
Project Staff:
(Dr. Mark L. Schattenburg and Prof. Henry I. Smith)

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Historically, the ability to observe and measure the results of processes has been critical to
advancing fabrication technology. Thus, improvements in optical microscopy (e.g., Nomarski
differential interference contrast) were a key enabler of the microelectronics revolution. In turn,
the scanning-electron and atomic-force microscopes are essential tools as we move into the
nanotechnology era. While the ability to print or resolve a particular feature size is a necessary
condition for the successful lithographic manufacturing of nanosystems, it is, by no means, the
only requirement. Equally important is the ability to measure and control the size and placement
of lithographic features with very high accuracy

All modern lithographic production and inspection tools, and all precision tools for that matter, are
based on the notion of a metrology frame. Such a frame is composed of three components: (1) a
rigid mechanical structure, (2) means to measure the motion of a workpiece with respect to the
metrology frame, and (3) means to project, image or detect patterns on the workpiece, such as by
use of an optical or electron lens. The preferred means for measuring workpiece motion has
been the laser interferometer. The accuracy of a lithographic tool is critically dependant on the
accuracy of its metrology frame, which, in turn, is dependant on the accuracy of the
interferometer. Due to a number of complex factors, however, interferometer accuracy is not
keeping pace with the shrinking tolerances as called for by the semiconductor industry roadmap
(see Fig. 1) and the future nanotechnology revolution.

To address this problem, we are developing a lithographic tool called the Nanoruler that is
designed to pattern gratings of such high accuracy that they may serve as the means for
detecting workpiece motion in precision tools, using a method known as optical encoding, with an
accuracy that is some 10-100X better than laser interferometers. The Nanoruler utilizes a
patterning method called scanning-beam-interference lithography (SBIL), developed in the Space
Nanotechnology Laboratory (SNL), that is capable of rapidly patterning large gratings (>300 mm
diameter) in only a few minutes with unprecedented accuracy (see Fig. 2). Such super-accurate
gratings can serve as optical encoder plates, as mentioned. Another important application for
the Nanoruler is the patterning of nano-accurate gratings necessary for locking an electron beam
using a novel technique called spatial-phase locked electron beam lithography (SPEBL) that is
under development in the NanoStructures Laboratory (NSL) and described elsewhere.

High fidelity gratings are also critical for advanced instrumentation and optics such as laboratory
and astronomical spectrographs, high-bandwidth optical communications and fusion energy
research. Conventional means of fabricating gratings, such as diamond ruling, holography, or
beam writing, can take many hours or weeks to complete, and typically produce gratings of poor
spatial-phase fidelity.

The concept of SBIL is to combine the sub-1 nm displacement-measuring capability of laser
interferometry to control a high-performance air-bearing stage, with the interference of narrow
coherent beams, to produce coherent, large-area, linear gratings and grids. Our ultimate goal is
to produce gratings with sub-nm distortion over areas many tens of centimeters in diameter.
SBIL requires sophisticated environmental controls to mitigate the effects of disturbances such as
acoustics, vibration, and air turbulence, and variations of temperature, pressure, and humidity.
The system also features real-time measurement and control of optical phase using heterodyne
fringe detection, acousto-optic modulator phase locking (see Fig. 3), and a high-speed digital signal processor (DSP) controller (see Fig. 4).

An important feature of SBIL is the ability to both write and read gratings with nanometer control of grating phase. Fig. 5 is a map of phase error for a grating that was first written in the Nanoruler, developed, and then placed back into the tool and read. The data demonstrates ~2 nm 3σ repeatability of the writing/reading process, which includes errors due to substrate chucking/unchucking.

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<tbody>
<tr>
<td>CD (nm)</td>
<td>130</td>
<td>115</td>
<td>100</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>65</td>
<td>45</td>
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<td>OVERLAY (nm, mean+3 sigma)</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>32</td>
<td>26</td>
<td>25</td>
<td>23</td>
<td>18</td>
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<td>9</td>
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<td>MASK IMAGE PLACEMENT (nm)</td>
<td>27</td>
<td>24</td>
<td>21</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>11</td>
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| METROLOGY FRAME ERROR (nm) | 11   | 10   | 8.8  | 8.0  | 7.0  | 6.3  | 5.8  | 4.5  | 3.3  | 2.3  |
| LENGTH SCALE ERROR (nm) | 2.8  | 2.5  | 2.2  | 2.0  | 1.8  | 1.6  | 1.4  | 1.1  | 0.8  | 0.6  |

Table 1. Summary of Metrology Efforts and Results

**Figure 1.** Semiconductor Industry Association (SIA) roadmap tracking critical dimension (CD) or minimum feature size, overlay error, mask image placement error, and metrology tool error. The MIT effort seeks to produce grating metrology standards with sub-nm errors, which would be used as planar metrology length scales or optical encoders in lithographic and other equipment, eliminating the laser interferometer.

**Figure 2.** Schematic of the scanning-beam-interference-lithography (SBIL) system under development in the SNL. A pair of narrow, low-distortion beams overlap and interfere at the substrate, producing a small grating “image.” The substrate is moved under the beams, writing a large area grating. Tightly overlapped scans ensure a uniform dose.
Figure 3. Schematic of SBIL acousto-optic (AO) modulator phase locking system. Both writing and reading modes are depicted. The phase of the grating image is measured by a small interferometer close to the writing surface. The AO modulators Doppler shift the beams into the megaHertz range, providing high-accuracy heterodyne measurement of phase. This information is processed by a digital signal processor and used to control RF frequency synthesizers which drive the AO modulators, thus locking the image phase to the moving substrate.

Figure 4. Schematic of SBIL system control architecture. The system utilizes a frequency stabilized HeNe laser (λ=632.8 nm) and heterodyne interferometry to measure substrate position, and argon ion laser (λ=351.1) heterodyne interferometry to measure image fringe phase. Phase error signals are processed by an IXTHOS 4x167 MHz DSP board which then drives the stage DC motors and the RF digital frequency synthesizer controlling the fringe-locking AO modulators.
Figure 5. Wafer phase mapping repeatability (nm), for a 400 nm-period grating that was written and then read by the Nanoruler.