Nanoelectromechanical Position-Sensitive Detector with Picometer Resolution

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Cite This: ACS Photonics 2020, 7, 2197−2203

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ABSTRACT: Subnanometer displacement detection lays the solid foundation for critical applications in modern metrology. In-plane displacement sensing, however, is mainly dominated by the detection of differential photocurrent signals from photodiodes, with resolution in the nanometer range. Here, we present an integrated nanoelectromechanical in-plane displacement sensor based on a nanoelectromechanical trampoline resonator. With a position resolution of 4 pm/√Hz for a low laser power of 85 μW and a repeatability of 2 nm after five cycles of operation as well as good long-term stability, this new detection principle provides a reliable alternative for overcoming the current position detection limit in a wide variety of research and application fields.

KEYWORDS: in-plane displacement sensor, position-sensitive detector, nanoelectromechanical resonators, photothermal effect

High-performance position sensing is a substantial cornerstone for challenging applications such as state-of-the-art atomic force microscopy for molecular- and mechano-biology,1,2 nanomechanical transduction and sensing,3−6 and experimental physics such as the tracking of single electron spins and trapped ions.7,8 Position-sensitive detectors (PSDs) that can measure the position of a light spot are an integral part of modern metrology. The two most common PSD designs are based on segmented or lateral effect sensors. The former PSDs consist of multiple sensor segments each giving its own photocurrent, while the latter is based on a single photodetector element. Typical segmented-quadrant position-sensitive detectors have a good position resolution of the order of 10 nm/√Hz to 100 nm/√Hz for light powers of 10−100 μW.9 Due to their quick response time and large operation bandwidth, they are dominating the commercial atomic force microscope market. Each detector segment is separated by a gap. The intensity profile of a spot is in general very nonlinear, which directly results in a strong nonlinear position response if the spot is not perfectly centered. In contrast, lateral effect position-sensitive detectors have no gaps and give positional information independent of beam shape, size, and intensity profile. Lateral effect PSDs have a good lateral resolution in the range of a few nm/√Hz, however, typically have a slower response speed than quadrant detectors.9,10 For both PSDs, as a characteristic of semiconductor photodetectors, the dark-current noise can limit the detector sensitivity to one to two orders higher than the shot-noise-limit without any considerations of external artifacts, setting an upper limit for the sensitivity of photodiode-based PSDs.9,11

Besides the common photodiode-based PSDs, it has been shown that a spatial resolution of 25 pm/√Hz can be achieved by direct transmission of a Gaussian beam through a slit.12 This transmission-based experiment, however, requires a photodetector behind the slit, which renders it impractical for the use in more general applications. Recently, a fundamentally new approach based on the directional scattering of a laser spot on a silicon nanoantenna has been demonstrated.13,14 This nanophotonic displacement sensor has reached a position resolution in the nanometer range. A nanomechanical displacement sensor using a mechanical coupler has also been reported with a sensitivity of 45 fm/√Hz.

Here, we present a nanoelectromechanical position-sensitive detector (NEMS-PSD) with a position resolution in the picometer range. Recently, similar nanoelectromechanical resonators have demonstrated unprecedented sensitivity for radiation15 as well as single nanoparticle and molecule absorption detection.16−18 The NEMS-PSD principle is based on the highly beam-position-dependent photothermal heating of plasmonic Au nanoparticles that are placed on top of a silicon nitride trampoline resonator, as schematically

Received: April 28, 2020
Published: July 15, 2020
depicted in Figure 1a. A scanning electron microscope image of the nanoelectromechanical trampoline resonator is shown in Figure 1b. The NEMS-PSD is transduced electrodynamically,\textsuperscript{19–21} as schematically depicted in Figure 1c. More details of the NEMS-PSD design can be found in the Supporting Information. During operation, due to the Gaussian power distribution of the beam, the displacement of the laser beam changes the power absorbed by the nanoparticles, resulting in a detectable frequency shift of the temperature-sensitive nanoelectromechanical resonator. In this way, the presented NEMS-PSD reached a position resolution of 4 pm/√Hz for a laser power of 85 μW.

## RESULTS AND DISCUSSION

**Theoretical Model.** The laser spot displacement Δx is measured in terms of the measured relative frequency shift δf = Δf/f₀ of the trampoline resonator

\[
Δx = \delta R^{-1} \delta f
\]

with the relative responsivity δR of the nanoelectromechanical resonator.

The displacement responsivity δR of the nanomechanical resonator is defined as its relative frequency change per laser spot displacement. Since the laser displacement and the resonant frequency change are connected by the change in absorbed laser power P, δR can be written as

\[
\delta R = \frac{1}{f_0} \frac{\delta f}{\delta x} = \left( \frac{1}{f_0} \frac{dP}{\delta P} \frac{\delta f}{dP} \right)_{\delta P} R_{\text{w}}
\]

with the well-investigated relative power responsivity δR\text{P,}\textsuperscript{18,22} and the beam displacement related power responsivity R\text{w}.

δR\text{P} can be modeled as the responsivity of a nanomechanical cross resonator, which represents the most extreme case of a trampoline that features no central area. A cross resonator has half the responsivity of a nanomechanical string resonator and can be written as\textsuperscript{22}

\[
\delta R_{\text{P,max}} = -\frac{1}{32 \kappa \sigma \alpha \omega} \frac{aE}{L}
\]

where α is the thermal expansion coefficient, E is the Young’s modulus, κ is the thermal conductivity, σ is the tensile stress, L is the tether length of the cross, w is the width, and h is the thickness of the cross resonator.

Since the dimension of the nanoparticle is around 10% of the laser beam diameter, the nanoparticle antenna can be approximated as a point absorber with an absorption cross-section σ_{abs}. Then, the power absorbed by the nanoparticle (P) at a position x₀ with respect to a Gaussian beam center, under different beam positions, which is the convolution of a point source and a Gaussian beam profile, can be expressed as
Displacement Responsivity and Resolution. As has been shown in the derivation of eq 5, the displacement responsivity is dependent on the relative position of an absorbing particle with respect to the laser spot, following the first derivative of a Gaussian function. To examine this, a single Au nanoparticle that is well-isolated from other particles in the center area of the trampoline resonator is selected, and a 3 μm × 3 μm area scan is done with a step size of 80 nm and a dwell period of approximately 300 ms for each step, as schematically shown in Figure 2a. As mentioned, the formation of the Gaussian frequency shift profile is a result of the convolution between a single point absorber and the Gaussian power profile of the laser, as illustrated in Figure 2b. The raw frequency signal for a scan across the single Au particle is plotted in Figure 2c. The rise time of the NEMS-PSD can be extracted by fitting the step frequency response with a first order exponential function, as shown in the inset of Figure 2c, yielding a 10% to 90% rise time of 53 ms. Therefore, a delay time of around 50 ms is set for each scan point. More details on the calculation of the rise time is provided in the Supporting Information.

Figure 2d shows the NEMS-PSD frequency shift for a scan across the center of the nanoparticle, as indicated by the white line in the two-dimensional frequency shift mapping in the inset of Figure 2d. The data points are fitted with a Gaussian function. The extracted full width at half-maximum (fwhm) of the Gaussian fit is 1.1 μm, corresponding to a beam radius of 0.93 μm, which is close to the nominal fwhm of the laser objective (NA = 0.55) of around 0.9 μm (beam radius of 0.75 μm). For the 200 nm Au nanoparticle an absorption cross-section of σ_{abs} = 9 × 10^{-12} m^2 for a wavelength of 633 nm can be calculated from Mie theory. With an input laser power...
of $P_t = 85 \, \mu W$, the expected peak frequency shift is calculated to be approximately 720 Hz, based on the finite element method (FEM) simulations, which fits with the peak frequency shift of 750 Hz in the measurement quite well.

Figure 2e shows the displacement responsivity, represented by the first derivative of the measured frequency shift profile shown in Figure 2d. A maximum responsivity of approximately 1400 Hz $\mu m^{-1}$ is reached at half of the beam waist of the Gaussian profile. As expected from the theoretical model, the responsivity is maximal for a particle position at half of the beam radius.

Figure 2f shows the Allan deviation for different phase-locked loop (PLL) target bandwidths. It can be seen that the thermal drift, represented in the positive slope for the large integration times is consistent for all target bandwidths. In contrast, the negative slopes for short integration times varies for specific target bandwidths, which is because the inductive readout is not limited by thermomechanical noise. From Figure 2f it can be seen that a target bandwidth of 800 Hz and integration time of 250 ms results in a frequency noise of about 250 mHz. This matches with the standard error of around 253 mHz calculated from the integrated data for individual scan points shown in Figure 2d (the calculations are presented in more detail in the Supporting Information). Together with the previously extracted responsivity of 1400 Hz $\mu m^{-1}$, a position resolution of 105 pm/$\sqrt{\text{Hz}}$ can be calculated from the current measurement according to eq 1. Since smaller target bandwidths yield lower frequency noise, it is possible to improve the position resolution with the trade-off of longer minimal integration times, for example, using a target bandwidth of 10 Hz results in a minimum frequency noise of 8 mHz for an integration time of 450 ms, which ultimately results in a position resolution of 4 pm/$\sqrt{\text{Hz}}$.

**Optimization of Trampoline Geometry.** As discussed previously in eq 2, the maximum responsivity depends on the design of the trampoline geometry. Figure 3 presents the study of trampoline resonators with various sizes of the center area, both measured and simulated using FEM. The window size is kept constant at 1 mm for all designs. The width of the trampoline tethers were kept constant at 5 $\mu m$ and a silicon nitride thickness of 50 nm. The curvatures of all trampoline geometries are optimized for an even stress distribution. Single 200 nm gold nanoparticles are used as absorber for all measurements, and the maximum displacement responsivity is extracted, as shown in Figure 2e. The measured responsivities share a similar trend with the FEM simulation, with decreasing responsivity for increasing center area from type A to type E trampoline. This can be explained by the resulting lower temperature profile for trampolines with larger center area, as shown in more detail in the Supporting Information, Figure S5. The most extreme design of type A trampoline has a responsivity close to the theoretical limit according to eq 6 of around 2100 Hz $\mu m^{-1}$, representing a trampoline with no center area.

However, the small center area makes it challenging to distribute nanoparticles on the surface by means of spin-coating. Type C trampolines have a large enough center area and show a high responsivity, only 10% less compared to the most responsive type A trampoline. Therefore, type C trampolines were the devices of choice used for the present study. Furthermore, since the nanoparticles are distributed randomly on the trampoline resonator, the position-dependency of the power responsivity is worth discussing. As shown in the finite element simulation in the inset of Figure 3, the power responsivity remains constant over the entire center area. It is not until the tethers of the trampoline resonator are reached that the responsivity starts to drop. Hence, the displacement measurement can be operated optimally over the whole center area, which is a precondition for the displacement sensing with type C trampoline resonators.

**Repetitive Displacement Measurements.** After the characterization of the displacement responsivity and the optimization of the trampoline geometry, a repetitive displacement measurement within a small range of 15 nm and small step size of 3 nm is performed. Therefore, the laser spot was placed randomly on the center of the trampoline in order to demonstrate the possibility to operate the NEMS-PSD without any fine alignment and calibration process demonstrating the practicability. Furthermore, the repeatability and long-term stability of displacement sensing is studied, as illustrated in Figure 4a. The integration time for each step remains 250 ms. As in the schematics of Figure 4b, the frequency shift is no longer a Gaussian profile; instead, an approximated linear relation between the frequency shift of the trampoline resonator and the beam displacement with an almost constant displacement responsivity can be expected for such a small scan range. The frequency signal from the PLL is plotted in Figure 4c, where the individual displacement steps of 3 nm can be clearly identified. The averaged frequency and standard deviation of each displacement step is then calculated and plotted in Figure 4d with respect to the laser beam position. For generalization, a reference position is then defined as the center point of the repetitive movement, and the frequency shift is then subtracted according to this reference frequency, as shown in Figure 4e. A linear fit is subsequently performed to

![Figure 3](https://dx.doi.org/10.1021/acsphotonics.0c00701)
extract the displacement responsivity within this range. The averaged displacement responsivity obtained from this measurement is 1.15 Hz nm$^{-1}$. The target bandwidth of the PLL is reduced to 200 Hz in these measurements, resulting in a frequency noise of around 0.025 Hz. This gives a position resolution of 12 pm/Hz, which is slightly worse than previous values, which were obtained for an optimized particle/beam position. With this measurement, NEMS-PSD demonstrates the feasibility of operation without fine optical alignment on a random absorber on the trampoline resonator.

The repeatability after 5 cycles of operation is within a maximum deviation of 2 nm. This deviation could also partly result from the accuracy of the nanopositioning stage that controls the position of the beam. With a drift below 500 nm within 4 h, as discussed in theSupporting Information, the long-term stability of NEMS-PSD is of the same order as of photodiode-based PSDs with 0.1 to 1 μm.9,12 The drift could be partly contributed by the whole optical system, including sample mounting. This high repeatability and long-term stability of NEMS-PSD can result from the localized absorption of nanoparticles, making the system less susceptible to background scattering and interference.

**CONCLUSIONS**

We presented a NEMS-PSD based on silicon nitride trampoline resonators with integrated electrodynamic readout and actuation. We demonstrated a sensitivity of 4 pm/√Hz with the potential of further optimization by using, for example, silicon nitride with lower stress. The stress can be engineered by the deposition condition in low-pressure chemical vapor deposition (LPCVD) process,25 by a post-treatment with the oxygen plasma,18,26 or by controlling the temperature of the samples.27 The NEMS-PSD demonstrated a repeatability of approximately 2 nm after 5 cycles of operation and showed a long-term stability better than 500 nm in 4 h. This position-sensitive detector design overcomes the issue of nonuniformity of multiple segments by measuring the direct absorption instead of differential current from photodiodes, which improves the sensitivity greatly and also requires minimum signal processing effort. Due to the localized nanoparticle absorber, the parasitic effect from the ambient is also minimized, which enables better long-term stability. It is also compatible with a small beam diameter and even irregular beams, since the artifact could be easily calibrated with a scan before operation to identify the beam profile. The presented NEMS-PSD is promising to provide a sensitive alternative to existing PSDs and could bring advances to a great variety of research and application fields.

**METHODS**

**Sample Fabrication.** The samples are fabricated with a bulk micromachining process. A silicon wafer with a thickness of 370 μm is coated with a 50 nm silicon-rich silicon nitride (SiN) with low pressure chemical vapor deposition (LPCVD). The prestress is approximately 150 MPa, which is extracted from the resonance frequency by means of a finite element method-based analysis. The 190 nm thick gold electrodes together with a 10 nm chrome adhesion layer for magneto-motive transduction are first defined with photolithography on the front side of the SiN wafer, and the SiN trampoline structure is then defined with another step of photolithography after lift-off. The excess SiN is then removed with reactive ion etching (RIE) and protected with a layer of photoresist. A window is defined from the back side and etched with KOH to release the trampoline resonator. Reactant-free gold nanoparticles with a diameter of 200 nm in 0.1 mM PBS stabilized suspension solution (Sigma Aldrich) are first diluted in Micropur deionized water (18 MΩ·cm, Milli-Q) at a ratio of 1:100 at room temperature and then spin-coated on the trampoline resonator at 2000 rpm.
Finite Element Method Simulation. The finite element simulations are done with the thermal stress module of COMSOL multiphysics, including first the simulation of the temperature field of a point heat source and, subsequently, the stress distribution and the eigenfrequency. The responsivity could be extracted by simulating the eigenfrequency at different powers of the point heat source. The thermal expansion coefficient ($\alpha$) used in the simulation is $2.2 \times 10^{-6}$ K$^{-1}$, the Young’s modulus ($E$) is 250 GPa, thermal conductivity ($k$) is 3 W m$^{-1}$ K$^{-1}$, and the prestress ($\sigma$) is 150 MPa. All the constants are also consistent with the ones used for theoretical calculations.

Measurement Setup. The optical setup is shown in the Supporting Information. In this experiment, a diode laser with a 633 nm wavelength (Toptica TopMode) is used. The beam passes through a beam expander and the power is reduced to approximately 85 µW before the vacuum chamber with a linear polarizer. A 50 times objective (0.55 N.A.; Mitutoyo) is mounted on the nanopositioning stage (PiMars, Physikinstrumente) for control of the beam position. All the measurements are done under a vacuum of $1 \times 10^{-3}$ mbar. The magnetomotive transduction is done with an enhanced Halbach array with the layout shown in Figure S1. The magnetic field in the center 5 mm region is measured to be above 1 T. The electrical signal from the trampoline resonator is first amplified with a home-built low-noise preamplifier (LT1028, Analog Devices) with a gain of 200, and fed to the lock-in amplifier with a phase-locked loop (HF2LI, Zurich Instrument), with its output driving the actuation.

■ ASSOCIATED CONTENT

Supporting Information
The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsphotonics.0c00701.

Detailed measurement setup and calculations of rise time, frequency noise, temperature field and long-term stability (ZIP)

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https://pubs.acs.org/doi/10.1021/acsphotonics.0c00701

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of Sophia Ewert and Patrick Meyer with the sample fabrication and preparation and the useful discussions with Markus Piller and Hendrik Kähler. This work is supported by the European Research Council under the European Unions Horizon 2020 Research and Innovation Program (Grant Agreement 716087-PLASMECS).

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