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Demonstration of atomic force microscopy imaging using an integrated opto-electro-mechanical transducer

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ABSTRACT

The low throughput of atomic force microscopy (AFM) is the main drawback in its large-scale deployment in industrial metrology. A promising solution would be based on the parallelization of the scanning probe system, allowing acquisition of the image by an array of probes operating simultaneously. A key step for reaching this goal relies on the miniaturization and integration of the sensing mechanism. Here, we demonstrate AFM imaging employing an on-chip displacement sensor, based on a photonic crystal cavity, combined with an integrated photodetector and coupled to an on-chip waveguide. This fully-integrated sensor allows high-sensitivity and high-resolution in a very small footprint and its readout is compatible with current commercial AFM systems.

1. Introduction

The semiconductor manufacturing industry has a continuous demand for improvement in resolution and speed of metrological instrumentation due to the ever-decreasing critical dimensions of integrated circuits. Atomic force microscopy (AFM) [1] has proven to be a powerful tool for the nanoscale characterization of semiconductor fabrication process steps [2] but at the cost of a low achievable throughput, which makes its application at an industrial level challenging. The predominant AFM imaging technique is the optical beam deflection (OBD) method, where a light beam reflecting from the back of the AFM cantilever is measured by a split-diode photodetector. While interesting adaptation of the OBD technique for parallel operation exist [3–6], they are not easily scalable to large arrays because of the requirements on alignment, minimum cantilever size and sufficient distance to the cantilever. The micromachining of probes, increasing the operation speed of AFM's, has also much advanced over the years [7]. As an alternative to OBD, electrical strain detecting sensors built in the cantilever have been developed based on piezoresistivity [8–10] or even piezoelectricity [11]. Cantilever displacement sensors based on optical interference using free space and fiber optics have been also reported [12,13]. More recently, optical AFM sensors, based on interference [14, 15] or evanescently-coupled resonant structures [16–18] with devices

implemented on the cantilever itself were introduced. An increased level of optical integration was reached with nano-optomechanical displacement sensors that include the photodetector and access waveguides in the same chip [19] or even in the same device [20,21]. The advantages of the optical sensors over the piezo-resistive/electric ones is that they tend to have lower noise, limited by thermomechanical noise of the cantilever, and that they are much less restricted in material choices and so offer more fabrication flexibility.

In the present work we demonstrate and characterize AFM imaging using an integrated nano-optomechanical AFM sensor head. The level of integration, including the built-in photodetector and access waveguides, exceeds previously reported chip-based photonic AFM sensors [17,18]. The employed photonic integration platform offers a prospect of ultimately integrating the optical source. Moreover, the out-of-plane operation of the sensor, as opposite to in-plane sensing [17,18], not only facilitates manufacturing, but potentially enables massive parallelization in two-dimensional arrays. The sensor is based on a double-membrane photonic crystal cavity (DM-PhCC) displacement sensor, integrated with an embedded photodetector and on-chip waveguide coupling [20], shown in Fig. 1(a). As previously demonstrated this integrated system provides a displacement sensing with inherently a high sensitivity and resolution, down to $7 \text{ fm/Hz}^{1/2}$ [20]. As the sensor belongs to the class of nano-opto-electro-mechanical systems (NOEMS)

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[22], combining optical, electrical and mechanical functionality, we will refer to it as NOEMS sensor throughout the paper.

2. Methods

The NOEMS sensor consists of a photonic crystal cavity etched in two mechanically-compliant, evanescently-coupled membranes [23], see Fig. 1(b). The upper membrane is equipped with an AFM tip, shown in Fig. 1(c). The cavity, along with the access waveguide, is fabricated from a layer stack of GaAs/Al_{0.73}Ga_{0.27}As via electron beam lithography and wet and dry etching steps (see Ref. [20] for the details of the fabrication process), where the AlGaAs acts as sacrificial (structural) material for the cavity (waveguide). To enable the photodetection a layer of self-assembled quantum dots (QDs) is embedded as absorber into the top membrane, which is vertically built as a p-i-n junction surrounding the QDs. The generated photocurrent displays a resonantly enhanced absorption of the laser light at the cavity wavelength. On the bottom membrane, a second p-layer is included to provide an actuation functionality [23], which is not employed in this work. The DM-PhCC is designed to display an antisymmetric (AS) mode in the wavelength range of the QD absorption, generating a resonantly enhanced photocurrent peak, which is used to measure the variation in the DM distance. As already demonstrated [20], we expect, due to the use of an AS mode, that the photocurrent peak red-(blue-)shifts when the DM separation increases (decreases). Thus, tuning the laser to the slope of the resonance peak, the displacement of the top membrane is directly transduced into the variation of photocurrent intensity, enabling the sensing.

The AFM tip, shown in Fig. 1(c), is built after the main fabrication process and is obtained via focused electron beam induced deposition (FEED) [24] of a dielectric organic compound, having as precursor the

tetraethyl-orthosilicate Si(OC₂H₅)₄ (TEOS) gas. The deposited tip has a height of $1.36 \pm 0.05 \mu\text{m}$, a base diameter of about 200 nm and a tip radius of curvature of about 30 nm. AFM imaging with metallic tips grown via FEED on micro mechanical structures [25] or on PhCC etched in a SiN cantilever probe [26] was previously reported. However, in the present work the tip should have a minimal interaction with the PhCC to avoid additional optical loss and therefore is made of amorphous silicon dioxide containing a substantial percentage of carbon up to 40% [27], which gives an estimated refractive index of 2. Despite the very close proximity to the PhCC, due to its small size and relatively low, predominantly real, refractive index, it produces a small perturbation to the cavity so that the tip introduces a small resonant wavelength shift of a few nanometers and a reduction of the quality factor of only about 15–20%, which do not significantly affect the performance of the device.

From simulations, and experiments on similar devices [20,21,23], the mechanical resonance ν_m is in the range of 1–2 MHz, with a low, air-damping limited, mechanical quality factor Q_m in the range 1–10 [23]. From these specs a bandwidth of the order of 1 MHz is expected, with a settling time $\frac{Q_m}{\nu_m} \sim 1 - 10 \mu\text{s}$, leading to scan times below 10 s for a 512×512 pixel image.

In the envisioned application of a parallelized system, the 2D array of sensors requires an accurate levelling control and feedback mechanism [28], which is not implemented in the present single-sensor proof-of-principle setup. A compact custom made dual sensor setup is employed, shown in Fig. 1(d), which is designed to be used as stand-alone AFM head for a commercial AFM. This setup consists of two connected parts. One is the NOEMS chip holder where six miniature spring loaded probes (XCFprobes DP1-028038-BG01) act simultaneously as clamps and as electrical connection to the chip contact pads.

Fig. 1. (a) Scanning electron microscope (SEM) image of the DM-PhCC (before tip deposition). The photonic crystal and the ridge waveguide are highlighted in yellow and blue, respectively. (b) Sketch of the DM cross section showing the various layers, the embedded QDs and the photocurrent readout. (c) SEM image of the NOEMS tip placed next to the PhCC. (d) Photos of the fiber-chip holder with the colored arrows indicating the locations of the NOEMS chip (orange), the electrical probes (dark red) and the lensed fiber (light blue). In the inset, the NOEMS chip where the two sets of electrical contacts, one on each side, and the two ridge waveguides, forming a Y shape, are visible. (e) Sketch of the measurement setup employed for the AFM imaging. The NOEMS device is highlighted in orange while the measured sample (colloidal cantilever) is in green. A trans-impedance amplifier (TIA) is used before the feedback control. (f) Expanded sketch of the colloidal tip and the DM, together with the spring system representing the two components.

The other part is a micro-positioning stage to align the lensed fiber to the chip waveguide facet and it is based on an elastic metal deformation construction [29,30]. The NOEMS chip has a rectangular design ($1.5 \times 3.5 \text{ mm}^2$), shown in the inset of Fig. 1(d), and it consists of two NOEMS sensors placed at the top corners, to facilitate alignment to the test surface, each connected to three contact pads and coupled to a $4 \mu\text{m}$ wide ridge waveguide.

For a future parallelized system, every sensor needs to be placed on an electrostatic or thermal actuator, driven by the feedback. The sensors will be evanescently coupled to waveguides, excited by one, or more, lasers. Every cavity can be tuned to the same laser wavelength by electrostatically adjusting the distance between the membranes, a function which is already implemented and demonstrated [23], but not used in the experiments presented here. The array excitation will be greatly facilitated when the laser(s) are also integrated on the same chip as foreseen. For this reason, the sensor is implemented in the III-V semiconductor system rather than in Si-photonics. While not compatible with CMOS fabrication processes, III-V technology has reached a high level of maturity as it is the basis for lasers and active photonic integrated circuits [31]. If external laser source are used it would be possible to realize the current sensor on silicon-on-insulator platform, or other nanophotonic platforms such as InP-membrane on silicon [32].

A commercial AFM system (Park NX20) is used to hold and control both the test surface and the custom head with the NOEMS chip. As presented in the experiment's sketch of Fig. 1(e), to mitigate levelling issues, the spherical colloidal tip of a commercial cantilever (Nano-AndMore CP-FM-BSG-B-5) mounted in the AFM system is used as test surface. The microscope objective of the AFM is used to observe the positioning on top of the NOEMS sensor using the AFM's XYZ stages. Once in contact, the colloidal cantilever and the NOEMS form a system

of springs in series, as depicted in Fig. 1(f). The light from the tunable laser is injected from the lensed fiber into the on-chip ridge waveguide coupled to the NOEMS sensor. The photocurrent signal I_ϕ , generated in the DM-PhCC, is collected via the electrical probes of the custom setup and it is amplified with a trans-impedance amplifier (TIA), with gain $A_{\text{TIA}} = 2 \cdot 10^7 \text{ V/A}$, and, finally, fed to the signal access module (SAM) card of the AFM controller.

Fig. 2(a) shows the photocurrent spectrum of the employed optical mode as measured before the TIA, by tuning the laser (2 mW power measured at the source) through the resonance. Fig. 2(b) shows the membrane deflection signal $D = A_{\text{TIA}} I_\phi$, i.e. the output of the TIA, during approach (FW) and retraction (BW) of the tip to and from the colloid surface. During this experiment the laser is tuned at the wavelength indicated by the red line in panel (a), on the side of the peak. The horizontal scale in panel (b), refers to the displacement of the piezo holding the colloidal sample, which does not represent the actual displacement of the NOEMS membrane due to the simultaneous displacement of the colloidal cantilever. In order to better understand the behavior during the interaction, the results of the experiment in panel (b) are also reported in panel (c), in terms of wavelength shift $\Delta\lambda = \lambda(z) - \lambda_0$ (as derived using the photocurrent spectrum in panel (a)) versus piezo displacement. Following the FW signal from right to left, firstly we see the absence of interaction and then the sudden jump-to-contact in which the NOEMS top membrane is pulled up, the AS mode red-shifts (panel (c)) and, consequently, the photocurrent drops (panel (b)). Then, the DM separation is constantly decreased, producing a blue-tuning of the mode and the increase of the photocurrent. When the initial separation is reached (point denoted with 0 on the horizontal axis), the photocurrent recovers its original value. Further pushing the cantilever down results in a reduction of the DM separation and the

Fig. 2. (a) Photocurrent spectrum of the used DM-PhCC mode together with its Lorentzian fit and the laser wavelength selected to perform the measurements. A laser power of 2 mW is used. (b) The amplified photocurrent voltage D as function of the piezo displacement, z_p , as measured by the AFM electronics. Both forward, FW, and backward, BW, measurements and the used set-point, SP, are indicated. (c) The same curve of (b) but converting the photocurrent signal to the corresponding wavelength shift $\Delta\lambda$, obtained using the Lorentzian fit in (a).

photocurrent follows the profile of the mode. As the piezo reaches the maximum position, the retraction starts (BW), passing through the previous configurations, corresponding to the red regions in the panels (b) and (c). Here, a mismatch between the peak positions during forward (FW) and backward (BW) measurements is visible, which could be related to the slip of the contact point during the motion, which could also explain the slight change of slope visible in the indentation region of the FW motion, right after $z_p = 0$.

Unexpectedly, at around 5 nm displacement in the BW movement, we observe an increase in photocurrent as if the membrane was moving FW. This trend continues till around 12 nm, where the jump-off-contact occurs and the initial optical mode and photocurrent are restored. This region is colored blue in both panels and the effect is tentatively attributed to the capillary forces generated by the presence of a water layer usually present in ambient conditions [33].

From the linear fit of the indentation region we calculate the slope of $d\lambda/dz_p = 0.15 \pm 0.01$ nm/nm. To derive the sensitivity $d\lambda/dz_{DM}$ we use the fact that $\frac{z_{DM}}{z_p} = \frac{k_C}{k_C + k_{DM}}$, where $k_C = 5$ N/m (separately characterized via thermal tuning [34]). Assuming a DM spring constant value $k_{DM} \approx 10$ N/m, measured in previous calibration runs performed with other devices with the same design, we obtain an optomechanical coupling $d\lambda/dz_{DM} \approx 0.4$ nm/nm. This value is somewhat higher than the previous measured values on similar structures [20], which could be caused by a different DM separation. Since the sensor sensitivity $\Sigma = \frac{dD}{d\lambda} \frac{d\lambda}{dz}$ and $\frac{dD}{d\lambda} \propto Q_0$, where Q_0 is the cavity quality factor, we have $\Sigma \propto Q_0 \frac{d\lambda}{dz}$. As compared to sensors based on ring resonator [16,17], and, assuming similar laser power and photodetector specifications, our $d\lambda/dz$ is about two orders of magnitude larger while our $Q_0 \approx 10^3$ is smaller by roughly the same factor, so that the sensitivities are comparable. Nevertheless, a large $d\lambda/dz$ is preferred over a large Q_0 because it strongly relaxes the requirement on linewidth or wavelength stability of the read-out laser and reduces environmental influences such as temperature variations.

In order to prove that the amplified photocurrent signal can be used for feedback control during lateral scanning, we performed an AFM imaging experiment in contact mode at ambient conditions. During those scans the set-point (SP) is fixed at 1.35 V, as indicated by the horizontal dashed line in Fig. 2(b), which defines the system sensitivity to be $\Sigma = dD/dz_p = 0.45 \pm 0.01$ V/nm for the employed power of 2 mW. The XY piezos are driven in an open-loop operation in order to reduce possible additional noise caused by the weight of the custom head on the XY piezo stage. This prevents the accurate measurement of the lateral dimensions. In order to obtain the correct scaling of the lateral axes a large area image of the measurable spherical sector is acquired. In Fig. 3 (a) the SEM image of the colloid is reported, which is used to obtain its actual diameter $R_{col} \approx 6$ μ m. Fig. 3(b) shows the 3D image of the spherical sector of the colloid measured with the NOEMS with a scan size of 12 μ m. We compare the expected and measured dimensions of this spherical sector h and d , as described in the sketch of Fig. 3(c). Firstly we see, from Fig. 3(b), that the maximum measured height h_{meas}

$= 1.32 \pm 0.07$ μ m matches with the NOEMS tip height, $h_T \approx 1.36$ μ m from Fig. 1(c) – as expected, for larger distances from the tip of the colloid, the colloid is in contact with the surface of the DM. Secondly, we calculate the expected diameter $d_{exp} = 2[R_{col}^2 - (R_{col} - h_T)^2]^{1/2} \approx 7.6$ μ m, and we compare it with the measured value, obtained using the scan dimension provided by the controller of the XY stage, that is $d_{meas} = 10.7 \pm 0.2$ μ m. This indicates that a correction factor of $\gamma = d_{exp}/d_{meas} \approx 0.7$ has to be applied to obtain the actual scan size.

In Fig. 4(a) an example of topography measurements at the apex of the colloidal is reported, with the corrected XY dimensions. From a spherical fit of this and similar surface profiles, the radius of curvature is achieved, providing $R_{meas} = 6.5 \pm 0.2$ μ m, close to the expected value. By subtracting the fitted spherical background from the original surface profile we obtain a roughness profile, which is reported in Fig. 4(b), and in this case an RMS roughness of 20 nm is detected, which is attributed to the surface roughness of the colloid. These images confirm the capability of mapping surface profiles using the integrated NOEMS sensor together with the standard AFM feedback control. Indeed, while

the dynamic range $z_{dyn} \sim \frac{z_0}{Q_0} \left(\frac{d\lambda}{dz_{DM}} \right)^{-1} \approx 5$ nm of the sensor is rather small, the data in Figs. 3 and 4 demonstrate that it is adequate to measure height variations in the 1–10 's of microns range, with the feedback adjusting the z-piezo position.

An experimental indication for the vertical resolution would consist of measuring atomic step edge heights on ultra-flat surfaces as highly-oriented pyrolytic graphite (HOPG). Such a test is precluded in the present setup because of the lack of a leveling system mentioned above.

Thus, the vertical resolution δz of the NOEMS sensor is characterized by measuring the voltage noise spectral density S_{DD} from the deflection signal during a single-point acquisition, where the sensor is maintained at fixed contact via the feedback control. From S_{DD} the vertical resolution is obtained according to $\delta z = \sqrt{S_{z_{DM}z_{DM}}} = \sqrt{S_{DD}} \left(\frac{dD}{dz_{DM}} \right)^{-1}$, where $S_{z_{DM}z_{DM}}$ is the DM displacement noise spectral density and we can rearrange $\frac{dD}{dz_{DM}} = \frac{dD}{d\lambda} \frac{d\lambda}{dz} \frac{dz}{dz_{DM}}$. In Fig. 5 the S_{DD} is reported for three different configurations, in order to identify the different noise components in the NOEMS sensor. Those correspond to measurements obtained: i) with the NOEMS sensor out-of-contact and with the laser switched off (NOEMS_{L-OFF}); ii) with the sensor out-of-contact but with the laser line tuned on the peak side (NOEMS_{L-ON}); and iii) with the laser on and the sensor in contact with the colloid (NOEMS_{col}). To calculate the resolution δz we use the value of NOEMS_{col} above 15 kHz, where we measure $S_{DD} \approx 10^{-8}$ V²/Hz. In this measurement a laser power of 3 mW is used, corresponding to $\frac{d\lambda}{dz} \approx 300$ A/m at the wavelength corresponding to the feedback set-point. Thus, considering $\frac{dD}{d\lambda} = A_{TIA}$ and $d\lambda/dz_{DM} \approx 0.4$ nm/nm, as estimated above, we estimate a displacement noise floor $\delta z \approx 40$ fm/Hz^{1/2} above 15 kHz. Note that this value may be affected by an uncertainty of up to a factor two as $\frac{d\lambda}{dz_{DM}}$ is not measure directly. By looking at Fig. 5, we note that this resolution is mainly limited by the

Fig. 3. (a) SEM image of the colloid. (b) 3D surface of the spherical sector of the colloidal measured with the NOEMS sensor. (b) Sketch of the imaging showing the dimension of measured spherical sector.

Fig. 4. (a) Close-up images of the central part of the colloidal performed with the NOEMS, 3D surface profile (left) and 2D map (right). (b) The surfaces roughness obtained subtracting the spherical background of the same region of (a), 3D surface profile (left) and 2D map (right). Both images consist of 512×512 pixels corresponding to a lateral step size of 7 nm.

Fig. 5. Noise spectral densities of the deflection signal for three different configurations of the NOEMS sensor: free standing out-of-contact and with the laser switched off ($NOEMS_{L-OFF}$), free standing but with the laser on ($NOEMS_{L-ON}$), and during contact with the colloidal cantilever ($NOEMS_{col}$). The measurements were all carried out with a bandwidth of 50 Hz.

noise generated by the power fluctuation of the laser source, as it is approximately the same in- and out-of-contact.

Compared to the noise floors demonstrated using an integrated interferometer [15] or a resonator [16,17], 35 and 2 $\text{fm}/\text{Hz}^{1/2}$ respectively, our values are similar or an order of magnitude larger. Using similar NOEMS structures without tip, in a different set-up and with different read-out electronics, we previously observed displacement noise floors down 7 $\text{fm}/\text{Hz}^{1/2}$ [20], which shows the potential for further improvement of the vertical resolution.

Ultimately, the noise floor is limited by photon shot noise in the detector. The detector current noise spectral density will then be given by $\delta I = \sqrt{2eI_{det}}$ with I_{det} the detector photocurrent. The current noise is converted to displacement noise δz via $\delta z \sim \frac{\lambda_0}{Q_o} \frac{1}{I_{det}} \left(\frac{d\lambda}{dz_{DM}} \right)^{-1} \delta I$, which decreases as $1/\sqrt{I_{det}}$, and so decreases with increasing laser power. With the currently achievable value of $I_{det} \approx 10 \mu\text{A}$ (absorbed power ≥ 10

μW), leads to a shot-noise limited noise floor below 1 $\text{fm}/\text{Hz}^{1/2}$.

3. Conclusion

The demonstration and the characterization of a complete AFM system based on a NOEMS sensor is presented. The read-out using the integrated NOEMS sensor shows higher sensitivity and comparable resolution than the OBD read-out of standard AFMs.

Compared to other integrated devices [14–18], this approach has the advantages of combining the photodetection inside the mechanical sensing element and the coupling to the ridge waveguide together with its very compact footprint. Additionally, the fabrication on a III-V material may enable the integration of lasers on the same chip, leading to a fully-integrated active tip which does not require any input/output optical coupling. This makes the NOEMS approach particularly suitable for the fabrication of scalable on-chip AFM systems. It may pave the way for the integration of large arrays enabling the high throughput required for industrial semiconductor metrology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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