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Volume 1985 | Number 3 Article 21

4-25-1985

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A. Yu. Sasov
Moscow State University

SCANNING ELECTRON MICROSCOPY/1985/III (Pages 1109-1120)
SEM Inc., AMF O'Hare (Chicago), IL 60666-0507 USA

0586-5581/85$1.00+.05

COMPUTERIZED MICROTOMOGRAPHY IN SCANNING ELECTRON MICROSCOPY

A. Yu. Sasov

Department of Geology, Moscow State University,
Moscow, 119899, U S S R

(Paper received January 11, 1985: manuscript received April 25, 1985)

Abstract

Non-destructive methods of inner object structure reconstruction in the scanning electron microscope (SEM) have been studied. For specimens with a size of about 1 mm a spatial resolution of 10 μm has been achieved. The reconstruction is made from a projection in X-ray radiation. Algorithms of conventional computerized tomography are used. The application of 3-dimensional reconstruction to different types of microobjects has been shown. As an example, microtomography of organic objects (grass grain, beetle head) and inorganic objects (semiconductor diode) has been carried out.

KEY WORDS: Full 3-dimensional reconstruction, microtomography, Radon transform, convolution, back projection, microcomputer.

*Address for correspondence:
A. Yu. Sasov, Department of Geology,
Moscow State University,
Moscow, 119899, U S S R
Phone No. 1393587.

Introduction

The main aim of an overwhelming majority of microstructure investigations is the study of the inner structure of objects. Conclusions about the inner structure of microobjects are made by fracture and thin section images in the scanning electron microscope (SEM). To guess the inner structure of an object before preparation from these images is rather difficult and sometimes impossible. The difficulty of SEM information interpretation may lead to errors and a collision of conclusions. At present, non-destructive methods of direct study of the inner structure of microobjects are of primary importance.

Data on the inner structure of a sample can be obtained as a shadow image from transmitted and low-attenuation radiation. X-rays, infrared radiation or ultrasound would very well do for the majority of microobjects. Shadow images correspond to the non-destructed structure and this determines their value for the investigators. At the same time they represent a 2-dimensional projection by which the 3-dimensional structure of an object cannot be determined.

Full 3-dimensional reconstruction of an object's inner structure from projection constitutes the subject of computerized tomography. The greatest practical achievements of this science are connected with the creation of X-ray tomography systems for medical applications. Rapid development of computerized tomography for the last decade has brought about the use of reconstruction from projection methods in many other branches of science from astronomy to transmission electron microscopy. X-ray tomography systems can reconstruct objects from 1 - 0.1 m with a spatial resolution of less than 1 cm. In transmission electron microscopy microobject structure is reconstructed with sizes of 0.1 μm with a spatial resolution up to 10 Å. This research work is explaining algorithms of full 3-dimensional reconstruction of the inner structure of non-destructed objects in SEM.

The suggested methods bridge the gap in the possibilities of microtomography investigation. 3-Dimensional reconstruction of microobjects in millimetre and micron ranges is necessary in defectoscopy, material sciences, in non-destructive tests of semiconductor devices and integral circuits in particular, as well as in biology, geology, physics, chemistry, medicine etc. X-ray and infrared radiation which is used for obtaining projection data undergoes little absorption in air: therefore the object in question can be separated from the SEM-vacuum and placed in the hermetically closed air microchamber. Investigation under normal atmospherical conditions is necessary for medical and biological specimens. Experimentally produced or natural alterations in the microstructure of the sample are useful in e.g., mechanical tests. In all cases computerized microtomography in SEM obtains unique data, which cannot be obtained by any other method of investigation.

Mathematical Fundamentals of Computerized Microtomography

Mathematic aspects of microobject image reconstruction from projection are mainly borrowed from conventional computerized tomography. A great deal of research has been devoted to these problems, and hence it would be useful to consider the main issues and peculiar features which appear in SEM investigation.

3-Dimensional investigation of objects by computerized methods is aimed at obtaining a 3-dimensional matrix of digits corresponding to local density (usually - to the local attenuation coefficient of initial radiation). The task of obtaining such a matrix is equivalent to several tasks of creating 2-dimensional cross-sections from 1-dimensional projections (Fig. 1). The part of the plane where the reconstruction takes place (the field of reconstruction) must be larger than that of the cross-section investigated. This is the main limit of all methods of reconstruction from projections. To facilitate the calculations, the field of reconstruction is square (rarely round) in shape. The object cross-section image in the field of reconstruction is calculated as a 2-dimensional matrix of digits. Each digit corresponds to the average of density (or radiation attenuation coefficient) in any small area of the object called a picture element (pixel). A small square is a pixel for a square field of reconstruction. Initial data for the reconstruction of cross-section is the integral attenuation coefficient of permeation radiation along the source-detector line, with different dislocations of this line in relation to the center of the field of reconstruction and to the different views. Thus it is necessary to calculate the distribution function of the local attenuation coefficients - $f(x,y)$ in Cartesian coordinates or $f(r,\varphi)$ in polar coordinates ($r^2=x^2+y^2$; $\varphi = \arctan(y/x)$) from integrals on information acquisition lines in coordinates $(1,\theta)$. The Radon transform operator R from function $f(1,\theta)$ is determined as a line integral from f along the source-detector line:

$$[Rf](1,\theta)=\int f((1^2+z^2)^{1/2},\theta+\arctan(z/1))dz \quad (1)$$

Thus the Radon transform links function f in coordinates (r,φ) with function f in coordinates $(1,\theta)$. Finding the cross-section image amounts to finding inversion of the Radon transform R^{-1}:

$$[R^{-1}Rf](r,\varphi)=f(r,\varphi) \quad (2)$$

To find the inversion of the Radon transform R^{-1} the projection theorem is used. The theorem links the operator R^{-1} with 1-dimensional and 2-dimensional Fourier transform operators. 1-dimensional direct F and inversion F^{-1} Fourier transform operators are defined as:

$$[F\varphi](U)=\int\varphi(u)\exp(-2\pi iUu)du \quad (3)$$

$$[F^{-1}\varphi](u)=\int\varphi(U)\exp(2\pi iuU)dU \quad (4)$$

2-Dimensional direct F_2 and inversion F_2^{-1} Fourier transforms in polar coordinates (r,φ) are defined as:

$$[F_2f](R,\phi)=\int\int r|f(r,\varphi)\exp(-2\pi irR\cos(\varphi-\phi))drd\varphi \quad (5)$$

$$[F_2^{-1}f](r,\varphi)=\int\int R|f(R,\phi)\exp(2\pi iRr\cos(\varphi-\phi))dRd\phi \quad (6)$$

If we apply the F_1 operator as a 1-dimensional Fourier transform with the fixation of one of the coordinates

$$[F_1p](1,\Theta)= Fp|_\Theta](1) \quad (7)$$

The projection theorem can be written as follows:

$$F_2= F_1R \quad (8)$$

For the majority of functions a 2-dimensional Fourier transform satisfies the equalization:

$$F_2^{-1}F_2f=F_2F_2^{-1}f=f \quad (9)$$

According to (8) and (9) we may conclude:

$$f=F_2^{-1}F_1Rf \quad (10)$$

The original cross-section $f=R^{-1}$ can now be found from projection data as:

$$f=F_2^{-1}F_1p \quad (11)$$

This formula is an algorithm of cross-section reconstruction from projections by Fourier transform methods. According to (11) the 1-dimensional Fourier transform of data in every view is firstly made, i.e., the data obtained from 1 and fixed Θ in fig. 1. By the results of these transforms for different Fourier coefficients, meanings are approximated in the field of reconstruction. Then the original cross-section is reconstructed by 2-dimensional inversion Fourier transform F_2^{-1}. The calculation algorithm based on 1-dimensional and 2-dimensional Fourier transforms is connected with a great number of calculations and is rather rarely used. There are other more rational algorithms.

The majority of 'rapid' algorithms of reconstruction is based on back projection. A back projection operator B is applied as

$$[Bp](r,\varphi)=\int p(r\cos(\Theta-\varphi),\Theta)d\Theta \quad (12)$$

Most widely used are ρ-filtering and convolution algorithms. A ρ-filtering algorithm is based on the equalization of Fourier and Radon transforms from image by back projection:

$$[F_2f](R,\phi)=|R|x[F_2BRf](R,\phi) \quad (13)$$

Image evaluation f is made by the formula:

$$f=F_2^{-1}(|R|x[F_2Bp]) \quad (14)$$

The corresponding algorithm consists of the back projection of initial data Bp, calculation of a 2-dimensional Fourier image F_2Bp, multiplying that in polar coordinates by $|R|$ and inversion by a 2-dimensional Fourier transform.

At present most widely used are algorithms based on convolution and back projection. Inversion Radon transform can be written as:

$$[R^{-1}p](r,\varphi)=1/2\pi^2\int\int(1/(r\cos(\Theta-\varphi)-1))(\partial p/\partial l)dld\Theta \quad (15)$$

This transform is divided into two parts, one of which is a back projection prescribed by the formula (12); the second part is the convolution with some specially selected functions.

It is possible to define the convolution of two functions p(u) and q(u) as follows:

$$[p*q](u)=\int p(v)q(u-v)dv \quad (16)$$

If we represent p(u) function as $p=-(1/\pi u)$, equation (16) will be transformed:

$$[p*q](u)=-(1/\pi)\int q(u)/(u-v)\,dv \quad (17)$$

Projection data is the function of two variables and therefore we introduce the notion of convolution on one variable while the other remains fixed:

$$[p*_\Theta q](l,\Theta)=[p|_\Theta *q](l) \quad (18)$$

Now (15) can be represented accurately within constants as a combination of back projection and convolution with the function:

$$q(u)=2\int_0^{A/2} UF(U)\cos(2\pi Uu)dU \quad (19)$$

where A is the spectrum width of initial data. The meaning of the F(U) function will be explained below. The reconstruction algorithm can with the help of convolution be written as:

$$f=B[p*_\Theta q] \quad (20)$$

First the convolution of projection data is made for each view and then the back projection. Unlike the reconstruction algorithms described above, convolution does not necessitate Fourier transforms. This considerably enhances the speed of computer calculations. The majority of X-ray tomography systems use the convolution

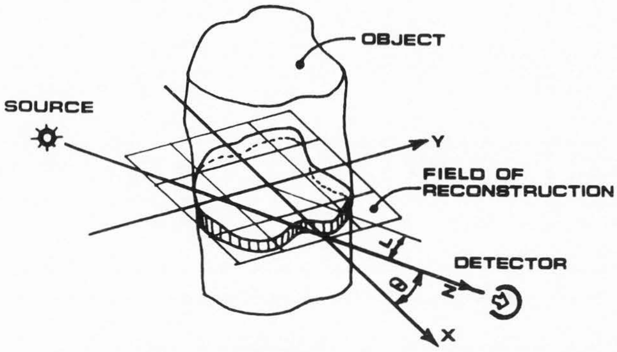


Fig. 1: Geometry of data acquisition in microtomography

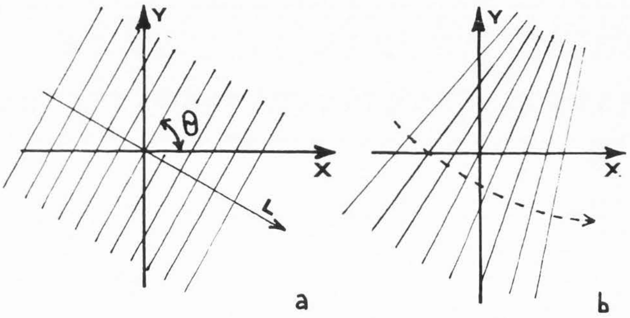


Fig. 2: Parallel (a) and fan (b) beam geometry

algorithm due to its relative simplicity of realization and high speed of reconstruction. The suggested algorithms presuppose the calculation (at the initial stage) of constant parameter projection data which corresponds to the parallel geometry acquisition of information (Fig. 2a). High speed set-ups for acquisition of projection data have a fan-beam geometry. (Fig. 2b) claiming the change of algorithms. In a simple case fan geometry is regarded as a group of beams from projections with different θ. By means of combining data from different projections the task may be reduced to the parallel geometry. Reconstruction algorithms presuppose ideal initial data without noise and device distortion. In real cases (especially in microtomography realisation in SEM) one has to deal with a low-level of radiation intensity and correspondingly with high levels of noise. A cross section reconstructed by such data can contain sufficient defects of reconstruction up to full loss of useful information. The main method of minimizing noise errors of reconstruction is signal spectrum limit in the high frequency range. In the convolution algorithm this is realised through the corresponding choice of F(U) function. In the absence of any noise ideal reconstruction takes place under F(U)=1. To minimize X-ray radiation noise F(U) of the following types are used:

COS: $F(U)=\cos(\pi U/A)$
SIN: $F(U)=\sin(\pi U/A)/(\pi U/A)$
General Hemming: $F(U)=\alpha+(1-\alpha)\cos(2\pi U/A)$
$0.5<\alpha<1$ (21)

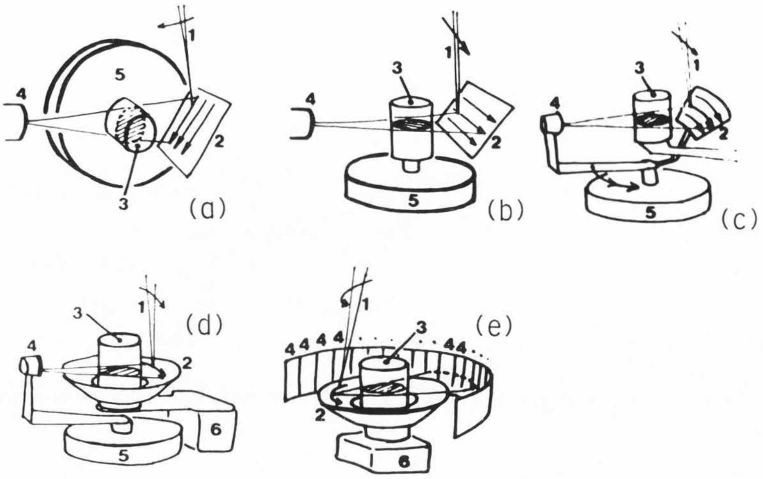


Fig. 3: Microscanner devices
1-electron beam
2-target
3-specimen
4-detector
5-step motor
6-system of vertical motion of the specimen

Spectral signal limit by functions of the type shown in (21) decreases somewhat the finest detail contrast of the reconstructed cross-section. In each particular case a compromising formula may be chosen to obtain sufficient spatial resolution and the necessary level of noise. For algorithms based on Fourier transforms a spectrum limit is made by multiplying the data in Fourier space by functions as in equation (21).

Initial data for cross-section reconstruction is the intensity measurements of the transmitted radiation I in a discrete number of points. I depends on original radiation intensity I_0 and the integral from attenuation coefficient:

$$I=I_0\exp(-\int\mu dz) \qquad (22)$$

Integrals from attenuation coefficients are initial projecting data $p(l,\Theta)$ (22) leads to the following:

$$p=\int\mu dz=\ln(I_0/I) \qquad (23)$$

It is necessary to take into consideration the dependence of attenuation coefficients on the energy of X-ray radiation. The spectrum changes considerably during the passage through the object.

The formulae (22) and (23) correspond to obtaining data from the source and detector with infinitesimal aperture. For real cases it is necessary to add the integral from μ on the source and detector aperture. Obtaining information in the discrete the number of points on l and Θ correspond to the change of the initial data spectrum - it acquires the shape of a comb. The use of low aperture detectors leads to the coincidence discretization data spectrum and device function which causes great defects of reconstruction. When obtaining data from 1 source-detector pair in order to exclude the coincidence of spectra the radiation beam aperture must be of bigger size than the pixel in cross-section images. Obtaining the information from a group of detectors there are other methods of minimizing coincidence of spectra.

In computerized tomography all algorithms are realized through discrete data and reconstruction is made by discrete analogues of the above formulae.

It is only natural that the question should arise on the minimum quantity of data for a given size cross-section reconstruction. It can be proven that for the field of reconstruction n x n the number of view of initial data m must satisfy the inequality:

$$m-1>\pi n/2 \qquad (24)$$

The pixel size of the field of reconstruction is usually determined by the resolution of the data acquisition system. Increasing the number of pixels of the field of reconstruction leads to an increase in the necessary memory of a computer and the time of calculation and therefore a compromise has to be made for each particular case.

Apart from the most popular algorithms based on convolution and Fourier transform there are lots of other approaches to image reconstruction from projections. For further information I refer to references (1, 4-6).

Set-up for Data Acquisition for Microtomography in SEM

The main difficulty in the realization of microtomography in SEM is the design of the microscanner. In medical X-ray tomography scanners only systems with immobile objects are realized. Microtomography scanners can have both immobile and rotating objects of investigation. A microscanner must provide the acquisition of projection data with a sufficient quantity of view in each plane of reconstruction. In X-ray radiation for radioscopy the object is formed from an electron beam bombarding a metal (usually copper) target. Infrared radiation is emitted by the target covered with the corresponding luminophore.

Five types of suggested microscanners in order of increasing difficulty are shown in Fig. 3a-3e.

Fig. 3a: An electron beam moving along the declining target creates a moving point source. The radiation passing through the object is received by a detector with a small aperture. The horizontally located specimen is rotated by the step motor to obtain the necessary number of views.

Fig. 3b: As well as in the first case the moving source is created by scanning an electron beam. Different views can be obtained by the rotation of a vertical object by a step motor.

Fig. 3c: Scanning in every view is carried out by moving the electron beam on the target. Change of view takes place by simultaneous rotation of the source-detector pair around the immobile object.

Fig. 3d: Scanning in every view and changing the view is carried out by moving the electron beam on the ring target around the immobile object. The corresponding location of the detector is created by rotating with the step motor.

Fig. 3e: A completely immobile system. With every location of the source on a ring target simultaneous fixation of the information by a great number of narrow-aperture detectors which encircle the system object-target takes place.

Specific features, adventages and disadventages of each of the systems are given in Table 1.

Let us consider in detail the main parts of microscanners:

The TARGET emits X-rays (or infrared) radiation under bombardment by an electron beam. The target is a polished copper surface which is tilted 45 degrees towards the beam. The DETECTOR of radiation depends on the kind of radiation and the configuration of the microscanner. The corresponding PM for the range 0.8-1.1 µm will be for infrared radiation. X-ray radiation for the systems with an immobile detector (3a and 3b types) is received by a proportional counter. In a simple case a standard semiconductor detector from X-ray analyzers of 'LINK' or 'Kevex' systems is used. Scintillation detectors are not recommended as the background of the reflected electrons is considerably higher than the useful X-ray signal. For microscanners with a mobile detector (Fig. 3c, 3d) or with a group of detectors (Fig. 3e) only semiconductor detectors will fit because of their small size. The spatial resolution of microtomography is mainly limited by the aperture of the source and the detector. The real size of the X-ray generation area in a metal target is about 1 μm^2. A conical beam is emitted from this source. The SEM geometry for microscanners of 3a and 3b types allows the positioning of the object at a distance of about 1mm from the target and the detector at a distance of up to 100mm. With this data a spatial resolution up to 5µm corresponds to a detector aperture of not more than 0.3mm. A STEP MOTOR is necessary in systems 3a and 3b for the precision rotation of the object. In a simple case the mechanism from a quartz wrist watch can be used. A step motor with a mobile magnet and with a step 1/60 of a complete revolution is used here. The maximum

Table 1

Microtomography scanner characteristics

microscanner configuration fig:	3a	3b	3c	3d	3e
Main part: 0-immobile, 1-mobile					
Object	1	1	0	0	0
Target	0	0	1	0	0
Detector	0	0	1	1	1
Advantages:					
1. the possibility of viewing the object in SE mode	+	-	-	-	-
2. using a microanalyzer detector	+	+	-	-	-
3. parallel beam geometry	-	-	-+	-+	-
4. high speed of data acquisition	-	-	-	-+	+
5. the possibility of influencing the object during the investigation	-	-	-+	+	+
6. electronic change of cross-sections	+	+	+-	-	-
Disadvantages:					
1. the difficulty of object assembly	+	+-	-	-	-
2. nonperpendicularity of the axis and the plane of projections	-	-	-	+	+
3. fan-beam geometry	-+	-+	-+	+	+
4. influence of the sample weight	+	-	-	-	-
5. change of data acquisition geometry along the projection	+	-	-	-	-
6. influence of the mechanical defects	+	+-	-+	-	-
Difficulty of mechanical parts	+-	+-	+	-+	-
Difficulty of electronic parts	-	-	-	-+	++

number of views is equal to 30. The 3a system with such a mechanism does not allow a resolution higher than 20 µm in cross-section and 100µm between the cross-sections because of the axis shift during the step motor rotation and the impact of its mobile magnet on the electron beam. In the 3b-system the axis is reclined on a conical bearing and therefore the spatial resolution in cross-section and through cross-sections increases up to 20 µm. For further improvement of the quality characteristics of the step motor a combination of a microampermeter with an immobile magnet and a watch reductor is used. The mechanism with an immobile magnet excludes the impact on the beam during rotation. The reductor provides 120 (or 240) view information acquisitions. The accuracy of the projection data considering the impact on the beam is less than 5 µm. In the systems 3c and 3d there are

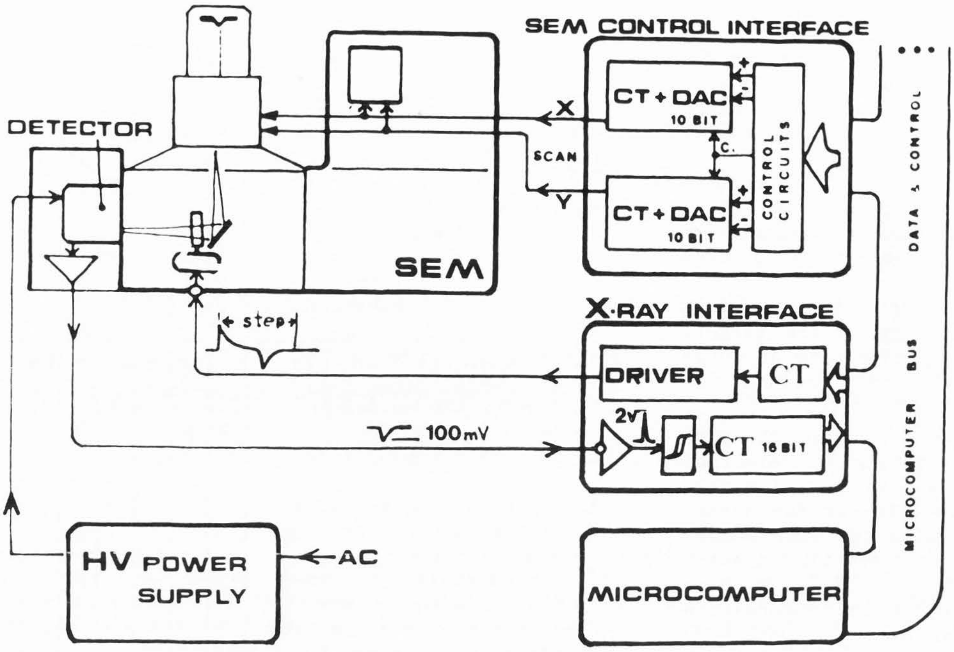


Fig. 4:
The diagram of microtomography set-up

no strict demands concerning the motors. The SPECIMEN should have such a shape as to guarantee the maximum filling of the field of reconstruction. Best suited are cylinder-shaped specimens with a diameter 1 - 0.1 mm and a length up to several mm. The maximum size of the specimen is limited by the low SEM magnification and can be up to 2 - 5 mm. In the 3a system the location of the object is changed under the influence of its weight and in general light specimens should be used. For other microscanners specimen weight is of no importance and in the 3b-system weight increase may even increase the accuracy of the mechanism. The most difficult operation is the assembly of the specimen especially in the 3a system. In 3a and 3b microscanners a thin tube is put on the axis of the mechanism where the specimen is placed and fixed with conductive cement. It is usually unnecessary to coat the specimen as it is not bombarded by the electron beam. The reflected electrons do not charge the specimen to a dangerous potential. It is recommended to coat only with low conductivity materials (as teflon etc.). In systems with an immobile object as 3c-3e the assembly of the specimen is not difficult. The SYSTEM OF VERTICAL MOTION of the specimen is necessary for microscanners with a ring target (3d, 3e). It can be realized by using piezoelectric or electromagnetic devices.

Apart from the microscanner itself the set-up of data-acquisition includes several electronic units. Let us consider the configuration of the most simple systems (3a and 3b). The block-diagram of the electronic units is given in Fig. 4. The microscanner is of the size of a standard SEM specimen stage and can be introduced in the column through the specimen exchange chamber without interfering with the general vacuum.

Control of the step motor is exercised through an output for testing the current of absorbed electrons. On the column window there is a proportional counter separated from the vacuum by a Be window. The window is covered with an aperture diaphragm with a size of 0.3 x 2 mm. The stabilized source provides the DC counter power supply voltage of 800 - 2000 V. The signal from the counter has an amplitude of several mV. A preamplifier is placed next to the counter. The signal from the preamplifier has the form of negative pulses with an amplitude of 100 - 200 mV. The reception of this signal and the control of the step motor is made by the X-ray interface of a microcomputer. Here the pulses are amplified up to 2-3 V and discriminated for noise limit. The number of pulses is fixed in the 16-bit counter. The count time is controlled by the program. The rotation of the specimen step motor is made by an interface driver which is controlled by a step counter. Programmed scanning of the electron beam on the target of the microscanner is carried out by the SEM control interface. In Fig. 4 one can see only that part of the interface which is used in microtomography. The information from the microcomputer is decoded in commands of beam motion in coordinates (x,y), return to the initial point and to the centre. These commands regulate the motion counters in the corresponding coordinates. The information from the counters is supplied to the digital-analogue converters. Analogue x and y signals control scans of the SEM electron beam and the point of the screen. The control circuit provides programmed switch-on and switch-off of the digital scans instead of the conventional scans. The digital scan format is 1024 x 1024 points. Programmable control of all parts of the set-up by a microcomputer provides maximum flexibility of the system. For 3c and 3d microscanners an analogous set-up can be used except for the detector preamplifier. A microscanner with electronic scanning 3e must be equipped with a sophisticated system of preamplifiers and counters. Utilization of such a complex system is expedient only in the case of a strong necessity for high-speed scanning.

Processing the Microtomography Information

To process the microtomography data one should use microcomputers. Utilization of more powerful computers makes the system more costly as the rate of calculation is mainly determined by the data acquisition speed, not the calculation speed. The minimum configuration should include a SEM, microcomputer with RAM of not less than 64K and corresponding interfaces. To widen the possibilities of microtomography investigation it would be preferable to have a high-scale memory on disks and different image output devices. In our case we used an 'Iskra 226' (USSR) microcomputer with 128K RAM ('BASIC' is loaded in 64K). The calculation speed is about 500,000 operations per second (16 bit processor). The microcomputer has a symbolic and graphic display and a cassette memory on magnetic tape. For storage the information disks (5 Mbytes) and dual floppy disks (2 x 0.5 Mbytes) are used. Information output can be given on the computer screen, on the symbolic-graphic printer, on the colour half-tone display and on the plotter. The microcomputer performs the functions of microtomography set-up control and reconstruction from projections. High quality software has been developed which include the following programs:

1. Back projection. Input data: angle Θ, information on 128 bytes line. Output data: the result of back projection (up to 256 views) in a matrix of 80x80x2 bytes. The time of back projection of each view is about 1 second.
2. Convolution of initial line containing 128 points with the F(U) function as a general Hemming window with parameter α from 0.5 to 1.0. The convolution time of each view is about 0.1 sec.
3. Fourier transform. The program performs a fast 2-dimensional Fourier transform, multiplying in Fourier space by any function and a fast inversion 2-dimensional Fourier transform. The main application is a ζ-filtration method. Working time is about 6 minutes.
4. Information output on binary and halftone displays. Output is performed onto the screen from a matrix 80x80x2 or 128x128x2 bytes. For a binary display a pixel is a 3 x 3 points square for an 80 x 80 field or 2 x 2 for a 128 x 128 field. In each such pixel 10 or 5 brightness levels are correspondingly reflected. The initial matrix has the size of 2 bytes in each point. The most informative cross-section image of the investigated structure is formed in a dialogue mode with an operator. The operator sets a black level and brightness gradation magnitude. The necessity of the dialogue mode is linked with an unpredictable background level and signals amplitude in a reconstructed cross-section.
5. Output onto a colour half-tone display. Reflection of a 3-dimensional image of object on a 2-dimensional display screen is rather difficult. Certain parts of the reconstructed object are usually displayed in isometry. To gain a 3-dimensional effect lighting illumination from a virtual source is used. In compound 3-dimensional objects it is practically impossible to imagine the structure by black and white isometry images. When reflected onto a colour display different pseudocolours are used to display elements of the object with different density. The 3-dimensional effect is created by a virtual light source. The human mind perceives the structure of each colour as separate 3-dimensional images. Difference in colour prevents mixing the information. Initial data for the work of programming are 15-60 cross-sections with a size of 80x80 bytes. In the beginning density discrimination levels are found for dividing parts of objects into colours. Then a pseudo-3-dimensional half-tone image in each colour is created. The full image of the structure is displayed onto a colour half-tone display with a buffer memory volume 3 x 256 x 256 elements with 16 brightness gradations each. When necessary a chosen cross-section is displayed separately which facilitates the interpretation of information.
6. Obtaining of data and SEM control. The programme consists of 2 independent parts. The first is dedicated to obtaining a shadow X-ray image of a microobject as in all scanners (except Fig. 3a) direct observation of a specimen is impossible. The scanning speed is controlled by the programme to obtain 200-250 impulses of calculation outside the object. Then an 80x80 bytes image is created, and shown on the display in the dialogue mode. The dialogue regime allows (as in programme 4) to obtain a more informative image. The main aim of this part of the programme is the alignment of the axis of the step motor till it coincides with the center of scanning and the choice of the reconstructed cross-section position. The second part of the programme is for acquisition of projection data. It allows the reading of a 128 points projection line at a given place of object. Then the step motor rotation begins and control is given to the convolution programme and back projection. The rotation time of the object by the step motor is 1 sec. During this time convolution and back projection take place and the programme begins to acquire the data of the next view. Information acquisition time depends on the intensity of X-ray radiation. For 120 views it ranges from 3 to 40 min. (1.5 - 20 sec. per view). The programme performs an automatic correction of counting live time for each point according to the level of X-ray radiation at the end of the information line, i.e. in those places where the object does not cast a shadow. It provides constant conditions of data obtained at all views. The problems of automatic stabilization during information acquisition are especially important for a field emission SEM (in our case - 'Hitachi S-800'). The result of the programme cooperates with programmes 1 and 2 in an 80 x 80 x 2 bytes matrix which is displayed on a screen with the

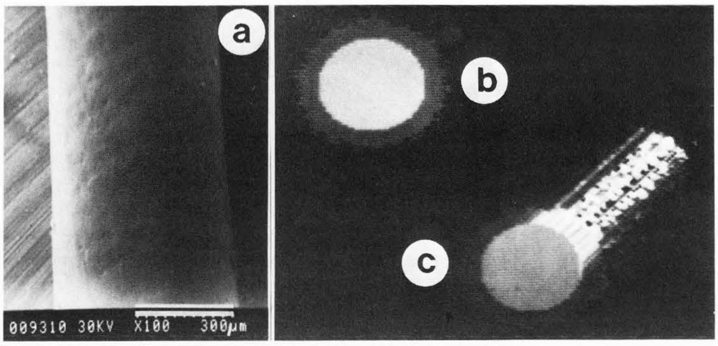


Fig. 5: Microtomography of a thin wire:
a- SE image
b- reconstructed cross-section
c- isometry image

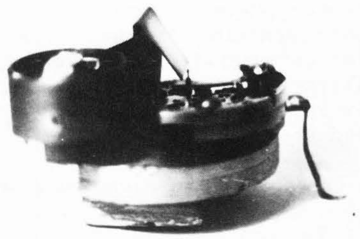


Fig. 6: Microscanner appearance

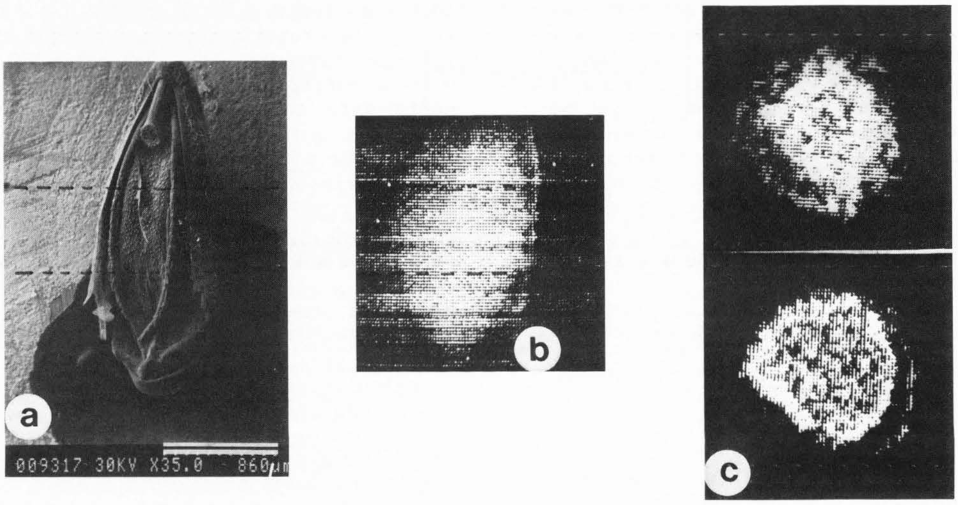


Fig. 7: Microtomography of a grass grain:
a- SE image
b- X-ray shadow image
c- reconstructed cross-sections

help of programme 4 and can be written on a disk.

In addition to the working programmes described above test programmes have been developed for all parts of the set-up. The longest operation in microtomography scanners with one source and one detector is information acquisition. The programme of information acquisition is self-controlled according to the SEM parameters and does not demand action from the operator. With the speed of data acquisition being several seconds per view the signal/noise equalization decreases considerably. When the level of X-ray radiation is about 200 pulses per point the useful signal can be within the interval of 10 pulses and even less. This especially concerns objects with sufficient attenuation. The method of reconstruction (convolution, ζ -filtering, Fourier transform) and the parameters of the smoothing function F(U) are chosen by the operator by means of tests or intuitively. Quite good results are achieved with the use of convolution methods with smoothing functions in the form of general Hemming windows with a parameter 0.54 - 0.65.

Application of SEM Microtomography

The first experiments on microtomography in the SEM were made in a microscanner of the 3a type with a horizontal object. With such a location the specimen can be viewed in the secondary electron mode. This facilitates alignment of the system and the choice of the field of reconstruction. The target is a polished copper plate. The step motor of the quartz watch provided data acquisition in 30 views. A 'LINK 860' microanalyzer detector was used. Calculated spatial resolution in data acquisition is about 25 μm. The first experiments were made in a SEM 'JSM 35CF' type Jeol (Japan) with the microcomputer 'Iskra 226' (USSR). For testing the system a simple specimen was chosen. It was a thin wire with teflon insulation with an outer diameter of 0.5 - 0.7 mm. The object image in the secondary electron mode is shown in Fig. 5a. 20 Cross-sections were being reconstructed each from 30 projections. The form of one of the cross-sections is given in Fig. 5b. An inner metal conductor has a regular spherical shape. Teflon insulation differs considerably in its thickness. The value of microtomography data is proven by the fact that all attempts to remove the teflon insulation led to conductor defects and change of its shape. At the same time one cannot draw any conclusions on the shape of the inner conductor by the secondary electron image. A pseudo-3-dimensional isometry image of object on a colour display was built based on 20 cross-sections. Unfortunately, in black and white (Fig. 5c) a considerable part of information is lost although a 3-dimensional effect remains. Investigation of such a simple sample has the character of a demonstration. It allows the demonstration of the main difference of microtomographic information from all other signals in SEM.

Further experiments were carried out in an 'S-800' type SEM (Hitachi, Japan). Using this SEM with a field emission gun led to the necessity of programmed stabilization of data acquisition conditions. At present a microscanner with a vertical axis of rotation is used. This prevents the deformation of the specimen under its own weight. The rotation mechanism contains a watch reductor. The axis where the sample is placed is based on a cone bearing. One anchor motion corresponds to 1/240 of a total circle. Current pulse causes rotation of the anchor and change of the microobject position of 1/240 revolution. In this way data is obtained in 120 views. For the realization of 240 views the mobile system of a microampermeter is kept in the deflection position. One anchor motion provides half the specimens rotation and correspondingly twice as many views. The microampermeter, the watch reductor with a specimen on it and a target are placed on a SEM specimen stage. A microscanner is shown in Fig. 6. A microscanner is positioned into the SEM through the specimen exchange chamber. Rotation pulses of the step motor are given to the SEM connector designed to measure absorbed current. This device is directly connected with the specimen stage which is isolated from the SEM column. The second wire is grounding the microscanner with a spring-contact which is shown in Fig. 6. To measure X-ray radiation a proportional counter is used. It has a high amplify coefficient and a low level of noise. Both counter and preamplifier are located at a window of the SEM column, separated from the vacuum by 0.1 mm thick Be foil. After 50 times amplification in the preamplifier pulses are transmitted to the microcomputer interface. To facilitate the alignment of the microscanner it is necessary that one motion of a specimen stage (for example - axis x) should coincide with the direction of the target-counter line.

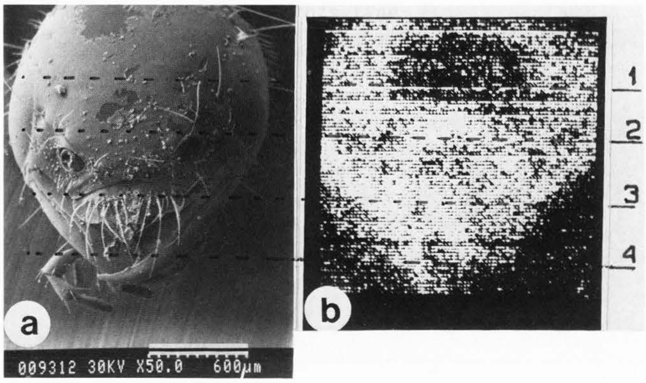
An object in microscanners with a vertical axis is not seen in the standard mode of the SEM. It is preferable to start the investigation of a sample in a secondary electron mode before the assembly in the microscanner. Then the sample is placed on the axis of rotation of the microscanner and using programme 6 one can observe a shadow X-ray image. It usually has a very low signal/noise ratio, but allows the choice of the site of cross-section reconstruction. Microtomography is realized through programmes 6, 1, 2 (or 3) with information output by programme 4. From several cross-sections we obtain a pseudo-3-dimensional image on a colour display by programme 5. Some other examples of reconstruction from projections are given below.

The most suitable objects for investigation by X-ray tomography are organic and biomedical objects with sizes up to several mm. An image of a grass grain in secondary electron mode in SEM is given in Fig. 7a. This object was investigated by microtomography. A shadow X-ray image of this sample is given in Fig. 7b. Here light areas correspond to higher attenuation. The image is obtained from the screen of a graphical binary display of the microcomputer in an 80 x 80 point matrix. Minimum and maximum brightness levels correspond to 220 and 100 pulses of X-ray counter per point. A reconstructed cross-section corresponding to the middle of the shadow image is given in Fig. 7c. The reconstruction was carried out on a convolution algorithm (α=0.54) from 120 projections. Cross-section discovers a complex inner-structure in the form of a tightly folded petal. The exfoliation petal is seen perfectly well (it can be seen on the shadow image too). The cross-section of the upper part of the grain, given in Fig. 7a is reconstructed in the same way. Here the petal structure becomes more vivid. By reconstructed sections one can objectively measure such parameters as object perimeter, its form and inner porosity.

Better spatial resolution can be realized on objects of smaller size. As an example, the reconstruction of a beetle's head is shown. The appearance of this sample in a standard mode of a SEM is given in fig. 8a. Reconstruction of the inner structure was made from planes, marked in Fig. 8a. A shadow X-ray image is given in Fig. 8b. The results of the reconstruction along 120 projections are given in Fig. 8c.

Microelectronic objects are more difficult to reconstruct. This is due to the high attenuation level of X-ray radiation. Infrared radiation can be used more effectively in this case. Sometimes the inner structure can be reconstructed by X-ray projection. A cross-section reconstruction of a miniature diode in a glass frame is given as an example. The appearance of the diode is given in Fig. 9a. An approximate structure of the diode is outlined in Fig. 9b. The upper wire is connected to an Si-plate with p-n junction. The second contact is a thin metal conductor, connected with the lower wire outer connector of the diode. In Fig. 9c a shadow X-ray image of the middle part of the diode is given.

The black level corresponds to 10 pulses in each point, the white level corresponds to 3-5 pulses. The initial radiation corresponds to 250 pulses per point. Because of such a strong attenuation the noise level is very high in the shadow image. The inner structure is seen very approximately. The reconstruction was made



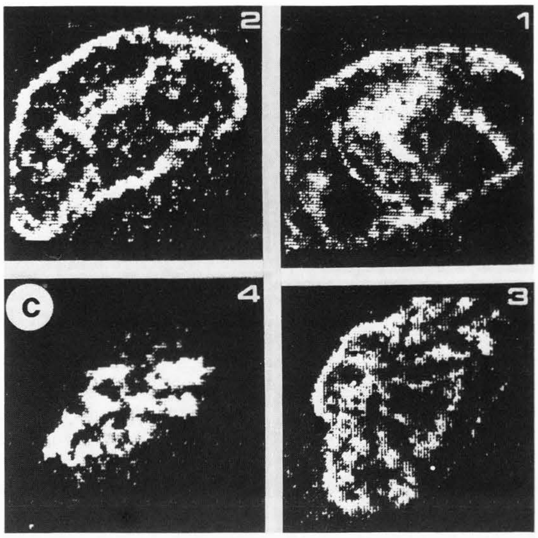
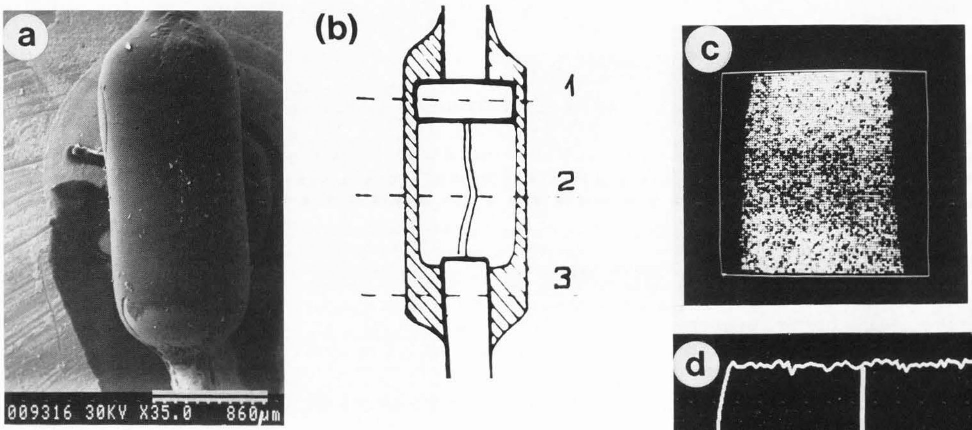


Fig. 8: Microtomography of a beetle's head:
a- SE image
b- X-ray shadow image
c- reconstructed cross-sections



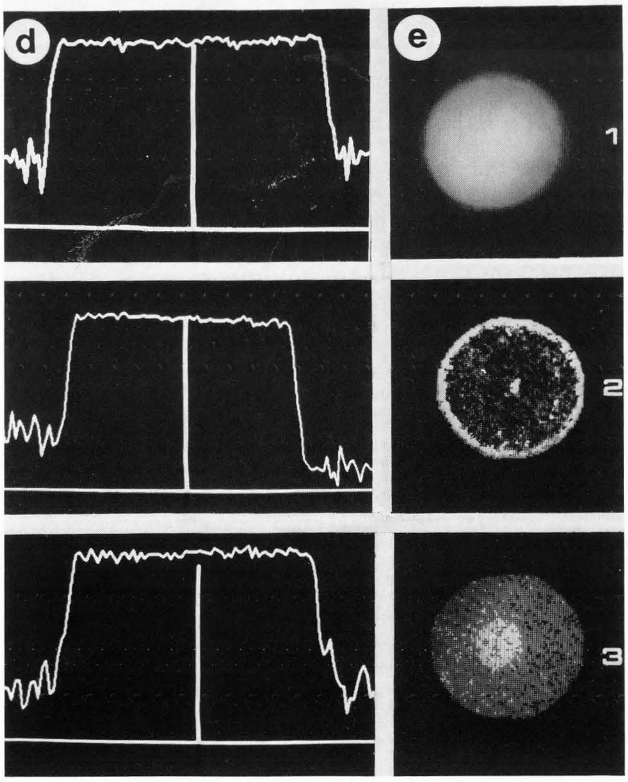


Fig. 9. Microtomography of a semiconductor diode:
a- SE image
b- diode design
c- X-ray shadow image
d- projection data
e- reconstructed cross-sections

from 120 projections in each of the three cross-sections marked in Fig. 9. Signals of one of the projections for each field of reconstruction are shown in Fig. 9d. They are very much alike in their appearance as only the upper part of the signal contains useful information. Despite the minimum quantity of useful information all 3 cross-sections of suitable quality could be reconstructed (Fig. 9e). Smoothing with the Hemming window with α =0.5 and acquisition of useful information from all the 120 views played a positive role. On the lowest of the given cross-sections is a wire output, soldered into the glass of the frame. On the middle cross-section a cylinder glass frame of a diode and a thin wire contact are seen. The upper cross-section corresponds to an Si-plate with a p-n junction. A thin layer of glass around Si is rather badly reconstructed because of the high attenuation gradient on the diode-vacuum boundary.

All the examples given above show the possibilities of microtomography in SEM. Additional information can be found in other sources (see references 2, 3).

Conclusions

Non-destructive methods of 3-dimensional reconstruction of the inner structure of microobjects allow the collection of data inaccessible to other investigation methods in SEM. The basis is a well developed mathematical device of computerized tomography. To obtain projection data different types of microscanners are developed. The first tests of the developed set-up and methods of microtomography produce encouraging results. Further development is expected in the direction of improvement of spatial resolution and increase of reconstruction speed. Transfer to microscanners with a minimum of mechanical parts will make the set-up more reliable and technological.

The value of the obtained data gives confidence that this direction of investigations in SEM will be developing rapidly.

To obtain informative data, apart from X-ray radiation, infrared radiation or ultrasound can be used. An alternative approach is the utilization of microstructures of a more suitable type of radiation with corresponding algorithms of reconstruction for each class.

References

1. Computerized tomography: the special issue IEEE, (1983), Vol. 71, No 3, pp. 293-431.

2. Gostev AV, Rau EI, Sasov AYu, Savin DO, Spivak GV (1984) Computerized microtomography in SEM, in: Proc. VIII Europ. Congr. on Electron Microscopy, Budapest, Hungary, Vol. I. pp. 275-276.

3. Gostev AV, Licharev SK, Rau EI, Savin DO, Sasov AYu, Sokolan SV, Spivak GV (1984) Experiments by computerized microtomography in SEM, in: Proc. of IV All-union symposia on electron microscopy, Nauka, Moscow, p. 38.

4. Herman G (1980) Image reconstruction from projections: the fundamentals of computerized tomography. Academic Press.

5. Hoppe W, Hegari R (1980) Three-dimensional structure determination by electron microscopy (nonperiodic specimens), in: Computer processing of electron microscopy images (Hawkes PW, ed), Springer-Verlag, pp. 127-185.

6. Rowland SW (1979) Computer implementation of image reconstruction formulas, in: Image reconstruction from projections: implementation and application (Herman G, ed.) Springer-Verlag, pp. 9-79.

Discussion with Reviewers

K. Kanaya: A method for three-dimensional reconstruction from, for example, a series of light or electron micrographs obtained by ultramicrotomy has already been accomplished by Baba et al. (1984, in Micron and Microscopica Acta). The merit or demerit of this device should be compared with such three-dimensional reconstruction methods.

Author: The main merit of microtomography in comparison with other methods is the study of the inner structure of microobjects WITHOUT DESTROYING them.

P.W. Hawkes: Do you anticipate that the energy deposited in the specimen will limit the usefulness of the technique?

Author: In my opinion, the energy deposited in the specimen will not limit the usefulness of the microtomography.

D. Sayre: I can imagine someone reading this paper and wanting to construct a similar unit, but then being discouraged by the present image quality, which does not seem very good. In the author's opinion, can the quality of imaging be improved in later versions, and if so, how?

Author: The images given in Fig. 7-9 were obtained from the binary computer display screen. Using half-tone display the quality of the results will be considerably better.

D. Sayre: What was the energy and spectrum of the X-rays used in these experiments? Was any attempt made to match the X-ray energy to the thickness and absorptivity of the specimen? Does the author think it would be useful to consider imaging with monochromatic X-rays to obtain microanalytical information from the specimen?

Author: The X-ray spectrum corresponds to the interaction of a 30 kV electron beam with the Cu target. The questions of spectrum modification in specimens were not considered. It is difficult to obtain microanalytical information from the spectrum modification because of low signal to noise ratio.

K.C.A. Smith: All of the micrographs shown are taken at 30 kV, presumably the highest available. If so, would a higher accelerating voltage be of benefit for image reconstruction?

Author: A higher accelerating voltage will allow investigation of objects with higher absorptivity by microtomography.

K.C.A. Smith: Could you give further details of your method of automatic stabilization of the field emission system during information acquisition?
Author: Programmed stabilization of data acquisition conditions is based on the control of the scanning speed to obtain a constant signal outside the object. Questions of field emission current stabilization were not considered.

K.C.A. Smith: Mention is made of infrared radiation as an alternative to X-ray radiation. How could this be applied in the SEM?
Author: Infrared radiation may be emitted from the corresponding luminophore on the target. Infrared photomultipliers are used for detection of the radiation.