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MODELING, MEASUREMENT, AND STANDARDS FOR WAFER INSPECTION

George W. Mulholland and Thomas A. Germer

National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD, 20899

301-975-6695 / george.mulholland@nist.gov; 301-975-2876 / thomas.germer@nist.gov

John C. Stover

The ScatterWorks, Inc., 4500 E. Speedway Blvd., Suite #24, Tucson, AZ, 85712

520-325-6322 / JCStover36@aol.com

Abstract

The major technical issues regarding the calibration of Surface Scanning Inspection Systems (SSIS) are presented including descriptions of the salient features of SSISs and the deposition system using the differential mobility analyzer. The role of the NIST SRM® 1963 (100 nm) as a calibration standard is discussed. Data from round robin experiments, which NIST has helped the SEMI SSIS Task Force run, are reviewed. The major features of the new standards is presented. In addition, recent advances made at The Scatter Works and NIST in regard to accurate particle sizing by light scattering are described.

1. INTRODUCTION

Scanning Surface Inspection Systems (SSIS) are used by the semiconductor industry to inspect millions of wafers per year. The goal of inspection is to prevent using wafers with "killer defects," that is, those defects large enough to block, or cut, a conduction line in a device or interfere with the performance of an active component The original rule of thumb was that defects larger than one third of a line width were to be considered "killer defects". However, calibrating a scanner to size defects is not easy [6]. The SEMI's Automatic Wafer Surface Inspection Specification Task Force has been working since May 2000 to assess the status of the existing methodology for SSIS particle size calibration and to develop new standards for specifying and calibrating SSISs. The current state of the art for the minimum detectable particle is about 60 nm and the National Technology Roadmap for Semicondictors specifies that by 2005, 43 nm particles must be detectable on bare silicon and nonmetallic films, and 56 nm particles on metallic films.

This paper focuses on issues identified by the Task Force and on the research and development of standards needed to address those issues. The next two sections provide an overview of the measurement challenges of SSISs and their particle size calibration issues. This section will include a description of the specifications for the calibration wafer required by the new Standard M-52, "Guide for Specifying Scanning Surface Inspection System for Silicon Wafers for the 130-nm Technology Generation." The Task force carried out a round robin with NIST's assistance to assess the uncertainty in the calibration of SSISs. The highlights of this intercomparison will be presented in Section 4. A key feature incorporated in many particle deposition systems is a differential mobility analyzer (DMA). In Section 5 a test protocol is presented for assessing whether a DMA deposition system is able to meet the requirements of M-52. A review of the operation principles of a DMA is presented in section 6 to help the reader relate the requirements given by the standard with a DMA's characteristics.

Studies at The ScatterWorks (TSW) and the National Institute of Standards and Technology (NIST) to improve SSISs led to the realization that it might be possible to accurately size particles using light scattering after deposition of the particles onto a surface. The recent light scattering work using nominal 100 nm calibration particles (NIST SRM® 1963) will be summarized in section 7.

2. SSIS PARTICLE CHARACTERIZATION

SSISs rapidly scan a wafer surface using a focused laser spot and detect light scattered by surface features. Surface roughness tends to produce a slowly varying background scatter signal, and discrete defects, such as particles and pits, cause brief flashes of light. Thus, roughness is responsible for the background noise that limits detection of the smallest defects.

Older SSISs generally consisted of an optical system that gathered as much scattered light as possible and directed it to a single detector. Estimating the average feature diameter is very difficult, because different features (pits, mounds, particles of different materials, etc.) all scatter differently. The scattered light changes in intensity, direction, and polarization as a function of feature characteristics. Changes also occur with the wavelength, polarization and incident angle used by the SSIS. In some cases, like surface roughness [7], there is a good understanding of the relationship between "how the surface is rough" and "how the light scatters." Unfortunately, we are still learning how many other surface defects scatter light. Even if the scatter from all known defects were well understood, however, it would still be difficult problem, because the SSIS attempts to solve "the inverse problem." That is, the SSIS attempts to identify or classify the defect, from a limited amount of scatter data. To make the problem a little more difficult, each year, as line widths are reduced, and the surface features that are considered "killer defects" get smaller, the list of critical surface features becomes larger.

3. SSIS CALIBRATION

Even the qualitative assumption that smaller signals mean smaller defects can not be made for single detector SSISs. To avoid these issues, defects were classified by the size of a polystyrene latex (PSL) sphere that would yield the same signal. Thus, they were sized by their "PSL equivalent" or "light scattering equivalent" (LSE). SSISs were calibrated using wafers having PSL spheres of varying sizes deposited onto them and determining how the signal varied with sphere diameter. PSL spheres are commercially available. They have a uniform refractive index, but their diameter distributions and uncertainty in modal diameter varies with commercial source and nominal size. It was recognized that scanners of different designs would not report the same LSE values for real defects, because a real defect does not necessarily scatter like a PSL sphere. Furthermore, it became apparent that differences were found even when PSL calibration spheres were measured. For awhile, this inconsistency was largely ignored because high device yields could be achieved by simply tightening the LSE particle size specification for wafer cleanliness.

Two things happened to change this situation. As device line widths got smaller, the minimum size defect signals were reduced below the roughness-generated noise floor, and it became difficult to meet the one third line width specification. Relaxing the diameter specification to one half of a line width temporarily solved, or delayed, this problem. The second change was the introduction of SSISs having multiple detector elements. By ratioing signals, the newer scanners could tell the difference between surface pits and surface particles, and it is believed that using more than two detectors allows identification of particle material by type (dielectric, metallic and semiconductor). The advent of defect identification leads to the possibility of true defect sizing [8]. As a result, removing the calibration inconsistencies became economically important, and an effort, coordinated by SEMI Standards, was initiated to overcome them. Four related standards form the basis for controlling PSL sphere calibration issues.

The first of these standards, now published as M52, documents the procedure for specifying SSISs, and among many other things, requires that the system be able to detect 65 nm PSL spheres with a capture rate of 95%. The text relating to PSL calibration spheres simply states: *"In order to reduce PSL sphere sizing uncertainty in the 65 nm to 200 nm range, the diameter distribution should have a full width at half maximum (FWHM) ≤ 5 %. In addition, it is desirable that the peak PSL diameter as deposited on the wafer have a relative expanded uncertainty at about 95% confidence level as small as possible but not greater than 3%."* The standard does not address three key issues: 1. How is the probability of detecting a PSL sphere near the noise floor limit quantified? 2. How is SSIS calibration performed? 3. How does one know if the deposited calibration particles used actually meet the specification of M52? These questions are addressed in three supporting standards. M50 outlines a method to statistically analyze scanner data to determine capture rate as a function of LSE diameter. M53 outlines the calibration procedure, but assumes that appropriate PSL sphere depositions are available. Finally, a draft document is being written to provide a method to determine if a particle deposition system actually meets the requirements quoted above from M52.

4. ROUND ROBIN FOR SSIS SIZING

It was natural for NIST to play an active role in coordinating a round robin on particle sizing, because of its long involvement in the development of PSL sphere calibration standards. As M52 was being written (some might even say negotiated), NIST participated in an experimental study to determine the root causes of the observed calibration inconsistencies. Essentially identical PSL sphere depositions of six different particle sizes were made on three wafers at SEMATECH. The depositions were made using PSL spheres whose sizes were accurately known. One of these was the NIST Standard Reference Material (SRM®) 1963. The diameter distribution of this particle source is narrow (about ±2 %) and has a modal diameter of 100.7 nm ± 1.0 nm [5]. Two other laboratories have confirmed these measurements. The other particle sizes were not as well characterized, but still represented the best peak diameter measurements available at the time. The three wafers were sent to labs in Japan, Europe, and the United States for scanner measurement, and the results were sent to NIST for analysis.. A total of eight facilities using 13 SSISs were involved in the study. The results of the measurements are shown in Figure 1.

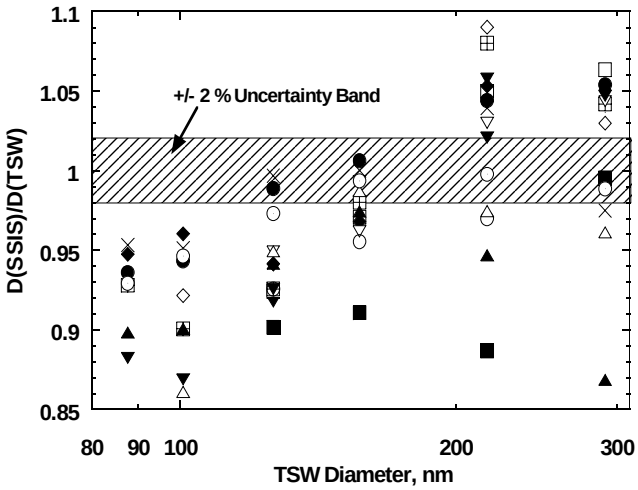

Figure 1. The ratios of the SSIS diameters to those determined by TSW are plotted versus diameter for six calibration particles. Thirteen SSIS's were used at eight facilities for this study.

For the two smallest particle sizes (87.6 nm and 100.6 nm), the particle size determined by the SSISs were low in every case, with the average values being about 8 % low compared to those measured by TSW. There are problems even for the largest two sizes (216 nm and 291 nm). For these sizes, only two of the 13 SSISs give values within 2 % of the TSW diameter, even though the averages from all the SSISs for both sizes were within 2 % of the TSW value.

This study shows that there is a problem with the current calibration method used by operators of SSISs. An 8 % effect is of concern because the size distribution of contaminant particles rises rapidly with decreasing particle size. The consequences can be illustrated by a hypothetical example where a SSIS is used to

count all particles larger than 100 nm by a seller of wafers. If the seller's SSIS underestimates the diameter by 8 %, then the number of particles reported for sizes greater than 100 nm will be less than the true number. It could be significantly less, say by 50 %, because of the rapid rise in the number of contaminant particle with decreasing size. If the buyer of wafers has a correctly calibrated SSIS, he will count 50 % more than the seller, and the wafers will be considered to be out of specification. This discrepancy could require great expense to resolve.

The study showed a clear problem with scanner calibration and caused considerable controversy. After months of discussion and additional measurements, a meeting was held at NIST to resolve the contested issues. In the end, the work prompted the generation of the three standards supporting M52 to resolve the issue of scanner calibration.

5. PROTOCOL TESTING FOR DEPOSITION SYSTEMS

The final supporting standard, presenting a method to check the capability to produce appropriate depositions of calibration particles, requires another experimental study to confirm the proposed technique. NIST will provide three sets of particles, which will be used to make depositions over a period of several days. The wafers will be sent to SEMATECH for scanner measurement and the results forwarded to NIST for analysis. Repeatability, peak uncertainty, and the width of the deposited diameter distribution will be determined. This study will show whether the deposition requirements of M52 can be met by using a carefully controlled differential mobility analyzer as a sizing filter in the deposition system.

6. OPERATING PRINCIPLE OF DMA

Deposition systems include a nebulizer for producing a PSL sphere aerosol by spraying and evaporating a suspension of PSL spheres in high purity water, a differential mobility analyzer (DMA) for selecting a monodisperse fraction of the aerosol, and then a chamber to electrostatically deposit the spheres onto wafers. Here we focus on the DMA, which is used for both isolating a monodisperse size fraction and for sizing the particles. A brief description of the instrumentation and methodology is given below; a detailed description is given by Kinney et al. [3].

The particles leaving the nebulizer pass through a bipolar charger that produces a charge distribution that depends only on the size of the particles and not on their initial charge. For 100 nm particles, about 45 % of the particles are uncharged, about 20 % have +1 electron, another 20 % have –1 electron, and much smaller fractions have multiple charges. As illustrated in Figure 2, the DMA consists of an inner cylindrical rod connected to a variable high voltage dc power supply and an outer annular tube connected to ground. Clean sheath air flows through the axial region, while the charged aerosol enters through an axisymmetric opening along the outer cylinder. The positively charged PSL spheres move radially towards the center rod under the influence of the electric field. Near the bottom of the classifying region, a fraction of the air flow consisting of near-monodisperse aerosol exits through a slit in the center rod. The quantity measured by the DMA is the electrical mobility, $Z_{p,}$ defined as the velocity a particle attains under a unit electric field. Knutson and Whitby [4] derived an expression for the average value of Z_p for particles entering the slit involving the peak electrode voltage, V, the sheath air flow rate, Q_c, the inner and outer radii of the cylinders, r_1 and r_2 , and the length of the central electrode down to the slit, L:

$$Z_p = \frac{Q_c}{2\pi VL}\ln(r_2 / r_1)$$

This equation is valid provided the sheath air flow, Q_c, is equal to the excess flow, Q_m, leaving the classifier. They derived an expression for the transfer function, defined as the probability that a particle will leave the sampling slit. The transfer function is of great importance, because the monodisperse concentration exiting the DMA is proportional to the convolution of the transfer function with the particle size distribution function. The transfer function has a triangular shape with a value of 1 when the voltage at which the computed particle mobility using the equation above is

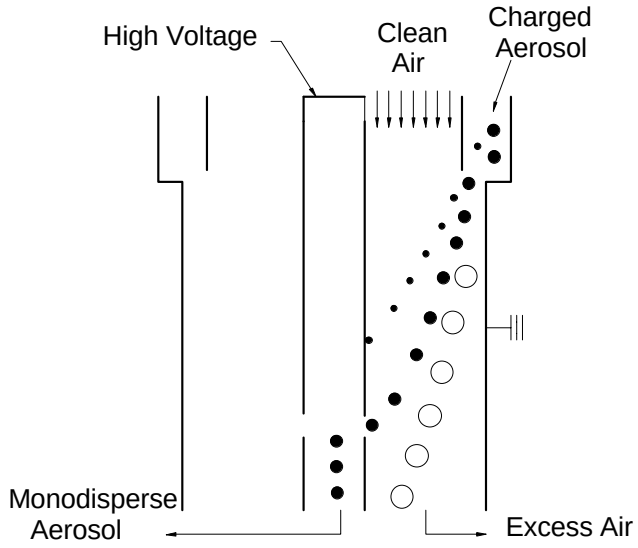

Figure 2. A monodisperse aerosol is "selected" from a polydisperse aerosol based on the size dependence of the electrical mobility.

equal to the mobility of the particle. The ratio of the base of the transfer function triangle in terms of voltage divided by the peak voltage is predicted to be $2(Q_s/Qc)$, where Q_s is the flow of monodisperse aerosol. From this one can see that the smaller the flow ratio the more monodisperse is the aerosol leaving the classifier.

The relationship between electrical mobility and particle size is obtained by equating the electric field force of a singly charged particle with the Stokes friction force,

$$Z_p = \frac{eC(D_p)}{3\pi\mu D_p}$$

where μ is the dynamic viscosity of air, and e is the electron charge. The Cunningham slip correction, $C(D_p)$, corrects for the non-continuum gas behavior on the motion of small particles.

Basically, the purpose of a test protocol for a deposition system is to assess whether the practical realization of DMA classification gives the desired enhancement in the accuracy and narrowness of distribution. In some cases the DMA is used directly to provide an accurate particle size, while in other applications it is cali-

brated with a known particle size such as the NIST SRM® 1963 (100 nm) PSL spheres.

7. ACCURATE PARTICLE SIZE VIA SURFACE SCATTERING

The development of improved technology for SSIS measurements has recently led to accurate measurements of the NIST SRM® 1963 (100.7 nm) with expanded uncertainties less than 2 % of the mean size based on angle-resolved light scattering measurements for the 100 nm particles deposited on a wafer. TSW was the first to realize the possibility of making such measurements using ratios of intensities for various angles together with a theory for predicting the scattering. TSW applied the technique to six monodisperse PSL sphere sizes ranging from about 90 nm to 300 nm. The size obtained for the 100.7 nm SRM® was 100.6 nm.

Motivated in part by the TSW work, NIST [2] performed similar measurements, measuring scattered intensity versus angle for the NIST SRM® 1963 PSL spheres deposited on a wafer. They used a vertically polarized helium-cadmium laser at 441.563 nm. All measurements were carried out with a fixed incident angle $\theta_i = 60°$, scanning the scattering angle from $\theta_r = -50°$ to $\theta_r = 50°$ in the plane of incidence. Measurements of the bidirectional reflectance distribution function (BRDF) were carried out on two samples, the wafer containing spheres and on another clean witness wafer, each at nine different locations. Figure 1 shows the measured BRDF obtained from seven locations on the wafer surface after correcting for the signal from the witness wafer.

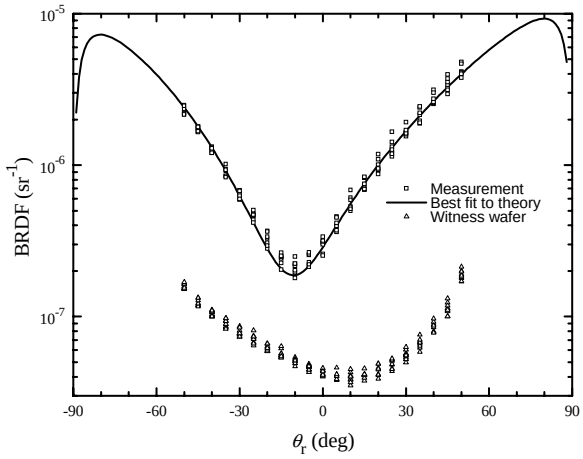

Figure 3 Light scattering of p-polarized light by PSL spheres on a silicon substrate measured in the plane of incidence at five different locations (squares). The solid curve represents the best fit to the theory as described in the text.

The theory of Bobbert and Vlieger [1] was used to evaluate the scattering of light by a sphere on a substrate. The theory was modified to include a substrate layer, to account for the oxide layer covering the silicon wafer.

The measurement yielded a value of 99.7 nm with an expanded uncertainty (95 % confidence limit) of 1.7 nm. The uncertainty is dominated by the reproducibility of the measurement. Uncertainties in the substrate optical properties, the thickness and optical properties of the substrate oxide, and the shape of the particle dominate the systematic uncertainty

8. References

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George Mulholland is currently the Fire Metrology Group Leader in the Building and Fire Research Laboratory at NIST. He has a PhD in Chemistry from Cornell University. His research interests include particle metrology, soot inception, and the characterization of the optical properties of soot.

Thomas Germer obtained a B.A. in physics from U.C. Berkeley and a M.S. and a Ph.D. in physics from Cornell University. He currently is a physicist in the Laser Applications Group of the Physics Laboratory at NIST, where he leads the program in optical scattering from surfaces.

John Stover has worked for thirty years in the field of light scatter measurement and analysis in both industry and academic settings. He is currently President of The Scatter Works, Inc in Tucson, AZ