmbH) spun on the wavers. After RIE, the depth of the etched patterns was measured using an optical profiler (Wyko NT 9100, Veeco). The highest etching rates were obtained with 30 W RF power, 10 ml min$^{-1}$ SF$_6$ flow, and $5 \times 10^{-2}$ mbar SF$_6$ pressure. Table 1 lists the etching rates for the various structural materials using the optimal RIE settings. Clearly, our etching process is very favorable for selective removal of silicon.

Inside the batch fiber holder, the fibers are clamped around the acrylate coating and slightly protruded from the holder, resulting in very little thermal contact between the fiber tip and the holder. To prevent overheating of the PR during the RIE process, we rely on a pulsed RIE process instead of continuous processing. Optimal results were found using a duty
cycle of 30% (2 min of etching alternated with 5 min cooling), during which the RF power supply and the SF6 flow were switched on and shut off. In this way, the etching of a 1 μm silicon layer can be completed after 3 duty cycles, (i.e. a total etching time of 6 min). All silicon fiber-top MEMS devices described in this work were produced using the optimal settings described above.

2.7. Step 7: photoresist removal

After the RIE process, the PR is removed using a PR dissolving solution (REM400, Micro Resist Technology GmbH) (figure 1(G)). Nevertheless, in several cases we observed the presence of PR residues around the sharp edges of the silicon structure. Because this thin PR veil may obstruct the chemical etching of the sacrificial layer, we routinely perform an oxygen plasma etch in the RIE chamber after chemical PR removal to ensure no PR remains on the MEMS device (30 W RF power, 10 ml min−1 O2 flow, 5 × 10−2 mbar O2 pressure, 4 min).

2.8. Step 8: chemical etching

To free the MEMS from the substrate, one has to remove the sacrificial layer (figure 1(H)). This step is performed via chemical etching by immersing the fibers in a potassium iodide (KI) solution, where we add 0.3% molecular iodine (I2) to speed up the etching process. The etching of the 3 μm layer of gold is performed by stirring the fiber continuously in the etchant and is stopped as soon as the silicon structure is completely suspended (i.e. 4 min after immersion).

Although the chromium adhesive layer has a thickness of only 10 nm, it may severely hamper the performance of the MEMS device by disturbing the coupling efficiency between the fiber core and the paddle of the cantilever. The chromium layer acts as a mirror, reflecting incoming light away from the fiber core, as illustrated by the strong reflection in the central circle in figure 7(A). Therefore, to prevent attenuation of the optical signal by the chromium layer, an additional chemical etch is performed for 1 min (Chromium etchant, Sigma-Aldrich), after which there is no reflection from the area below the cantilever (figure 7(B)). Figure 7(C) demonstrates a scanning electron microscope (SEM) image of the suspended V-shape cantilever after all the processing steps.

3. Results and discussion

Four different suspended cantilever structures have been successfully fabricated out of silicon directly on top of an optical fiber in a batch process. We report an overall manufacturing yield of around 80% during the processing of the last batch of 18 fibers. The remaining 20% did not present a functional sensor, mostly due to contamination of the deposited layer when the fiber was positioned at the edge of the batch holder, or, due to mishandling during the manual processing steps (see table 2). Figure 8 reports an overview of the fabricated structures on top an optical fiber. The single arm cantilever is 20 μm long and 5 μm wide, matching very well the dimensions of the mask fiber. The suspended paddle has a diameter of 10 μm. From the SEM images the thickness of the cantilever is estimated to be around 1 μm, which corresponds well with the target value for the silicon layer during the sputter deposition.

To demonstrate that our MEMS devices are working according to design, we have coupled the other end of the fiber to a commercial interferometer (OP1550, Optics11) (for a description of the readout method, see [12]). Figure 9 shows the interferometric output signal of the cantilever structure upon contact with a sharp tip, periodically driven by a piezoelectric translator. One can observe that, when in contact, the interferometric signal follows the movement of the piezoelectric translator. The optical signal can thus be used as a direct readout for cantilever displacement.

The optical signal may be distorted by deviations in the alignment of the pattern during the AS procedure, in particular when the applied photoresist is not evenly distributed over the circumference of the target fiber. In our experiments we have experienced a maximum deviation of around 2 μm. All cantilever designs are equipped with a central circular paddle of 10 μm diameter for the reflection of the light coming from the core of the fiber. Since the core of the single-mode fiber is 8 μm in diameter and the light bundle is divergent, we never experienced any problems in the optical readout of our devices.

In figure 10 we report a characterization of the spring constant of our MEMS devices. Force and displacement data of the sensors have been obtained by pushing the paddle of the MEMS devices against a macroscopic cantilever, which has been calibrated according to a protocol developed by our group [31]. To ensure that the contact is made at the center of the paddle, a 10 μm borosilicate sphere is glued onto the paddle. Force data is recorded for bending of the MEMS cantilever from 10–1500 nm. The average spring constant of the single cantilever arm, recorded on two sensors, was 40 N m−1 and was independent on cantilever bending. This value is consistent with simulations performed for the single arm cantilever and indicates that the silicon layer was slightly thicker than 1 μm (figure 10(A)). The spring constants of the more complex MEMS devices are found to be dependent on the bending of the lever as illustrated in figures 10(C) and (D). For the first 200 nm of bending the force resistance of the flexible element was high. Afterwards, when the lever is pushed further, the force resistance decreased and the spring constant leveled off to a constant value for larger displacements. Therefore, we estimate the spring constants of the V-shape and the cross structure at 90 N m−1 and 510 N m−1, respectively. One can observe that the spring constant for the V-shape structure approximates double the value for the single arm cantilever, indicating that our devices are fabricated according to design.

Table 1. Effective RIE rates of various structural layers and standard photoresist. Values are obtained after 10 min of etching using the optimal settings for the RIE parameters.

| Material    | Etch depth (nm) | Etch rate (nm s−1) |
|-------------|----------------|--------------------|
| Silicon     | 4000           | 6.7                |
| Silicon oxide| 160            | 0.27               |
| Silicon nitride | 100          | 0.17               |
| PR (maP1205)| 200            | 0.33               |
4. Note on residual stress

Residual stress in thin films is a major concern for the operation and reliability of MEMS, especially in the fabrication of suspended membranes. Residual stress can be compressive, which makes the film expand parallel to the surface, or tensile, causing the film to shrink. A compressive membrane may buckle, whereas a tensile membrane can break in the presence of pressure or high temperature gradients. During our initial fabrication process our MEMS sensors demonstrated a high amount of compressive stress, most evident in the cross structure, as illustrated in figure 11. The silicon layer was, in this batch, 0.3 μm thick. When the chemical etch process was stopped before the central paddle was completely separated, the legs of the cross appeared to be highly bent (figure 11(A)). The legs, however, did not break, demonstrating the high flexibility of the silicon. After the completion of the etch process one can observe a high amount of buckling in the structure (figure 11(B)).

In order to reduce the amount of stress in our silicon films we have optimized our deposition process. Because our deposition rate, argon flow and argon pressure were already within...
reasonable boundaries, we have mainly focused on optimizing the substrate temperature during deposition. Since silicon has a melting temperature of 1961 K, a room temperature deposition results in a homologous temperature \( T/T_{\text{melting}} \) of 0.15. Films deposited at homologous temperatures between 0.1 and 0.5 are typically in the transition zone of the Thornton zone diagram for sputtered films [25]. Films in this zone can have either tensile or compressive stresses depending on the remaining deposition parameters [32]. Other reports, however, suggest a temperature of 250 °C to be the transition temperature from tensile to compressive stress in sputter deposited silicon films [33]. Each deposition system has its own peculiarities so definitive parameters can only be obtained experimentally. Moreover, as previously discussed, there is a poor thermal contact between the fibers and the batch holder, so the effective temperature of the fiber tip is not known.

During the layer deposition, heat is generated by the sputter source. Initially, the fiber holder was placed in close proximity (15 cm) from the sputter target to obtain the high deposition rate necessary to produce a thick film. A thermocouple, connected to the fiber holder, indicated an increase of 20 °C above room temperature during silicon sputtering. However, at this distance the top of the plasma was just hitting the tips of the fibers. The impact of highly energetic argon and silicon ions from the plasma onto the substrates increases the surface mobility of the atoms on the substrate, leading to a higher effective substrate temperature during film growth. As a second heat source we applied RF plasma heating around the batch holder. Using 30 W RF power the temperature of the fiber holder increased to 150 °C. Combined with the additional heat input of the plasma sputter source and the increased surface mobility on the substrate during deposition, we estimate the effective substrate temperature to be around 250 °C.

In several experiments we stepwise decreased the RF power of the plasma heating and increased the distance between the target and the fiber holder, thus reducing the heat input and the added surface mobility. Consequently, increasing the distance to the substrate reduced the deposition rate. The best layer quality was achieved at a substrate distance of 30 cm with discontinuation of the plasma heating. At this distance the deposited silicon layer may still be subjected to a minor amount of stress. Therefore, we increased the thickness of the silicon layer to 1.0 μm, as suggested in [25]. Although not evidently visible in the SEM images (figure 8), the minimal residual stress in the layer is revealed by the behavior of the
spring constant of the sensors. From these results we estimate the buckling of the sensors to be around 600 nm.

5. Conclusions

We have demonstrated that, using our AS process coupled to sputter deposition, PR spraycoating, RIE, and chemical etching, all optimized towards optical fiber processing, we are able to reliably produce silicon MEMS devices directly on top of an optical fiber via a batch process. Four different MEMS devices have been realized on the top of a standard optical fiber based on a suspended cantilever supporting a round paddle above the fiber core. We tested the performance of the fabricated devices by mechanically actuating the silicon cantilever while looking with an interferometric readout at the displacement thereby induced. Furthermore, we characterized the spring constant of the various cantilever structures by pressing against a pre-calibrated cantilever. The process yield during the processing of the last batch consisting of 18 fibers was around 80%, making our technique feasible for series production of multifunctional fiber-top MEMS devices. The yield may be improved by further optimization of the deposition process and the photoresist application and removal. The throughput time may be reduced by automating the AS photolithography process and the wet etching steps further. We believe that our work paves the way for a large variety of remote sensing applications that make use of MEMS based devices fabricated directly on top of an optical fiber.

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Competing interests

DI is co-founder of Optics11. DI and MS are shareholders of Optics11.

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