Metrology requirements for lithography's next wave

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ABSTRACT

Lithographic technology has progressed through a number of "waves," beginning with contact printing and progressing to today's DUV step-and-scan exposure methods. Measurement capabilities have also evolved commensurate with changes in the exposure technology and feature sizes. The greatest measurement challenges today are related to gate CD control requirements, as these have been greatly accelerated during the past 10 years. Scatterometry represents a new method that may help to address this need, but something else is likely required for measurement of line-edge roughness (LER). More direct measurements of parameters such as lens aberrations, are also required. Overlay measurement will also be challenged to meet the needs of future lithographic technologies, and solutions must address the interplay between lens aberrations and overlay errors. Next-generation lithographic technologies will require a host of new metrology capabilities, and the late availability of the means for measurement could delay the introduction of the new technologies.

Keywords: Lithography, metrology

1. INTRODUCTION

Lithographic technology has evolved through a succession of "waves," each characterized by a range of feature sizes and a primary type of exposure tool. (Table 1) There was also a metrology capability associated with each wave. As feature sizes and process technologies have changed, so have the measurement technologies. Both process and measurement technologies have progressed in the direction of greater sophistication, complexity and cost.

Early lithographers required the ability to measure only a few key parameters, such as linewidth and overlay. Often, a value for linewidth or overlay was not necessary; only a measure of whether these parameters met specifications or not was needed. As time progressed, quantitative data became important, and as the required quality of these data became more stringent, the measurement tools that were used changed from manual instruments (e.g., image shearing linewidth measurement) and visual observations in microscopes (e.g., optical verniers for overlay measurement) to automated systems capable of improved accuracy and productivity.

Automation is an important example of an improvement in metrology that enabled additional capabilities. Automation was first introduced as a means of improving productivity, increasing accuracy, and eliminating the subjectivity associated with manual measurements. There were additional benefits to the automation. For example, large amounts of data could be collected efficiently and with low error rates, facilitating the implementation of statistical process control (SPC). With the advent of networking, the automated capture of data could be taken another step, by providing automatic feedback to exposure tools. Automated data collection led ultimately to Automatic Process Control (APC). These important process control tools, SPC and APC, rest on a base of measurement technology.

As time progressed, lithography became sustained by a strong scientific foundation. Image simulation is an example of the application of science to lithography. This scientific base required accurate measurements of parameters such as refractive indices (real and imaginary parts) and film thicknesses. Later, it was found important to be able measure aerial images and lens aberrations. Placing lithography on a scientific footing expanded the list of factors that required measurement beyond the key parameters, such as linewidth and overlay, to a host of other types. More will be said about these additional metrology requirements later in this paper.

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Wave	Dimensions	Years	Primary exposure tool	CD measurement tool	Overlay measurement	Additional measurement tools
1	> 5 μm	Prior to 1975	Contact and proximity printers	Filars	Pass/fail boxes	Reflectometers
2	5 μm - 1.5 μm	1975 - 1983	Perkin-Elmer scanners	Image shearing	Pass/fail boxes → verniers	Reflectometers
3	1.5 μm - 0.35 μm	1983 - 1993	Step-and-repeat	Optical → SEMs	Verniers → automated optical	Reflectometers, n&k
4	350 nm - 100 nm	1993 - 2003	Step-and-scan	SEMs → scatterometry	Automated optical	Reflectometers → ellipsometers + many more tools
5	100 nm - ~ 45 nm	2004 and beyond	Step-and-scan	Discussed in the paper	Discussed in the paper	Discussed in the paper

Table 1. The waves of lithography and their key characteristics.

2. MEASUREMENT OF CRITICAL DIMENSIONS

Nowhere in its application to lithography has metrology been challenged more than in the measurement of linewidths. This has resulted from an incredible acceleration of microprocessor (MPU) gate lengths during the past ten years. If one considers the MPU gate length projected for the year 2003 in the 1994 SIA Roadmap with what actually was produced by manufacturers of MPUs, one finds an acceleration of 11 years! That is, actual gate lengths produced in 2003 were predicted by the 1994 SIA Roadmap not to occur until 2014. Such an enormous technology acceleration could not occur without stressing much of the lithography infrastructure, and metrology has been one area particularly challenged.

Final gate CDs on mainstream MPUs were targeted for 45 nm in 2003. (Table 2) While this was not the feature size printed in resist, the final gate dimension imposes a requirement on linewidth control, which places constraints on permissible measurement accuracy and repeatability. As one can see from Table 2, lithography is challenged to produce the level of CD control specified in the ITRS, and metrology is challenged to provide the required measurement precision.

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Node (nm)		*90*			*65*		
MPU Printed Gate Length (nm)	*65*	*53*	*45*	*40*	*35*	*32*	*28*
MPU Physical Gate Length (nm)	*45*	*37*	*32*	*28*	*25*	*22*	*20*
Printed Gate CD Control (nm)	▤ 4.0	■ 3.3	■ 2.9	■ 2.5	■ 2.2	■ 2.0	■ 1.8
Wafer CD metrology tool precision (nm), 3 sigma at P/T = 0.2	▤ 0.8	▤ 0.7	■ 0.6	■ 0.5	■ 0.4	■ 0.4	■ 0.4

Table 2. From 2003 ITRS. For cells with white backgrounds, manufacturing solutions exist. With horizontal lines in the background, there are interim solutions, while cells with a black background indicate that no known solution exists.

For many years the mainstream linewidth measurement tool for lithographers has been the scanning electron microscope (SEM). This indispensable tool has provided adequate measurement capability, but performance has always been close to the edge of requirements, and capability for features well below 50 nm has often been questioned. A recent development in metrology that appears poised to supplement the SEM is scatterometry. (Fig. 1.)

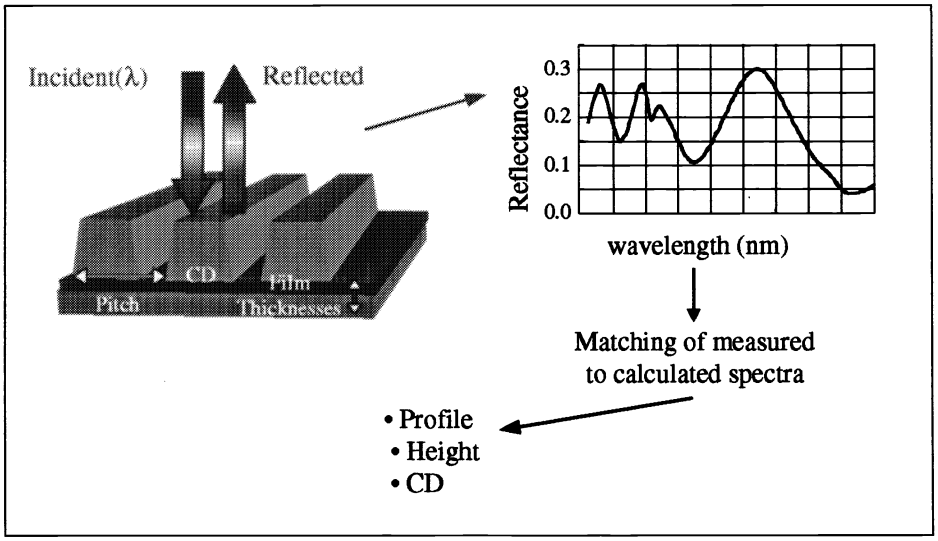

Fig 1. The basic process for scatterometry. Measurements for parameters such as reflectance versus wavelength are compared to calculated spectra. Best fits provide linewidth, film thickness and profile information.

Scatterometry is providing a wealth of data, including image profile and film thickness, which cannot be obtained by SEM. However, there are new parameters that are not measurable by scatterometry. One of the most important of these is line edge roughness. Scatterometry measures over a large area, and hence an average linewidth measurement is produced. However, the linewidth may vary along the length of lines (Fig. 2), and it is necessary to measure this variation in order to reduce it. For this, the SEM or other measurement techniques will be required.

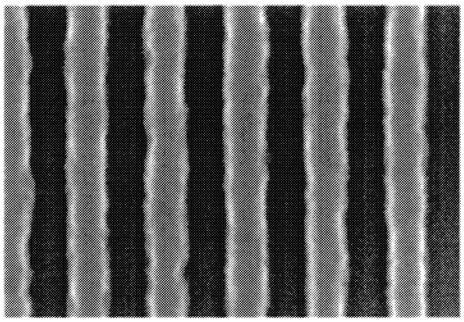

Fig. 2. Resist lines (90 nm lines and spaces) printed on an 0.1 NA EUV Engineering Test Stand.

Even with the superb measurement precision of scatterometry, there remain some aspects of linewidth variation that are best characterized by means other direct linewidth measurement. An example is the linewidth difference between two closely spaced lines that is caused by the lens aberration, coma. This line asymmetry occurs in situations where there are two closely spaced lines which do not have additional features in similarly close proximity. The lens aberration, coma, can cause the widths of these two lines to be different on the wafer, even though they are sized the same on the mask.

For earlier technologies, such as the 0.35 μm node, the differences between these two lines could be quite sizable, as large as 30 nm. Such linewidth differences were readily measurable by existing SEM metrology tools or electrical linewidth measurement, and the effects of coma could be readily characterized by linewidth measurement. With the impressive improvements in projection optics of exposure tools that have occurred over the course of the past decade, the difference in width of adjacent lines has shrunk to only a 1 – 2 nanometers. Given the gate linewidth requirements shown in Table 2, these differences are significant, as small as they are. Characterizing this situation, where the linewidth differences due to coma are only 1 – 2 nm, is best done by direct measurement of the lens aberrations. Multiple techniques have been developed to do this on exposure tools.[1, 2] Measurements of aberrations provide additional data that can be used to assess linewidth variation for features other than closely space lines, so direct measurements of aberrations are more useful than linewidth measurements, only.

Lens aberrations are not the only sources of linewidth errors. For example, scattered light (also referred to as flare) in the optical system can induce linewidth changes.[3] Characterization of scattered light requires a set of measurements separate from direct CD measurement.[4] Linewidth variations can also be caused by the resist processing equipment, such as by the hotplates used for baking resist. Controlling hotplates is best achieved by directly measuring hotplate temperature, rather than by measuring linewidths. Many resists today have sensitivities to post-exposure bake on the order of several nanometers per °C. Given the CD control requirements of Table 2 it will be necessary to control hotplate temperatures to only a few tenths of a °C, which means that the measurement capability must be measured in hundredths of a °C.

3. OVERLAY MEASUREMENTS

Overlay is another parameter that will soon require measurement capability with accuracy to 1 nm or less. (Table. 3) For many years, overlay has been measured using "box-in-box" or "frame-in-frame" structures. Because optical methods are used, the feature sizes for these structures has been fairly large, on the order of 1 μm, or larger, even when the features in the devices have been sub-micron. This differences in feature sizes between the overlay measurement structures and features actually in the circuits were of minor consequence prior to the advent of lithography with low k_1. With low k_1 processes, the placement errors of small features due to lens aberrations will be different from the placement errors of larger features. (Fig. 3) Without a change in the overlay measurement structures, there will be overlay errors as a consequence.

Year of Production	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Node (nm)	100	90	80	70	65	57	50
Overlay (nm)	35	32	28	25	23	21	19
Overlay measurement precision (3 sigma, nm)	3.5	3.2	2.8	2.5	2.3	2.1	1.9

Table 3. Near term overlay requirements from the 2003 update to the International Technology Roadmap for Semiconductors. For cells with white backgrounds, manufacturing solutions exist. With gray in the background, there are interim solutions, while cells with a black background indicate that no known solution exists.

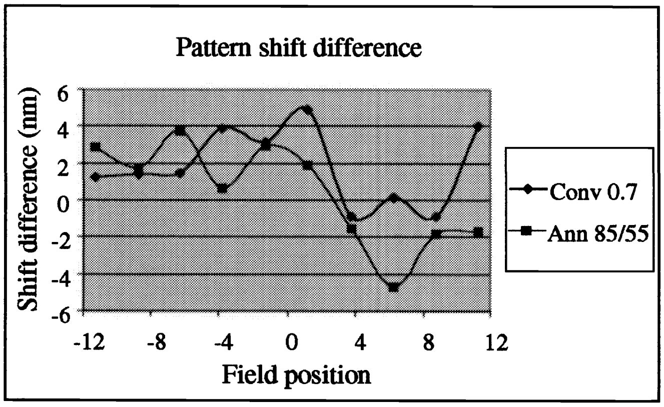

Fig. 3 Pattern shift of 120 nm line / 360 nm pitch features compared to 1 μm features.[5]

New overlay measurement structures have been developed that can better mimic the features in the circuits. (Fig. 4) Such overlay measurement structures offer the potential to reduce new sources of overlay error, such as coma-induced error. In Fig. 4, there are also measurement errors resulting from chemical-mechanical polishing that occur when older-style overlay measurement marks are used.

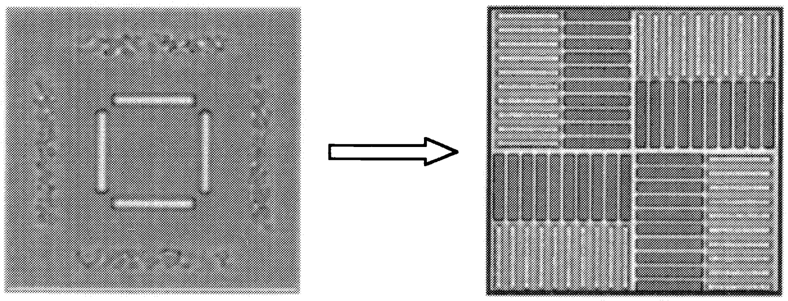

Fig. 4. On the left is a traditional frame-in-frame measurement structure, damaged by chemical-mechanical polishing (CMP), because the width of the frame feature is much larger than the features in the circuit, for which the CMP process is optimized. The new type of overlay measurement structure[6] more closely replicates the features in the circuit.

4. MEASUREMENTS BEYOND LINEWIDTH AND OVERLAY

As discussed on the section on linewidth measurement, there are many characteristics that lithographers need to measure in addition to the key parameters of linewidth and overlay. For example, photomasks contribute to overlay errors, and it is therefore necessary to ensure good registration on masks. In a world in which every nanometer is precious, these registration measurements must be made properly. During the past few years it has been recognized that mask distortion can changed by the attachment of a pellicle.[7] Thus, to ensure good registration, it becomes necessary to measure mask registration after pellicle attachment. Since good acquisition of the registration marks requires high resolution optics, to produce optics with such resolution as well as a long working distance becomes a challenge for the designers of tools that measure mask registration.

It has now become necessary for wafer fab lithographers to measure chemicals in their facilities, and extremely good sensitivity is often required. It has long been appreciated that it is necessary to maintain levels of bases in the air to less than 1 ppb in order to control lithographic processes involving chemically amplified resists. This implies a need for measurement capability considerably better than this, perhaps to 0.1 ppb sensitivity and accuracy, or better. It has also recently become appreciated that optics in DUV exposure tools can become contaminated from small amounts of chemicals in the air,[8] and it will be necessary to measure the gases supplied to exposure tools to very levels of contamination. The problem becomes worse for as the wavelength gets shorter, and even more effort is necessary to protect the optics. Table 4 is a list of some monitoring techniques that are currently being assessed for 157 nm exposure tool monitoring.

Detection method	Measured substances	Detection limits
Photo-ionization detection	Organics, Si-compounds, amines	10 ppb
Thermal desorption techniques	Organics, Si-compounds, amines, NH3	100 ppt
Ion mobility spectroscopy - positive ion mode	NH3, amines	100 ppt
Ion mobility spectroscopy - negative ion mode	Acids, NOx, SO2, halogens	100 ppt
Photo-acoustic IR	Hydrocarbons, Si-compounds, amines, NH3	100 ppt
Chemiluminescence	Amines, NOx	100 ppt
Flame ionization detection	Organics	10 ppt
Ion chromatography	SO2, NOx	100 ppt

Table 4. Examples of measurement methods used to detect trace materials in lithography environments.[9]

Flatness measurement is another type of metrology that is important for lithographers. In the ITRS, wafer flatness must equal the node. Consequently, wafers now need to be flatter than 100 nm, and this requires commensurate measurement capability. Even though lithographers do not routinely measure wafer flatness, it is something that is driven by lithography requirements.

For those involved with resists and integration, materials characterization is also important. These involve a host of techniques, from infrared spectroscopy to measurements using x-rays and charged particle beams. A number of these measurement methods, such as time-of-flight secondary ion mass spectroscopy, are now used routinely, even though they did not exist only a few years ago. As features become smaller and detection must become more sensitive and accurate, the list of characterization methods can be expected to grow.

Immersion lithography brings with it a host of unique metrology requirements. In order to design lenses, it has been necessary to know the index of refraction of water to about five places. At this level, the optical properties of the water can be modulated by very small traces of contaminants, so liquid analytical techniques must be at their best. An alternative or extension to immersion lithography is 157 nm lithography, where the optics are made primarily from CaF_2. Crystals of CaF_2 are birefringent intrinsically, and they can also have stress-induced birefringence. It is possible to correct for the intrinsic birefringence, if known accurately enough, while the stress-induced birefringence must be maintained at a very low level. Thus, very accurate measurement capability of birefringence is needed. For this, the semiconductor industry has been fortunate of receiving support from the outstanding scientists of the National Institute of Standards and Technology.

5. BEYOND THE FIFTH WAVE

It has long been predicted that optical lithography will be replaced by alternative lithographic methods, because of the limits to resolution inherent to optics. These predictions have often been premature, because the constraints were not imposed by the laws of physics, but were simply engineering problems that appeared insurmountable. Human ingenuity has proven capable of solving engineering problems, but the laws of physics are absolute constraints. Improvements in optics and materials, moving to shorter wavelengths, and introducing immersion to lithography have extended (or are expected to extend) optical lithography very far. However, even if we assume perfect lenses and materials, along with the ability to print at the very limit of optical modulation ($k_1 = 0.25$), and with 157 nm (the shortest possible optical wavelength) immersion lithography, the smallest printable ½-pitch is ~30 nm (with a single exposure). To extend lithography beyond 30 nm, alternatives to optical lithography have been pursued. Any radically new lithographic technology will necessarily require a large metrology infrastructure. One of the lead post-optical candidates, extreme ultraviolet (EUV) lithography, will be used as an illustrative example.

Since there are no transparent materials at EUV wavelengths (~11 - 14 nm), EUV masks and optics must be all-reflecting. Masks can be made by coating a substrate with a multilayer film that has been designed to have moderately high reflectance (60 – 70%) and then patterning an absorber on that. Light will reflect from exposed multilayer but not from the absorber. The multilayer is typically a stack of molybdenum films alternating with silicon films. Film thickness is just a few nanometers, and small differences in thickness and composition can modulate the reflectance by a significant amount. Consequently, measurement of the multilayer reflectance is needed at EUV wavelengths to ensure consistent performance. This is a requirement that is completely new for EUV lithography, in contrast to the evolution of some measurement technology from optical generations. It may also be necessary to measure defects in EUV multilayers at wavelength, which will require development of tools even more sophisticated than reflectometers (which are quite complex at EUV wavelengths).

Should we succeed at developing exposure technologies that will enable the 32 nm node and beyond, the metrology challenges will be formidable. As daunting as the requirements for linewidth metrology appeared to be in Fig. 1, for more near-term objectives, the needs for the 45 nm node and beyond are frightening! (Table 5) If we assume a precision/tolerance ratio of 0.2 as a requirement, then the CD measurement tool precision must be on the order of 2Å. If we look at a scanning tunneling micrograph of a piece of graphite (Fig. 5), we see that this precision requirement is on the order of natural atomic roughness. Simple extrapolation of dimensional shrinking must lead eventually to features that are on the order of atomic dimensions. As one can see, for lithography this will be encountered in the context of linewidth control for microprocessors.

Year of Production	*2010*	*2013*	*2016*
Node	*45*	*32*	*22*
MPU Printed Gate Length (nm)	*25*	*18*	*13*
MPU Physical Gate Length (nm)	*18*	*13*	*9*
Printed Gate CD Control (nm)	1.6	1.2	0.8
Wafer CD metrology tool precision (nm) 3 sigma at P/T = 0.2	0.3	0.2	0.2

Table 5. Linewidth control requirements from the 2003 update to the International Technology Roadmap for Semiconductors. Black cells indicate no known solution.

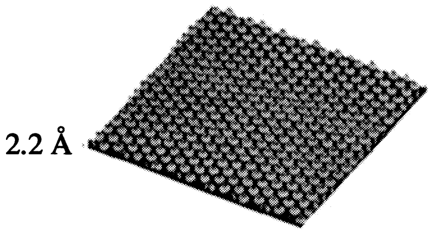

Fig. 5. Scanning tunneling micrograph of graphite. The surface roughness is 2.2Å.[10]

6. DEFECT MEASUREMENT

Defect metrology is another area in which will be greatly challenged in the years to come. Automated defect inspection has been an extraordinarily enabling technology for our industry. For example, at AMD, our first lot of Am486 microprocessors had quite low yield. With automated defect inspection, the source of the problem was quickly identified. It was found that approximately one contact per million was failing to develop properly. Given the number of contacts on the parts, this was sufficient to suppress yields to very low levels. It would have been impossible to have identified this defect source without automated inspection. The levels of integration for the Am486 microprocessor were much lower than we achieve routinely today, so the requirements for good automated inspection have grown, and this trend is expected to continue as long as levels of integration increase. Increasing levels of integration are expected for many more years to come.

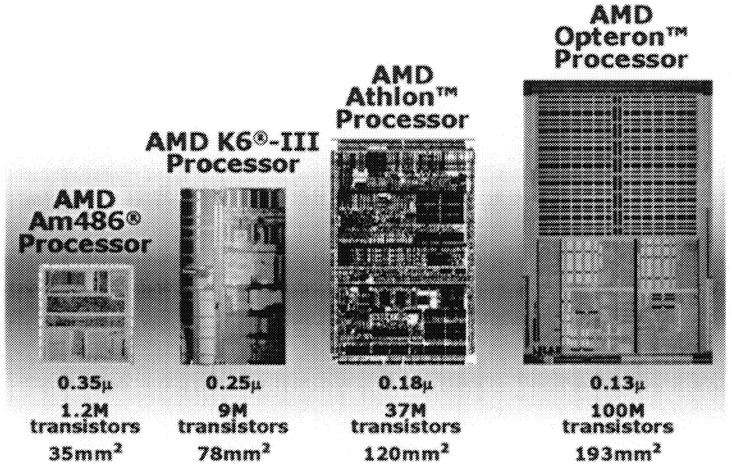

Fig. 6. Comparative die sizes and transistor counts for several generations of Windows™-compatible microprocessors.

In order to achieve very low defect densities it is necessary to be able to inspect large areas quickly. This has been possible with optical techniques, but the resolution of optics is limited. As feature sizes shrink, so does the size of the defects which can have a detrimental impact on yield. Shown in Fig. 7 is a defect which caused yield loss. It was a break in a gate that was less than 45 nm wide. If we extrapolate to the 22 nm node, this indicates that it will be necessary to detect defects that are 10 nm or smaller. This represents a formidable challenge to optical defect inspection.

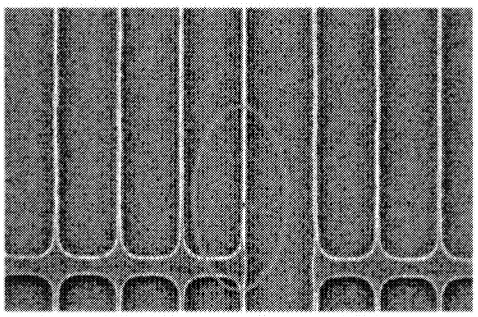

Fig. 7. Defect in a line that is less than 45 nm wide.

7. SUMMARY

As lithography as progressed from wave to wave, several trends have been discernible with respect to metrology. Most obviously, measurement capability has needed to become more accurate and capable of dealing with smaller features. Also, the number of critical measurement capabilities has expanded with each succeeding wave. Lithographers need tools for measuring linewidths and overlay on wafers, but also for measuring quantities such as refractive indices and film thicknesses. There are many requirements outside of direct wafer metrology, such as the ability to measure hotplate temperatures or lens aberrations. With each succeeding generation, the accuracy of the measurements must improve, and more types of measurements are needed. The requirements of the latter nodes of the ITRS will truly challenge human ingenuity.

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