Nanometrology Optical Ruler Imaging System for Wafer-Scale Precision Metrology for Tip-Based Microscopes

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This paper describes the Nanometrology Optical Ruler Imaging System (NORIS) which demonstrates 2×10^{-7} (17.2 nm) precision nanoscale metrology over wafer length scales. Tip-based nanofabrication such as dip-pen writing or thermal surface modification [1, 2] is a promising technology that will enable future computational, sensor, and actuator technologies. However, the success will rely critically on fast, precise nanometrology of nanoscale features at length scales varying up to seven orders of magnitude. State-of-the-art capacitive and strain sensors lack long travel range. High precision optical encoders only work along a single beam axis, requiring a large reflective block which in turn requires a large massive stage which limits the frequency of movement. The resulting technological roadblock is the inability for a scanning probe microscope to quickly return to the same location after moving distances even as small as tens of microns, much less an entire wafer. Consequently, time is laboriously spent searching for nanoscale features, limiting the throughput of nano-science and technology, e.g. tip-based nanofabrication requiring nanometer precision placement across a wafer in real-time.

NORIS (Fig. 1) alleviates these problems. The metrology precision and stability is derived from an atomically-stabilized laser (Fig. 1a), yielding a base precision down to parts per billion. Just as atomic clocks use alkali atoms to stabilize a frequency source over long times, here the atoms stabilize the optical source for a long-term stabilized wavelength-determined optical ruler. The wavelength-stabilized laser beam is diffracted by a microfabricated metal thin film (Fig. 1b). The metal is etched with an ebeam lithography pattern of circles. The pattern is quasiperiodic, designed by using the vertices of a Penrose tiling pattern [3]. The resulting diffraction pattern is a translationally asymmetric optical pattern with dense, sharp features which projects over the wafer-scale workspace and acts as a precise optical ruler (Fig. 1c). Nanometrology is accomplished by sampling this optical ruler with a modest imaging array attached to the tip (Fig. 1d). A gain-sweep method is used to drastically reduce the discretization noise of the imager, yielding precision sampling of the optical ruler. The sample image is compared with a reference image which can be calculated or previously taken from of the optical ruler; the calculated change in position between the two images determines the imager's new position. Fourier cross correlation with upsampling calculates the positioning with sub-pixel resolution down to 2 nm (Fig. 1e).

Figure 2 demonstrates the precision of NORIS, a marked improvement from similar, previous work [4]. A quasiperiodic metal thin film diffracts a 1.5×10^{-8} stabilized external cavity laser. A CMOS imager is placed on a piezoelectric flexural stage, then moved within the optical ruler. The camera position calculated by NORIS is compared to the position calculated by the high precision but low range capacitive sensors of the stage. Note that NORIS lacks the half-wavelength ambiguity that is present in interferometric systems.

Figure 3 shows the deviation of the NORIS position from the capacitive sensor measurement. NORIS demonstrates a mean absolute deviation of 17.2 nm from the capacitive sensor position.

Figure 4 demonstrates the stability of NORIS by measuring a nonmoving imager over six hours. Due to the laser wavelength lock to a quantum mechanically well-defined atomic transition, the optical ruler is long-term stabilized so that NORIS is able to precisely calculate the position over long times: intermittent calibrations are not required. A stability within 20 nm over six hours is demonstrated.

Therefore, NORIS demonstrates wafer-scale nanometrology that is spatially unique and will enable fast scanning probe operation with multiple tips or simultaneous translational and rotational metrology.

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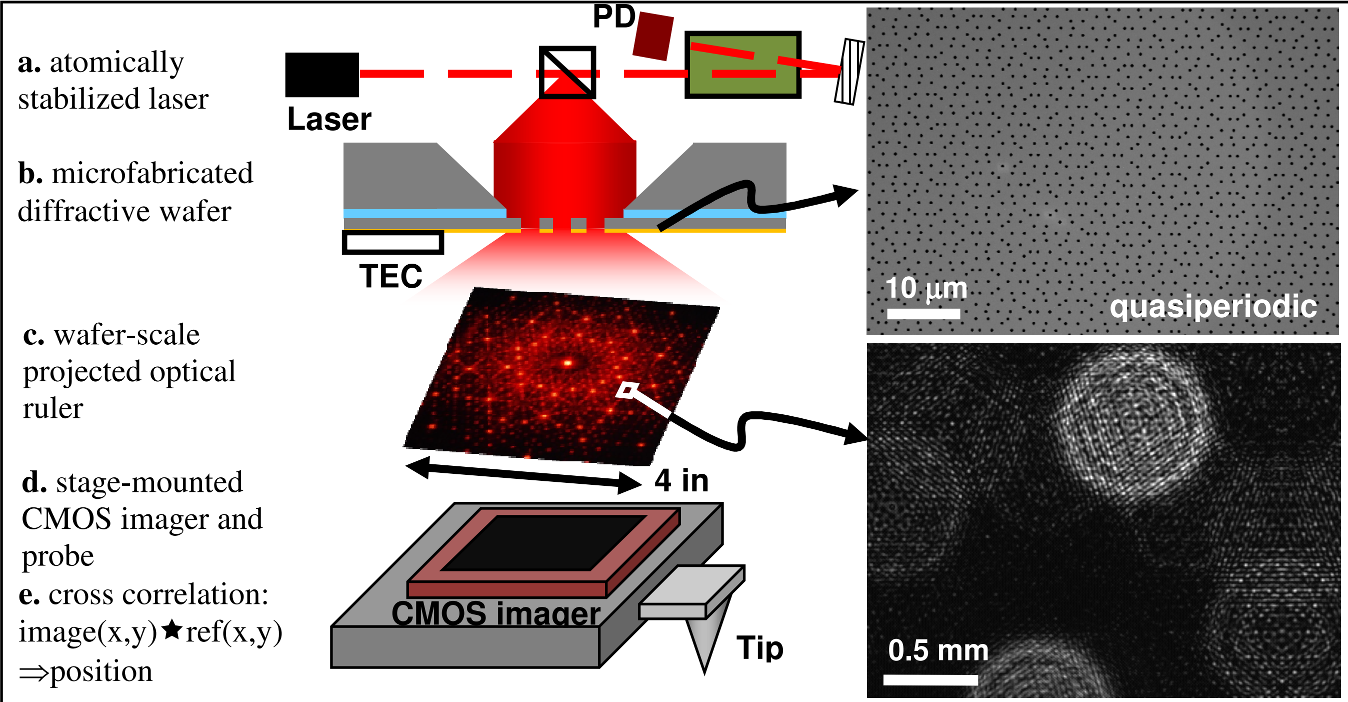

Fig. 1 NORIS: **a.** An external cavity laser is frequency stabilized within 6 MHz, or a relative accuracy of 1.5×10^{-8}, to a saturated resonance (F=2 to 1) of the D2-line of ^{85}Rb. **b.** A 22.77±0.03 °C temperature stabilized microfabricated Penrose vertices grating diffracts the laser beam (fabricated using ebeam lithography on SOI device layer; device layer Si etch; thru carrier wafer backside KOH etch; buffered HF release; Ti/Au evaporation). **c.** Wafer-scale optical ruler is shown, and CMOS camera acquired image of a small section of the optical ruler. **d.** Tip/CMOS imager is mounted on a commercial stage. **e.** Upsampled Fourier transform cross correlation calculates the CMOS imager position within the optical ruler.

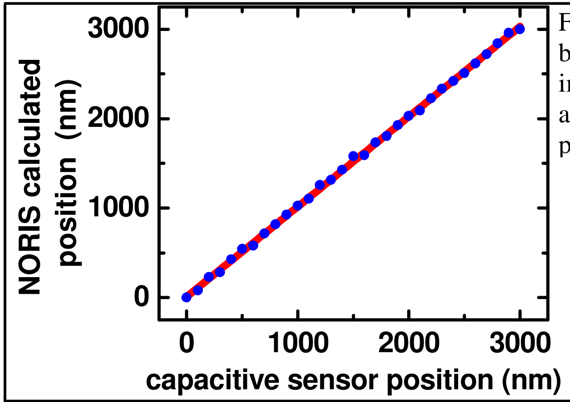

Fig. 2 NORIS calculated position compared with position measured by capacitive sensor integrated to piezoelectric stage. Stage moves imager in steps of 100 nm up to 3000 nm. Note lack of wavelength ambiguity present in interferometric metrology systems: NORIS position is uniquely encoded within the optical ruler.

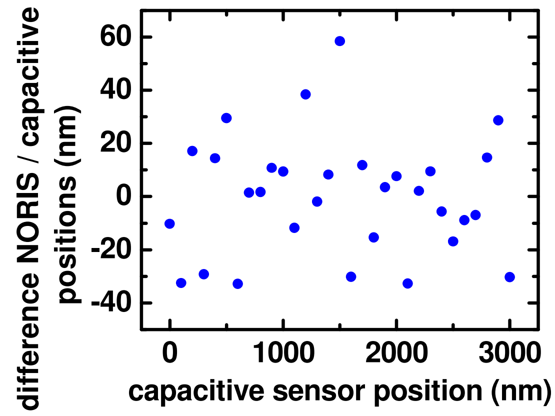

Fig. 3 Residual between NORIS calculated position and capacitive sensor measured position, derived from data shown in Fig. 2. NORIS shows mean absolute deviation of 17.2 nm from capacitive sensor measurement.

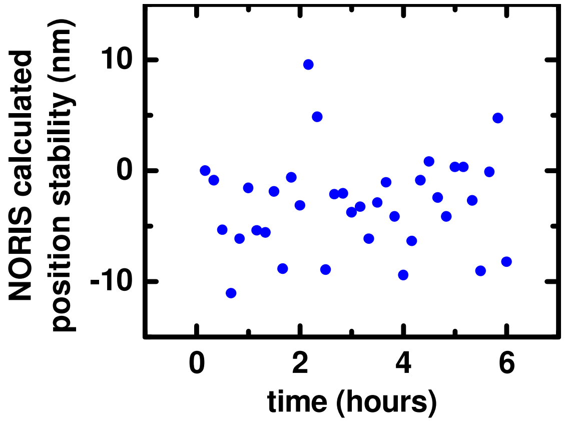

Fig. 4 Long term (6 hour) stability of NORIS, stable to 20 nm over six hours