SUPPORT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY TO INDUSTRY: THE SEMICONDUCTOR INDUSTRY

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The National Institute of Standards and Technology (NIST) is a United States Government Agency that develops metrology for the use and advancement of commerce. The Office of Microelectronics Programs (OMP) is supporting the semiconductor industry. We discuss some of the research projects at NIST in support of this industry as an example of how NIST fulfills its mission in support of the national metrology infrastructure.

1. INTRODUCTION

On March 3, 1901, the United States Congress created The National Bureau of Standards (NBS). In 1988 the U.S. Congress changed its name to The National Institute of Standards and Technology (NIST). Its mission is to develop and promote measurement, standards, and technology to enhance productivity, facilitate trade, and improve the quality of life.

Presently, NIST consists of 8 measurement laboratories, the Manufacturing Extension Program (MEP), and the Baldrige National Quality Program. There are approximately 2,800 employees in Gaithersburg, Maryland, Boulder, Colorado, and Charleston, South Carolina, 1,800 guest researchers from all over the world, and 850 users of facilities. The 8 measurement laboratories are: Building and Fire Research, Chemical Science and Technology, Electronics and Electrical Engineering, Manufacturing Engineering, Materials Science and Engineering, Physics, Technology Services, and Information Technology. There are three Nobel laureates in Physics working at NIST: Bill Phillips (1997), Eric Cornell (2001), and Jan Hall (2005).

NIST serves a broad base of customers in environmental technologies, transportation, pharmaceuticals, law enforcement, food and nutrition, biotechnology, computer software and equipment, construction, manufacturing, and microelectronics. In serving these customers, NIST partners with companies, other National Laboratories, academia, and other Agencies of the State and Federal Governments.

2. THE MICROELECTRONICS INDUSTRY

In 1990, the U.S. Congress created the National Semiconductor Metrology Program (NSMP) to address the metrology needs of the semiconductor industry. NIST, in turn, created the Office of Microelectronics Programs (OMP) to manage these programs internally. OMP funds researchers in different NIST laboratories to address semiconductor industry needs. Personnel from OMP spend significant time collaborating with semiconductor companies, e.g., IBM, Intel, and TI; consortia, e.g., the Semiconductor Research Corporation (SRC), the Semiconductor Equipment and Materials International (SEMI), and SEMATECH; and academia. These interactions allow the NIST researchers to stay current on the fast changing, increasingly demanding, industry needs.

OMP has research programs in the following areas: Lithography, Critical Dimension and Overlay, Front-End Processing, Interconnect and Packaging, Process, Analysis Tools and Techniques, Device Design and Characterization, System Design and Test, and Manufacturing Support. There are several projects within each program area being conducted throughout NIST.

The Semiconductor Industry Association (SIA) has developed a way of communicating with research institutions to inform them of their needs in the future called the International Technology Roadmap for Semiconductors (ITRS) which is published every two years with an update in the intermediate years. Table 1 [(1)] shows one of the tables in the 2005 ITRS indicating the critical dimensions (CD) expected during the forthcoming years for the different products that the industry manufactures. CD is the minimum width of the lines printed on a chip. There are different definitions depending on the type of chip. Table 2 [(1)] shows a typical depiction of some properties that, according to the ITRS, will be of importance in future years for different CDs. The ITRS uses a color code to identify the state of the technology that addresses those issues: white indicates that manufacturable solutions exist and are being optimized; yellow, manufacturable solutions are known; and red, manufacturable solutions are not known. When interim solutions are known, a white background with yellow lines and a red rhombus to indicate that work is going on appears. We will now address in more details some of the OMP supported projects.

3. HIGH RESOLUTION MICROCALORIMETER X-RAY SPECTROMETER FOR CHEMICAL ANALYSIS

During electron excitation in a scanning electron microscope, X-Rays are produced in addition to back-scattered and secondary electrons. The latter two produce the image that we normally associate with an electron microscope scan. The removal of secondary electrons from inner levels in the atoms of the samples creates vacancies. Then, other electrons in higher orbitals decay to the lower orbitals to fill in the vacancies; the excess energy is liberated in the form of X-Rays. These X-Rays are characteristic of the atoms that emit them and can be used for elemental identification and, under suitable conditions, for quantification of the elements of the sample.

Presently, there are two techniques for the detection of those X-Rays: Energy-Dispersive and Wavelength-Dispersive X-Ray Spectrometry, EDS and WDS, respectively. EDS usually has a resolution of approximately 130 eV at excitation energy of 6 keV, while WDS has a resolution of approximately 15 eV, 7 eV, and 3 eV to 4 eV at excitation energies of 6 keV, 1.5 keV, and 700 eV, respectively. The acquisition of an EDS spectrum is usually faster than the acquisition of a WDS one, since the latter involves switching crystals in the spectrometer. WDS has a higher resolution than EDS, but it comes with the price of significantly longer acquisition times.

A new type of detector, using a microcalorimeter that is maintained at 0.1 K, has been developed. It provides WDS-type resolution at EDS speeds. A description of the technique has been presented elsewhere [2-5]. NIST holds the record for energy resolution for an EDS X-Ray detector of 2.0 eV at 1.5 keV. Fig. 1 shows an energy resolution of 2.4 eV at 5.9 keV.

It has been shown that, in some cases, the shifts in the line position caused by the different chemical environments surrounding a specific atom can be observed using the EDS-X-Ray microcalorimeter detector.

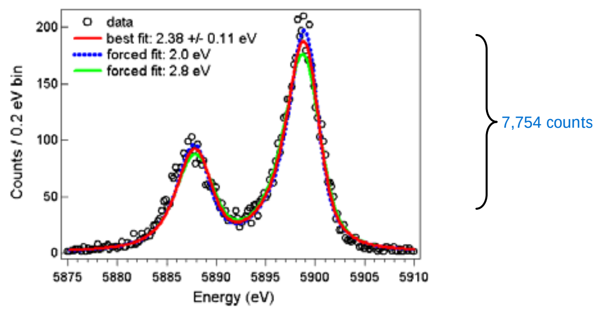


Figure 1. Pulse height spectrum of the Mn Kα complex measured with an X-Ray energy dispersive microcalorimeter spectrometer.

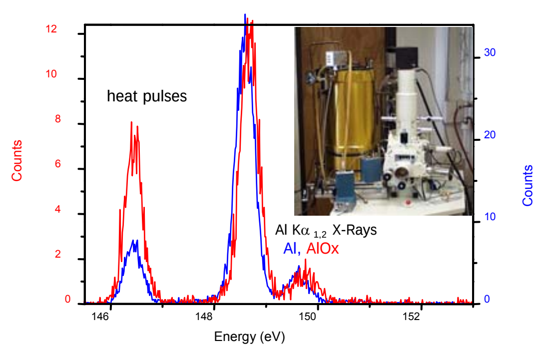


Figure 2. Energy-dispersive X-Ray analysis detected by using a microcalorimeter for Al in samples of Al and Al_2O_3 showing the shift in line position due to different chemical environment.

Table 1a Product Generations and Chip Size Model Technology Trend Targets—Near-term Years

Year of Production	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*
DRAM ½ Pitch (nm) (contacted)	*80*	*70*	*65*	*57*	*50*	*45*	*40*	*36*	*32*
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)	*90*	*78*	*68*	*59*	*52*	*45*	*40*	*36*	*32*
MPU Printed Gate Length (nm) ††	**54**	**48**	**42**	**38**	**34**	**30**	**27**	**24**	**21**
MPU Physical Gate Length (nm)	**32**	**28**	**25**	**23**	**20**	**18**	**16**	**14**	**13**
ASIC/Low Operating Power Printed Gate Length (nm) ††	**76**	**64**	**54**	**48**	**42**	**38**	**34**	**30**	**27**
ASIC/Low Operating Power Physical Gate Length (nm)	**45**	**38**	**32**	**28**	**25**	**23**	**20**	**18**	**16**
Flash ½ Pitch (nm) (un-contacted Poly)(f)	**76**	**64**	**57**	**51**	**45**	**40**	**36**	**32**	**28**

Table 1b Product Generations and Chip Size Model Technology Trend Targets—Long-term Years

Year of Production	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*
DRAM ½ Pitch (nm) (contacted)	*28*	*25*	*22*	*20*	*18*	*16*	*14*
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)	*28*	*25*	*22*	*20*	*18*	*16*	*14*
MPU Printed Gate Length (nm) ††	**19**	**17**	**15**	**13**	**12**	**11**	**9**
MPU Physical Gate Length (nm)	**11**	**10**	**9**	**8**	**7**	**6**	**6**
ASIC/Low Operating Power Printed Gate Length (nm) ††	**24**	**21**	**19**	**17**	**15**	**13**	**12**
ASIC/Low Operating Power Physical Gate Length (nm)	**14**	**13**	**11**	**10**	**9**	**8**	**7**
Flash ½ Pitch (nm) (un-contacted Poly)(f)	**25**	**23**	**20**	**18**	**16**	**14**	**13**

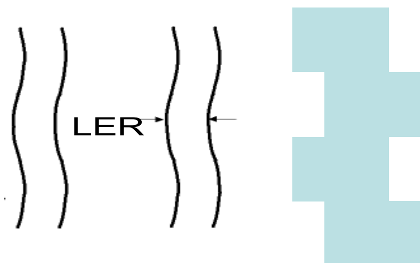
Table 2 Metrology Technology Requirements—Near-term Years

Year of Production	2005	2006	2007	2008	2009	2010	2011	2012	2013	Driver
DRAM ½ Pitch (nm) (contacted)	80	70	65	57	50	45	40	36	32	
MPU/ASIC Metal 1 (M1) ½ Pitch (nm)(contacted)	90	78	68	59	52	45	40	36	32	
MPU Physical Gate Length (nm)	32	28	25	22	20	18	16	14	13	
Microscopy										
Inline, nondestructive microscopy process resolution (nm) for P/T=0.1	0.29	0.25	0.22	0.2	0.18	0.16	0.14	0.13	0.12	MPU Gate
Microscopy capable of measurement of patterned wafers having maximum aspect ratio/diameter (nm) (DRAM contacts)	15	16	16	17	17	>20	>20	>20	>20	D1/2
	95	85	76	67	60	50	40	35	30	
Materials and Contamination Characterization										
Real particle detection limit (nm)	32	28	25	22	20	18	16	14	13	MPU
Minimum particle size for compositional analysis (dense lines on patterned wafers) (nm)	27	23	22	19	17	15	13	12	11	D1/2
Specification limit of total surface contamination for critical GOI surface materials (atoms/cm2)	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	5.00E+09	MPU Gate
Surface detection limits for individual elements for critical GOI elements (atoms/cm2) with signal-to-noise ratio of 3:1 for each element	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	5.00E+08	MPU Gate

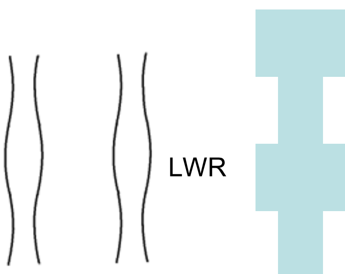
Manufacturable solutions exist, and are being optimized
Manufacturable solutions are known
Interim solutions are known
Manufacturable solutions are NOT known

When an Al film was deposited on a sapphire substrate, the measured X-Ray spectrum shows that there is a slight shift in the Al lines for both species, as can be seen in Fig. 2. In it, a shift of about 0.2 eV was observed between the Al lines for Al metal and for Al_2O_3.

3a



3b



3c

Figure 3. Different models associated with LWR and LER. 3a shows that the actual width of the line is constant; 3b shows the width of the line varying; and 3c is actually a mixture of the other two.

4. CROSS SECTION AND LINE EDGE ROUGHNESS FOR EUV LITHOGRAPHY USING CRITICAL DIMENSION SMALL ANGLE X-RAY SCATTERING

In the last few years, problems related to linewidth roughness (LWR) sometimes expressed in terms of its single-edge roughness (LER) (since the features are usually observed from above) have emerged as issues of high importance. As the width of the lines decrease, the roughnesses of those lines have become a higher percentage increasing the uncertainty with which the width of the line is known. In addition, there have been electrical problems associated with increasing roughness.

LWR and LER can be understood with reference to Fig. 3 (as viewed from top down). In Fig. 3a, the actual width of the line is constant, but there is a distribution in periodicity that can be modeled as a series of identical rectangles offset from one another. In this case, the linewidth is the same no matter where it is measured. In Fig. 3b, the actual line width is changing. It can be modeled as a series of rectangles of different widths. The question that comes up is whether we should calculate the actual width at a point or compute an average of several measured widths. Which of these options is the most operationally appropriate one is still being debated. In Fig. 3c, we have a combination of the previous two cases. In all these examples, we are looking at the sample from above and assume that the walls of the feature followed exactly what we are seeing from the top. It is conceivable that the walls may have variability different from what is being observed from the top view. Use of these simple models provides for a direct way of calculating parameters such as those outlined in Fig. 4 since the equations obtained are analytical in nature.

Experimentally, small angle X-Ray scattering (SAXS) is a technique that NIST researchers have been utilizing to measure these parameters [6, 7]. The technique consists on passing X-Rays through a sample and observing the transmitted beam on an x-y plane, as can be seen in Fig. 5. From the images obtained, plots of the intensity of the scattered beam versus the x and y positions, expressed in reciprocal space, can be made as a function of the angle, ω, formed by the sample surface with the incident beam. The parameters of interest can be extracted from the model discussed above, as presented in the references given [6, 7].

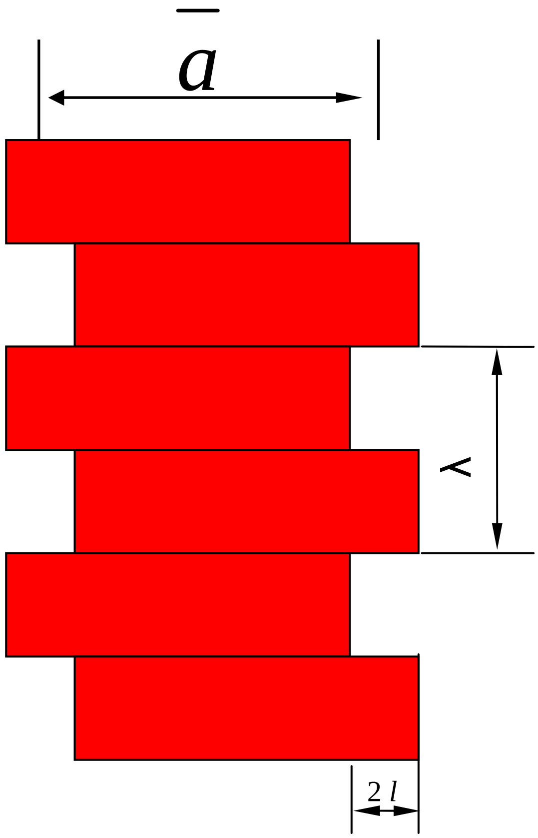


Figure 4. Parameters that can be calculated from the model in Fig. 3 that provides an estimate of the quantities of interest

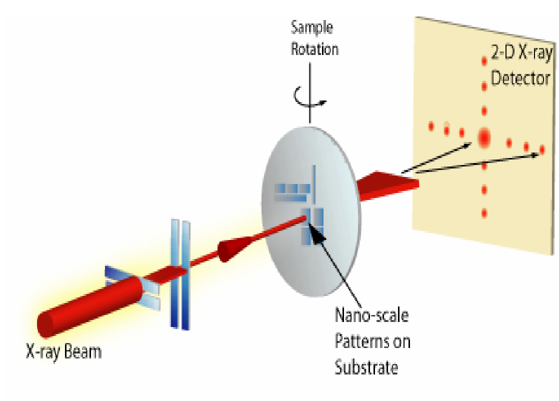


Figure 5. Experimental arrangement for SAXS

5. CONCLUSIONS

Having a national metrology laboratory supporting growing and important sectors of the industry can be of extreme importance to that industry. NIST has focused a significant part of its resources to the support of the semiconductor industry. Recent contributions have played a significant role in the development of needed metrology in support of the new technologies that will be implemented in the near future. Among these contributions are the following:

- The development of a microcalorimeter-based energy dispersive X-Ray spectrometer
- The development of small-angle-scattering X-Ray methods for the determination of line-width and line-wall roughness
- The determination of the intrinsic birefringence of CaF_2 crystals
- The development of a model to account for the filling of structures by electrodeposited Cu with high aspect ratios
- The development of measurements of electrical properties at high frequencies
- The determination of low part-per-billion level of H_2O concentration in gases
- The ability to calibrate the diameter of small particles for the study of scattering from particles on wafers

For more details on these programs and others being conducted by NIST in support of the semiconductor industry please go to the OMP website www.eeel.nist.gov/omp/.

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