SCANNING VOL. 20, 1–9 (1998)

Received October 27, 1997
Accepted November 14, 1997

Image Sharpness Measurement in Scanning Electron Microscopy—Part I

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Summary: This study introduces the idea of the sharpness concept in relationship to the determination of scanning electron microscope (SEM) performance. Scanning electron microscopes are routinely used in many manufacturing environments. Fully automated or semiautomated SEMs as metrology instruments are used in semiconductor production and other forms of manufacturing where the ability to measure small features with the smallest possible errors is essential. It is felt that these automated instruments must be routinely capable of 5 nm (or better) resolution at or below 1 kV accelerating voltage for the measurement of nominal 0.18–0.35 μm size parts of the integrated circuits. Testing and proving on a day-by-day basis that an instrument is performing well is not easy, but, understandably, is an industry need and concern. Furthermore, with the introduction of fully automated inspection and metrology instrumentation, not only does an appropriate, easy to obtain or manufacture sharpness measurement sample have to exist but also an objective and automated algorithm must be developed for its analysis. Both of these have been the object of a study at the National Institute of Standards and Technology (NIST), and the fundamentals are discussed in this paper and the computer-based automated analysis in a companion paper (Part II; Vladár *et al*. 1998). The method described in these papers is based on the analysis of the frequency domain representation of the SEM image and can also be used to check and optimize two basic parameters—focus and astigmatism—of the primary electron beam as related to a measure of image sharpness. The application of this technique to check regularly the resolution of the SEM in quantitative form will also be discussed.

Key words: scanning electron microscopy, electron beam diameter, focus, astigmatism, sharpness, Fourier transform

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Introduction

Fully automated or semiautomated scanning electron microscopes (SEMs) are now commonly used in semiconductor production and other forms of manufacturing. According to the SIA Roadmap for Semiconductors (SIA 1994), SEM-based measurement instruments will remain the production tools of choice until at least the year 2005. It is required that these automated instruments be routinely capable of 5 nm (or better) resolution at or below 1 kV accelerating voltage for the measurement of a nominal 0.18–0.35 μm size parts of the integrated circuits; however, testing and proving that the instrument is performing at this level for production on a day-by-day basis is not readily employed. These instruments are often operating 24 h a day by various operators, which makes evaluation more difficult. Because of the importance of the measurement data taken by these instruments, this presents an industry need and concern that the National Institute of Standards and Technology (NIST) has attempted to address. No good procedure or wafer-type performance standard currently exists to support this task. The NIST SEM performance standard, SRM 2069 (ASTM 1986a), is not useful for production-type instrumentation, and samples such as coated latex spheres can introduce particle contamination and the possibility of noble metal contamination. Furthermore, with the introduction of fully automated inspection and metrology instrumentation, both an appropriate sample has to exist and an objective and automated algorithm must be developed for its analysis. Both of these needs have been the objects of an extensive study at NIST. The fundamentals of this work are reported in this paper, and details of the automated algorithm are described in the companion paper (Part II). The method described in these papers is useful not just for the highly specialized instruments used in production in the semiconductor industry, but it is also beneficial for other research laboratory SEMs as well.

Scanning Electron Microscope Performance

The spatial resolution of the secondary electron (SE) image is one of the comparative factors used in the determination of the performance of SEMs. Table I outlines the typical performance specifications of several classes of SEMs. Overall, the attainable resolution of the SEM has improved by

one order of magnitude over the past decade (Joy 1995), and many of the reasons for these incremental improvements in performance have been presented previously (Postek 1994, 1997). Concern over the resolution and its limits have always interested researchers and a number of studies exists regarding this topic, which theoretically and practically investigate the measurement of resolution (Broers 1970, Catto and Smith 1973, Ze-Jun and Shimizu 1989).

There are three major parameters that can be considered when attempting to determine the on-line performance of an SEM. These parameters are beam diameter measurement, resolution measurement, and the concept that is introduced here—sharpness measurement.

Beam Diameter Measurement

Numerous studies describing methods of measurement of electron beam diameter have been published. Clearly, the knowledge of the diameter of the electron beam is valuable, especially where electron beam lithography and electron beam-based metrology is concerned. For accurate metrology to be achieved in the SEM, a measurement of the electron beam diameter is essential. The electron beam diameter is an input parameter for the electron beam modeling (Lowney *et al*. 1996) and for measurements of small, for example, 100 nm dimensions, thus it must be taken into account in these calculations. Since resolution and probe size are interrelated, attempts have been made to develop techniques for the measurement of accessible instrument parameters such as beam diameter, and to extrapolate the results to determine the potential resolution of the electron microscope. One of the earlier studies was published by Joy (1974). The determination of probe diameter is described in this paper. With this technique, the electron beam is scanned across a sharp, opaque straight edge and the line profile of the video signal is recorded. A measurement of the linear dimension of the profile from specified points on the waveform was then related to the electron beam diameter. Other techniques for the measurement of probe diameter and the measurement of the incident electron current are also described. Rishton *et al*. (1984) used vertical edges of etched silicon single crystal as one workable sample for this measurement technique. With the measurements of beam diameter, a good deal about the performance of a particular SEM can be determined and a prediction regarding the SEM resolution could be made. In a similar fashion, Reimer *et al*. (1979), utilized a diode electron detector in the scanning tunneling electron microscopy (STEM) mode for the measurement of the electron beam diameter where the island structure of evaporated films was used as test specimens. Wells (1977) described a unit that could be inserted between the electron gun and the first condenser lens in the instrument which allowed for the measurement of the source size, electron gun brightness, and the column demagnification. The National Bureau of Standards (NBS, later NIST) developed the Standard Reference Material (SRM) 2069 for the determination of the performance of an SEM. The American Society for Testing and Materials (ASTM) issued a paper about the standard practice for SEM performance characterization (ASTM 1986a). Hamerlick (1987) used the actual semiconductor circuit as the test sample. Rajopandhye and Raja (1989) developed a technique for directly monitoring the electron beam intensity profile as the beam is rocked across a very sharp knife-edge. Several other authors dealt with the measurement of electron beam diameter measurements (Gentili *et al*. 1991, Ghisholm 1988, Oho *et al*. 1985, Vaughn 1976, Weisner 1976). All the aforementioned techniques require some degree of experimental expertise and are not readily adaptable to fully or semiautomated SEMs.

Table I Achievable SEM resolution

		Instrument "class"				
Detector position	Accelerating voltage	In-lens FE	Extended FE	Post-lens FE	Post-lens LaB_6	Post-lens tungsten
Upper	30.0 kV	0.6 nm	1.2 nm			
	1.0 kV	3.0 nm	2.5 nm			
Lower	30.0 kV			1.5 nm	2.5 nm	3.5 nm
	1.0 kV			5.0 nm	7.5 nm	10.0 nm

Abreviations: SEM = scanning electron microscope, FE = field emission.

Resolution Measurement

The measurement of the best resolution is one of the most important characteristics of an SEM. This is especially important when the acceptance of a new instrument is concerned, both for the instrument user and the manufacturer. Table I shows the expected performance of different classes of SEMs. Most SEM manufacturers provide comparative specifications for the expected performance of their instruments. Measurement of the resolution is typically a subjective procedure done on special samples constructed for the specific purpose of proving resolution. The most common test samples used for this procedure in laboratory instrumentation are gold-on-carbon (GoC) and coated magnetic tape (Fig. 1). Since the resolution is calculated at a given magnification, the accurate magnification correction has to be accomplished first. This can be done with accepted procedures using, for example, an NIST SRM 484 (ASTM 1986b), the SEM magnification calibration standard.

Resolution Samples

Ultimately, measurement of all the SEM parameters comes down to the realization that the good quality of the image (as a data array) is the foremost goal. This requires some sample to be used as an evaluation standard in the instrument. Ballard (1972) prepared one of the earliest reviews on this subject, and in it he indicated the restrictive nature of such a sample. One of the more frequently used samples for the de-

termination of resolution performance is the GoC sample (Fig. 1). GoC is advantageous because it yields a good quality image on a relatively easy to produce sample (Humenansky 1987). The high SE yield of the gold in comparison to the poor SE yield of the carbon gives excellent contrast and edge definition. Gold-coated magnetic tape, coated zinc oxide (Fig. 2), and etched biphasic glass have also been found to be good at demonstrating the overall SEM performance (Postek 1987). However, if the set of materials available for resolution samples was limited, as discussed by Ballard, then those useful for semiconductor production are even more restrictive.

Sharpness Measurement

The sharpness concept described in this paper is a more practical approach to the evaluation of instrument resolution. The sharpness concept actually draws the two previously described desirable features together into a unified concept. Initially, the sharpness concept relied upon the fact that the human eye can be employed as a very good evaluation tool when it comes to the comparison of micrograph quality (AMRAY 1977). The human eye may perceive spatial resolution on a micrograph of about 0.2 mm. That being the case, Table II summarizes the size of a 1 mm feature in a micrograph as a function of magnification, as well as the smallest feature resolvable by the human eye (at 0.2 mm resolution). This represents the actual calculated resolution necessary for the micrograph to appear sharp to the unaided eye. Implied in this evaluation is the proper SEM magnification calibration and that the photographic CRT is properly focused to < 0.2 mm, which is readily possible.

The data presented in Table II can be analyzed in a number of ways. For this discussion, one of the conclusions made in the early AMRAY Technical Bulletin was that for a micrograph to appear perfectly sharp to the eye at 100,000 × magnification, the SEM must function at 2 nm resolution or better. In 1977, when that article was first published, 2 nm resolution was generally unattainable even in SE detection mode of most SEMs, and so a micrograph at 100,000 × always appeared unsharp to the eye and thus contained some "empty" magnification. To obtain a resolution of 7 nm, a micrograph at 28,750 × should appear sharp to the eye or at least contain some sharp elements. Similarly, at 20,000 ×, the instrument needed to perform at 10 nm or better resolution. The important fact presented by this Technical Bulletin was the suggestion that a trained eye could be used to evaluate the day-by-day performance of an SEM without any special procedure. The main requirement is that the operator needs to be trained regarding what a "good" or benchmark performance level is for the particular instrument for comparative purposes. Obtaining that benchmark micrograph is a very important first step.

Figure 2a demonstrates a micrograph that conveys little information about the performance of the SEM by itself. However, in comparison with Figure 2b, it is apparent that the second image is much sharper, implying that the instrument was functioning much better than when the first image was taken. The second micrograph becomes the benchmark. This now provides an ability to form comparisons. Unfortunately, this approach to sharpness remains to be useful but a highly subjective approach. This is especially true when micrographs are close in sharpness. The success of this approach is based upon the archiving of good micrographs, the understanding of the concept of image sharpness evaluation, and the training of the operator. Because of the differences in operators, their visual acuity, and subjectivity of evaluation, a reasonable amount of uncertainty is expected. However, this overall idea provided the basis for this paper because, with advanced computer processing, the subjectivity can be eliminated.

The sharpness concept implies that the micrograph shown in Figure 1 will exhibit some lack of sharpness at 70,000 × magnification since the micrograph was taken with an instrument equipped with a thermal emission lanthanum hexa-

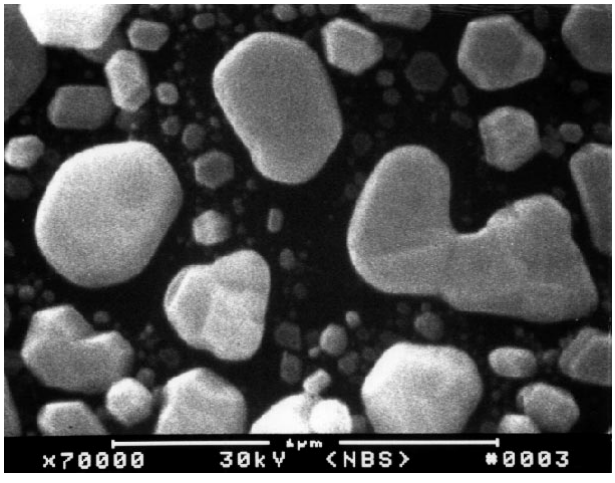


FIG. 1 Scanning electron microscope micrograph of gold-on-carbon taken with an LaB_6 instrument with the specified resolution of 4 nm. (Field width = 1.58 µm.)

Table II Image feature size versus micrograph magnification[a] (AMRAY 1977)

Magnification	True size of 1 mm feature	True size of 2 mm feature
100,000×	10 nm	2 nm
50,000×	20 nm	4 nm
28,750×	35 nm	7 nm
20,000×	50 nm	10 nm
10,000×	100 nm	20 nm
5,000×	200 nm	40 nm
2,000×	500 nm	100 nm
1,000×	1,000 nm (1 µm)	200 nm
500×	2,000 nm (2 µm)	400 nm
200×	5,000 nm (5 µm)	1,000 nm (1 µm)

[a] Proper instrument calibration to a (NIST) standard is assumed.

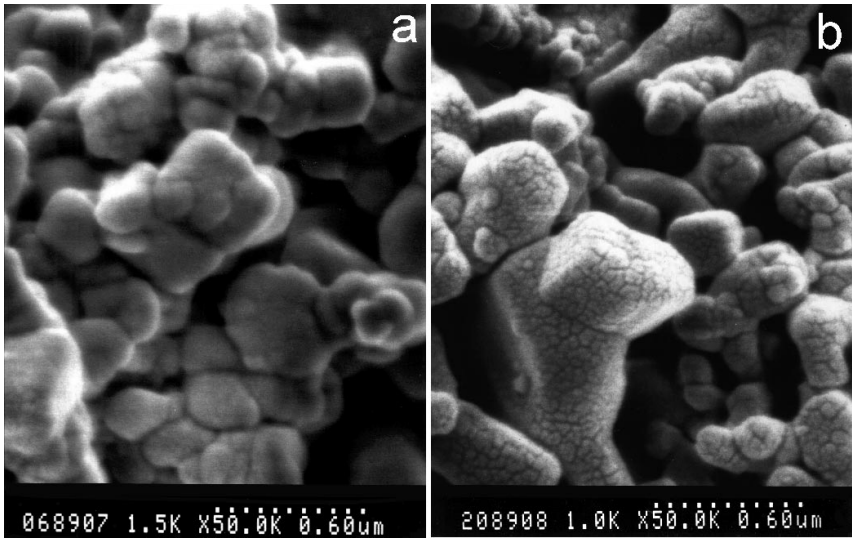


FIG. 2 Scanning electron microscope micrographs of heavily gold-coated zinc oxide powder at low accelerating voltage. (a) Poor quality image. (b) High quality image. (Field width = 1.7 μm.)

boride (LaB_6) filament. The instrument is specified to function at 4 nm resolution at 30 kV accelerating voltage. Looking at the chart, a sharp micrograph should be attainable at 50,000 ×, and if the instrument produces a micrograph with the quality of the one displayed, it can be concluded that the instrument is meeting and likely exceeding its fundamental specification. Today, contemporary SEMs (especially those equipped with field emission cathodes) perform far better, and Table II can be expanded to include the enhanced performance afforded by the high-resolution field emission (FE) instruments; this is found in Table III. Comparing Table I with Tables II and III, it can be seen that this expansion permits some "empty" magnification to be again a component of even the highest resolution images. The majority of SEM users do not or cannot operate at the ultimate performance level of their instruments, and Table III is likely not relevant to the majority of the instruments currently in use, even for many high accelerating voltage applications. One advantage presented by these tables is that they can be applied to low accelerating voltage SEM applications as well. This means that if an instrument is specified to provide 10 nm resolution at 1 kV accelerating voltage, it should be capable of producing a sharp micrograph at 20,000 ×. This should be possible for most tungsten filament instruments and all LaB_6 instruments. A sharp 50,000 × micrograph at 1 kV should be attainable by most postlens FE instruments specifying 4 nm resolution (Fig. 2b).

Table III Image feature size versus micrograph magnification (field emission extension)

Magnification	True size of 1 mm feature	True size of 0.2 mm feature
500,000×	2 nm	0.4 nm
450,000×	2.2 nm	0.44 nm
400,000×	2.5 nm	0.5 nm
350,000×	2.9 nm	0.6 nm
300,000×	3.3 nm	0.7 nm
250,000×	4 nm	0.8 nm
200,000×	5 nm	1 nm
150,000×	6.7 nm	1.3 nm
100,000×	10 nm	2 nm
50,000×	20 nm	4 nm

Criteria

The goal of the work described in this paper was fourfold. The first was to attempt to explore the usefulness of the sharpness criteria as a practical method of assessing instrument performance. The second goal was to develop a sample or samples suited for the determination of the sharpness of an SEM. The third task was the development of an automated, objective technique to analyze the image and determine the sharpness in a quantitative manner, and the final goal was to apply the automated procedure to real-world production samples. The first part of this paper presented here outlines the application of the sharpness criterion to general SEM performance, and the second part of the paper presents the technique expanded to include computer acquisition and analysis of samples for semiconductor production.

Materials and Methods

Scanning Electron Microscopes

The laboratory SEMs used in the initial part of this work were either an analog electronics Hitachi[1] S-800 or a digital electronics equipped S-4000S cold FE instrument. The latter instrument had a linewidth measurement firmware feature and two frame buffers which were capable of storing images with resolution of 1024×1024 pixels and 8 bits of pixel depth (256 gray levels). The images were either photographed normally (digitized later with a scanner) or digital images were stored on a PC-DOS compatible, 128 MB magneto-optical disk. For measurements of full semiconductor wafers, a Hitachi S-6280H metrology SEM was also used. This low, 0.7–1.3 kV accelerating voltage, specialized SEM acquires 512×512 pixels at 8 bits of pixel depth (256 gray levels) resolution from TV-like images. Using the special software, this instrument is capable of carrying out "automated" dimensional measurements. The images can be printed on a video printer or saved on disk using a frame grabber; the image used in the calculation done by the machine is unfortunately not accessible in its digital form.

Imaging System

The imaging system used in this, the initial portion of the study, was the NIST developed, personal-computer-based Isaac Image Analysis System described in an earlier paper (Postek and Vladár 1995). The original Isaac system was built with an Apple Macintosh II fx. Subsequently, an improved, faster version was developed around an Apple Macintosh Power Mac 8100/80 computer; both versions of this system were used during this study. For the CD SEM, a Hewlett-Packard Vectra XU 6/200 computer-based imaging system with a DT 3152 (Data Translation) frame grabber board was used.

Samples

The "ideal" sample for the sharpness evaluation would have diversified size features with exactly known structure in all directions and dimension ranges. This sample would be "fractal-like" and would allow the user to measure accurately the geometric parameters of the primary electron beam. Since no such sample exists, the only choice is to find or produce artifacts that, at least in the most important magnification ranges, have satisfactory structure. Beyond the geometry requirement, the sample must yield reasonably noiseless images with good contrast at least in the upper magnification range. Several different types of samples were tested for their applicability to the sharpness technique. The conclusion was that the following characteristics should be present in any sample used for determination of sharpness. First, the sample must be able to be formed or placed on or into a semiconductor wafer. Since the technique is used in automated wafer fabrication instrumentation, the sample must be able to approximate the product being viewed. Second, the sample must be solid to avoid any possible particle contamination of the semiconductor processing. Therefore, latex spheres or zinc oxide powder (used in early portions of this work) were later eliminated from the possibilities. Third, the sample cannot be a source of doping material. Many semiconductor wafer-processing facilities are trying to avoid any use of samples containing gold because of the fear of unwanted doping of silicon wafers. Therefore, samples such as GoC were eliminated from the potential samples as well.

During the initial phases of this work, the best sample for laboratory instruments was a platinum-coated GoC sample. As the methodology improved, two other samples were also found to be useful in the determination of sharpness: gold-coated etched biphasic glass and a semiconductor wafer-etching artifact named "grass". The etching artifact "grass" meets the major characteristics of the evaluation sample (as described above) and can be used for both laboratory and on-line instrumentation. A small quantity of the grass samples was developed in collaboration with Dr. Brian Newell at Texas Instruments, Dallas, Texas. The grass sample was chosen as the sample of choice used in later portions of this work. The micrographs of samples used in this paper are of the early evaluation of the sharpness concept using the other samples.

Software

The image processing software generally used in the initial phase of this work was a commercially available scientific image analysis program called IPlab Spectrum (Scanalytics, Inc.). This software was designed to work on images of 8 or 16 bits of pixel depth, permitting high-quality image processing and accurate 32 bits calculations on the high-resolution data arrays or images generated by the Isaac Image Analysis system. The Fourier calculations were done within this program using its built-in, fast Fourier transform (FFT) routines with resolution of 1024 elements. A public domain program, named NIH Image, was also useful in this work. The TV-rate frame grabber card connected to the laboratory SEMs was controlled through this software. NIH Image was used for data acquisition for the 8 bits gray level resolution images, and IPlab Spectrum for analysis of both the 8 or 16 bits of pixel depth (256 or 65,536 gray levels) images acquired using the system. Newer versions of NIH Image are able to perform Fourier analysis as well. The software used for evaluation of images taken with metrology SEMs will be described in the second part of this paper.

[1] Certain commercial equipment is identified in this paper to describe adequately the experimental procedure.Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it mean that the equipment identified is necessarily the best available for the purpose.

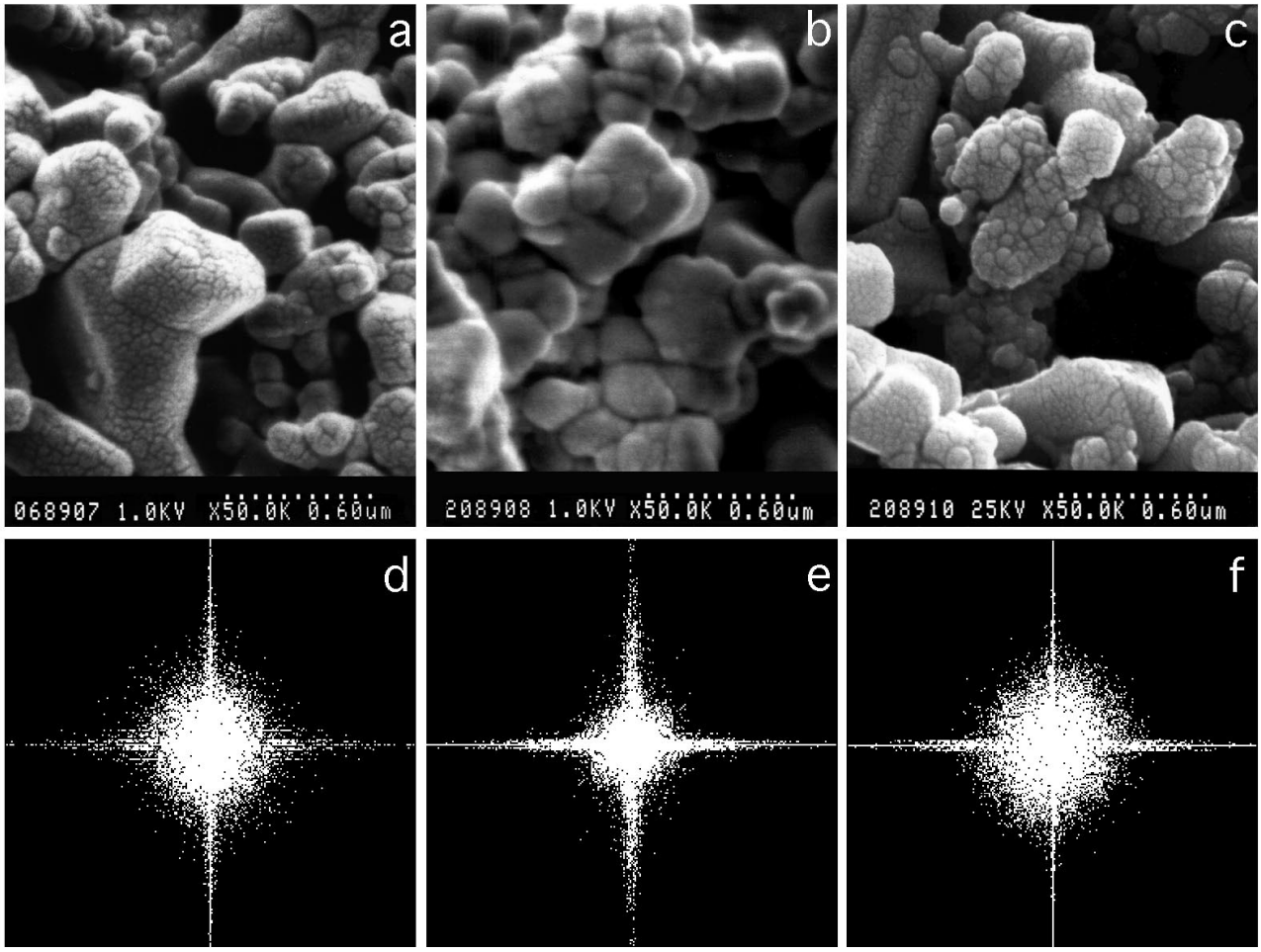


FIG. 3 Scanning electron microscopy micrographs of heavily gold-coated zinc oxide powder at low accelerating voltage and their Fourier frequency magnitude distributions in logarithmic, isometric view. (a) Low accelerating voltage image when the instrument was functioning properly. (b) Fourier frequency magnitude distribution. (c) Low accelerating voltage image when the instrument was functioning poorly. (d) Fourier frequency magnitude distribution. (e) High accelerating voltage image when the instrument was functioning properly. (f) Fourier frequency magnitude distribution. (Field width = 1.7 μm.)

Results

Subjective Sharpness Evaluation

Figure 3a demonstrates the performance of a cold FE SEM on a coated zinc oxide test sample at low accelerating voltage. Figure 3b was taken with the same conditions following a tip exchange. Note that the image appears to be far less sharp than the previous one. Figure 3c shows the sample at 25 kV accelerating voltage. This high-accelerating voltage image demonstrates reasonable quality and meets the resolution criteria for instrument acceptance. However, as Figure 3b shows, if the instrument is tested at low accelerating voltage the performance is quite unacceptable in comparison with Figure 3a. In an instance such as this, the performance difference is sufficiently striking that there is little question that the instrument performance needs to be improved. The smaller incremental losses in resolution with time need a finer method of analysis and thus resulted in the use of the ISAAC system for micrograph evaluation.

Image Analysis

As the primary electron beam scans the sample, the low-frequency changes in the video signal show information about the larger features and the high-frequency changes give data on the finer details. A sharper image has more high-frequency components than a “blurry” or “soft” image; therefore, a method which is adequately sensitive to the intensity of higher frequencies can be used to measure the sharpness of an image. Earlier works by Erasmus *et al.* (1980) and Dodson and Joy (1990) have pointed out that the Fourier transform of an image could be applied to this task. The Fourier transform

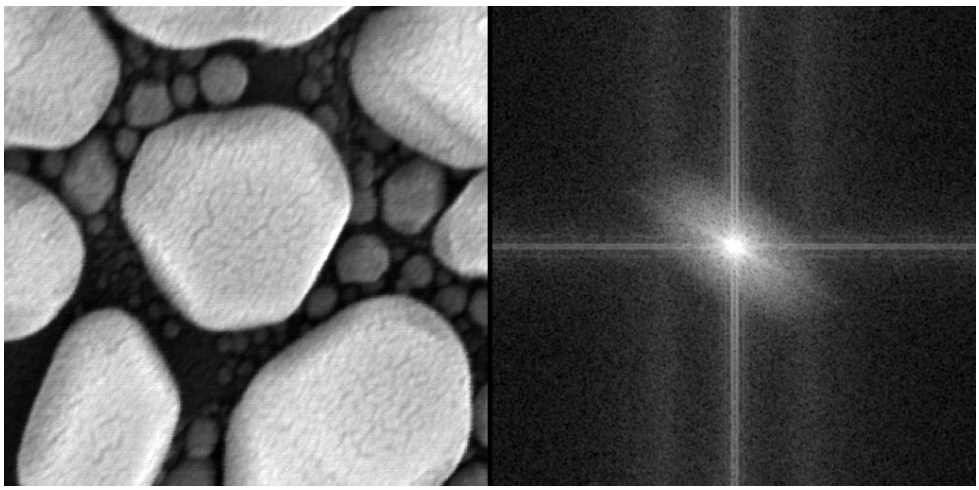
is a reversible mathematical operation that turns an image, which is essentially an intensity (gray level) distribution of the video signal along the X and Y coordinates in the spatial domain, into a magnitude and phase distribution in the frequency domain. The characteristic (in linear view very slim) cone-like magnitude distribution that shows is the magnitude of a given frequency. In the origin, the zero frequency represents the overall brightness of the image, while the noise is visible around the outskirts of the cone. As the image gets sharper, that is, the focus becomes sharper, this cone widens and this change can be quantified with a suitable method. The center part close to the origin carries the overall sample information, and it is visible even on Fourier frequency magnitude distributions of quite blurry images.

Image analysis is very powerful in the examination of sharpness from these images. Both the frequency and the phase information are available for use, but currently the phase distribution information is discarded. Turning the Fourier domain image into a binary distribution with a simple threshold operation at a suitable level or color-coding (assigning various colors to certain gray levels) of the frequency magnitude distribution reveals a small difference in sharpness. Figure 3d–f proves that there is a detectable difference in sharpness between the images above them. Figure 3f also demonstrates that the 25 kV image could have been better if the small amount of residual astigmatism present in the image had been corrected. This is apparent since the cross section of its distribution is not circular. The cover image of this issue shows two images and their color-coded Fourier frequency distributions of a heavily gold-coated zinc oxide sample. Note that the blurry image (upper) has a much smaller spot in the Fourier domain (i.e., it contains less high-frequency changes and less detail). Figure 4 shows the SEM image of a Pt-coated GoC sample where the astigmatism in the image was intentionally not properly corrected. The image is sharper in one direction, so it is apparent that the Fourier cone is wide in the properly corrected direction but it is narrow in the other direction due to the noncircular cross section of the primary electron beam.

Figure 5a–c demonstrates an early application of the technique to the comparison of the method with the performance of three instruments from the same manufacturer on the same polysilicon sample. The Fourier magnitude distributions as binary (threshold at 128) images are shown under the original images. These images have been analyzed using an early quantitative analysis algorithm which is fast, but gives roughly estimated values. The numerical results are shown in Table IV. The algorithm used in this comparison computes the Fourier transform of 32 X and 32 Y direction lines at the center of the image. The algorithm then finds the sum of the 50 frequency magnitudes starting after the first 16 values related to the sample and gives the sum of the next 50 values as the noise figure. Note that the image sharpness and noise visible to the operator and the results of the quantitative analysis correlate quite well.

Conclusion

In conclusion, the first part of this work describing the sharpness methodology has demonstrated that the sharpness concept is a viable approach to the determination of SEM performance in both laboratory and automated production SEMs. This approach provides the potential for an objective manner to eliminate the biases applied to instrument evaluation by operator-to-operator differences. The next step in this approach is to automate the procedure and make it user friendly and quantitative, and to determine its limitations by objective comparisons. Further analysis, including quantitative evaluation of image sharpness, and the use of the grass sample will be presented in the second part of this paper.



(a) (b)

FIG. 4 Scanning electron microscope micrograph (field width = 900 nm) of a Pt-coated gold-on-carbon sample where the astigmatism was not corrected well (a) and its Fourier magnitude distribution (b).

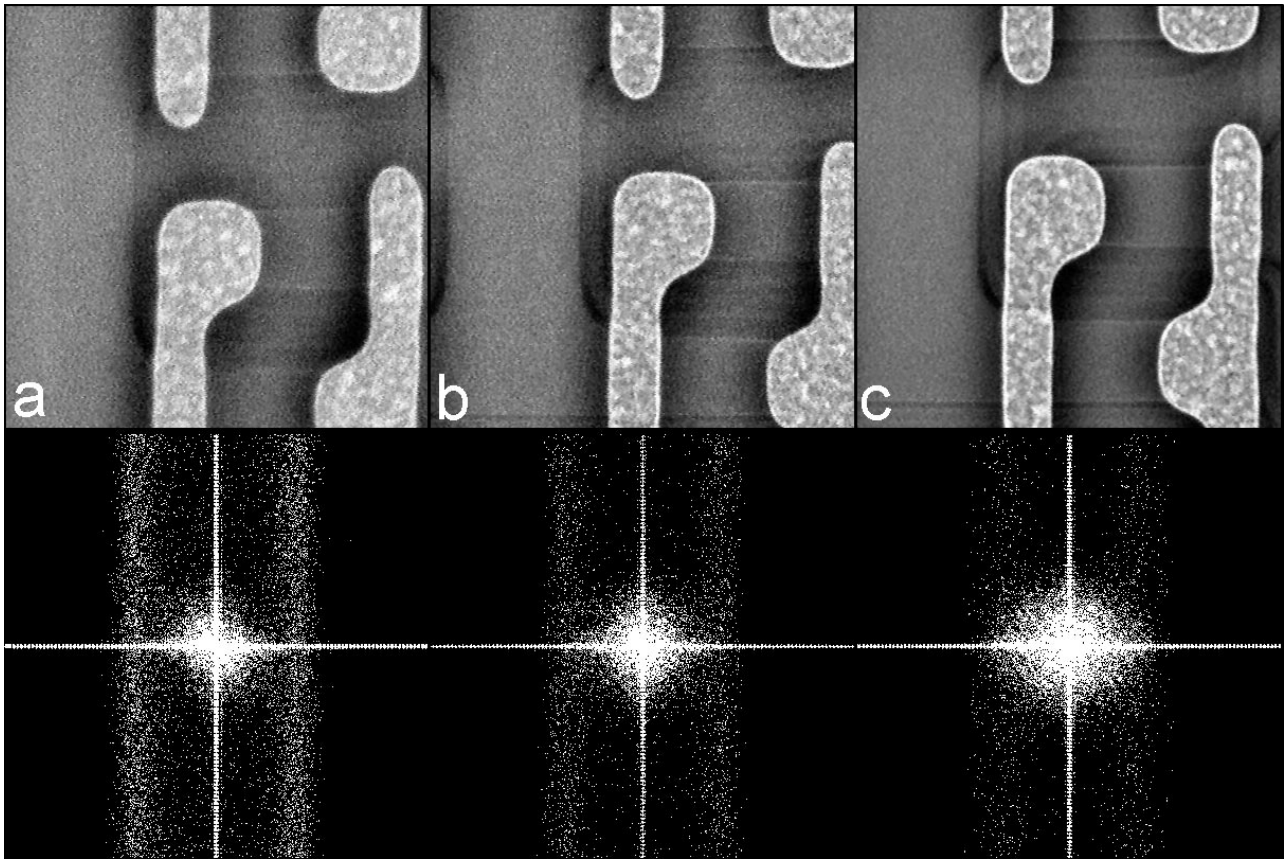


FIG. 5 Comparison of three different scanning electron microscopes from the same manufacturer on the same polysilicon sample and their Fourier magnitude distributions (field width = 4 μm). The images and the Fourier magnitude distributions are quantitatively compared in Table IV.

Table IV Quantitative fast-Fourier tranform of image sharpness and noise

Figure	X sharpness figure	Y sharpness figure	X noise figure	Y noise figure
5a	19.6	18.6	10.7	8.92
5b	22.2	18.8	9.91	8.41
5c	24.4	19.9	7.05	6.73

Acknowledgments

The authors would like to express their appreciation to Dr. Sheldon Moll of AMRAY Inc., Bedford, Massachusetts, for recommending this original idea and for discussions on the application to the sharpness concept. They would also like to thank Mr. Phil Gleason of Corning Glass for the biphasic glass samples; Dr. Brian Newell of Texas Instruments, Dallas, Texas, for his assistance in the development of the etched silicon grass sample; Mr. Neil Sullivan of Digital for the micrographs of the production instrument comparison; and Mr. Samuel Jones for his SEM expertise. The authors would also like to acknowledge funding from SEMATECH and the National Semiconductor Metrology Program.

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