A Brief History of Gratings and the Making of the MIT Nanoruler

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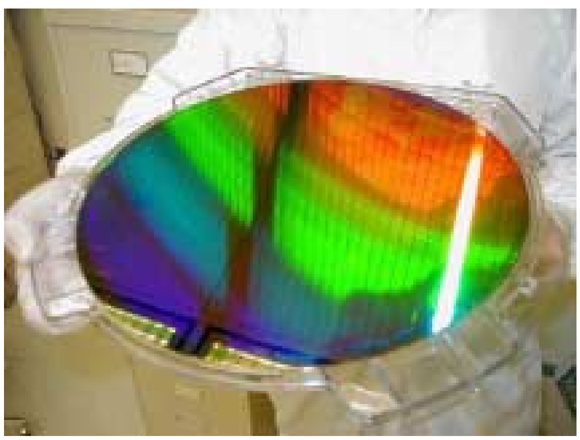
MIT Makes the World's Most Precise Ruler

A team of MIT students, scientists and engineers has developed the world's fastest and most precise tool for patterning large gratings. This new tool, called the Nanoruler, is capable of fabricating gratings 10-1000 times faster and more precisely than previous methods. This revolutionary technology will enable breakthroughs in many areas including semiconductor manufacturing, advanced lithography, metrology, nanotechnology, diffractive optics, space physics, fusion energy research, magnetic storage and flat panel displays. The Nanoruler continues a line of research in advanced grating fabrication technology initiated at MIT in the late 1940's by Prof. George R. Harrison, placing MIT once again at the forefront of grating fabrication technology.

The Nanoruler took the team five years to develop. Now fully operational, it makes the most precise "rulers" that the world has ever seen. Figure 1 shows a photograph of a 400 nm-period grating covering a 300 mm-diameter silicon wafer that was written in around 20 minutes. The team, led by Dr. Mark L. Schattenburg of the MIT Center for Space Research, was comprised of physicist Dr. Ralf K. Heilmann and students Paul T. Konkola of mechanical engineering and Carl G. Chen of electrical engineering, with significant technical assistance from Mr. Robert Fleming. (Chen and Konkola received Ph.D.'s in June of 2003.) Results of initial trials of the tool were published in the Nov/Dec 2003 issue of the *Journal of Vacuum Science and Technology B.* NASA and DARPA supported the research, for which a patent is pending.



Ralf Heilmann

Figure 1. *White light from an overhead fluorescent lamp diffracts off the surface of a 400 nm-period grating and resolves into its color spectrum. The substrate is a 300 mm-diameter silicon wafer (around 12 inches), the largest of all current wafers in semiconductor manufacturing.*

The Nanoruler – A Revolutionary New Tool

The machine standing inside the Space Nanotechnology Laboratory (SNL) in the MIT Center for Space Research has a commanding presence. Its enclosure, the size of a small bedroom, is hard to miss. This specially designed cleanroom, which is itself housed inside a much larger temperature-controlled cleanroom, is designed to hold air temperature fluctuations in its interior to a fantastically small 0.005 degrees Centigrade. The job of the enclosure is to protect the tool from heat plumes, noise, and other disturbances that are the bane of high precision. Of course, humans, who emit large amounts of noise, heat and dust, are strictly banned from the enclosure except during maintenance. Inside this inner sanctum sit several tons of granite and gleaming stainless steel, sheaves of electronic and fiber optic cables, and a maze of optical components shepherding a criss-cross of red and ultraviolet laser beams, all controlled by a bank of high-speed computers.

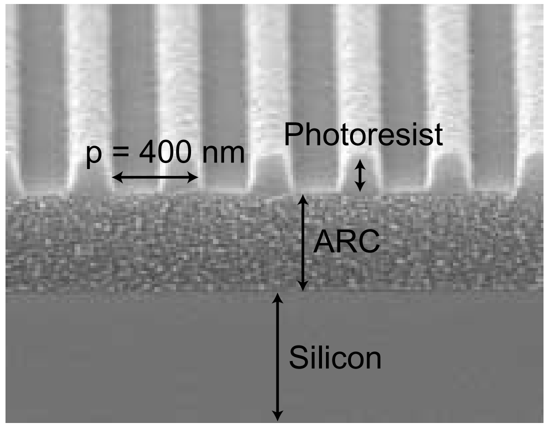
Visitors to the SNL cleanroom must clad themselves in dust-free bunny suits before being allowed to enter. Once inside, they enter an unfamiliar world of nanofabrication tools and monitoring equipment, surprised by the yellow illumination and constant humming of giant air filtration units above. It is in here that the MIT team has successfully demonstrated a novel form of interference lithography (sometimes called holographic lithography). The new technique is capable of patterning gratings with periods down to 150 nanometers and with distortions that are hundreds of times smaller than traditional techniques. Patterning on substrates well over one meter in size should also be possible.

The new interference lithography (IL) technique overcomes a host of long-standing problems that have plagued conventional grating fabrication methods such as mechanical ruling, interference lithography and scanning electron-beam lithography. Its IL predecessor has been practiced for decades and is very simple in principle. By crossing and interfering two ultraviolet (UV) laser beams, periodic interference fringes result which are captured and imaged in a photosensitive coating. In practice, however, pattering large gratings with precise control has bedeviled labs around the world for a long time, despite great efforts.

The new IL technique causes narrow beams to interfere, creating a small grating "image." Large gratings are written by scanning a substrate under the image with a high-precision air bearing stage. The MIT team calls this new technique *scanning beam interference lithography* (SBIL) and christened the first-ever SBIL tool the *Nanoruler*, because it "rules" gratings by scanning the substrate, similar to the time-honored "ruling" technique of scratching a diamond tip over a substrate (more on this below), and because it makes very accurate rulers which can be used as length scales. The SBIL method can be thought of as a hybrid of the older ruling and holography techniques, but with the added virtue of sophisticated electronic feedback that ensures long-range fidelity.

What is a Grating?

Conceptually, a grating is a simple pattern constituting periodic lines and spaces. Figure 2, for example, shows a scanning-electron micrograph (SEM) of the cross section of a grating patterned by the Nanoruler. The grating structure is defined in a thin layer of light-sensitive polymer called photoresist – "resist" because of its resistance to chemical or plasma etching, which is often used to subsequently transfer the pattern into an underlying substrate. The spatial period of the grating is defined as the distance in which the line-space pattern repeats itself. The grating in Figure 2 has a period of 400 nanometers or 0.4 microns. (A human hair has a diameter of approximately 100 microns.)



Carl Chen

Figure 2. *Scanning-electron micrograph of the cross section of a grating written by SBIL. ARC is the acronym for anti-reflection coating. The ARC is present so that during the lithography process, light reflection off the polished silicon substrate is minimized. Unchecked, this spurious reflection leads to unwanted secondary interference and loss of line width control.*

A Brief History of Gratings – the MIT Connection

Gratings are of particular interest to scientists and engineers. Our world is bathed in a sea of electromagnetic (EM) radiation. The human eye, for instance, can perceive EM radiation in the wavelength range of 380 nm (violet light) to 750 nm (red light). When the period of a grating is comparable to the wavelength of light, a physical phenomenon called diffraction is manifested wherein the interplay between the incident beam and the periodic structure gives rise to multiple output beams, the so-called orders of diffraction. The angles of the diffracted orders vary as a function of the wavelength of the incident light. If the incoming light is multicolored, i.e., comprised of more than one wavelength, then the angles of diffraction differ from one particular color to the next, resulting in a so-called spectrum of the incoming light. Figure 1 shows just such an effect. The white light from an overhead fluorescent lamp diffracts off the grating and resolves into a color spectrum that is much like a rainbow.

The ability of a grating to physically disperse light into its constituent spectrum has made it one of the most powerful analytical tools for the study of physical sciences. MIT professor George R. Harrison (1898-1979), the former head of the Spectroscopy Lab and later Dean of Science and one of the pioneers in the design of modern grating ruling engines, once wrote: “No single tool has contributed more to the progress of modern physics than the diffraction grating, especially in its reflecting form [1].” MIT played, and is continuing to play, a leading role in developing state-of-the-art diffraction gratings.

Not without argument [2], the making of the first diffraction grating is often credited to the American astronomer David Rittenhouse (1732-1796) in 1785. He had a watchmaker cut very fine screws out of two pieces of small brass wire, and in the thread of these screws he laid hairs. Crude as it may be, this simple grating was sufficient to demonstrate the effect of light diffraction. Unfortunately, “want of leisure” made Rittenhouse pursue the idea no further, and his work, though published [3], attracted little attention at the time.

It was not until 1813 that the German physicist Joseph von Fraunhofer (1787-1826) reinvented the diffraction grating. A master instrument maker, Fraunhofer was dissatisfied with the quality of screw-wire-wound gratings and proceeded to build the first-ever grating ruling engine. A ruling engine, in a most simplistic description, is composed of two key parts: a carriage which holds the grating blank, and a very sharp tool, which is almost exclusively a diamond point, for burnishing the blank. During ruling, the diamond is “dragged” across the blank—one of Fraunhofer’s first trials used a glass substrate covered with a thin layer of gold. When the ruling of one groove is complete, the carriage moves across by one grating period under the guidance of a well-made leadscrew so the next groove can be ruled. Thus he produced gratings with much finer periods than previously achieved. With these improved gratings, he was able to accurately measure the absorption lines in the solar spectrum, now known as the Fraunhofer lines [4].

Diffraction grating development, especially in the early years, was driven primarily by the demands of spectroscopists like Fraunhofer. Since larger gratings permit higher spectroscopic resolution to be achieved, the push to attain ever finer resolution drove a new generation of engineers to design better engines capable of ruling larger gratings. Henry A. Rowland (1848-1901) is perhaps the most dominant of these figures, whom Harrison called the “father of the modern diffraction grating” [1]. He and his successors at the Johns Hopkins University designed and implemented a series of ruling engines, each mechanically superior to its predecessor, incorporating advanced ideas such as temperature control and kinematic isolation. Rowland engines, capable of producing gratings as large as 7.5 inches, essentially supplied most of the gratings desired by the world’s scientific community for nearly 50 years [5]. Albert A. Michelson (1852-1931), the celebrated Nobel laureate who demonstrated that the velocity of light is a constant in all inertial reference frames, and inventor of the Michelson interferometer, tackled the problem of ruling gratings that were even larger than Rowland’s. Reportedly, he was able to produce gratings as large as 10 inches with excellent resolution, although very few of the gratings survived.

One of Michelson’s engines later ended up at MIT in 1947, at Professor Harrison’s lab. The modern era of ruling dawned when Harrison and his team equipped their engine with interferometric position feedback control in 1955 [6]. A displacement measuring interferometer (DMI), such as the design by Michelson, is a device that can measure the distance between two mirrors in terms of the wavelength of the light source, and with high resolution. Errors in the ruling motion, which were once unobservable and due to the imperfections in the mechanical system, could now be seen and compensated for. Far superior to any prior art, Harrison’s design has become standard practice in modern ruling engines. The so-called MIT B Engine, built by Harrison, was moved to the Richardson Grating Laboratory (now Spectra-Physics, Inc.), Rochester, NY, and is still in use today.

Even though the modern ruling engine stood at the pinnacle of precision machine design for a long time, the ruling process suffers major drawbacks. Due to its serial nature, mechanical ruling is painstakingly slow. Large gratings can take weeks or even months to complete, meaning that they are extremely uneconomical. The accumulated travel by the diamond tool is measured in tens of kilometers (km), which imposes significant tool wear. Under an ideal scenario where the best diamond crystal is used to rule the purest aluminum, the diamond can only last about 15 km [7]. The limited tool life thus requires one to make concessions on how fine a period and/or how large a grating to produce. A 12-inch grating with a period of 400 nm, which is easily patterned by the Nanoruler in around 20 minutes, would require a tool travel of greater than 230 km. This is impossible for any mechanical ruling engine to achieve. Environmental control and vibration isolation, both critical for a successful ruling run [8,9], are also extremely difficult to maintain over the lengthy time of operation.

Scanning electron-beam lithography (SEBL) is another popular tool for fabricating gratings. This method is also very slow and expensive, although not nearly as slow as mechanical ruling. In addition, gratings written by SEBL suffer from large distortions and errors due to beam deflection jitter and drift.

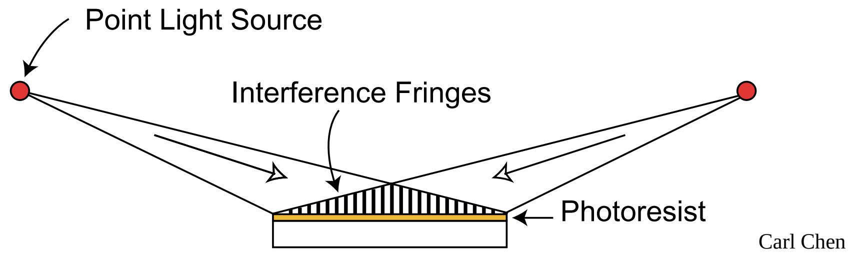


Figure 3. *A schematic of the MIT interference lithography system.*

Interference Lithography

Interference lithography is a widespread tool for making diffraction gratings. The principle of IL is straightforward. Figure 3 illustrates the concept schematically. Two coherent beams of light interfere and produce interference fringes–parallel planes of high and low light intensity. A useful analogy is to imagine two expanding circular water waves, excited perhaps by the dropping of two stones into a quiet pond. Where the two waves intersect, a stable interference pattern, called a standing wave, appears. These fringes are recorded in photoresist, which after wet development, become grating lines (Figure 2). Chemical etching and other processes can then be used to transfer the grating structure permanently into a substrate.

Michelson outlined the concept of IL in 1927 [10], yet the first interference gratings were not recorded until the late 1960s [11,12]. The lack of suitable light sources and the poor quality of photoresist were to blame for the initial slow pace of development. However, with the development of the laser and high-quality resists, IL research soon caught on. MIT has played a leading role at the forefront of interference lithography research since 1973, with a patented IL system operating at the Space Nanotechnology Lab [13]. The system has been used to pattern gratings for a number of NASA missions. Most notably, gratings for the High Energy Transmission Grating Spectrometer on the Chandra X-ray Observatory, one of NASA's four Great Observatories, were manufactured and tested at MIT [14]. When not involved with space missions, the IL system has played a critical role in a variety of ongoing research that requires periodic structures.

The IL process is extremely fast compared to ruling since all the grooves are formed simultaneously in a single exposure. The exposure time on the MIT IL system is typically below one minute. This significantly relaxes the requirements on environmental stability. The process is static, i.e., there are no mechanical moving parts, and the long coherence length of the laser determines the spatial coherence of the grating. As a result, spectral defects called "ghosts," which can be prominent in ruled gratings [15,16], are absent in interference gratings. As noted earlier, the size and/or the period of a mechanically ruled grating is governed by diamond wear. In principle, IL is capable of patterning meter-sized gratings with deep-sub-micron periods, the real-world limitations being the laser's wavelength, coherence length and power.

The early interference gratings did not have the same high diffraction efficiency as their ruled cousins, because of an apparent lack of control in shaping the groove profile. However, with the maturing of the fabrication technology, a large number of techniques can now be leveraged to properly manipulate the grating profile in order to yield the desired efficiency. For example, metallic reflection gratings have been produced through IL that have a diffraction efficiency exceeding 95% for the first order. In other words, nearly all of the incoming light energy is concentrated in one diffracted beam [17].

Where IL fails to shine is in the area of producing large linear gratings with uniform diffraction efficiency. Figure 4 graphically depicts the difference between a linear and a nonlinear grating. The only way that traditional single-exposure IL can generate linear gratings is if the two interfering beams are plane waves. While perfectly suited for textbooks, plane waves, especially ones that can cover substrates hundreds of millimeters wide, are difficult to generate in practice. Even though the optics in a traditional IL setup can be formed to yield "pseudo" plane waves, their wavefronts can never be truly planar and the gratings thus produced will carry in them inherent nonlinear distortions on the order of dozens to hundreds of nanometers.

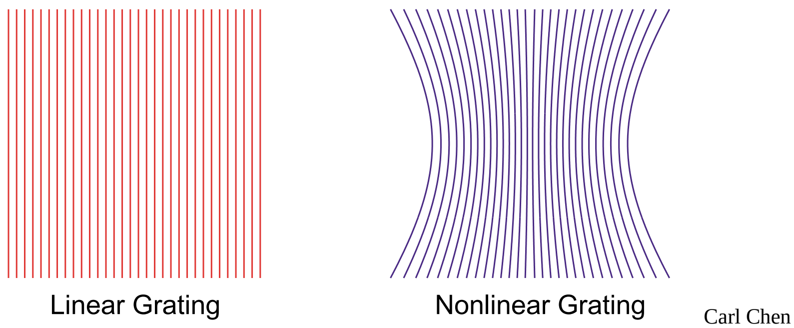


Figure 4. *A linear grating vs. a nonlinear grating (schematic only). The grooves on the linear grating form perfect parallel straight lines, whereas those on the nonlinear grating are a family of curves.*

The Breakthrough - Scanning Beam Interference Lithography

To produce gratings that are not only large but also perfectly linear and uniform, scanning beam interference lithography was invented. The Nanoruler was designed to pattern gratings with a precision of better than 1 nm across a 300 mm substrate, and its current performance comes very close to that goal. That is the equivalent of hitting a target the size of a nickel in Manhattan all the way from San Francisco.

The concept of SBIL was the brainchild of SNL director, Dr. Mark L. Schattenburg (MIT Ph.D., Physics, 1984). Schattenburg originally conceived of the possibility of having perfect linear gratings that could be used as fiducials for conducting nanometer metrology [18]. Today's advanced computer chips are nano-engineering marvels packed with millions of transistors—the tiny on-off switches that form the heart of a modern computer. Every eighteen months or so, according to the well-known Moore's Law, the number of transistors on a chip will double. Increasingly, however, it becomes a challenge to stuff more and more of these ever-shrinking features into an area no larger than a thumbnail. What Schattenburg wanted in essence was an extremely well-made "ruler" whose ticks are spaced not millimeters but nanometers apart, and whose size was comparable to the largest commercial silicon wafers. If such a ruler could be created, it would help chip makers do a much better job of laying down the Lilliputian circuitry.

The semiconductor industry is by no means the only beneficiary here. Remember displacement measuring interferometry? All of today's state-of-the-art DMI systems are laser based. To acquire one, including the laser head, optics, measurement electronics and the necessary environmental enclosure, the cost is high. Measurement accuracy is a concern, too. Since the technology relies on the presumed stability of the laser, any factor that changes the laser's wavelength (e.g., fluctuations of atmospheric pressure, temperature, etc.), however slightly, tends to introduce measurement errors. Yet another concern is the system's bulky size. On the other hand, grating-based interferometers are cheap, compact and when made appropriately, very stable [19]. However, because of a lack of large accurate gratings, they have not been available as substitutes for laser interferometers when ultra-precision work is concerned. With SBIL, grating interferometers may finally gain the technological edge over laser interferometers—a complete paradigm shift is in sight.

More generally, any field that relies on periodic structures may benefit from the new MIT technology. These include integrated optics, telecommunications, magnetic information storage, field emitter array displays, distributed feedback lasers, and high-resolution spectroscopy. An excellent example is the research headed by MIT Professor Henry I. Smith whose group has succeeded in employing gratings to accurately steer and position an electron beam for advanced lithography, achieving an accuracy that is over 20-30 times better than the best commercial systems [20].

In terms of implementation, SBIL can be thought of as a hybrid of mechanical ruling and traditional interference lithography. Figure 5 demonstrates the SBIL concept in its skeleton. Two narrow UV laser beams, roughly 2 mm in diameter, interfere and produce a small patch of interference fringes. The fringes expose a small spot in the photoresist coating on a substrate. The substrate is affixed to a stage. As the stage moves along the fringe direction, a strip of resist is thus exposed. This is called a scan. In order to build up a large grating, the stage must move so as to stitch together many scans. Because of its motion, which is similar to that of a ruling engine, and because of its product of nanometer-accurate gratings, the SBIL tool has been named the Nanoruler.

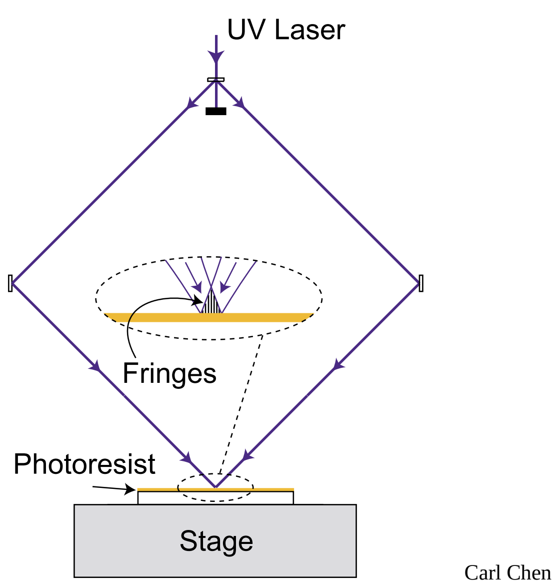


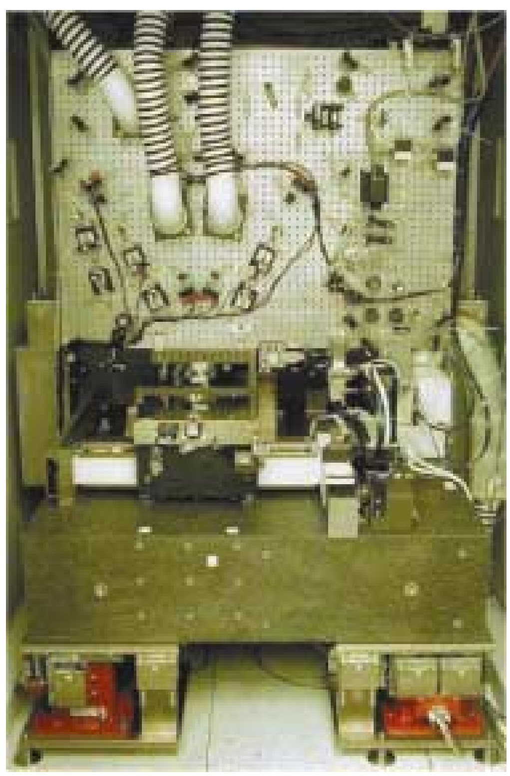
Figure 5. *A schematic of the SBIL concept.*

SBIL offers significant advantages over ruling and IL. The small beams used in SBIL provide a major benefit in ease of obtaining small wavefront distortions and thereby highly linear fringes within the interference spot. By scanning the fringes, nonlinear distortions along the scan direction can be averaged out. Overlapping adjacent scans leads to further and more significant smoothing. Instead of a single diamond tip, SBIL in a sense writes with thousands of “tips” in parallel, which dramatically improves the system throughout. For example, to create a grating 300x300 mm in size (about the size of a dinner plate) with a period of 400 nm, a current state-of-the-art ruling engine, under a most ideal scenario (assuming its tip stays intact!), has to run continuously for 50 days, whereas the Nanoruler can finish the job in around 20 minutes.

Team Had to Overcome Many Obstacles

To turn SBIL into reality, Schattenburg enlisted the help of a staff scientist and two graduate students: Dr. Ralf K. Heilmann, Paul T. Konkola (MIT Ph.D., MechE, 2003) and Carl G. Chen (MIT Ph.D., EE, 2003). Konkola and Chen were tasked to solve the difficult problems of synchronizing (i.e., locking) the interference fringes to the moving substrate, and of measuring the fringe period and minimizing fringe nonlinearity [21,22]. Heilmann implemented the complicated optics required to lock the interference fringes.

The project had its share of trials and tribulations. Over the course of five years the system saw no fewer than five major upgrades. Towards the end of the project, Chen was stuck in Beijing due to a visa delay. In those six months, he was able to work out some of the fundamental physics validating the SBIL concept, while Konkola plowed through a long series of mechanical and electronic problems and finally churned out the first-ever SBIL grating in early 2003 [23]. For both, the experience of building the Nanoruler from scratch has been immensely rewarding and something they believe that no school other than MIT could have provided. That a small team of bright and dedicated MIT students was able to design and build a tool of such power and complexity is testament to the school’s spirit of excellence, and a tribute to the trust and support of the faculty and sponsors.



Paul Konkola

Figure 6. *Photograph of the MIT Nanoruler.*

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