The critical role of metrology in nanotechnology.

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ABSTRACT

The nascent nanotechnology revolution promises many benefits to humankind. An exciting and sometimes bewildering variety of new nanofabrication technologies and nanodevices based on electrical, optical, magnetic, mechanical, chemical and biological effects are reported almost daily. It is prudent to ask, however, how many of these breakthroughs will remain laboratory curiosities and how many will proceed to widespread industrialization. We argue that a metrology infrastructure has underpinned all industrial revolutions, and that this infrastructure is weak or nonexistent for many of the proposed nanosystems. More attention needs to be paid to metrology or progress will be derailed in a number of areas.

Keywords: nanotechnology, metrology, nanometrology, nanostructures, lithography

1. INTRODUCTION

In many ways the nanotechnology era is already upon us. The study of biological systems and the engineering of many materials, such as catalysts, have been in the nanometer regime for centuries. What has changed recently is an explosion in our ability to image, engineer and manipulate systems on the nano-scale.

A remarkable convergence of scales looms large on the horizon. Coming from one direction is the relentless shrinkage of device scale that is fueled, in large part, by massive economic and intellectual investments in the semiconductor, opto-electronic, and related information technology industries. This push is expected to terminate at the 10-30 nm level in the next two decades. Coming from the other direction is an exponential growth in our ability to manipulate and assemble individual atoms, moving up from the atomic level (0.1 nm) to the 10-100 nanometer regime. At the convergence of these scales exciting new discoveries are bound to be waiting.

A number of visionaries have successfully sold the idea of this nascent nanotechnology revolution to policy makers as “the next big thing.” This has unleashed a flood of new initiatives in industry, government and academia. One of the difficulties in this effort is the near-impossibility of adopting a consistent definition of the field and its goals. This problem is exacerbated by the extremely broad range of potential applications for nanotechnology, ranging from electronics, optical communications and biological systems, to new materials.

Some define nanotechnology by simply requiring that a critical dimension (CD) of a structure be below 100 nm. Using this definition the semiconductor industry should enter the nano-era in a couple of years. Others add the additional requirement that the salient behavior of the nanostructure needs to be dominated by physical properties intrinsic to its small size. This could be due, for example, to quantum effects that do not become dominant until the structure is small compared to the de Broglie wavelength or the scattering length. Another example would be properties driven by surface-area-to-volume considerations, or dimensional comparability to biological molecules or organelles.

These efforts are starting to bear fruit. Researchers are reporting an increasing number of interesting and potentially useful nanodevices, systems and materials. A few companies have even been started to exploit these discoveries. However, it is not widely recognized that the critical infrastructure necessary to underpin any large-scale industrialization of nanotechnology is equally important and is receiving much less attention.

We argue that a metrology infrastructure has underpinned all industrial revolutions, and that nanotechnology is no exception. For example, the mass production of automobiles, sewing machines and firearms was critically dependant on an accurate, interchangeable, and easy-to-use system of dimensional measurements. This metrology was realized by the wide distribution of sets of accurate gauge blocks that transferred accuracy to the workpiece by use of calipers. An accurate length scale based on the wavelength of light similarly underpins the modern semiconductor industry. This metrology is realized by the wide distribution of interferometers that transfer accuracy to the workpiece by means of optical and electron microscopy.

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The relentless push to smaller dimensions has brought us to the threshold of the nanotechnology era. However, there are signs that the infrastructure necessary to support its widespread industrialization, of which metrology is a critical component, is not at hand and may be difficult to realize.

2. THE IMPORTANCE OF METROLOGY INFRASTRUCTURE

The bewildering variety of proposed future nanotechnologies, much of it the result of wishful thinking, makes the situation difficult to analyze. In this regard it is useful to differentiate nanosystems based on electronic, magnetic, mechanical, optical, or biologic devices, organized to perform some useful function such as information processing, storage, or transmission, from nanodispersed materials or biological agents that, by their passive nature, confer a useful property such as increased strength or more effective drug delivery. In this paper we concentrate primarily on organized nanosystems.

Metrology is the engineering discipline of measurement. A stroll through any manufacturing plant will demonstrate the critical importance of metrology. For example, a petrochemical plant depends on hundreds of measurements of temperature, flow, pressure, viscosity, chemical composition, and a host of other quantities. A modern semiconductor manufacturing plant is similarly bristled with an even more complex metrology infrastructure that is essential for effective process control. Literally thousands of measurement points monitor the environment, tools, and ultra-pure feedstocks used to manufacture chips. However, this is not enough. No matter how exquisitely a semiconductor process is controlled, the outcome is still not adequately determined. Early in a new chip's manufacturing cycle this is due to the "learning curve" uncertainty of how a particular process variable affects circuit performance. Later it is due to subtle shifts in the calibration points of process instrumentation, to drift, wear or malfunction of equipment, or changes in feedstock quality. For these reasons manufacturers are forced to provide infrastructure for the direct metrology of device structures on test and product wafers. Quantities such as feature linewidth, pattern overlay error, film thickness and composition, and dopant concentrations are measured. Because this metrology is directly in the manufacturing path, high speed and low cost are paramount.

All manufacturing plants, producing everything from bread to jet aircraft, are subject to these considerations. Would a factory manufacturing nanosystems somehow be exempt? This is an important question that merits close study. It is possible that there may be a broad class of nanotechnologies that, while they may be exciting in the laboratory, cannot be economically manufactured due to the lack of metrology infrastructure. At the very least, this exercise may reveal critical nanometrology technologies that need to be developed.

3. WHY IS METROLOGY IMPORTANT?

Future nanosystems based on electrical, optical, magnetic, mechanical, chemical and biological devices will require metrological means to characterize such critical parameters as structure dimensions and composition, stiffness, surface smoothness and stickiness, dopant concentration, magnetic coercivity, and a host of other properties on the nano scale. In this paper we focus on dimensional metrology considerations.

Nanostructures need tight dimensional control to ensure manufacturability. The very fact that the small size of a structure confers some useful property implies that a lack of control of that parameter will lead to large variations in performance. For example, we recently manufactured atom filters for a space mission that utilized 45 nm pores in a gold foil to block ultraviolet light. We found that if our manufacturing process allowed the pores to grow by only 10 nm this caused a 10x degradation in the filter's efficiency [1].

Organized systems generally require some type of communication conduit between devices. This can be accomplished by many means, such as wires, fringing fields, optical waveguides, or chemical transmitters. This in turn requires accurate control of the size and placement of the information conduits and interfaces. For example, a carbon nanotube that is utilized in a circuit will cause an open circuit if it is too short or may cause a short to a neighboring circuit if it is too long.

Current microelectronic systems are characterized by an extremely high degree of fault intolerance. A single defect in a chip may render it useless, while one can kill a fairly sizable number of brain cells and still thrive (as any college student will attest). The mounting difficulties of device yield and metrology on the nanoscale may be telling us something. Perhaps we need to look at system architectures that are designed to be highly fault tolerant on a micro-scale. While such a system would not eliminate the need for dimensional control of nanostructures, it would go a long way towards addressing many manufacturability issues.

There are a variety of ways that dimensional control can be accomplished. In biological systems, for example, proteins are identically self-assembled from smaller components using information ultimately derived from the reading of genes in a DNA template. Larger structures are assembled from these proteins using cellular machinery that, while fascinating, is not fully understood. While the initial stages of this process are marked by a high degree of perfection (i.e., proteins are nearly identical) biological systems are characterized on larger scales by a high degree of structural disorder and have needed to develop a variety of methods for repair and fault tolerance. Perhaps to cope with these issues, biological systems utilize a large number of feedback control loops.

Based on these biological inspirations, many researchers have proposed various self-assembly schemes for manufacturing nanosystems. The building blocks in this scheme could be engineered macromolecules combined with inorganic components such as nanocrystals or carbon nanotubes. This is attractive since it obviates the need for slow, expensive and coarse lithographic patterning and seems to eliminate the need for metrology. While this vision is seductive, it seems wishful thinking to expect that self assembly would be so perfect that it would manufacture flawless and highly ordered systems simply by design. To be successful, this process would require flawless design, feedstock, and assembly, and a perfect understanding of the interactions between the nanocomponents. Fault tolerant architectures would alleviate but not eliminate this problem, since design errors or contaminated/defective feedstock will result in a non-operative system and no means to detect why. It is instructive to consider that natural biological systems have successfully evolved “self metrology” to solve these problems by the use of natural selection over millions of years. Unfortunately, these tools are not available to designers.

Chemists have developed a number of schemes for building nanostructures, such as block copolymer patterns and nanocrystal quantum dots, based on surface chemistry considerations. While a number of interesting nanostructures have been made this way, control of critical dimensions is determined by control of the chemical process. In contrast to protein assembly, this process is not template (gene) driven and the production of elements identical at the atomic level is problematic. Hence accurate nanometrology is essential for manufacturability.

Many researchers have proposed using planar templates to impose short- or long-range order on the self-assembly processes. For example, Cheng *et al.* [2] used a nano-imprinted grating to establish long range order on block copolymers for the purpose of patterning nanomagnet arrays. Recently Kirakosian *et al.* [3] proposed using an atomically accurate silicon grating with 5.73 nm period as a self-assembly template with short-range order. To be successful, this technique requires templates with a high degree of perfection that would need to be metrologically verified and controlled. If proven, this method could be an attractive means for the assembly of periodic patterns, but does not address the general self-assembly problem.

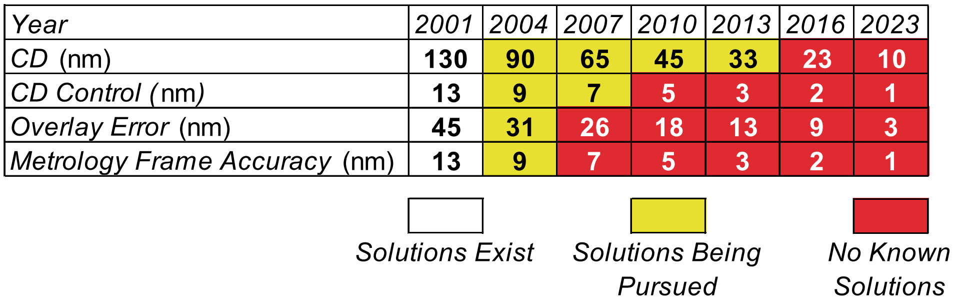
4. THE END OF THE “METROLOGY VACATION”

Despite all the excitement and hoopla surrounding the nanotechnology initiative, we still have only one viable paradigm for the large scale manufacturing of general nanosystems, and that is based on extensions of current lithographic patterning technology into the nanometer domain. Industry consensus is that this process can be extended down to ~30 nm CD (see Fig. 1). Below this is an open question [4-5]. However, even if tomorrow a breakthrough fabrication paradigm is demonstrated, it is likely that the current path of the industry will continue for some time due to the existence of a tremendous industrial infrastructure and knowledge base. In this section we examine the implications of metrology on the further scaling of lithographic technology into the nanometer domain.

For all its high-tech glamour, the dimensional metrology infrastructure in the industry is based on old technology. The measurement of the minimum feature size, the so-called critical dimension (CD), until only a few years ago was based on the optical microscope, a technology that has not significantly changed in over a hundred years. Now that features have finally shrunk well below the wavelength of light, manufacturers have turned to electron microscopy, utilizing electron optics essentially unchanged in 50 years. Dimensional accuracy is provided by laser interferometers that have not appreciably changed in 30 years. Thus during the last several decades manufacturers have enjoyed a “metrology vacation” by exploiting these simple, well-known technologies which are perfectly adequate for large feature sizes. Unfortunately, as we move into the sub-100 nm era this holiday is rapidly coming to an end.

4.1 The crisis in CD metrology.

Over the next two decades the minimum feature size of electronic circuits is expected to shrink from ~130 nm today to ~10 nm (see Fig. 1) [6]. This requires a CD control of 13 nm today shrinking to 1 nm. Many factors contribute to CD control, including mask errors, lithographic distortion, resist roughness, and pattern transfer fidelity. The need for CD metrology is independent of lithographic choice. In particular, nanoimprint lithography is not exempt. Indeed, since 1x imprint mandrels are required, the CD control problem may actually be worse than the situation for optical reduction lithography, where mask errors are reduced by the optical demagnification ratio.



Year	*2001*	*2004*	*2007*	*2010*	*2013*	*2016*	*2023*
CD (nm)	**130**	**90**	**65**	**45**	**33**	**23**	**10**
CD Control (nm)	**13**	**9**	**7**	**5**	**3**	**2**	**1**
Overlay Error (nm)	**45**	**31**	**26**	**18**	**13**	**9**	**3**
Metrology Frame Accuracy (nm)	**13**	**9**	**7**	**5**	**3**	**2**	**1**

☐ *Solutions Exist*

🟨 *Solutions Being Pursued*

🟥 *No Known Solutions*

Figure 1. Chart adapted from the International Technology Roadmap for Semiconductors 2000 [6]. The first row gives the year and the second indicates the target minimum feature size (*CD*). The third (*CD Control*) indicates the required tolerance on CD variation. The fourth (*Overlay Error*) indicates the pattern overlay error tolerance. The fourth (*Metrology Frame Accuracy*) indicates the error tolerance of displacement metrology in the lithography tool, as provided, for example, by laser interferometers. The dark regions (red) indicate where industry is unaware of any effort or means to provide a manufacturing solution to the requirement.

Until recently the industry relied on optical microscopy for CD measurement in manufacturing. As we've moved into the deep sub-wavelength regime the CD metrology of choice has shifted to the scanning electron microscope (CD-SEM). However, CD SEMs are far from ideal. They are slow and expensive and the electron beam damages resist. To ensure accuracy, metrologists are required to perform comparisons of CD-SEM measurements with detailed modeling results for large libraries of calibration samples patterned with features with known geometries and materials, as verified, for example, by AFM and TEM [7-9]. Calibration sample standardization and distribution across companies and the industry is difficult. These problems are inevitably going to cause a ballooning in the cost and complexity of CD metrology as we go forward.

The accuracy of CD-SEMs is dependent on a host of factors, a fundamental one being the scattering length of electrons. As electrons from a focussed beam penetrate the sample surface they scatter into a teardrop-shaped halo. Current generation CD SEMs, with 1 keV beam voltage, have a scattering halo of around 25 nm. An electron detector measures the flux of electrons that scatter out of the sample as the probe beam is moved across a feature. At feature sidewalls this halo partially leaks through the sample surface, causing a measurement artifact due to the increase in detected electron flux. Moreover, the magnitude of this blur is highly dependent on the geometry and material composition of the feature and any underlying structures. When the size of the scattering halo is small compared to the feature size this effect is negligible. As 10 nm CD is approached, however, this effect becomes increasingly severe and dominates all other error sources.

A number of technologies have been proposed to resolve this crisis. None have been proven. Manufacturers have recently begun to complement CD-SEMs with optical scatterometry tools because of their much lower cost. At best this is a stopgap measure. Ultra-low voltage SEMs have been proposed which should have much smaller scattering halos. Unfortunately, the lower voltage also implies lower beam current, which slows measurement throughput and increases cost. Scanning probe techniques based on carbon nanotubes have also been proposed. With tip sizes of ~1 nm the uncertainty caused by probe size can be tremendously reduced. Unfortunately, probe techniques are also extremely slow. Perhaps a serious look needs to be taken at new microscopy techniques based on atom or electron holography [10], or methods based on massively parallel arrays of scanning probes or low-voltage micro-column electron beams.

4.2 The crisis in pattern placement metrology.

Pattern placement metrology is an equally important enabling technology for nanosystem manufacturing. We believe that future nanosystems based on electronic, mechanical, optic, magnetic, chemical and biological nanodevices will require accurate pattern placement and measurement. These considerations apply to a broad class of tools for patterning nanostructures such as lithography machines and pattern generators utilizing electron and laser beams, or proximal probes such as scanning tunneling and dip pen tools. Accurate pattern placement measurement tools utilizing optical and electron microscopes or proximal probes such as atomic force microscopes will also be essential.

The accuracy of pattern placement metrology is determined by a host of factors that ultimately derive from a substrate stage metrology frame determined by a set of laser interferometers. We first examine this issue as it applies to traditional (lithographic) manufacturing of nanosystems.

Over the next two decades the minimum feature size of electronic circuits is expected to shrink from ~130 nm today to ~10 nm (see Fig. 1). Circuit patterns must be carefully overlaid on the wafer during manufacturing, building up the twenty or more layers of metals, dielectrics and dopants that constitute circuits. For proper circuit functioning, the patterns must be lithographically transferred such that image distortion and stage overlay errors sum to a small fraction of the minimum feature size, typically <30%. The error budget leaves only a small fraction of the error apportioned to the stage metrology frame, typically about 10% of CD or ~1 nanometer. This is ~10x better that the best available wafer stage technology. Moreover, the lithography roadmap indicates that the industry believes there is *no known solution* to this problem.

Patterned nanomagnetic media is another technology where accurate pattern placement metrology will be critical. Disk capacity is increasing so rapidly that bit sizes should approach 25 nanometers within a decade. Many engineers believe that pre-patterned vertically encoded magnetic media may be required [10-14]. This is a radical departure from current practice where the bit boundaries are written onto the disk media during formatting, thus ensuring that disk sectors are accurately concentric to the spindle. For optimal packing, the magnetic dots need to be pre-patterned on the disk such that their placement error is a small fraction of their size, typically about 20% of CD or ~5 nanometer. This is similar to the task of CD or DVD mastering but on a much smaller scale. If this cannot be achieved then read/write heads will be unable to track the dots as the media moves at high speed. Again, an error budget analysis leaves only a small fraction of the error apportioned to the stage metrology frame, typically about 5% of CD or ~1 nanometer.

Another nanotechnology requiring accurate pattern placement metrology is optoelectronic devices such as Bragg-grating-based channel add/drop filters to be used in future high bandwidth all-optical switches [15]. These devices utilize waveguides on optical chips that have been patterned with very accurate submicron-period surface-relief gratings. The waveguides are generally several millimeters long, and yet for efficient phasing require the placement accuracy of grating lines to be better than 5 nanometers. This is significantly better than the accuracy of the best commercially available electron-beam pattern generators. Again, an error budget analysis leaves only a small fraction of the error apportioned to the stage metrology frame, typically about 5% of CD or ~1 nanometer.

Yet another area where nanoaccurate patterns may be essential is for proposed self-assembled nanostructure schemes. Many researchers are developing template-driven self-assembly processes such as block copolymers patterned over surface relief gratings [2]. In many of these schemes the template grating needs to have a pattern placement accuracy that is small compared to the block regions, which are typically 10-50 nanometers in size. Thus the template accuracy needs to be ~1 nm.

Finally, a critical application for nanoaccurate displacement metrology is for coordinate measuring machines, which are also dependent on laser interferometers [16]. These tools are used to characterize errors in precision optical surfaces, diamond turned assembly tooling, precision metrology structures, micro-electrical mechanical systems (MEMS), and planar high-resolution patterns. The accuracy of lithographic and metrology tools is limited, in many cases, by the accuracy of the coordinate measuring tools that are used to build and calibrate them. For example, the extreme-ultraviolet (EUV) optics under development by the semiconductor industry and the national laboratories, and planned for device fabrication down to the 30 nm level, require an optic figure of well under 0.5 nm and assembly tolerances in the nanometer range [17].

For the last several decades the industry has depended on the laser interferometer to establish accurate coordinate reference frames. This was adequate for large features but is becoming increasingly unworkable as we move into the nanotechnology era. The preferred tool for establishing an accurate length scale is the heterodyne laser displacement measuring interferometer (DMI) [18], illustrated in Fig. 2. DMI sensors are sophisticated electro-optic systems utilizing interference between heterodyned pairs of beams, essentially comparing paths to mirrors affixed to the stationary metrology frame with paths to mirrors attached to the moving workpiece stage. Several vendors provide DMI systems that have resolutions below one nm. However, the accuracy of DMI systems can vary from ~10 nanometers to well over 100 nm depending on the length of travel, the environment, and a host of other factors [19-21].

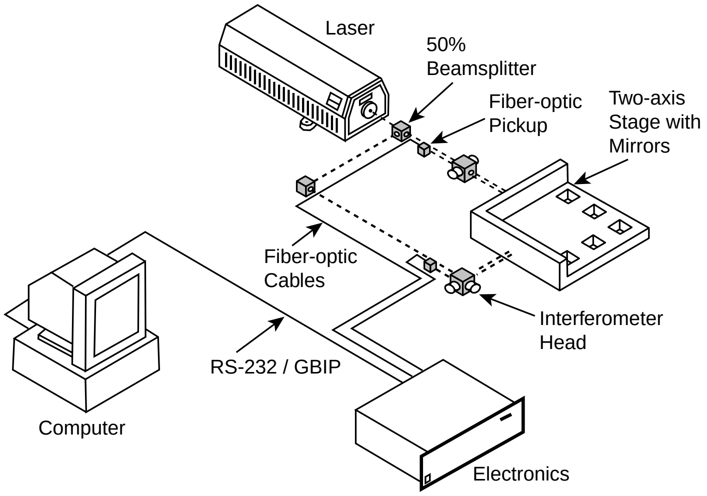


Figure 2. Schematic of a commercial two-axis laser heterodyne displacement-measuring interferometer used with a substrate stage. Accuracy is compromised by the long variable-length beam paths, especially in air. The heavy stage mirrors also compromise accuracy and performance.

Figure 3 depicts the use of a DMI system in an advanced lithography scanner. A number of error sources conspire to degrade interferometer accuracy in real-world metrology systems. DMI systems measure motion in units of the laser wavelength in the interferometer arms. Thus accuracy is severely degraded by such effects as wavelength drift in the laser cavity, and by air turbulence, air pressure, temperature, and humidity variations in the interferometer arms, all which cause refractive index drift and thus wavelength variations. Variable beam paths also compromise accuracy in a number of ways due to diffraction, position-dependant wavefront distortion, and Abbe and cosine errors [22-26].

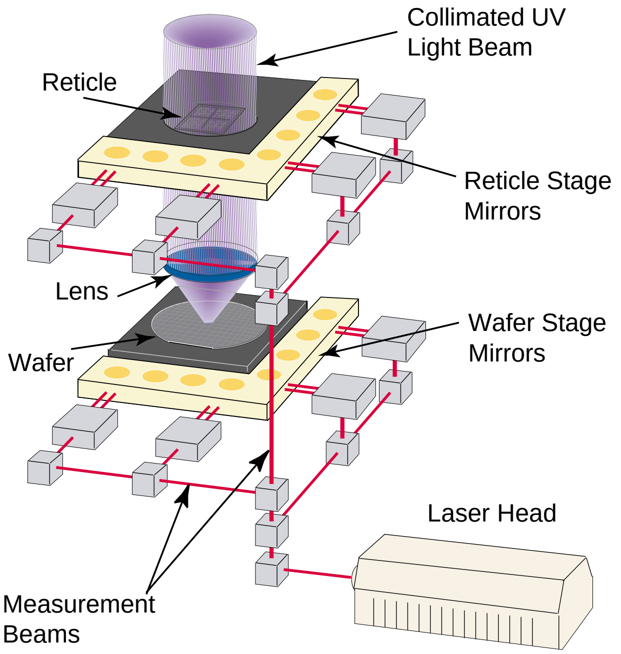


Figure 3. Simplified schematic of modern lithography scanner. The reticle (mask) is imaged onto the substrate using reduction optics. The reticle and substrate stages scan continuously during exposure with a tight 4:1 speed synchronization. The reticle and substrate stage positions are controlled using information from as many as eight heterodyne interferometers.

DMI systems also have the disadvantage of being bulky and expensive, and are difficult to integrate into precision systems. For high accuracy they require exquisite control of the environment or operation in vacuum. Finally, DMI systems require that the workpiece be affixed with heavy interferometer mirrors, resulting in a slow, low-resonant-frequency stage. In high performance stages a significant limit to accuracy and performance is due to ringing of the workpiece platform with respect to the interferometer mirrors.

Fortunately, a simple displacement measuring technology, called the optical encoder, solves nearly all of these problems. This technology is accomplished by affixing stable optical encoder plates to a stationary metrology frame, and reading these plates using sensors affixed to the moving substrate stage. The encoder plate is patterned with an accurate, fine-period grating. Figure 4 depicts the principle of operation. The sensor head measures the displacement of the workpiece with respect to the encoder plate by counting and dividing individual grating lines. The stage mirrors are eliminated. Higher resolution is achieved by measuring the phase shifts of beams diffracted from the grating. Figure 5 depicts the same lithographic tool as shown in Fig. 3, but now modified to accommodate encoder plates.

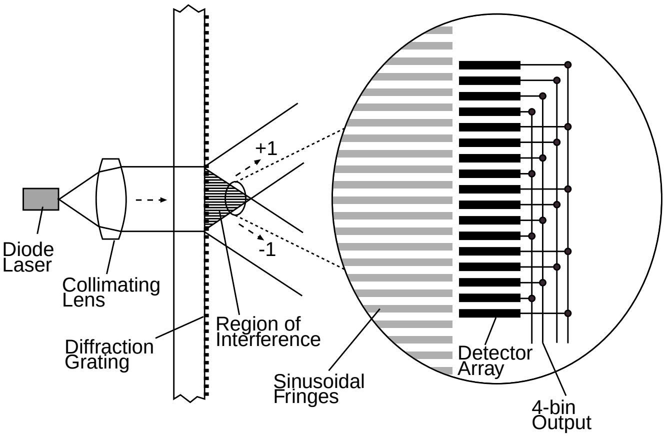


Figure 4. Schematic of a high-resolution optical encoder utilizing interference between ±1 order diffracted beams (MicroE Systems Corp.).

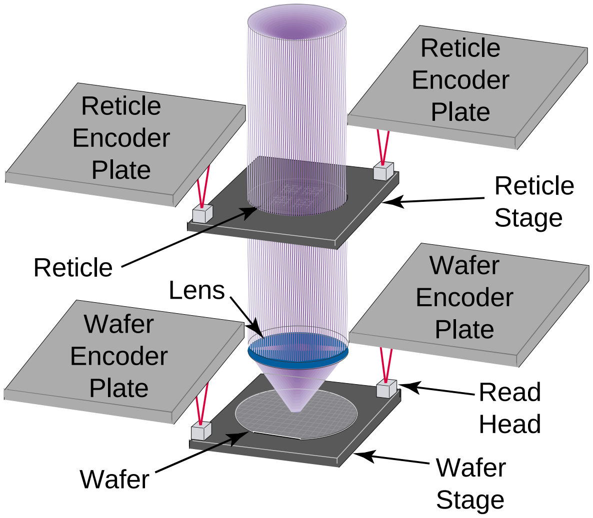


Figure 5. Lithography scanner where the laser interferometers have been replaced with high-accuracy encoder plates. Fixed encoder plates provide positional information to sensors attached to the moving wafer and reticle stages.

Encoders utilize short and constant-path-length beams traveling between the sensors and the encoder gratings, eliminating the effects of the atmosphere. Encoders require a much simpler, more compact, and less expensive optical system. These advantages could be instrumental in the widespread dissemination of new nanotechnology.

Encoder systems with resolutions well below one nanometer are commercially available. Unfortunately, the poor quality of even the best commercially available encoder plates generally limits their accuracy to ~100 nm. To resolve this problem we are developing new technology in our laboratory for the rapid patterning of large-area, sub-nanometer-distortion encoder plates, utilizing a tool called scanning beam interference lithography (SBIL), depicted in Fig. 6 [27-29].

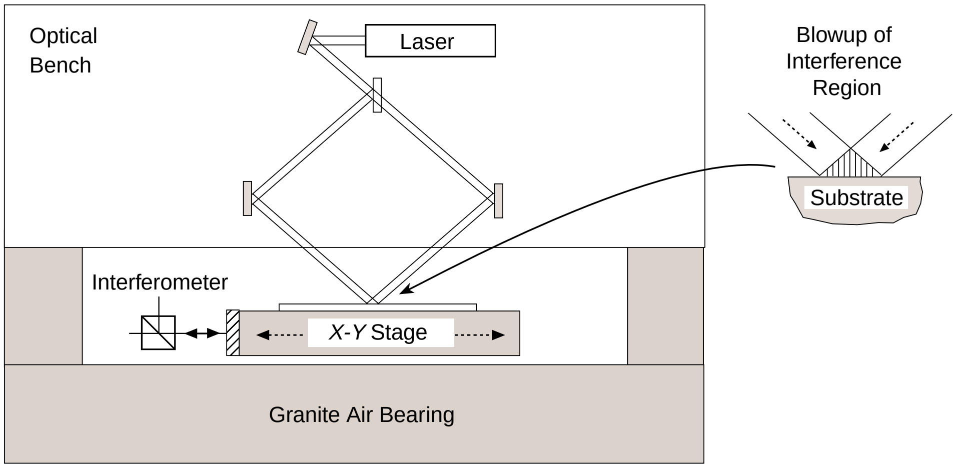


Figure 6. Depiction of SBIL tool. A writing interferometer forms phase-locked fringes in a small region of the substrate. A high-performance interferometer-controlled air bearing stage scans the substrate under the fringes to write a large grating with extremely low distortion. The substrate is raster-scanned under the image in tightly overlapping strips, thus ensuring a uniform exposure dose. A high-speed electro-optic system, not shown, keeps the fringes locked during scanning.

We have also demonstrated how large-area, low-distortion gratings can be used directly in electron-beam lithography tools, via a technique called spatial-phase-locked electron-beam lithography (SPLEBL), depicted in Fig. 7. The objective of this research is to eliminate the need for accurate stage metrology and compensate in real time for beam position drift [30-33].

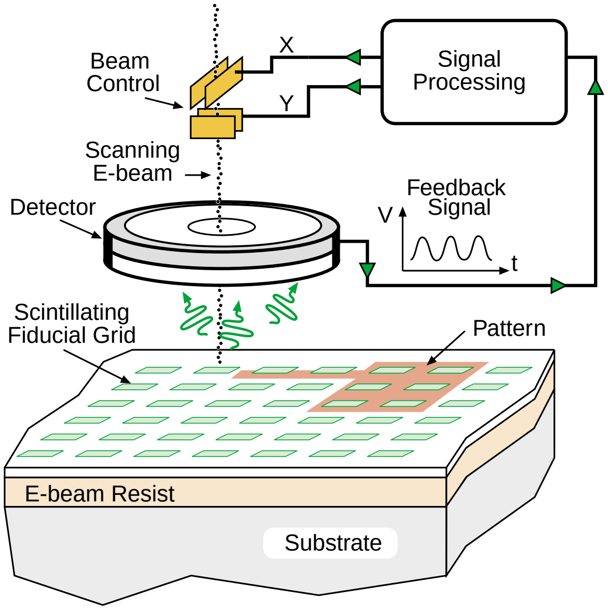


Figure 7. Depiction of spatial-phase-locked electron-beam lithography (SPLEBL) in the global, real-time mode. Scintillation from the fiducial grid, which is transparent to the electron beam, enables phase-locking the writing beam to the fiducial grid while writing patterns, thus eliminating stage and beam-deflection errors.

5. SUMMARRY

We are poised on the threshold of the exciting new era of nanotechnology. However, many of the research efforts now underway will fail to achieve success if means cannot be provided to bring these technologies to industrialization. History teaches that a metrology infrastructure has underpinned all industrial revolutions, yet there are signs that the necessary infrastructure is weak or missing for nanotechnology. Much more attention needs to be paid to all areas of nanometrology, especially to technologies that have the potential for rapid measurements that are critical for manufacturing process control.

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