Past, present and future of backscatter electron (BSE) imaging

Oliver C. Wells[1], Michael S. Gordon[*2] and Lynne M. Gignac[2]
[1]Emeritus
[2]IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 USA

ABSTRACT

We describe developments in backscattered electron (BSE) imaging in the scanning electron microscope (SEM) beginning with the pioneering work of Von Ardenne and Knoll in Germany in the 1940's and Charles Oatley, Dennis McMullan, Kenneth Smith and others in the 1950's. Recent work on BSE imaging with very high energy (100's of KeV) electron beams, such as the inspection of voids in metallurgy under thick dielectrics in semiconductor back-end-of-the-line (BEOL) structures will be presented. Finally, we will look toward the future of BSE imaging in terms of the SEM's, detectors, and application areas.

***Index Terms*— Electron, Backscattering, BSE, Imaging, SEM, history**

1. INTRODUCTION

In this paper, we discuss BSE imaging in the scanning electron microscope (SEM). First, we present an historical perspective discussing the successive accomplishments of early pioneers in the SEM field. We further discuss several pertinent features of contrast formation in BSE and distinguish differences between the information content gained from secondary and BSE. Several current uses of BSE imaging are discussed with applications to the semiconductor industry. Finally we discuss our view of what the future holds for BSE imaging.

2. THE PAST

2.1 The distant past

Reviews of the early years of the development of practical scanning electron microscopes have been given by Wells[1], Oatley[2], McMullan[3], and more recently by Wells and Joy[4], and Smith, Wells and McMullan.[5] Some of the relevant details of this history and its application to backscatter electron imaging will be given in this section.

The origin of the *scanning* electron microscope is credited to the work of Knoll in 1935.[6] His early device was actually a pair of cathode-ray tubes (CRT's). In the first CRT, the beam was focused onto and scanned over the sample. In the second CRT (the viewing CRT), the beam was scanned over the phosphor screen, in synchronism with the scanning of the beam in the first device, and the intensity of the viewing CRT was modulated by the current from the emitted secondary electrons in the first CRT. No demagnification lenses were employed by this device and the spot size was limited to about 100 μm.[1-6]

In 1938, a publication by Von Ardenne described the development of a scanning Transmission Electron Microscope (STEM), which avoided the chromatic aberrations observed at the time, by eliminating a magnetic lens below the substrate. The microscope had two magnetic lenses to demagnify the source to the plane of the sample which provided a sub-micron spot size. The beam scanning coils were located immediately upstream from the lower lens. Photographic

[*] gordonm@us.ibm.com, phone: (914) 945-2802, fax: (914) 945-2141

Scanning Microscopies 2012: Advanced Microscopy Technologies for Defense, Homeland Security, Forensic, Life, Environmental, and Industrial Sciences, edited by Michael T. Postek, Dale E. Newbury, S. Frank Platek, David C. Joy, Tim K. Maugel, Proc. of SPIE Vol. 8378, 837802 · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.920001

film was used to capture the images. The film was translated in synchronism with the beam deflection. Poor resolution was obtained when the microscope was used as a SEM due to a lack of an acceptable detector.[2,3,5]

Publications in 1942 by Zworykin and colleagues at RCA in the USA, described their progress building a series of SEM's. Like Knoll's device, the origin of the Zworykin SEM's was based on modified CRT's. In the last device, a field emission source and a series of electrostatic lenses were used. The immersion lens located at the plane of the sample, accelerated the secondary electrons emitted from the sample (while retarding the incident beam electrons) onto a fluorescent screen which was viewed by a photomultiplier tube. Magnetic deflection coils were used to scan the beam over the sample. Although the electron optics and imaging system were cleverly designed, to solve the signal to noise problem, the long scan times of 10 minutes and the lack of a real-time viewing screen made this SEM impractical.[2,3]

2.2 The Oatley legacy

Oatley, at Cambridge University, supervised a series of graduate students who each contributed to and added to the success of the prior and current students. Oatley's first gradate student was Dennis McMullan in 1948, followed by Ken Smith in 1952, Oliver Wells in 1953, Thomas Everhart in 1955, Peter Spreadbury in 1956, Richard Thornley in 1957, Gary Stewart in 1958, Fabian Pease in 1960 and finally Alec Broers in 1961. During their work, they developed a total of 5 SEM's.[2]

McMullan's account of the details and eventual success of his SEM is detailed in reference 7. He recognized the need for a high energy primary beam to avoid the ill effects of surface contamination from poor chamber vacuum conditions.[3,7] Additionally, by that time it was clear that sample contrast due to atomic number could be obtained by illuminating samples at normal angles of incidence, whereas it was necessary to tilt the sample about 65 degrees from the beam axis to obtain topological contrast. A key to the success of this microscope was the use of an electron multiplier that was used to amplify the backscatter electrons. The output from the electron multiplier modulated the intensity of a real-time CRT used to display the sample as the beam scanned over it. McMullan published micrographs of etched aluminum, with resolution of about 500A, with between 1000-3000X magnification.[7] McMullan proposed the use of low-loss electrons to improve the resolution of backscattered electrons, but it was Wells and Conrad Bremer who later demonstrated it experimentally.[3,7,8]

Smith made improvements upon McMullan's SEM, by adding a stigmator coil and double-deflection scanning of the incident electron beam, which improved the spot resolution down to about 250A and increased the electron detection efficiency. Secondary electrons could be now be collected by the application of a positive bias on the detector.[1,2,5]. He also designed a new sample stage that allows the sample to be rotated and tilted with respect to the beam.[1,5] Smith was the first to observe voltage contrast in an image,[1,5] and, later, Oatley and Everhart, observed voltage contrast in p-n junctions.[9] Later, Smith built a new SEM, (SEM3) using magnetic lenses for the Pulp and Paper Institute of Canada, in Montreal, and joined the staff there. Wells and Joy mentioned that this SEM, "gave micrographs of present-day quality" of wood and fiber.[4] The Pulp and Paper Institute was interested in a SEM due to its excellent depth of focus and resolution as compared to an optical microscope.[10,11]

Wells designed and built a new SEM called SEM2. According to his account, this SEM included "o-rings", for the first time in a SEM (to replace the gaskets that had been used before), as well as adding mechanical means for centering objects in the column rather than centering the beam.[12] Wells researched techniques to prevent electrical charging on insulating samples, since he was interested in imaging fibers and spinneret holes (which were difficult to observe using optical microscopes due to the small depth of focus compared to the SEM, and impossible to view using transmission electron microscopes).[13] Wells also pioneered the use of stereoscopic imaging, where pairs of images taken from the SEM were used to learn about the sample's topology, and applied the method to metallurgical research.[2,12] Wells used an electron multiplier as a first stage of a two stage detection system. The exiting electrons from the first stage were directed onto a fluorescent screen and then directed to a photomultiplier tube with a light pipe. The importance of this detector was that the output was a ground potential, instead of at high voltage as in Smith's SEM1.[2]

Everhart's main contributions to the development of the practical SEM were in the improvement of the electron detectors and in measuring and developing an explanation and model for the signal contrast. By biasing a grid in front of the existing electron multiplier, he determined that the majority of the electrons in Smith's detector were in fact secondary electrons.[14] Using SEM1 (the one modified by Smith) he replaced the original detector system with one that included a plastic scintillator, close to the sample, and a photomultiplier tube to amplify the signal. Later, a new design incorporated a hemispherical scintillator, and a light pipe to transmit the light to a photomultiplier.[14] Everhart's simple theory of the dynamics of electron *backscattering* predicted that contrast was generated by the sample's atomic-number and tilt angle between the primary beam and the normal angle of the sample.[14,15] Everhart also worked to understand the role of sample contrast via secondary electron collection, by using ray tracing using an electrolytic tank . The early work showed the dependence of the slow electron trajectories on collector bias, the emission angle and sample bias.[14]

Thornley took over SEM2 (the one built by Wells) and made several incremental improvements, including: reducing the electrical noise, adding an aperture at the position of the source cross over to force the shape of the cross over to be round, adding a stigmator, as well as adding the means to adjust the axial position of the tungsten filament.[2,16] His publication with Everhart, describes the development, and the measured efficiency and performance of their electron detector in the quest to obtain large-amplitude, low-noise signals. By reversing the polarity of the bias on the mesh, the detector could be used as either a secondary or backscatter detector.[17,18] Thornley was one of the first microscopists to use the SEM with very low beam energy to investigate non conducting samples. He found that at sufficiently low beam energy, (when the ratio of secondary electrons to the primary beam was > 1) the effects of surface charging were greatly reduced.[2,16] Thornley examined ceramics and freeze-dried biological samples with low beam energy.[16]

Spreadbury designed and built a "simple scanning electron microscope" with moderate resolution, using two electrostatic lenses and a laboratory oscilloscope for viewing the sample. Building upon the success of his predecessors, he used a gun as designed by Smith, and the detector system as designed by Everhart.[19]. Parameters related to the performance of the gun (cross over size, brightness, beam profile) were measured with a simple test setup. He also developed methods for standardizing the making tungsten hairpin filaments.[19]

Stewart initially used Spreadbury's simple scanning electron microscope, according to Oatley's account,[2] then adapted a SEM that Oatley was building, SEM4, to include a positive ion source for sputtering the sample.[2,20] Backscattered electrons were used to observe in real-time the surface that was being sputtered.[20]

Pease designed and fabricated SEM5, specifically with the goal of obtaining resolution close to what had been calculated, 10 nm. The previous SEM's from Oatley's students produced no better than 35 nm resolution.[21] Pease realized that the resolution depended on both the beam size and the penetration of the electrons into the sample,[22] and mentioned that the area of emission for secondary or backscattered electrons would likely be on the order of the size of the beam, and ~ 1 um for a 15 keV beam, respectively. Pease chose to use magnetic lenses instead of the electrostatic lenses used in the previous 4 SEM's since: (1) they had lower spherical and chromatic aberrations than electrostatic lenses, (2) they were easier to operate since there was less material to be contaminated, and (3) stable current supplies were available.[23] He took great care in the fabrication of the final lens to ensure roundness and alignment to minimize astigmatism. Anti-vibration mounts, and mu-metal shielding were used to reduce the effects of mechanical vibration and stray AC magnetic field, respectively.[23]

Broers took over SEM4 from Stewart and made the following improvements: (1) the electrostatic electron lenses were replaced with magnetic lenses to reduce the aberrations, (2) the vacuum system was improved to reduce the vacuum and pumping time for the sample, and (3) a mass filter in the ion beam was added to eliminate oxygen ions coming from the ion source.[24] Using the SEM and ion beam, his early experiments demonstrated that the electron beam could be used to pattern submicron features (first in gold, and then in photoresist).[24]

In the late 1960's developments by Broers and Crewe, and concurrently improvements by others in vacuum technology, led to the development of high brightness, and long-lived electron sources using LaB_6 and field emission emitters, respectively.[25-28]. These high brightness sources led to smaller probe sizes and higher resolution. In fact, by

1970, Crewe had an operational scanning microscope and demonstrated resolution of 5A by observing biological samples.[27]

2.3 Backscatter fundamentals

Backscattered electrons are incident beam electrons that are scattered with the nucleus of the sample atoms and are emitted back into the chamber. For thin or bulk samples, the number of backscattered electrons increases: (1) monotonically with the *charge*, Z of the sample, (2) linearly with the sample *thickness* (up to the point where the thickness is more than ½ of the range of the electrons in the material, then it remains constant, eg. saturates with further sample thickness), (3) with *tilt angle* and (4) proportionally as $1/E_0^2$ where E_0 is the energy of the primary beam, as expected from the Rutherford scattering cross section.[18] In general, for normal incidence, backscattered electrons are useful for the determination of the chemical makeup of the sample.

3. THE PRESENT (NOT TOO DISTANT PAST)

3.1 Normal incidence

Niedrig has shown several detector arrangements used for the efficient collection of backscattered electrons including an annular semiconductor detector as well as scintillator detector, both positioned between the final lens and the sample.[18] Wells showed an example from the literature of a pair of backscatter detectors on either side of the sample. The sum of the outputs from these detectors is as if a large detector was used, however, the difference is sensitive to the topology of the sample.[29]

3.2 Low-loss imaging

The resolution of the backscattered image can be significantly enhanced, and the angular distribution of the backscattered electrons (in forward direction) is similarly enhanced by tilting the sample to large angles with respect to the beam.[18,30]

Wells described experimentally a new (at the time) contrast mechanism in an early experiment using a scintillator and photomultiplier tube, observing backscattered electrons in both “high” and “low” positions for a sample with oblique angle of incidence.[31] The electrons backscattered in the “high” position underwent multiple scattering events and the electrons therefore penetrated the sample to a larger depth, compared to the electrons backscattered into the “low” position which underwent less scattering, and penetrated the sample at a shallower depth. These electrons have lost less energy than those detected at larger angles. The resolution shown in the mircrographs was better for the images from the detector in the “low” position and showed surface topology.

Images obtained from backscattered electrons from which the incident electrons have suffered only a small loss of energy are referred to “low-loss images”.[8] The theory of the low-loss electrons, in terms of the penetration depth is given in reference 30.

A spherical grid energy filter was used by Wells to examine the electrons backscattered from samples where the electrons suffered less than an 800 eV energy loss. He found that these electrons were from the top ~ 100A of the sample.[8] Another energy filter was examined in which the sample was placed obliquely in the bore of the final lens of a SEM. The lower-energy backscattered electrons were deflected more than those near the beam energy by the magnetic field in the lower half of the lens.[32]

Another advantage of the low-loss imaging is that there is no sensitivity to the substrate onto which the sample is mounted since the backscattered electrons are only sensitive to the surface, ~100A or so.

3.3 Electron channeling

An excellent review of electron channeling is given by Joy et. al.[33] Channeling refers to the change in the backscatter of the electrons depending on the orientation between the incident electron beam and the sample's crystal lattice. As such, it is possible to measure the crystal orientation, and even defects in the sample. Wells mentions that the modulation in the normal secondary or backscatter electron signal caused by channeling can be a few percent or 40% respectively. Further, in low-loss mode, the modulation can be as large as 75%.[34] Channeling contrast is improved for thin samples, and varies as $1/E_0$.[33] In order to observe channeling, the beam semiangle has to be much smaller than the Bragg angle of the crystal lattice. The beam resolution degrades as the beam is approaching collimation. In order to sweep the angle of the beam with respect to the sample (through the Bragg angle), either both scanning coils are used so that the deflection is made to pivot about the final lens, or the upper scanning coil is used to rock the beam about the sample (and the focal length of the final lens appropriately adjusted) or slightly above or below it.[33]

Signal processing methods, by for example, subtracting the background, or differentiating the signal to improve the contrast from channeling. To make sure that what is being observed is due to channeling, Joy, et. al., suggests two tests which will change the channeling contrast (but not the topological contrast) (1) tilting the sample or changing the beam energy E_0 (which will change the Bragg angle).[33]

3.4 Electron Backscattered Patterning (EBSP)

Electron backscatter patterning (EBSP) is a method where a channeling pattern is formed from a stationary electron beam incident on a crystalline sample.[35] EBSP is related to Kikuchi patterns that are seen in an electron diffraction pattern from a thick region of a transmission electron microscope sample and EBSP can be used to determine the crystal orientation of a sample using SEM. EBSP is commonly referred to as electron backscatter diffraction (EBSD) or backscatter Kikuchi diffraction (BKD) most likely due to its relevance to Kikuchi patterns but Wells has pointed out that the mechanism of EBSP formation is channeling and not diffraction.[36] EBSP patterns are generated from a highly tilted sample (typically 70^o sample tilt relative to the incident electron beam) and patterns can be recorded using an array of backscattered electron detectors, photographic film, or a phosphor screen viewed by a CCD camera. The EBSP is a surface sensitive technique since the pattern is created from a region ~20nm from the surface. There are several commercial EBSP systems that can be purchased for a SEM where EBSP analysis of a sample surface can be obtained in an automated fashion as an electron beam is scanned in one or two dimensions across a sample. From the acquired data sets, the sample can be characterized for local grain orientation, grain size, texture, strain, phase identification and phase distribution. The commercial systems can be installed in dual beam focused ion beam (DB-FIB) tools and automated data sets can be obtained in 2-dimensions after the sample is sliced with the Ga^+ ion beam on the FIB.[37] Here, the data can be used to obtain 3-dimensional grain orientation/size information about a sample. EBSP has been used in a variety of different metallurgical applications but has the limitation of analysis from crystals with dimensions in the tens of nanometers and therefore has found only limited application to the semiconductor industry.

4. THE FUTURE

4.1 Use of large solid angle detector arrays

The idea of using a large-area segmented backscattered (pixilated) detector has already been proposed and couple of initial experiments performed.[38-41] The detector array was developed for collecting images in an EBSP system. The advantage of using an array of backscatter detectors in a SEM is obvious: (1) information from each detector could be analyzed offline, (2) different detector elements could be combined to capture the backscattered electrons efficiently with large effective solid angle, (3) some detector elements could be combined in the "high" mode for large angle scattering where atomic contrast dominates, and others in the "low" mode for topological contrast sensitivity and (4) the detectors could be combined to form images synchronized with the scan of the incident electron beam.

In principle, the operation of each individual detector could be checked and the effective solid angle determined by using a point β-source at the position of the sample. This would allow detectors that were not functioning properly to be excluded when combined off-line, and the amplitude from the functioning detectors could be corrected for solid angle and combined.

An application of the detector array was envisioned by Wells, et. al., to investigate topology in etched silicon.[41]

4.2 Applications to high- energy BSE

With high incident beam energies (100-400 keV), it is possible to use secondary and backscattered electrons to image subsurface features (< 5um below the surface) in samples due to the added penetration of the *incident* electrons.[42-44] Since most commercial SEM systems have a maximum incident electron beam energy of 30 keV, the high energy analysis is performed in a scanning transmission electron microscope (STEM) equipped with SE and BSE detectors. With the higher beam energy, (1) the range of the incident electrons is increased, (2) the resolution of the beam is improved, (3) however, the range of influence of the backscattered electrons is also increased. This last point is usually not desirable since it worsens the contrast of the images.

As an example, backscattered electrons were used to image multilevel copper interconnects well below the surface for several samples using incident electron beam energies up to 400 keV and these images were used to find voids in Cu lines. The images from the backscattered electrons show excellent contrast between materials with largely varying atomic numbers so Cu interconnects in SiO_2 dielectric are excellent subjects for high energy BSE. Reference 44 shows that BSE image resolution of a subsurface feature is dependent on the incident beam energy, depth below the surface, and the materials above of the feature. For Cu interconnects imaged with 400 keV electrons, beam sizes of 30 nm and 90 nm were measured for Cu lines encapsulated with 0.65 μm and 2.7 μm of SiO_2, respectively.

Plenty of areas for future research exist for high energy beams, smaller feature dimensions, thicker structures, tilted samples, tomographic reconstruction by energy filtered BSE, and smaller beam sizes due aberration corrections in the SEM and STEM.

4.3 Micro miniature SEM

One area of SEM research that the authors feel should be pursued more comprehensively is the micro-miniature SEM.[45-46] When the size of an SEM is scaled down, the lens aberrations also scale and an SEM with improved image resolution can be obtained. This type of SEM was initially made for electron beam lithography[45] but Khursheed has simulated and then built a SEM that has 55 mm total length with a permanent magnet objective lens outside the chamber.[46] The on-axis spherical and chromatic aberration coefficients were predicted to be about 10X smaller than those obtained for a full-size SEM with similar working distance.[46] Though micro-miniature SEM systems can be built, they have limited sample size and could be impractical as a commercial system.

4.4 Other interesting developments

A project known as "bugscope" is a program that lets students operate a SEM remotely to examine bugs or other interesting specimens.[47] This allows students to learn about the fundamentals of SEMs to view common objects (eg bugs) without their schools having to undergo the costs associated with purchasing and maintaining SEM's. In the bugscope program, three live sessions, lasting about an hour, are run per week.[47] Educational programs like this, can encourage young students to pursue careers in science, or engineering.

Tabletop SEMs have been commercially developed and are available to bridge the gap between conventional optical microscopes and high-resolution SEMs.[48,49] The lower cost, automatic operation, and the lack of surface preparation in these SEMS make them quite desirable for small laboratories, or schools. Skilled operators are not required to use or maintain these small and simple SEMs.

5. SUMMARY

We have discussed some of the important developments in the history of the SEM and BSE. In addition, current topics in BSE have been presented including the use of detectors at normal incidence, low-loss imaging, electron channeling and electron-backscatter patterning. Finally, we have discussed some of our views on the future of BSE, including the use of large array detectors, applications of high beam energy BSE for semiconductor fabrication, the use of micro-miniature SEM's, the remote operation of a SEM by students, and finally the development of simple-to-use table-top SEM's.

6. ACKNOWLEDGEMENTS

The authors wish to thank Conal Murray for proving useful insight.

REFERENCES

[1] Wells, O.C., Boyde, A., Lifshin, E., Rezanowich, A., [Scanning Electron Microscopy], McGraw-Hill, New York, Introduction (1974).
[2] Oatley, C.W., "The early history of the scanning electron microscope," J. Appl. Phys. 53(2), R1-R13 (1982), and references therein.
[3] D. McMullan, "Scanning electron microscopy, 1928-1965," Scanning 17, 175-185 (1995), and references therein.
[4] Wells, O.C., and Joy, D., "Early history and future of the SEM," Surf. Interface Anal. 38, 1738-1742 (2006).
[5] Smith, K.C.A., Wells, O.C., and McMullan, D., "The 50th anniversary of the first applications of the scanning electron microscope in materials research," Phyics Procedia 1, 3-12 (2008), and references therein.
[6] Knoll, V.M., "Aufladepontential und sekundaremission elektronenbestalhter korper," Z. Tech. Phys. 16, 467-475 (1935).
[7] McMullan, D., "An improved scanning electron microscope for opaque specimens," Proc. Inst. Elec. Eng. (London) 100, Part II, No. 75, 245-259 (1953).
[8] Wells, O.C., "Low-loss image for surface scanning electron microscope," Appl. Phys. Lett. 19(7), 232-235 (1971).
[9] Oatley, C.W. and Everhart, T.E., "The examination of p-n junctions with the scanning electron microscope," J. Electron. 2, 568-571 (1955).
[10] Atack, D., and Smith, K.C.A., "The scanning electron microscope a new tool in fibre technology," Pulp Pap. Mag. Can. 57, 235-251 (1956).
[11] Smith, K.C.A., "Scanning electron microscopy in pulp and paper research," Pulp Pap. Mag. Can. 60, T366-T370 (1959).
[12] Wells, O.C., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.3 (2004).
[13] Everhart, T.E., "Persistence pays off: Sir Charles Oatley and the scanning electron microscope," J. Vac. Sci. Technol. B 14(6), 3620-3624 (1996).
[14] Everhart, T.E., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.4a (2004).
[15] Everhart, T.E., "Simple theory concerning the reflection of electrons from solids," J. Appl. Phys. 31(8), 1483-1490 (1960).
[16] Thornley, R.F.M., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.6 (2004).
[17] Everhart, T.E., and Thornley, R.F.M, "Wide-band detector for micro-microampere low-energy electron currents," J. Sci. Instr. 37, 246-248 (1960).
[18] Niedrig, H., "Electron Backscattering from Thin Films," J. Appl. Phys. 53(4), R15-R49 (1982).
[19] Spreadbury, P.J., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.5 (2004).
[20] Stewart, A.D.G., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.7b (2004).
[21] Pease, R.F.W., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.9a (2004).
[22] Pease, R.F.W., "The determination of the area of emission of reflected electrons in a scanning electron microscope," J. Sci. Instrum. 42, 158-159 (1965).
[23] Pease, R.F.W., and Nixon, W.C., "High resolution scanning electron microscopy," J. Sci. Instr. 42, 81-85 (1965).
[24] Broers, A.N., [Advanced in Imaging and Electron Physics], Elsevier Academic Press, San Diego, 133, chapter 2.10 (2004).
[25] Brenton, P.J., "From microns to nanometers: early landmarks in the science of scanning electron microscope imaging," Scanning Microscopy 13(1), 1-6 (1999).
[26] Broers, A.N., "Electron gun using long-lie Lanthanum hexaboride cathode," J. Appl. Phys. 38, 1991-1992 (1967).
[27] Crewe, A.V., and Wall, J., "A scanning microscope with 5A resolution," J. Mol. Bio. 48, 375-393 (1970), and references therein.

[28] Crewe, A.V., Eggenberger, D.N., Wall, J., and Walter, L.M., "Electron Gun Using a Field Emission Source," Rev. Sci. Instr. 39, 576-583 (1968).
[29] Wells, O.C., Boyde, A., Lifshin, E., Rezanowich, A., [Scanning Electron Microscopy], McGraw-Hill, New York, Chapter 6 (1974).
[30] *ibid*., Chapter 3.
[31] Wells, O.C., "New contrast mechanism for scanning electron microscope," Appl. Phys. Lett. 16(4), 151-153 (1970).
[32] Wells, O.C., Broers, A.N., and Bremer, C.G., "Method for examining solid specimens with improved resolution in the scanning electron microscope," Appl. Phys. Lett. 23(6), 353-355 (1973).
[33] Joy, D.C., Newbury, D.E., and Davidson, D.L., "Electron channeling patterns in the scanning electron microscope," J. Appl. Phys. 53(8), R81-R122 (1982).
[34] Wells, O.C., Boyde, A., Lifshin, E., Rezanowich, A., [Scanning Electron Microscopy], McGraw-Hill, New York, Chapter 7 (1974).
[35] Schwarzer, R.A., Field D.P., Adams B.L., Kumar M. and Schwartz A.J., [Electron Backscatter Diffraction in Materials Science**],** Springer, Berlin, 1-20 (2009).
[36] Wells, O.C., "Comparison of Different Models for the Generation of Electron Backscattering Patterns in the Scanning Electron Microscope," Scanning 21, 368-371 (1999).
[37] Uchic, M.D., Groeber M.A., Dimiduk D.M. and Simmons J.P., "3D microstructural characterization of nickel superalloys via serial-sectioning using a dual beam FIB-SEM," Scripta Mat. 55, 23-28 (2006).
[38] Wells, O.C., "The history and future of the SEM- a personal view," Microsc. Microanal. 12 (Supp2), 154-155 (2006).
[39] Wells, O.C., Gignac, L.M., Murray, C.E., Frye, A., and Bruley, J., "Use of backscattered electron detector arrays for forming backscattered electron images in the scanning electron microscope," Scanning 28, 27-31 (2006).
[40] Gignac, L.M., Wells O.C., Hu C.-K., Bruley J., Murray C.E. and Frye A., "Backscattered electron imaging in the scanning electron microscope: the use of either: (a) an array detector or (b) high incident energy," Microscopy & Microanalysis 14, 120-121 (2008).
[41] Wells, O.C., Murray, C.E., Rullan, J.L., and Gignac, L.M., "Top-down topology of deeply etched silicon in the scanning electron microscope," Rev. Sci. Instr. 75(8), 2524-2528 (2004).
[42] Gignac, L.M., and Wells, O.C., [Handbook of Instrumentation and Techniques for Semiconductor Nanostructure Characterization], World Scientific, New Jersey, 1, Chapter 1 (2012).
[43] Gignac, L.M., Kawasaki, M., Boettcher, S.H., and Wells, O.C., "High energy backscattered electron imaging of subsurface Cu interconnects," JEOL News 40(1), 13-17 (2005).
[44] Gignac, L.M., Kawasaki, M.,. Boettcher, S.H., and Wells, O.C., "Imaging and analysis of subsurface Cu interconnects by detecting backscattered electrons in the scanning electron microscope," J. Appl. Phys. 97, 114506 (2005).
[45] Kratschmer, E., Kim, H.S., Thomson, M.G.R., Lee, K.Y., Rishton, S.A., Yu, M.L., and Chang, T.H.P., "An electron-beam microcolumn with improved resolution, beam current and stability," J. Vac. Sci. Technol. B 13(6), 2498-2503 (1995).
[46] Khursheed, A, "Magnetic axial field measurements on a high resolution miniature scanning electron microscope," Rev. Sci. Instr. 71(4), 171-1715 (2000).
[47] http://bugscope.beckman.uiuc.edu/
[48] http://www.jeolusa.com/PRODUCTS/ElectronOptics/ScanningElectronMicroscopesSEM/Benchtop/NeoScopeBenchtopSEM/tabid/511/Default.aspx
[49] http://www.hiscope.com/tm3000.html