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Qualitative and Quantitative study of SEM images in terms of sharpness analysis

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QUALITATIVE AND QUANTITATIVE STUDY OF SEM IMAGES IN TERMS OF SHARPNESS ANALYSIS

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By

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ABSTRACT

QUALITATIVE AND QUANTITATIVE STUDY OF SEM IMAGES IN TERMS OF SHARPNESS ANALYSIS

by Annu Radha Sharma

Quantification of the image quality of the Scanning Electron Microscope's (SEM's) micrographs in terms of sharpness and as a function of magnification, image size, spot size, accelerating voltage and working distance on the Philips XL50 SEM has been done. A software program called SEM Monitor/Measure, developed by the SPECTEL Corporation, has been used to obtain sharpness values for each experiment conducted for this paper. The experimental results and analytical study shows that if magnification, image size and spot size are adjusted to optimum values then the sharpness of low accelerating voltage images solely depends upon the change in working distance.

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1 Introduction

The Scanning Electron Microscope (SEM) is a metrology instrument that has the ability to measure nm-sized features with the smallest possible errors. It is an industry need and concern to prove that the instrument is performing well. Fully automated and semi-automated SEMs are used in semiconductor industry and other forms of high tech manufacturing. It requires that these automated instruments be routinely capable of 5 nm resolution at or below 1 kV accelerating voltage for the nominal 0.18 to 0.35 μm design rules of integrated circuits.(1)

Wafer processing in lithography and etch has been and continues to be driven by critical dimension (CD) control. As the geometry of the circuits has decreased, so has the CD error budget and the corresponding amount allotted to the CD measurement tool. CD tool precision of 3 nm is now expected, and requests for precision of 1 nm or less are not uncommon. For the critical dimension scanning electron microscope (CD-SEM), the primary means for collecting measurements, the ultimate limiting factor for improved measurement control is the resolution performance at low voltage. (2)

While the means for collecting the data have become increasingly automated, with advanced pattern recognition and measurement algorithms, the means for controlling the CD metrology tools have not. Maintaining the electron beam of a CD-SEM through the beam alignment remains largely a manual effort, in which the degree of

training and subjective judgment of the user comes into play. Automation of the beam alignment process first requires a quantitative measure of the beam sharpness. Andras Vladar and Michael Postek (1) have devised such a method for SEM performance analysis, and their 'sharpness analysis' algorithm has been implemented in the Spectel Research SEM Monitor System. The SEM Monitor provides useful feedback that helps to improves the quality of the electron beam and therefore the accuracy and precision of the CD measurements. (2)

A major advantage of using the software 'SEM Monitor' is that it detects any change in resolution below 0.2 mm, which is the spatial resolution of the human eye. In this way it is a powerful tool in indicating the best performance of the instrument.

The generation, focusing and astigmatism correction of the primary electron beam are the first steps in the imaging of a SEM. It is therefore critical that the electron beam be optimized to provide the best resolution, since any other improvements downstream in the signal detection and analysis would otherwise be wasted. This paper also includes an overview of the basic components of the SEM.

The sharpness value is the single most important indicator of the overall performance of the scanning electron microscope, therefore a careful study of the parameters that affect the calculation of the sharpness is done in this paper. The SEM

Monitor software yields the sharpness values as a unit-less number, which increases as the resolution of the image does.

The sharpness value should be analyzed in conjunction with its micrograph. There are several factors, both controlled and uncontrolled, that may unjustly affect the sharpness values giving it an unrealistic value. Among the uncontrolled factors is the environment such as ventilation and temperature of the room and instability of the stage that causes the sample to vibrate. These factors can be identified from the image.

It is very important to understand how to adjust the parameters of the SEM to best settings that will produce an image of highest resolution. The information from this high-resolution image is then fed into the SEM Monitor that will calculate the sharpness value.

Various experiments were conducted for this paper to determine how each parameter affects the sharpness value. The parameters considered are magnification, working distance, accelerating voltage, image size and spot size. The data yield a number of conclusions, which can be divided into qualitative and quantitative results.

In the qualitative analysis four points have been discussed. First, the operator should be aware of noise and how it affects resolution. Second, the operator should also observe how contrast and brightness should be adjusted so that it reflects an adequate sharpness value. Third, how to chose the proper location on the sample to image and

consequently what area of the image should be fed into the SEM Monitor for the purpose of the calculation of sharpness and finally, what information to look for when comparing sharpness of same images collected in real time or digitally.

The quantitative analysis explores three parameters; the magnification, accelerating voltage, and spot size that can be set to optimum values where the effects of working distance can be observed separately. Changing the working distance for a constant accelerating voltage, under the optimum conditions improves the resolution of the image. This will be explained in terms of the lens aberrations and sample-beam interaction.

2 Components of the Scanning Electron Microscope

In the scanning electron microscope (SEM) it is the amount of the current in the focused electron beam impinging on a specimen that determines the magnitude of the signal emitted, and also it is the size of the final probe spot that determines the resolution of the instrument. (4)

With this in view, the electron optical signal system on SEM is designed so that the maximum possible current is obtained in the smallest possible electron probe. In order to use the instruments intelligently, it is important to understand how the optical column is designed, how the various components of the optical system function, and which components are most important in determining the final current and spot size.(4)

Given below is a brief overview of the basic components of SEM that apply in particular to the Philips XL50. See figure 1.

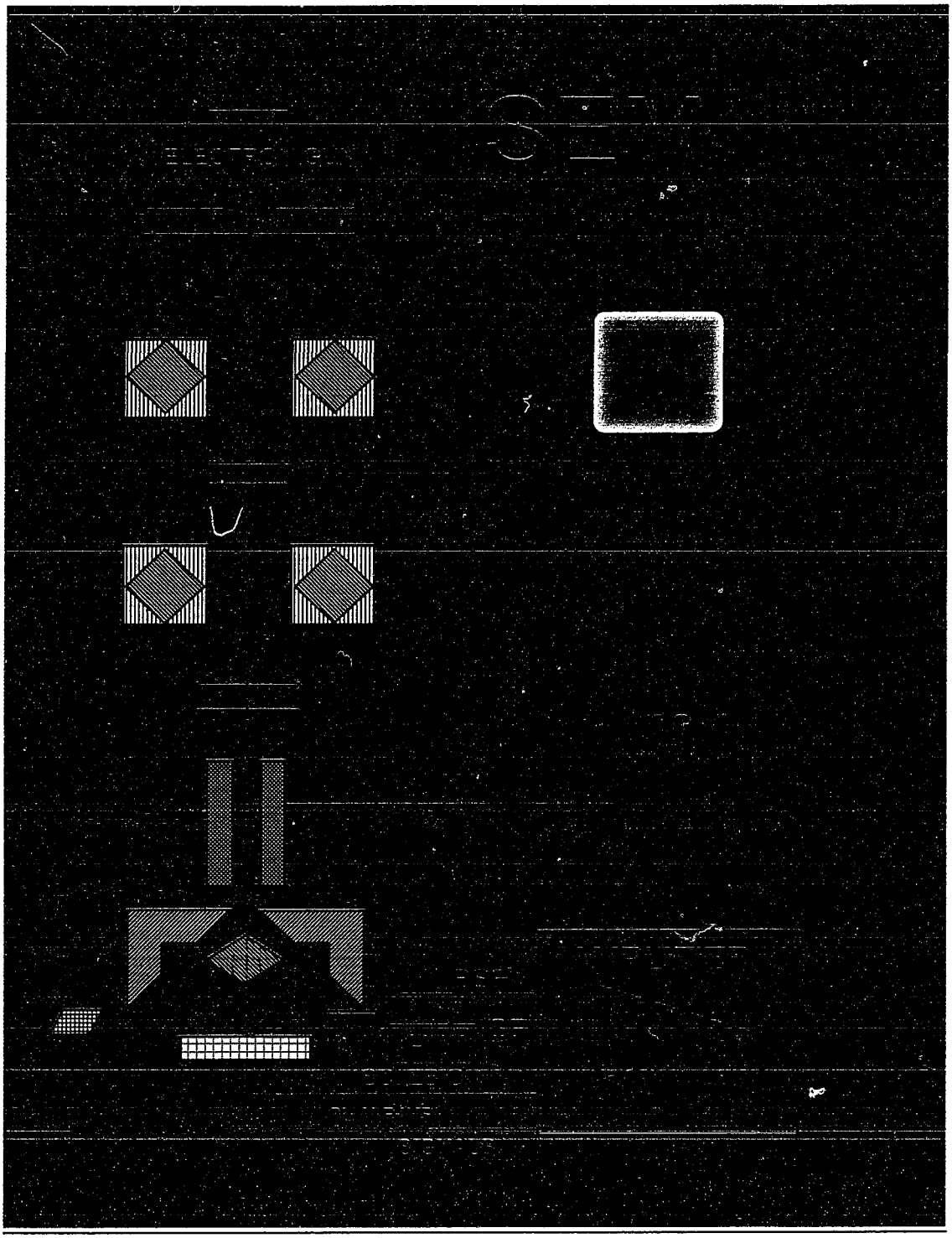

Fig. 1. Basic Components of the Scanning Electron Microscope

i) Electron Source

An electron source, which is potentially very bright, is the field emission gun. For the field emission process, a negative voltage is applied to a very sharp metal point and this high negative field gradient drives electrons out and away from the point. (4)

Electrons are drawn from the filament tip by an intense field set up by an anode that lies beneath the tip of the filament. Electrons are then pulled from a very small area of the pointed tip and proceed down the column. Often this is aided by a second anode beneath the first. Acting like an electrostatic lens, the two anodes serve to further coalesce and de-magnify the beam. The lost electrons are replenished by an electron source attached to the tungsten tip.

The major problems with the field emission guns are the stringent vacuum required, and the relative instability of the cathode tips, but in the modern SEM's these have been taken care of. (4)

ii) Electromagnetic Lenses

Electron optical columns for the SEM consist of the electron gun and two or more electron lenses. For the case of the Philips XL50 there are two condenser lenses.

The condenser lens systems are used to demagnify the electron image formed at crossover in the electron gun to the final probe size on the sample. The condenser lens system, which is composed of one or more lenses, determines the beam current, which impinges on the sample. The final lens, often called the objective lens, places the focused probe exactly on the specimen surface. (4)

Conventional electromagnetic lenses are used and the electron beam is focused by the interaction of the electromagnetic field of the lens with the moving electrons.

iii) Electron Beam and Specimen Interaction

The focused electron beam impinges on a sample surface producing the following signals: secondary electrons (SE), backscattered electrons (BSE), characteristic x-rays, continuum x-rays and Auger electrons (AE). These signals are obtained from specific emission volumes within the sample, which are strong functions of electron beam energy and atomic number of sample. Each of these effects carries information about the sample. In fact, the resolution for a particular signal in the SEM is primarily determined by its excitation volume. (4)

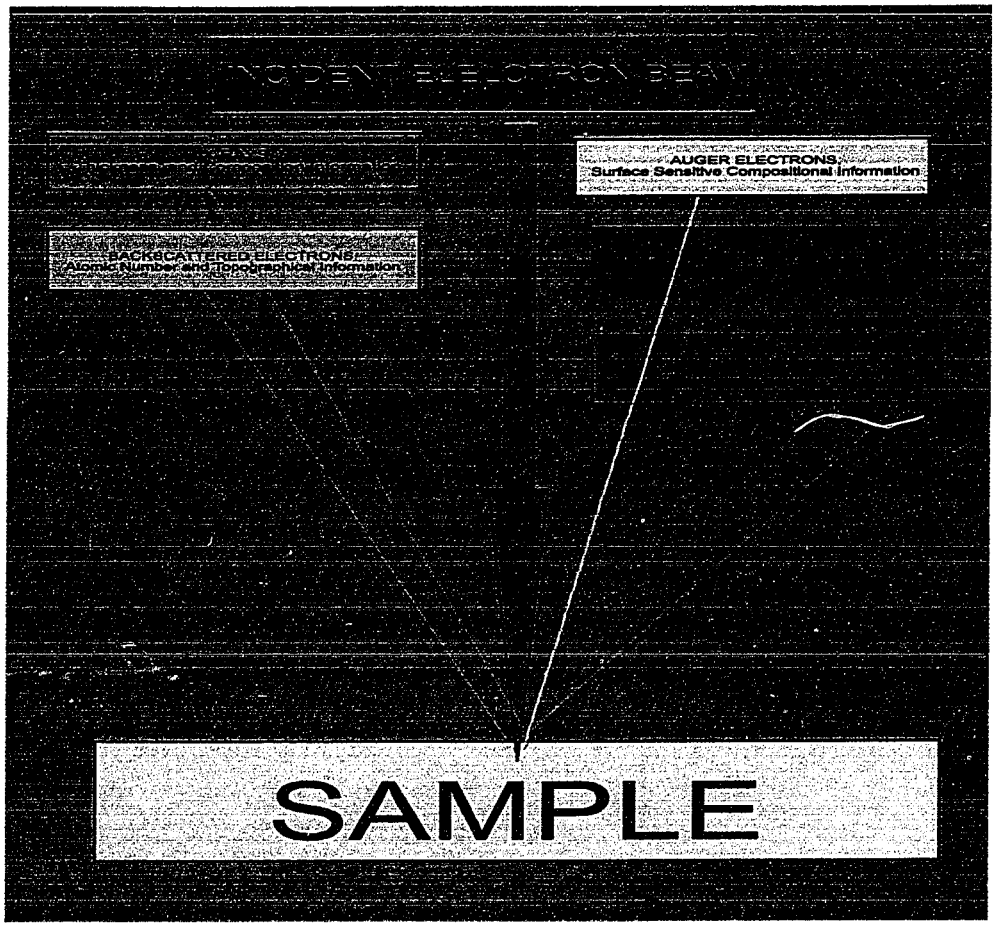

Fig. 2. Signals emitted when an electron beam interacts with the sample

Image formation in an SEM is dependent on the acquisition of signals produced from the interaction of the specimen and the electron beam. These interactions can be broken down into two major categories. First, those that result in elastic collisions of the electron beam on the sample, in which there is change of direction with negligible energy loss and second those that result in inelastic collisions in which there is energy loss with negligible change in direction. (4)

One refers to the illumination beam as the "primary electron beam". The electrons that comprise this beam are thus referred to as being primary electrons. Upon contacting the specimen surface a number of changes are induced by the interaction of the primary electrons with the atoms contained in the sample. Upon contacting the surface of the specimen most of the beam is not immediately bounced off in the way that light photons might be bounced off in a light dissecting microscope. Rather, the energetic electrons penetrate into the sample for some distance before they encounter an atomic particle with which they collide. In doing so, the primary electron beam produces what is known as a region of primary excitation. Because of its shape this region is also known as the "tear-drop" zone. See Fig. 3. A variety of signals are produced from this zone, and it is the size and shape of this zone that ultimately determines the maximum resolution of a given SEM working with a particular specimen. (4)

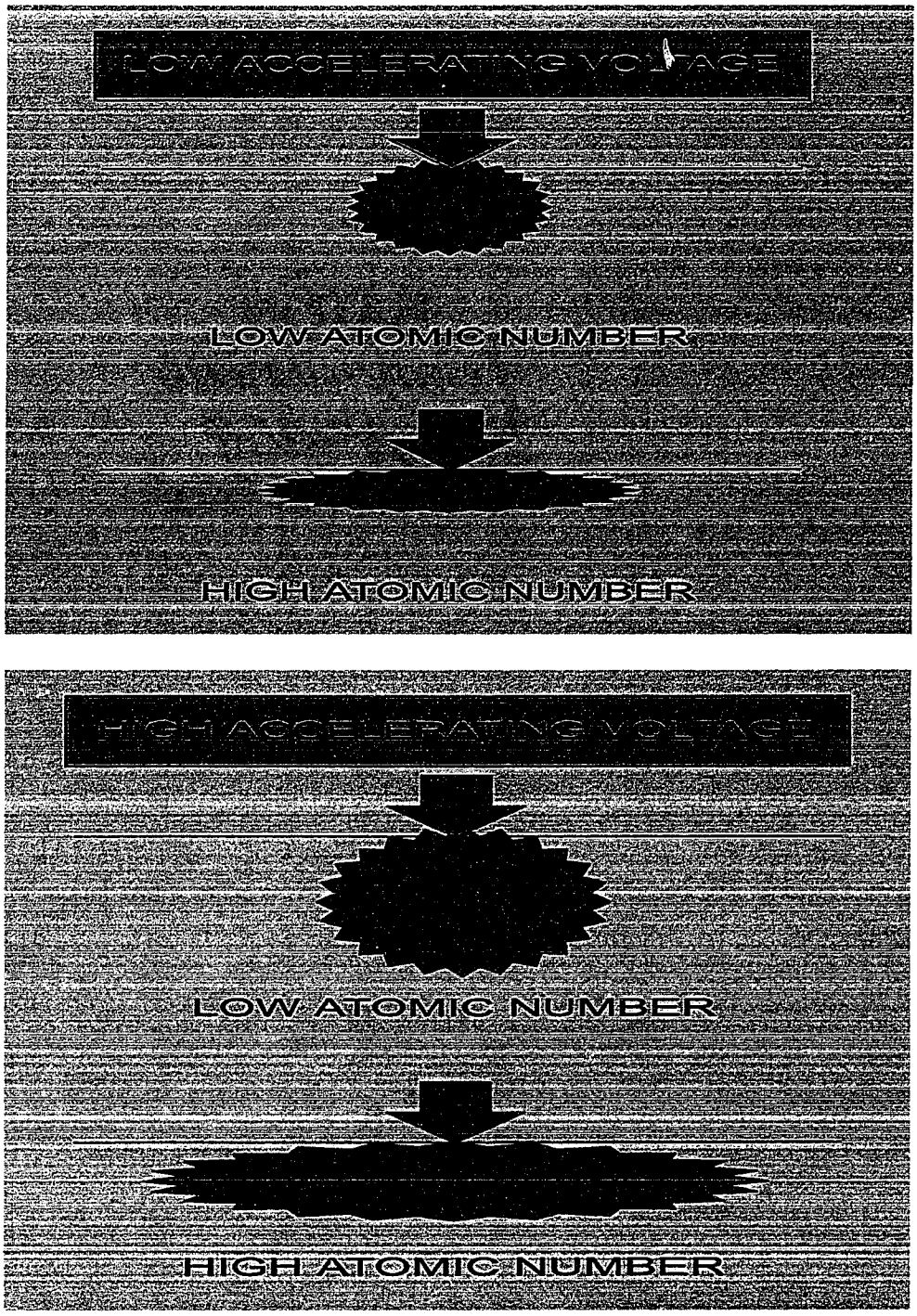

Fig. 3. Diffusion of incident electrons

iv) Detectors

The standard detector for most SEMs is Everhart-Thornley detector (ETD). The acceleration of secondary electrons with exit energies below 50 kV by a bias of 10 kV, and the detection by a scintillator- photomultiplier combination, is the most efficient detection system for SE, due to high gain. (3)

The secondary yield is confined near the beam impact and gives information of surface topography.Everhart-Thornley detector first converts the energy of the secondary electrons into photons. The main component that achieves this is the scintillator. The scintillator is composed of a thin plastic disk that is coated or doped with a special phosphor layer that is highly efficient at converting the energy contained in the electrons into photons. When this happens the photons create a cascade of electrons in the photomultiplier. Such a system creates a very large gain in amplification.

The signal thus produced can now be used to control the intensity of brightness on the Cathode Ray Tube (CRT) screen in proportion to the number of photons originally produced. See figure 4. (4)

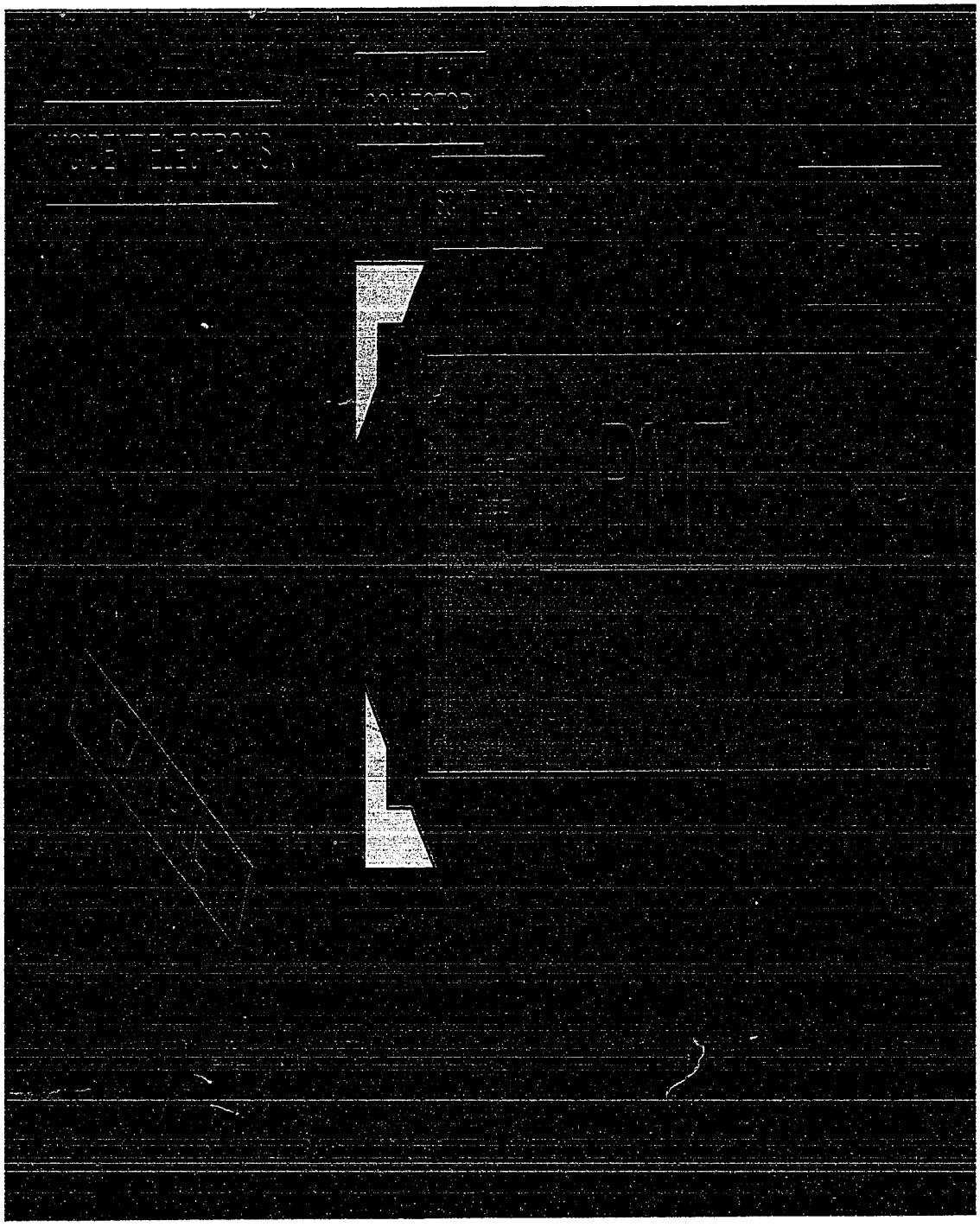

Fig. 4. Secondary Electron detector

v) Signal formation

The components of the image formation system are: the scanning system, the signal detectors, the amplifiers and the display. (4)

A variety of effects are produced by the interaction of the beam and the specimen. Each of the effects carries information about the specimen. All of the interactions effects can be monitored (even simultaneously) by the use of appropriate detectors. The signals are suitably amplified and used to control the brightness of the CRT (intensity modulator).

For each point on the specimen, a point is established on the CRT, and the brightness of this point is related to a detector signal derived from the characteristics of the beam-specimen interaction. Since the interaction varies from point to point on the specimen, the signals produced by detectors will vary, hence different values of brightness will be generated at a point in the CRT. The geometrical relationship of a group of points on the sample is reproduced on the CRT, and at each point, an intensity is produced which is related in some way to the specimen (usually topography). (4)

3 Sample and Equipment

3.1 Sample and data limitation

Sample: High Resolution Gold on Carbon Test Specimen. Scanning electron microscope resolution is tested in terms of a combination of criteria, namely resolved gaps and the number of gray levels in the image. This is to ensure that the resolution has not been distorted by using the contrast to maximize visibility of edges. High-resolution images ideally should show fine details together with a lack of noise evidenced by a good range of gray levels. A suitable sample for test of SE and BSE imaging and for chemical mapping in high-resolution systems is the High Resolution Gold on Carbon Test Specimen. (6)

The gold on carbon specimen yields a good quality image on a relatively easy to produce sample. The high SE yield of the gold in comparison to the poor SE yield of the carbon gives excellent contrast and edge definition. (6) Below are shown examples of the images of gold on carbon taken on the Philips XL50. See figure 5 and 6.

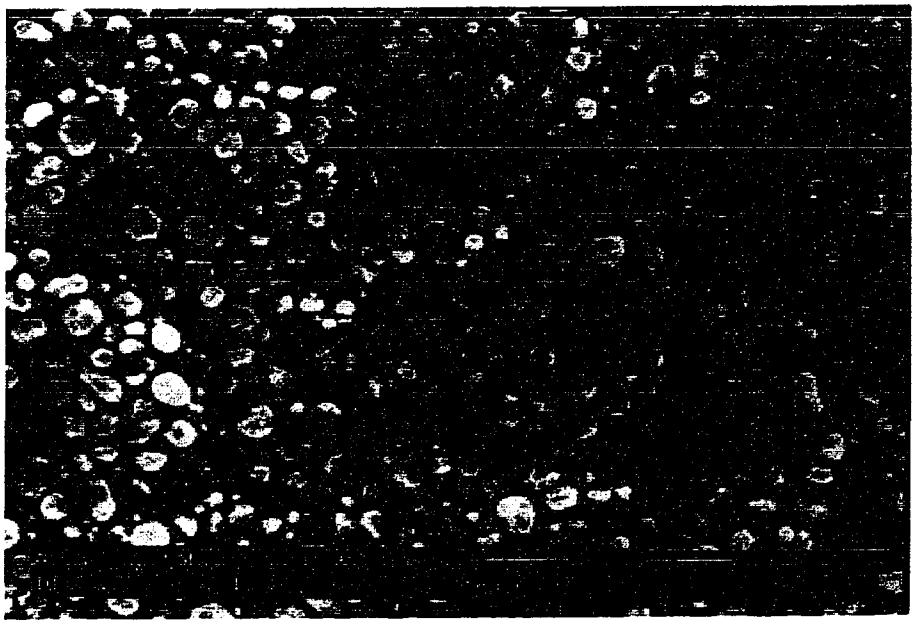

Fig. 5. Philips XL50 Image at 73784x Magnification, 10 kV accelerating voltage and working distance of 5.0 mm

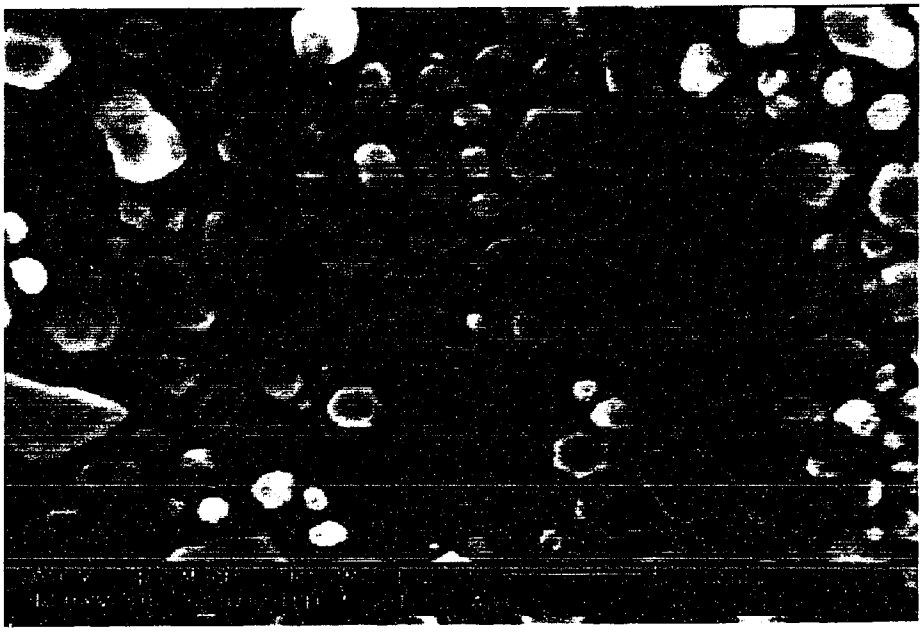

Fig. 6. Philips Xl50 Image at 122973x Magnification,10 kV accelerating voltage and working distance of 4.2 mm

The data points shown on the graphs used in this paper are the sharpness values computed by the SEM Monitor of images taken on different locations on the sample. Each data point is a distinct image. The reason for not using the same location on the sample repeatedly is charging and contamination (chamber) of the sample. If the electron beam remains on the same location for a prolonged time, that area becomes contaminated, affecting both the collection of the secondary electron signal and distorting the scan raster.

In the case of a non-conducting sample if the location becomes positively charged (dark appearance) or negatively charged (bright appearance) it affects the resolution as well as the calculation of sharpness value. Charging can be corrected with the proper scan speed and the direction of the incident beam. For this paper, all images where taken with the beam impinging on the sample at a perpendicular angle.

3.2 Software equipment - SEM Monitor

SEM Monitor is designed to be a diagnostic aid for semiconductor SEM based metrology. It provides a quantitative framework for monitoring an SEM's resolution, astigmatism, and image quality both over time and as compared to other machines. It can also be used to adjust an SEM for optimum performance. (7)

Any image generated by SEM is a result of the sample and electron beam interaction. As the primary electron beam is scanned across the sample, secondary electrons, backscattered electrons, characteristic x-rays, Auger electrons and photons of various energies are generated and a suitable detector converts some of these into a video signal. The low-frequency changes in the video signal contain information about the larger features and the high-frequency changes in the video carry information about the finer details. (1)

The SEM Monitor uses Fast Fourier Transform which is a reversible mathematical operation that turns an image, which is essentially an intensity (gray level) distribution of the video signal along x and y coordinates in the spatial domain into magnitude and phase distribution in the frequency domain. (1) It calculates the power spectrum, the smaller axes of the power spectrum gives the sharpness value.

3.3 Hardware equipment – Philips XL50

SEM: The scanning electron microscope used for this paper was Philips XL50, except for two experiments that used Hitachi S4000. Philips XL50 is known for its exceptional stage accuracy.

The scanning electron microscope Philips XL50 FEG (Field Emission Gun) employs a Schottky based gun design using a point source cathode of tungsten, which has

a surface layer of zirconia (ZrO). The working temperature of the emitter is 1800 ^{o}K. It takes only a minute to become fully operational for a long period. The bright electron source possess both low energy spread and low current fluctuations, as a consequence higher effective currents in smaller probes. This instrument has the additional advantage to be more reliable for microanalysis of light elements: an EDS energy dispersive x-ray detector with a thin window is mounted. This allows the collection of analytical information. In order to attain the optimal settings for both, SEM and analytical work, the microscope is equipped with a multiple objective lens aperture. A CCD camera is mounted to allow the user to control the position of the sample inside the specimen chamber. (8)

The SEM operates within the Microsoft Windows environment NT 4.0. Images can be stored on a hard disc, diskettes or a zip. It has a resolution of 2.0 nm at 30 kV and 5.0 nm at 1 kV. (8) Shown below is a diagram of Hitachi SEM/EDS integrated system.

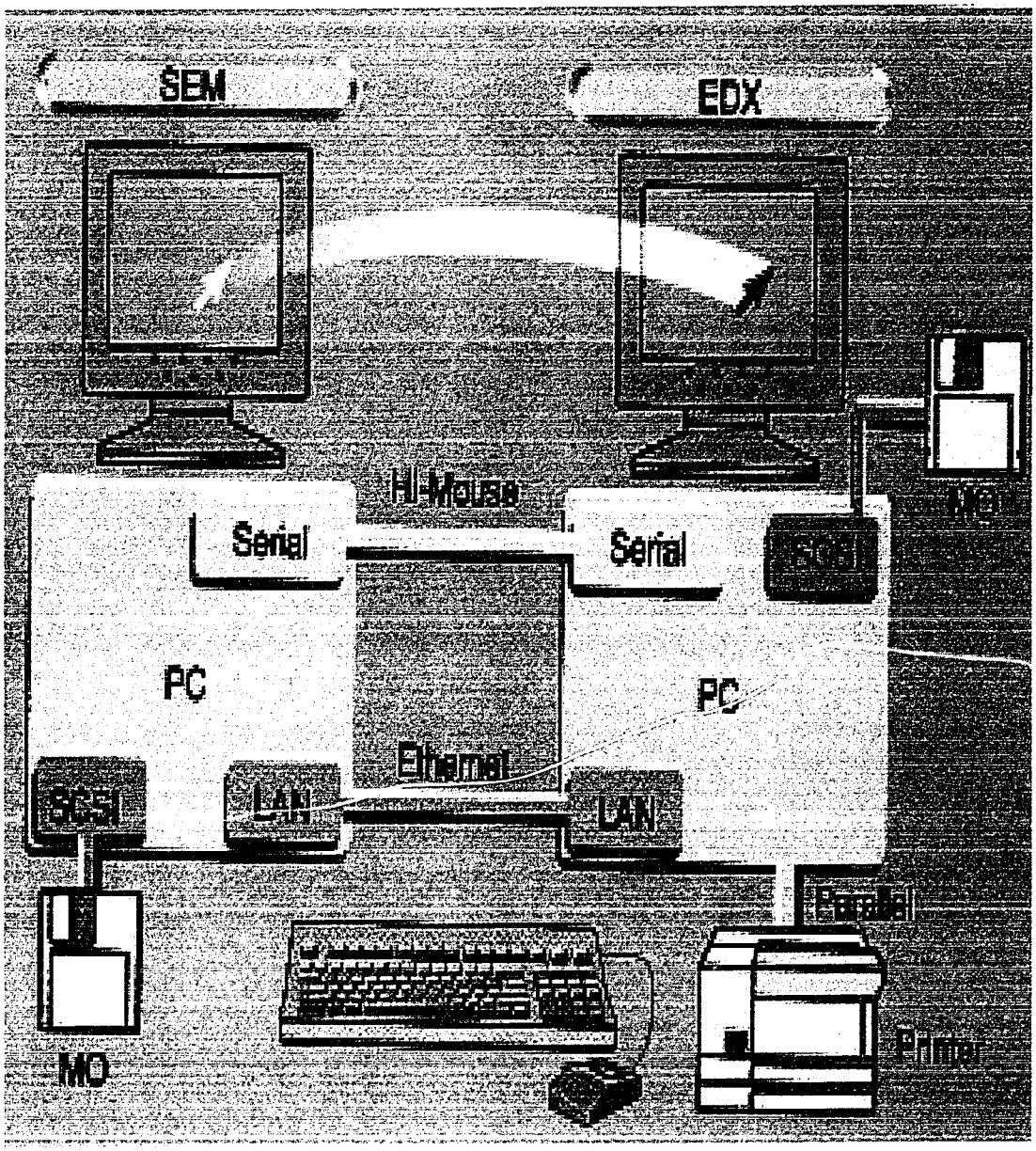

Fig.7. Hitachi SEM/EDS integrated system (9)

4 Experiments and Results

4.1 Qualitative Results

4.1.1 Noise

One of the factors that affect resolution in the SEM is the signal to noise ratio that exists. This ratio is often represented as S/N and the operator seeks to maximize this value for each micrograph. Noise is defined as any cause which distorts the image resolution. The electronic noise introduced to the final image is influenced by such factors as primary beam brightness, condenser lens strength, and detector gain. As the resolution of a picture is increased, its brightness decreases and the operator must balance all the competing factors to maximize the S/N ratio by increasing the total number of electrons recorded per picture point. Although this can be done by varying lens strength, spot size, stigmator strength, working distance, and detector gain, still all of these factors are dependent on the initial electron source.

The SEM Monitor has a provision to exclude the information from noise in the calculation of the sharpness value. For example Zero Band can be set up to any number of pixels to exclude noise that shows up along the x-axis and the y-axis. Noise along the y-axis comes from the discontinuity the electron beam encounters at the boundary of the

image frame when it scans through horizontally from left to right in a band of a few pixels.

4.1.2 Contrast and Brightness

SEM operators manually manipulate the brightness and contrast of the images to obtain the best visual resolution. The image will seem sharper if contrast is decreased and brightness is increased in most cases. While this does not actually mean that the true resolution is improved, it only gives the visual illusion that better sharpness of image has been obtained, consequentially it can yield a biased sharpness value. Manipulation of contrast and brightness affects the shades of gray of the screen. The gray spectrum is fed into the SEM Monitor software that integrates the information from the different shades of gray, and calculates the power spectrum that in turn gives us the sharpness value. The Philips XL50 has a built-in automatic contrast and brightness dial that can be adjusted at any point while getting the image. When comparing two images, its contrast and brightness values should be the same provided the same computers are being used in all cases.

4.1.3 Image Information

The SEM Monitor algorithm offers three different image sizes for the evaluation of sharpness, these are: 256 pixels by 256 pixels, 512 pixels by 512 pixels and 1024

pixels by 1024 pixels. Image size translates into the amount of information to be evaluated by the SEM Monitor algorithm. The chosen image size should be compared with the original size of the image obtained by the SEM. The appropriate size should be chosen such that any text on the image should be cropped out and most of the useful information should be included in the evaluation, excluding any voids or large defects present on the original image. Generally for Philips XL50, images size 512 is the most appropriate and it shall be used for the subsequent experiments.

Second point that can be highlighted in this section is how to set the values of the maximum radius and the minimum radius of the power spectrum in order to isolate the information about the larger and the finer features present on the original SEM images. By setting the minimum radius to 0 and maximum radius to 100 yields a sharpness value that included information from the entire power spectrum. By setting the minimum radius to 0 and the maximum radius to 50 yields a more realistic sharpness value because it includes information of the larger features of the image. Finally, by setting the minimum radius to 50 and the maximum radius to 100 isolate information of finer features. This region usually includes noise due to the finer features.

For all the subsequent experiments conducted for this paper the SEM Monitor input values were set to 1 Zero Band to eliminate noise around the x and y axes. The minimum radius was set to 0 and maximum radius was set to 45 to eliminate any noise due to small features in the original images.

4.1.4 Real Time Images and Digital Images

This experiment illustrates the difference in magnitude when sharpness is obtained from a real time image and digital image. Nevertheless, the trend in sharpness values should not change when same images are evaluated in real time or digitally. See Table 1. The graph below shows how sharpness values change when working distances are varied.

Table 1

Comparison between Digital Image Sharpness and Real Time Image Sharpness

Images	Name	SHARPNESS Digital Images	SHARPNESS Real time images
1	Au/C_5kV_**WD3.0**	3.4	7.3
2	Au/C_5kV_**WD3.5**	2.8	8.3
3	Au/C_5kV_**WD4.0**	4.4	7.9
4	Au/C_5kV_**WD4.5**	2.9	6.1
5	Au/C_5kV_**WD5.0**	2.2	5.6
6	Au/C_5kV_**WD5.5**	1.8	4.9

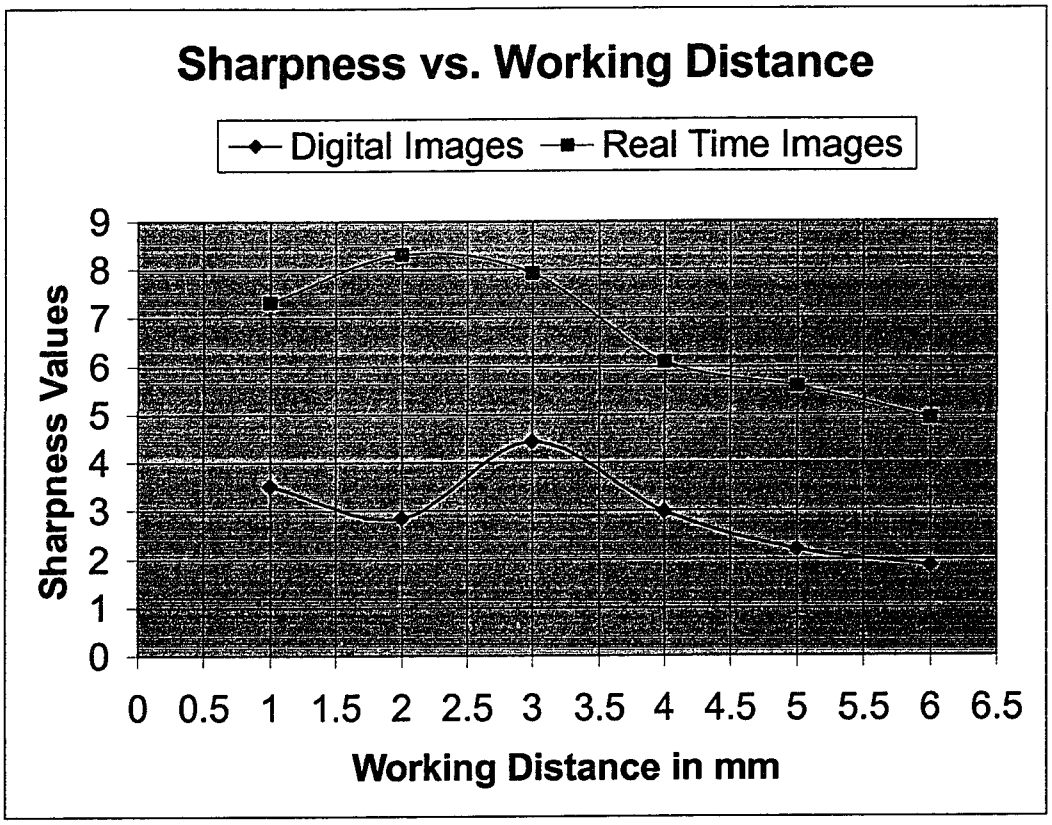

Fig. 8. Sharpness versus Working Distance

These images were taken on the Philips XL50 when accelerating voltage was 5 kV, magnification of 250,000x and spot size 3 (≈1.5 nanometers). The SEM Monitor is set at minimum radius of the power spectrum at 0 and its maximum radius at 45.The SEM Monitor evaluated the image at 512 pixels by 512 pixels size.

In Fig.8, the upper curve shows sharpness values from the real time images. The lower curve shows sharpness values from the same images, once they were saved digitally. Notice the trend is the same for both curves, but the real time curve has higher

magnitude than the digital curve. There is only one off-point in the digital images curve, which is due to the fact that too much time elapsed before saving that image. This prolonged time caused the sample to be contaminated, giving the image a darker appearance thereby causing the sharpness value to go down.

The reason why magnitudes of both curves are different is that the sharpness was calculated on different computers for each curve. The real time image sharpness values were calculated in lab, as in line CD-SEMs would, and the digital images where obtained from a desk computer, which is an example of research SEM.

The different electronics of each computer affect the calculation of sharpness because its color spectrum has different number of frequencies. When research results are to be implemented to in line SEMs, this difference in magnitude of sharpness values should be taken into account

4.2 Quantitative Results

4.2.1 Magnification

Magnification plays a predominant role in the calculation of the sharpness value. Experiments show that sharpness values are high at low magnification and decrease as the magnification is increased. This is true because of the very nature of the SEM

Monitor algorithm, which is appropriate for samples with a large number of features per image frame. As magnification is increased, the number of features per frame decrease and the sharpness value goes down. Large number of features per frame supplies sufficient information to the SEM Monitor for it to yield a realistic sharpness value.

By increasing the magnification of SEM one can reach the empty magnification of the microscope. This means that after certain magnification is achieved there is no additional improvement in resolution. Resolution is the minimum distinguishable distance between two adjacent objects.

The following experiment was done to estimate the empty magnification of the Philips XL50. Each data point on the graph shown below represents the sharpness value of a distinct image. In this experiment the accelerating voltage and spot size were held constant at 3 kV and 2 respectively. The only two parameters affecting the outcome of sharpness value are the magnification and working distance. Working distance is the distance between the objective lens and the sample.

The SEM Monitor is set up to evaluate the image size at 512 pixels by 512 pixels. The maximum radius of the power spectrum is set up at 45 and its minimum radius is 0, with the Zero Band at 1.

Table 2

Variation of Sharpness Values due to the change in Magnification

	SHARPNESS VALUES		
Acc. Vol. 3 kV	**REAL TIME IMAGES**		
Magnification	WD=4.2 mm	WD = 2.19 mm	WD = 1.8 mm
25, 000x	19.0	27.6	30.9
100, 000x	14.2	15.5	18.2
150, 000x	10.8	14.6	14.1
200, 000x	5.4	11.4	10.5
250, 000x	6.4	8.5	8.1
350, 000x	5.5	6.2	5.6
500, 000x	3.6	4.3	3.4

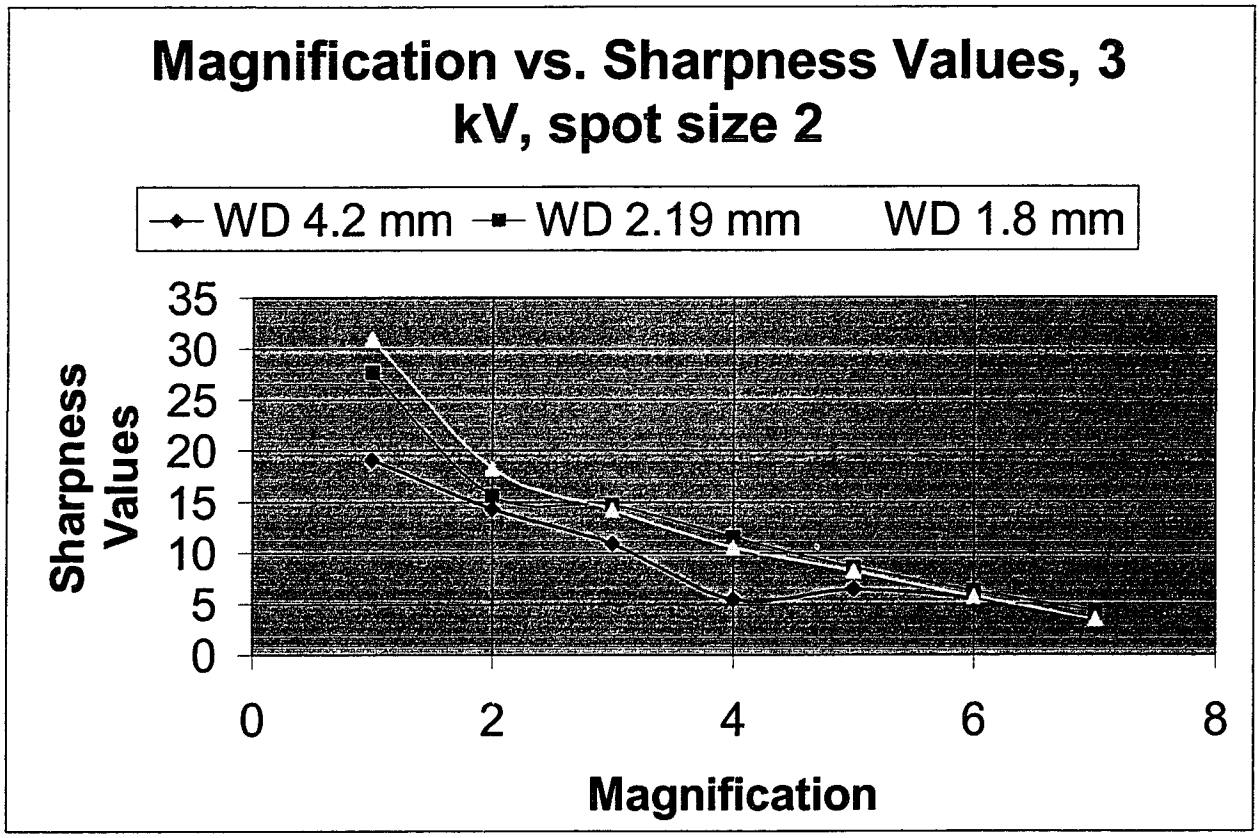

Fig. 9. Sharpness versus Magnification

Observe that at lower magnification, the chosen working distance has a great effect on the resolution of the image. Lower working distance further increases the sharpness value. The empty magnification for Philips XL50 is estimated to be about 250, 000x.

4.2.2 Accelerating Voltage

The Hitachi S4000 was used to take 5 images of the gold on carbon sample. Each image is taken at a distinct location on the sample. Below is a graph of sharpness versus accelerating voltage. This graph illustrates how the change in accelerating voltage affects the resolution of an image. For this experiment the magnification of 200,000x and a working distance of 5 mm is kept constant. The SEM Monitor is set up to evaluate at image size of 512 pixels by 512 pixels. The maximum radius of the power spectrum is set up at 45 and its minimum radius is 0, with the Zero Band set at 1.

Table 3

Variation of Sharpness Values due to the change in the Accelerating Voltage

	DIGITAL IMAGES				Sharpness Values
Image 1	wd5	**5kV**	x200,000	150nm	2.78
Image 2	wd5	**10kV**	x200,000	150nm	3.26
Image 3	wd5	**20kV**	x200,000	150nm	4.38
Image 4	wd5	**25kV**	x200,000	150nm	4.09
Image 5	wd5	**30kV**	x200,000	150nm	3.01

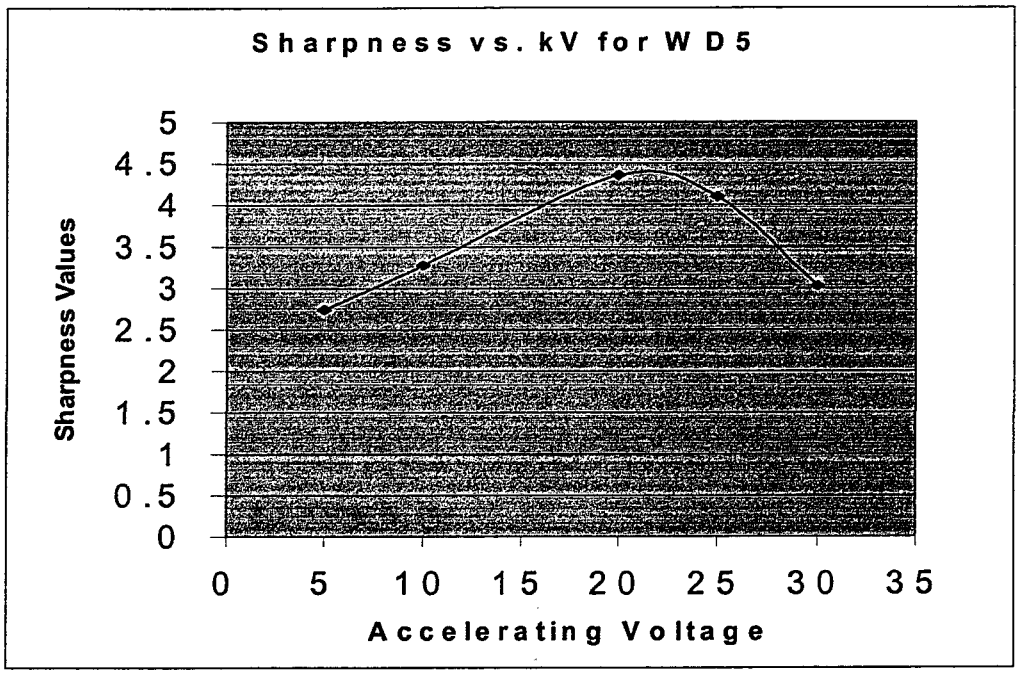

Fig. 10. Sharpness versus Accelerating Voltage

The graph shows that under these conditions, 20 kV yields the highest sharpness value. Justification for this can be given in terms of sample-beam interaction and lens aberrations.

In terms of sample- beam interaction, low accelerating voltage does not produce sufficient secondary electrons to be collected by the detector. There are dark regions in the image, which represent areas from where no information was collected. Hence producing images of low resolution.

At higher accelerating voltages, the beam penetration and diffusion area become larger, resulting in unnecessary signals (e.g. backscattered electrons) being generated by the sample. This not only eliminates the contrast of surface microstructures, but also produces a different contrast due to backscattered electrons from the material within the sample. And these signals reduce the image contrast and veils fine surface structures.

For an accelerating voltage above 20 kV, the electrons are more energetic which corresponds to small wavelength. This increases the diffraction effect, which in turn widens the spot size. As a small spot size is desirable, the increase in the diameter of the spot size decreases the resolution of image.

Another consequence of high accelerating voltage is the contamination/charging of the sample under the electron beam, affecting the collection of the secondary electron signal, which decreases the resolution of the image. Fig. 11 summarizes the effect of increasing or decreasing the accelerating voltage on the resolution of the images.

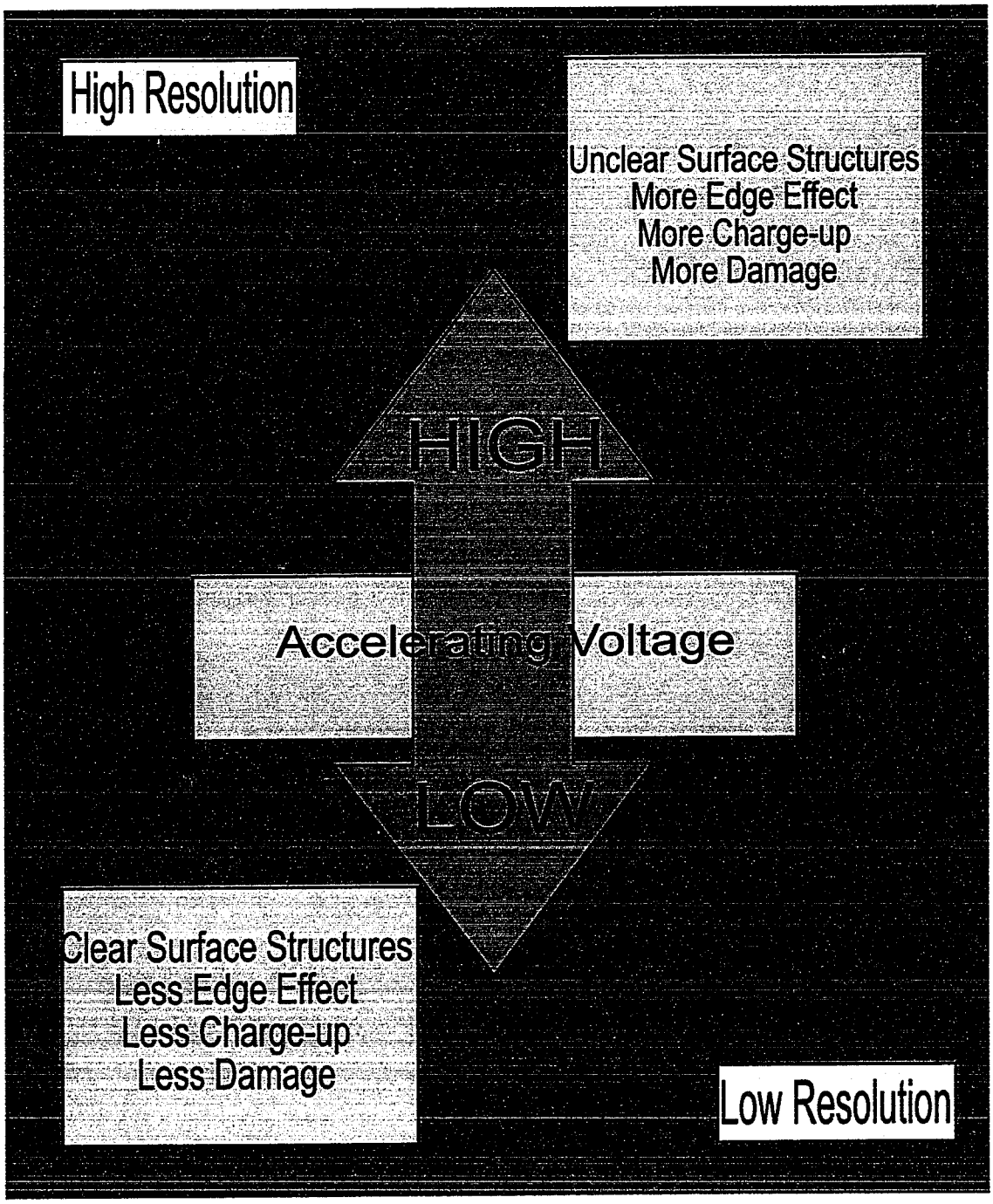

Fig. 11. Effect of Accelerating Voltage

4.2.3 Spot size

The resolution of the SEM is dependent upon the spot size of the primary beam. The smaller the spot size the better will be the image resolution, assuming that all other factors remain unchanged. Spot size is influenced by the current strength of the condenser lenses and the apertures used. It is further influenced by the geometry of the final lens field. Despite precision machining and lens construction each lens will be slightly elliptical rather than perfectly circular. The geometry of the final spot size will match that of the lens field and be slightly elliptical rather than perfectly circular. The net effect of this is to increase the spot size and reduce resolution. (4)

In the spot size versus sharpness graph shown below the parameters held constant are magnification at 12000x, accelerating voltage of 5 kV and working distance of 6.9 mm. These images were taken at distant locations on the gold on carbon sample on the Philips XL50, which produced images of 484 pixels by 712 pixels.

The SEM Monitor is set up to evaluate at image size of 512 pixels by 512 pixels. The maximum radius of the power spectrum is set up at 45 and its minimum radius is 0. The Zero Band is set at 1.

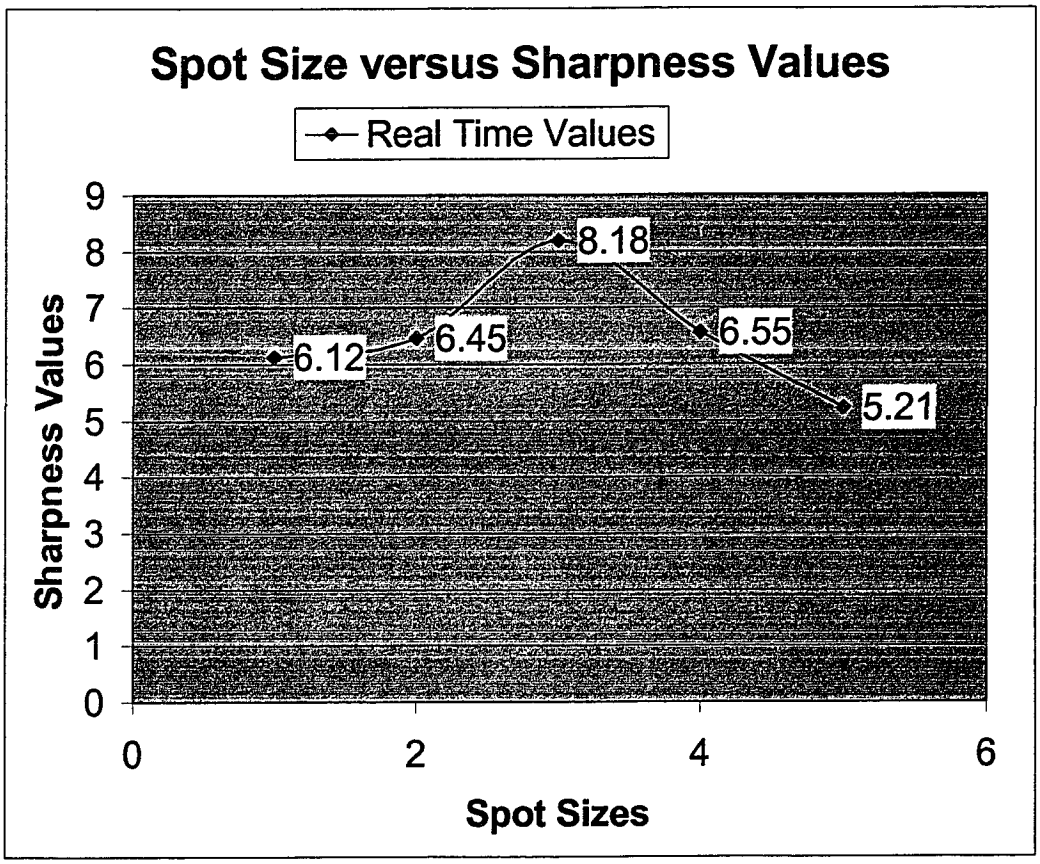

Fig. 12. Sharpness versus Spot Size Graph

As spot size is increased for fixed accelerating voltage, there is a change in the sharpness value.The wavelength for 5 kV accelerating is 1.79×10^{-2} nanometer, which was calculated using the following formula

$$\lambda = h/\sqrt{2 m_e e V} = 1.23 \times 10^{-9} / \sqrt{V} \quad \text{meters} \qquad (3)$$

Since this wavelength is not comparable to even the smallest spot size used for the experiment, which is spot size 1 ($\approx$ 0.5 nanometer) the diffraction effect in not significant in this experiment.

It is observed that spot size 3 is recommendable for accelerating voltages between 5 kV and 20 kV. For lower accelerating voltages (less than 5 kV), spot size 2 was used.

4.3 Low Accelerating Voltage Images Resolution

Since the semi-conductor manufacturing industry currently uses low accelerating voltage SEMs, there is a need to document its performance to assure the good quality of its products. The experiments relating magnification, spot size and image size were very important in the sense that they yield the optimum values for these parameters so that the low accelerating voltage resolution can be studied solely as a function of the working distance and the correction of astigmatism.

For semiconductor applications, low voltage operation is preferred because it enhances surface details, minimizes sample damage, reduces excessive image contrast, while generally improves sample charging. (10)

With this knowledge and with the aid of SEM Monitor the operator should be able to get consistent results and monitor the performance of its SEM. Note that the optimum values may differ for different brands of SEMs.

Below is shown a graph for 1 kV accelerating voltage. The parameters held constant are magnification at 250 000x, which is the empty magnification for Philips XL50; spot size is 2, which is approximately equal to 1 nanometer. The working distance range allowed for these conditions is from 1.5 mm to 3.1 mm, which is determined by the microscope.

The size of the original images produced by the Philips XL50 is 480 pixels by 640 pixels. The image size evaluated by the SEM monitor is 512 pixels by 512 pixels. The minimum radius of the power spectrum is set at 0 and its maximum radius at 45. This means that the sharpness obtained will be mostly due to the larger features in the image. The Zero Band was set at 1 to exclude noise. Astigmatism was corrected for each image. Astigmatism is the inability to focus to a point in different focal planes.

Table 4

Variation in Sharpness Values due to the change in Working Distance for 1 kV and constant empty Magnification

Acc. Vol. 1 kV Mag. 250,000x	**REAL TIME IMAGES**
WD (mm)	SHARPNESS VALUES
1.5	5.49
1.7	5.42
2.0	4.52
2.3	4.63
2.6	3.32
3.1	3.29

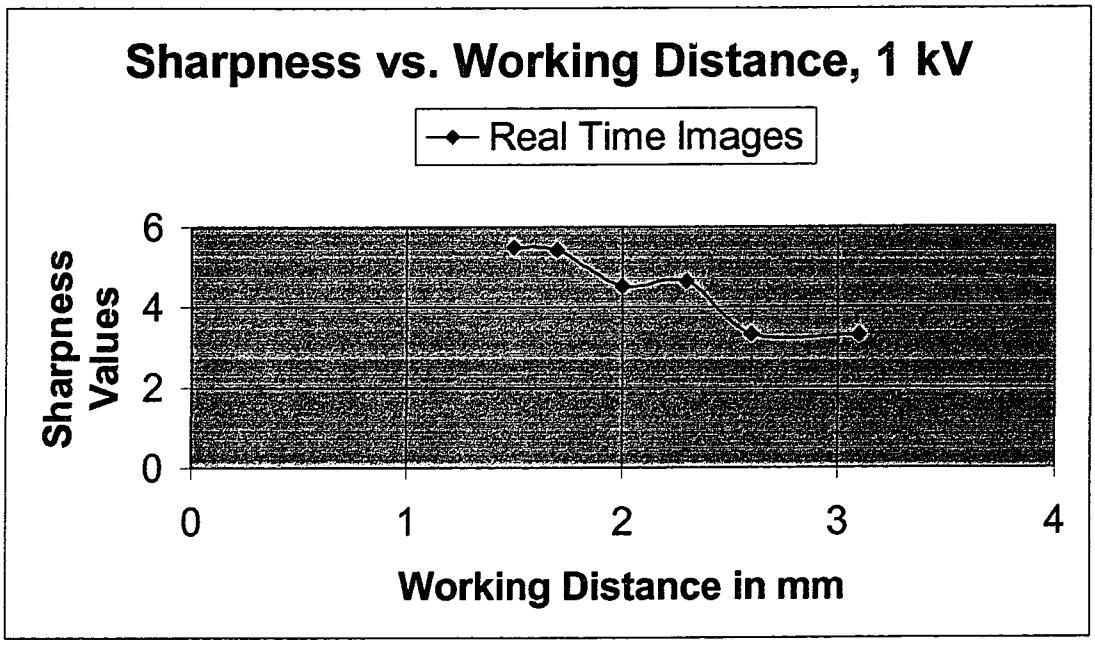

Fig. 13. Sharpness versus Working Distance, for fixed 1 kV

It is clear from the graph that the sharpness values are higher for shorter working distances. Theoretical resolution cannot be achieved because of lens aberrations that are assumed to be significantly caused by the final lens, which is the objective lens.

The spherical and chromatic aberrations can be decreased to some degree by decreasing the aperture size. This is the reason why spot size 2 ($\approx$ 1 nanometer) was chosen for this experiment. In general, the diffraction effects can become worse by decreasing the aperture size because the wavelength of the electron beam may become comparable to the aperture size. The following formula relates the wavelength to the accelerating voltage.

$$\lambda = h / \sqrt{2 m_e e V} = 1.23 \times 10^{-9} / \sqrt{V} \quad \text{meters} \qquad (3)$$

Now for 1 kV, we have $\lambda = 3.88 \times 10^{-11}$ meters $= 3.88 \times 10^{-2}$ nanometers. Since this wavelength is very small in comparison to the aperture size, the diffraction effect is negligible for this case and may be neglected.

The spherical and chromatic aberrations can be further reduced by decreasing the working distance by placing the sample closer to the final lens.

Due to the energy spread ΔE of the electron gun, which results in a disc of least confusion of diameter d_c .The diameter of the disc is given by

$$d_c = C_c (\Delta E / E_o)\alpha,$$

where C_c is the chromatic aberration coefficient, which is approximately the focal length for weak lens excitation, (3) α is the divergence angle at the sample. ΔE is the energy spread of the electrons, due to the initial Maxwellian distribution of velocities of emitted electrons.

The chromatic aberration coefficient is directly related to the focal length of the lens. A variation in the energy E_o and the corresponding velocity v of the electrons passing through the lens or a variation in the magnetic field H of the lens will change the point at which electrons emanating from a point P are focused.

Variations in both E_o and the magnetic field H may occur from imperfect stabilization of the various power supplies. If the lens current or high voltage is stabilized

to one part in 10^6 per minute, the effect due to the variation in H and E_o will be unimportant. Nevertheless, we still have a variation ΔE in the energy of the electrons due to the Maxwellian distribution of initial velocities, that is, the spread of initial velocities (energy) leaving the cathode. At low E_o, the ratio (ΔE / E_o) becomes large, which implies d_c is also large, thereby lowering the resolution.

The values of d_c can be minimized by decreasing the divergence angle α at the sample. As the working distance is increased the effect of aberrations becomes more prominent that is why the sharpness values went down.

The data points for the 3 kV graph is taken under the same conditions as in 1 kV case. The results as well as the justification of this graph are the same as that for the 1 kV graph. The only difference is that the sharpness values for the 3 kV graph have higher magnitude because of the higher accelerating voltage. Higher accelerating voltage produce more SE for the detector to collect and hence produce images of higher resolution.

Table 5

Variation in Sharpness Values due to the change in Working Distance for 3 kV and constant empty Magnification

Acc. Vol. 3 kV	**REAL TIME IMAGES**
Mag. 250,000x	
WD (mm)	SHARPNESS VALUES
2.2	12.07
2.7	11.62
3.2	9.20
3.7	8.92
4.2	6.81

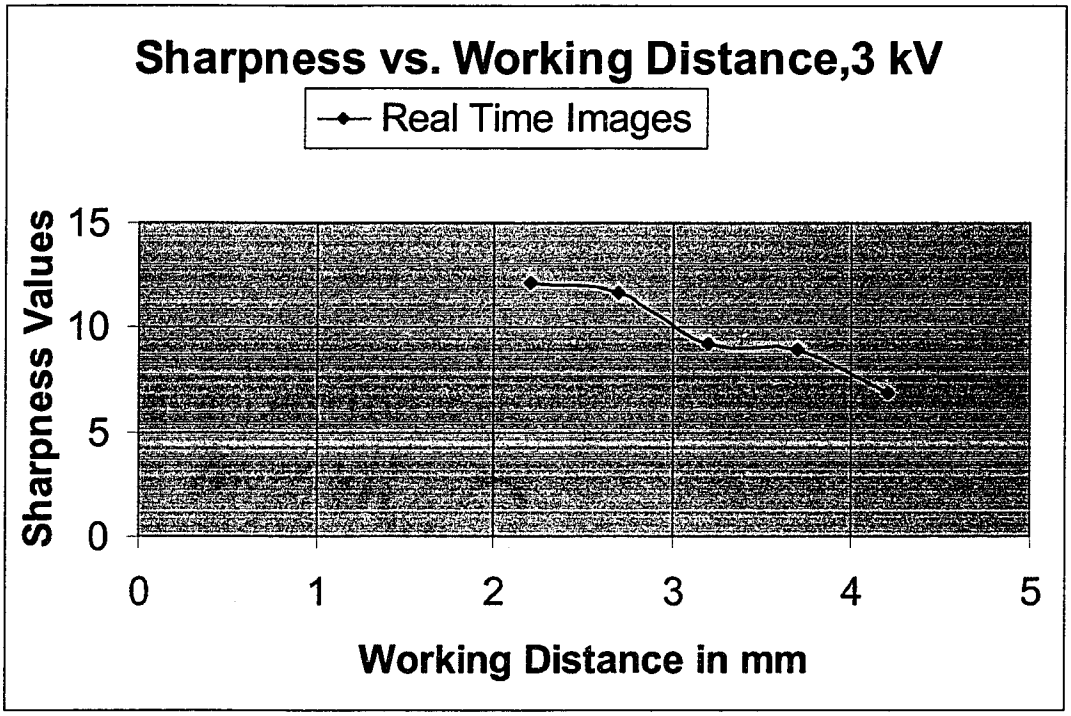

Fig. 14. Sharpness versus Working Distance, for fixed 3 kV

5 Conclusion

Low-voltage scanning electron microscopy (LVSEM) has the main advantage of a lower electron range, with the information more concentrated on the thin surface layer. Image analysis requires a good knowledge of electron-sample interaction causing and influencing the signal intensities. (3)

A number of experiments were conducted to study each parameter separately that affects the resolution of SEM images. These were classified into qualitative analysis which primarily focused on the 'software' (SEM Monitor) parameters and quantitative analysis which focused on the 'hardware' (Philips XL50 SEM) parameters. The experimental results showed that if magnification, spot size and the settings of the SEM Monitor software are adjusted to optimum values then the sharpness of low accelerating voltage images solely depends upon the working distance.

Low accelerating voltage experiments were conducted for 1 kV and 3 kV. Both experiments yield consistent result that the decrease in working distance improves chromatic and spherical aberrations. The sharpness technique of analysis also aids in the study of physical phenomena such as lens aberrations, sample-beam interaction and lens aperture that are present in the microscope as a function of magnification, accelerating voltage, spot size and working distance.

6 Suggestions for Additional Research

The use of Fast Fourier Transform (FFT) Image Analysis software packages, such as SEM Monitor, proves to be of an enormous help not only in identifying the resolution of an image quantitatively, but also aids in verifying that the SEM instruments meet the specifications. The FFT based algorithms also help in tracking and optimizing the SEM's performance during use. The experiments carried out for this project, however indicate that there are several factors that can falsely influence the calculation of sharpness value, thereby yielding unrealistic results. Below are some considerations and suggestions that can aid in further improving the Fast Fourier Transform algorithms and ensure reliable and meaningful results.

The Fourier based Analysis provides a framework to monitor astigmatism, but its correction is still highly dependent on the operator's experience. Even though provisions to eliminate most types of noise from the calculation of sharpness value are available in most software, still how much noise is eliminated is subjective to the operator. The settings of minimum and maximum radii of the power spectrum and of zero band are subjective to the operator's decisions. Even when standard settings of radii are chosen, they may not be suitable for every image being analyzed. It would be better if the distinction between Noise and Signal were analyzed by the software.

The sharpness value is highly dependent on the electronics of each computer used. Each computer has a different intensity spectrum into which the collected signals are subdivided and this division directly affects the magnitude of the sharpness value. Thus we obtain different sharpness values for the same image when calculated using different computers. The FFT based algorithms should offer a provision of standard width of spectrum so that the calculation of sharpness value becomes independent of the electronics of any computer in which this software is installed.

Sharpness values depend on the Brightness and Contrast, which are major variables in SEM and which affect the spectrum of signals being collected from the sample. The calculation of sharpness value should be accomplished using normalized values of Contrast and Brightness, avoid any bias due to Brightness and Contrast.

Two major considerations, when using any software based on FFT procedure, are the magnification of the microscope and the comparison between the test sample and the actual objects being resolved in the industry. Since magnification has a profound effect on the sharpness value, it is preferable to always operate the microscope at the empty magnification. At this magnification the resolution is determined by the probe size, electron beam and sample interactions, rather than by the pixel size of the image. The chosen test sample is usually quite atypical of the types of objects that are normally to be imaged, so resolutions determined in this way may not be properly representative of noise routine performance of the instrument. (12)

It would be also desirable if FFT Image analysis software packages offered a provision of feedback of focus and astigmatism values to the SEM. For this procedure to be useful in production or research, the software need to control the SEM by optimizing the focus and astigmatism values automatically based on the FFT calculations.

Due to the limitations of the FFT procedure mentioned above and the fact that each data point represents a distinct location on the sample, it was difficult to obtain an acceptable level of repeatability of results, which is the industry goal. Nevertheless trends could be noticed, that can be justified by physics and the material science.

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