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REVIEW ARTICLE

Silicon waveguide cantilever displacement sensor for potential application for on-chip high speed AFM

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Abstract This paper reviews an initial achievement of our group toward the development of on-chip parallel high-speed atomic force microscopy (HS-AFM). A novel AFM approach based on silicon waveguide cantilever displacement sensor is proposed. The displacement sensing approach uniquely allows the use of nano-scale wide cantilever that has a high resonance frequency and low spring constant desired for on-chip parallel HS-AFM. The approach consists of low loss silicon waveguide with nano-gap, highly efficient misalignment tolerant coupler, novel high aspect ratio (HAR) sharp nano-tips that can be integrated with nano-scale wide cantilevers and electrostatically driven nano-cantilever actuators. The simulation results show that the displacement sensor with optical power responsivity of 0.31%/nm and AFM cantilever with resonance frequency of 5.4 MHz and spring constant of 0.21 N/m are achievable with the proposed approach. The developed silicon waveguide fabrication method enables silicon waveguide with 6 and 7.5 dB/cm transmission loss for TE and TM modes, respectively, and formation of 13 nm wide nano-gaps between silicon waveguides. The coupler demonstrates misalignment tolerance of ±1.8 μm for 5 μm spot size lensed fiber and coupling loss of 2.12 dB/facet for standard cleaved single mode fiber without compromising other performance. The nano-tips with apex radius as small as 2.5 nm and aspect ratio of more than 50 has been enabled by the development of novel HAR nano-tip fabrication technique. Integration of the HAR tips onto an array of 460 nm wide cantilever beam has also been demonstrated.

Keywords atomic force microscopy (AFM), silicon waveguide, silicon coupler, high aspect ratio (HAR) nano-tips

1 Introduction

Atomic force microscopy (AFM) was invented in 1986 [1] for 3D atomic scale visualization of hard surface morphologies. Although this incredibly useful scientific tool enables manipulation, investigation, and interrogation at atomic scale, its application in many areas of science and technology is limited due to its slow operational speed. As a result, enhancing the operational speed of AFM has been a subject of research and led to the emergence of high speed atomic force microscopy (HS-AFM) for its significance in fields of life science [2], nano-manufacturing [3] and data storage [4]. Despite some successes, HS-AFMs are still limited in terms of scan speed and size, and such limitations have become the bottleneck in enabling further breakthroughs and scientific discoveries in many areas of science and technology.

In the current HS-AFM configurations, small cantilever plays a critical role in improving AFM speed of operation. The smaller the cantilever on which the tip is formed, the higher the resonance frequency becomes, thereby allowing faster response time and thus wider feedback bandwidth that ultimately determines the maximum possible imaging rate [5]. The current size of the cantilever is, however, limited by the optical beam dimension required for the optical beam deflection (OBD) detection system. OBD detection system does not allow the use of small cantilevers because of the significant diffraction of laser beam from the cantilevers [6]. In addition to being an impediment to cantilever size, OBD system is not amenable to parallel AFM implementation [7]. Implementation of parallel AFM requires deflection detection of each cantilever individually, but it is hard to detect multiple deflections simultaneously from the OBD readout due to a presence of significant cross-talk. Piezo-resistive sensors are another alternative method used for measuring cantilever deflection, and they have been integrated with individual cantilevers for parallel imaging [8]. Better noise performance of piezo-resistive detector compared with

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OBD readout is achievable when the size of piezo-resistive detector reduces [9]. However, the cantilever size is still significantly larger than the minimum cantilever size used with OBD system. Other deflection measurement methods such as piezoelectric detection [10], capacitive detection [11] and interferometer detection [12] have also been reported. The drawback of these deflection measurement methods is that the detection limit scales down with size and achieving good noise performance and resolution at nano-scale will be difficult. Therefore, new generation of deflection measurement methods that allow scaling down in size without significant compromise to noise performance and resolution and amenable to parallel implementation are desperately required to push HS-AFM research into the next generation.

We have proposed a novel AFM system based on silicon waveguide cantilever displacement sensor. The approach of the displacement sensing uniquely allows the use of nano-scale wide cantilever with high resonance frequency and low spring constant desired for on-chip HS-AFM. It also allows self-sensing and actuation integral for parallel AFM implementation.

2 High speed AFM design

The schematic of the proposed AFM system consisting of inverse taper couplers, silicon waveguide cantilever with tip, silicon waveguide cantilever displacement sensor, and electrostatic actuator is illustrated in Figs. 1(a) and 1(b). The sensor consists of input and output silicon waveguide cantilevers facing each other and separated by a nano-gap. It detects displacement of input silicon waveguide from intensity modulation of optical power received at the output silicon waveguide. In addition to playing displacement sensing role, the input silicon waveguide cantilever also acts as an AFM cantilever with a nano-tip integrated to it and an electrostatically driven actuator.

The silicon waveguide cantilever displacement sensor has been studied to maximize responsivity and satisfy the requirements of high resonance frequency and low spring constant using optical finite-difference time-domain (FDTD) and COMSOL simulation, respectively. From the simulation results, the optimal cantilever thickness of 180 nm with smaller gap provides maximum responsivity. Considering fabrication limitations, silicon waveguide cantilevers with 200 nm thick, 500 nm wide, 9.5 μm long and having 20 nm gap have been chosen. The results show the responsivity of 0.31%/nm for the sensor, resonance frequency of 3 MHz and spring constant of 0.2 N/m are achievable with the proposed system. The analysis also shows that the silicon cantilever displacement sensor yields a better noise performance than the typical OBD measurement technique with such responsivity. Furthermore, the resonance frequency can be increased to 5.4 MHz with the same spring constant by decreasing the cantilever thickness to 120 nm, which slightly compromise the sensor responsivity. It should be noted that this resonance frequency is much higher than the existing AFM cantilevers with such small spring constant.

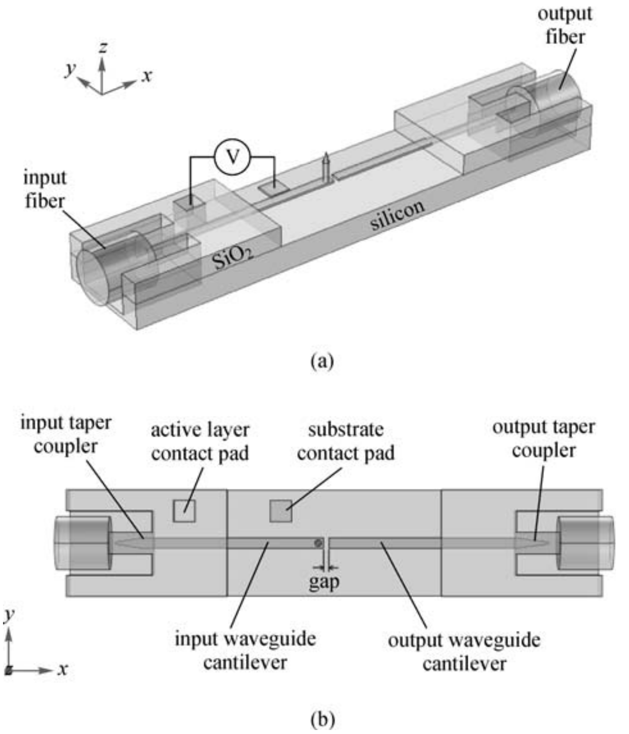


Fig. 1 Schematic diagram of the optical sensor system. (a) 3D view; (b) top view

3 Fabrication of silicon waveguide with nano-gap

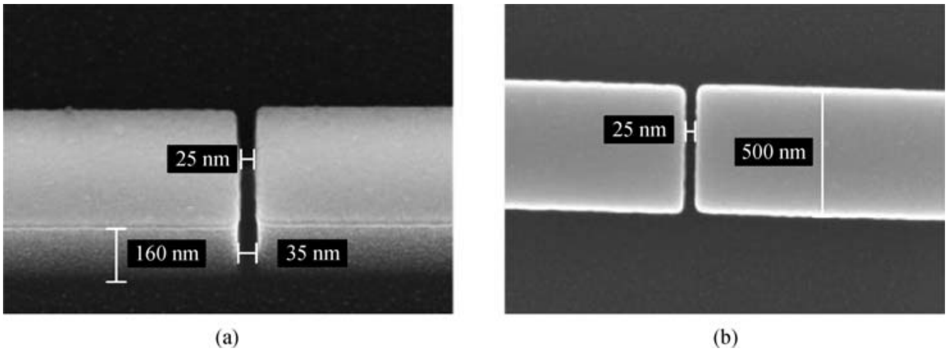
The silicon waveguide is one of the key elements of the proposed AFM system. In addition to guiding and transmitting light, it also plays the role of deflection sensor and AFM cantilever in the system. Hence, its successful fabrication and further integration into the system is critical for the development of the proposed AFM system.

Silicon waveguides are often fabricated on silicon-on-insulator (SOI) substrate, which has become an attractive photonic integrated circuit platform due to the excellent optical waveguide properties of device layer of silicon, significant device scaling enabled by large refractive index of silicon and its complementary metal oxide semiconductor (CMOS) fabrication process compatibility. Although SOI substrates are available for silicon waveguide fabrication, fabricating a sub-micron wide silicon waveguide with low transmission loss has been a challenge as the loss is significantly affected by scattering loss due roughness. Low-loss silicon waveguides have been reported with transmission loss less than 1 dB/cm [13–15]. To achieve such low loss, most of waveguides are fabricated using wet etch [16] or etchless processes [17] to avoid damages arising from dry etching process. Other waveguide fabrications using dry etch have employed sidewall smoothing process such as long oxidation [18].

The realization of the proposed displacement sensor requires the fabrication of low-loss nano-scale silicon waveguides with nano-gaps, in order of 20 nm, in a repeatable and reliable manner. We developed a fabrication process for sub-micron wide silicon waveguides with small line edge roughness, and smooth and vertical sidewall while allowing incorporation of nano-gaps [19]. The waveguides and nano-gaps are first patterned on PMMA using electron-beam lithography (Raith-two). Chromium film of 15 nm thickness is then evaporated and lifted off to define the Cr mask for inductively coupled plasma-reactive ion etching (ICP-RIE) on SOI wafer. Finally, the active layer is etched in ICP-RIE with the Cr mask followed by the Cr etching to remove the Cr on the waveguide. The waveguide propagation loss is very sensitive to roughness for sub-micron waveguides. To reduce propagation loss, the waveguides are subjected to dry thermal oxidation at 950°C for 20 nm SiO_2, which reduces root mean square (RMS) roughness due to line-edge and sidewall to 2.1 nm and maintains vertical sidewalls. The scanning electron microscope (SEM) image of the waveguide with a 25 nm gap is shown in Fig. 2. A minimum gap of 13 nm is achievable using the developed fabrication process. The developed fabrication method enables silicon waveguides with 6 and 7.5 dB/cm transmission loss for TE and TM modes, respectively.

4 Low loss and misalignment tolerant inverse taper coupler

As the silicon waveguide dimension reduces, launching light into a sub-micron silicon waveguide from a standard single-mode fiber with minimal coupling loss becomes challenging. That is because the traditional butt-coupling approach introduces a significant coupling loss due to large mode field diameter mismatch between the silicon waveguide and standard single-mode fiber. Grating and inverse taper couplers are the main approaches that have been employed to improve the coupling efficiency between a silicon waveguide and a single-mode optical fiber. Grating couplers exhibit a narrow bandwidth when designed for high coupling efficiency and their fabrication process is relatively complex [20,21]. Both low coupling efficiency and narrow bandwidth increase the cantilever deflection sensor noise resulting in decrease in sensitivity. In contrast, inverse taper couplers have been demonstrated with wider bandwidth and higher coupling efficiency [22,23]. Inverse taper couplers provide a large mode field by tapering the dimension of waveguides, and lensed fiber is usually needed to further reduce the mode field dimension mismatch. However, taper couplers are prone to fiber-to-coupler misalignment that results in substantial loss, especially when beams with small spot size are used. Previously reported approaches of using large input spot size with low coupling loss and large misalignment



(a) (b)

Fig. 2 500 nm silicon waveguide with 25 nm air gap. (a) 45° view; (b) top view tolerance require a relatively complicated design and fabrication process [24,25]. Hence, low-loss misalignment tolerant optical coupler without requiring complicated fabrication process is critical for the realization of the proposed AFM system to facilitate coupling of light from optical fiber to sub-micron waveguide. To this end and as a requirement to the proposed AFM approach, we designed, fabricated and tested a cantilever inverse taper coupler consisting of a 100 μm long cantilever waveguide, an inverse linear taper silicon waveguide (SiW) embedded in the middle of the SiO_2 waveguide and a SiO_2 gap between the SiO_2 waveguide facet and the taper end as shown in Fig. 3 [26]. The waveguide is terminated by the inverse linear taper structure from the initial width of 500 to 80 nm in a length of 100 μm. The SiO_2 gap represents the portion of the SiO_2 cantilever waveguide between the taper end and SiO_2 waveguide facet. The SiO_2 waveguide has identical width and height of either 6 μm or 8 μm depending on the design for input spot sizes of 5 μm or 10.5 μm, respectively. By introducing a 10 μm SiO_2 gap in front of taper waveguide, the 6 μm × 6 μm coupler effectively increases the 3 dB misalignment tolerance to ±1.8 μm with coupling loss of less than 0.49 dB/facet for 5 μm spot size lensed fiber in both TE and TM modes. Introduction of the 15 μm SiO_2 gap with 8 μm wide coupler improves TM mode coupling loss from 4.05 to 2.12 dB/facet while maintaining large misalignment tolerance for input spot size of 10.5 μm. The proposed couplers are superior in comparison to other reported couplers in that they improve misalignment tolerance or coupling loss without significantly compromising the other, requiring complicated design and fabrication process.

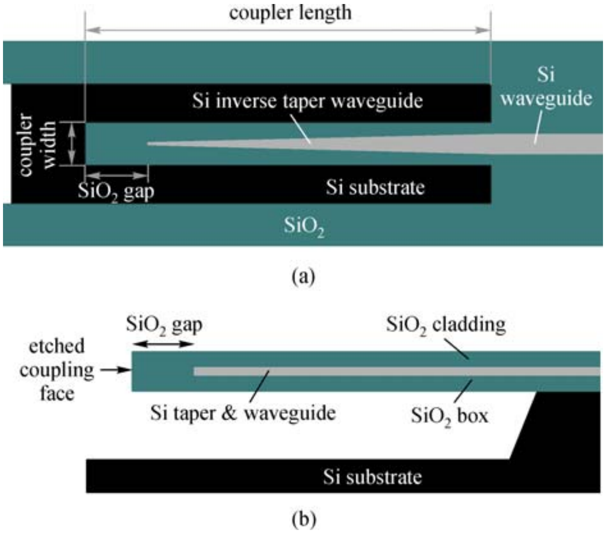


Fig. 3 (a) Coupler schematic top view; (b) coupler schematic side view

5 High aspect ratio AFM nano-tip

In AFM, tip sharpness and aspect ratio play a critical role in improving scanning capability and resolution. For enhancing scan speed and size, having an array of small cantilever probe tips for parallel imaging is desired. However, fabricating HAR ultra-sharp tips on an array of small cantilevers with high yield and density has been a real challenge. To add to this challenge, a low thermal budget fabrication path way is required for integrating AFM structures in a post-CMOS process approach as it is indispensable for enhancing system performance, miniaturization and cost reduction.

Silicon tips are typical in most AFM applications because of high throughput and small tip radius enabled by the silicon micro-fabrication techniques. However, formation of silicon tips with HAR for small AFM cantilevers is not only difficult but also becomes more challenging when post-CMOS integration [27–29] is desired. Electron beam induced deposition (EBID) is the common technique used to form HAR tips on small cantilevers [30,31], but its low throughput leads to high cost and the difficulty of batch processing. Another method to form HAR tip on small cantilevers is based on growing nanowires, such as silicon nanowires and carbon nanotubes [32,33], but its low repeatability in growing single tip on a cantilever make this approach not feasible for practical consideration [32]. The requirement of high temperature processing makes such approach incompatible with post-CMOS integration. Spindt nanotips, used typically in field emission applications [34–36], may be appropriate for low temperature processing. However, these traditional Spindt tips are micro-size and exceedingly difficult to form ultra-sharp Spindt tips with a HAR. To overcome the existing limitations, we developed a novel low temperature nanofabrication approach that enables the formation of ultra-sharp HAR and high density nanotip structures and their integration onto nanoscale cantilever beams [37].

The nanotip structure consists of a nanoscale thermally evaporated Cr Spindt tip on top of an amorphous silicon rod. To form the Cr Spindt tips, an array of poly-methyl methacrylate (PMMA) openings are patterned by electron beam lithography (EBL). The Cr is then thermally evaporated on PMMA film until the openings are completely closed with the cone shaped tips inside cavities. After lifting off the Cr film in NMP (N-methyl-2-pyrrolidone), array of Cr tips is uncovered on the silicon substrate. The results show that slower evaporation rate and lower aspect ratio of the PMMA opening providea sharper tips. An apex radius of the tip, as small as 2.5 nm, has been achieved, and is significantly smaller than any other Spindt tips reported so far. To achieve HAR tips, the Cr Spindt tips are used as a self-aligned mask on an amorphous silicon film to form HAR sharp tips using

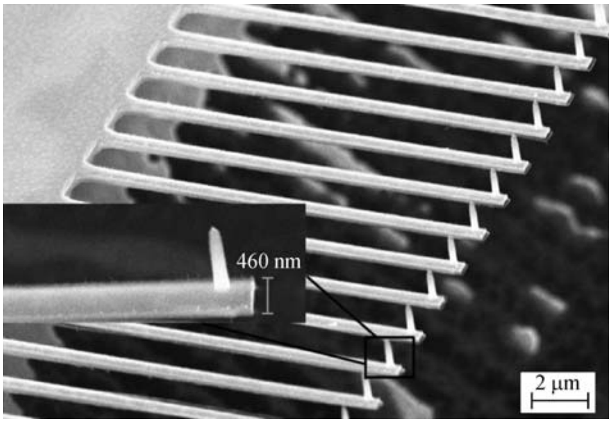


Fig. 4 SEM image of array of HAR nanotips integrated with array of nanocantilever viewed at 45°

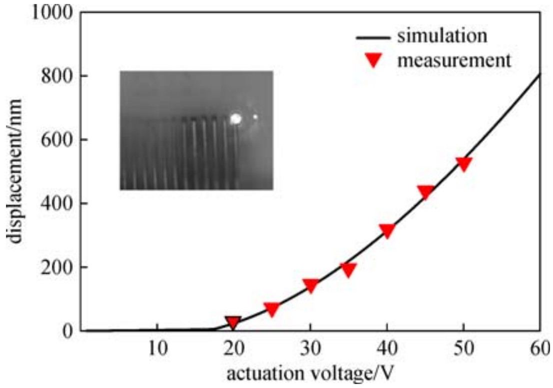


Fig. 5 Measured and simulated cantilever displacement as a function of actuation voltage

ICP- RIE with a SF_6/C_4F_8 chemistry that is able to achieve high selectivity of Si to Cr, exceeding 10000:1. By using this method, 100 nm wide tips with aspect ratio of more than 50 and tip density of more than 5×10^9 tips·cm^{-2} have been fabricated. Furthermore, the HAR tips have been integrated onto an array of 460 nm wide cantilever beams with high precision and yield (Fig. 4). In comparison with other approaches, this approach allows the integration of HAR sharp nanotips with nano-mechanical structures in a parallel and CMOS compatible fashion for the first time to our knowledge, meeting the design requirements with enhanced resonant frequency, tip sharpness while maintaining low spring constant. Although the approach uses amorphous silicon for tip formation and single crystalline silicon for the cantilever beam, it does not exclude the possibility of using polysilicon or silicon nitride for the cantilever structure.

6 Electrostatic cantilever actuator

To incorporate z-scanning capability with individual cantilevers in a parallel AFM system, excitation and actuation of individual cantilevers for the desired AFM mode of operation are required and need to be integrated with the silicon waveguide cantilever. Piezoelectric [38], thermal [39], optical [40] and electrostatics actuators [41] are typical actuating methods that are often used to drive cantilevers. Although any of these actuation mechanisms can be potential candidates, electrostatic actuation mechanism is chosen in this work due to its relatively easier fabrication and integration capability, low power consumption and fast response time. The electrostatic actuator is realized between the cantilever formed from the SOI active layer acting as a top electrode and the passive substrate layer as a bottom electrode. The separation between the cantilever and the silicon substrate is defined by the 1 μm SiO_2 BOX thickness. Contact pads are made to the active and passive layer to establish electrical contacts. Driving voltages are applied to the cantilever actuator via the contact pads and the resulting cantilever displacement is measured using Polytech MSA 500. The measured and simulated cantilever displacements are plotted in Fig. 5. The measurement results agree quite well with the simulation results. The maximum displacement of 525 nm is achieved with 50 V. Such displacement range is sufficient for AFM operation. The voltage larger than 50 V caused pull-in situation in which the cantilever snapped to the substrate.

7 Conclusions

In this paper, a novel approach for high-speed, high resolution and parallel AFM on chip based on silicon waveguide cantilever displacement sensor is proposed. The optimal sensor design shows better noise performance than OBD system typically used as displacement sensor in existing AFM systems, AFM cantilever tip with resonant frequency of 5.4 MHz and spring constant of 0.21 N/m. Toward realizing the proposed AFM system, the important constituting mechanical, electrical and optical components have been developed. A low optical transmission loss and robust silicon waveguide fabrication process that provides small line-edge and sidewall roughness and also allows incorporation of nano-gaps in the order of 20 nm with the silicon waveguides has been fabricated and tested. A low coupling loss and highly misalignment tolerant inverse taper cantilever coupler has been developed. The coupler improves the misalignment tolerance for 5 μm lensed fiber and the coupling efficiency for standard cleaved fiber without compromising other performances. Furthermore, a novel approach for fabricating ultra-sharp, HAR and high density nanotips integrated with nano-scale cantilevers at low thermal budget is demonstrated for the first time. The nano-cantilevers are designed, fabricated and tested for electrostatic actuation to provide sufficient displacement range required for the AFM operation. Future work will focus on integrating the components to realize the proposed AFM system on a single chip. Integration of the system with high-bandwidth *XY* micro-scanner will be required to enable a truly HS-AFM configuration and will also be the subject of future work. Such integration may lead to the fastest and smallest AFM systems on a single chip, which is yet to be demonstrated.

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