Volume 1 | Number 3 Article 11

7-29-1987

Scanning Electron Microscope Solid State Detectors

Zbigniew J. Radzimski
North Carolina State University

Scanning Microscopy, Vol. 1, No. 3, 1987 (Pages 975-982) 0891-7035/87$3.00+.00
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

SCANNING ELECTRON MICROSCOPE SOLID STATE DETECTORS

Zbigniew J. Radzimski

Dept. of Materials Science and Engineering
North Carolina State University, Raleigh, NC 27695-7916
Phone No. (919) 737-2933

(Received for publication April 02, 1987, and in revised form July 29, 1987)

Abstract

Solid state detectors (SSD) are the most commonly used backscattered electron (BSE) detectors in scanning electron microscopy (SEM). They have been used for at least 20 years and many types are described in the literature. These detectors can be designed in many shapes and forms but in commercially available SEMs two semiconductor detectors (A and B) are usually placed below the polepiece where they are used for compositional (A+B) and topographic (A-B) contrast enhancement. The range of SSD applications available from BSE is quite extensive. The kind and quality of information depend strongly on the shape and position of the detector in relation to the specimen and the electron beam. Also very important is the current gain vs. electron energy dependence, which can be controlled by detector manufacturing technology. This paper reviews various possible applications of semiconductor detectors in SEM, as well as factors which influence the quality of information obtainable from BSE by semiconductor detectors.

Key words: Scanning electron microscopy, backscattered electrons, solid state detectors.

Permanent address:
Technical University of Wroclaw,
ul. Janiszewskiego 11/17, 50-370 Wroclaw, Poland

Introduction

The detection and analysis of backscattered electrons is an important source of information about materials investigated in SEM (Newbury et al., 1986; Reimer, 1985; Robinson et al., 1984; Stephen et al., 1975). To date, many types of detectors have been proposed for BSE detection. In particular one can distinguish Faraday cages, scintillators, BSE to secondary electron converters, solid state detectors, channeltrons and fluorescent screens or films. The detectors are designed in many various shapes and forms. Commercial SEMs are mostly equipped with either a solid state detector or a scintillator (also called a Robinson type detector). The other detectors are used mainly for special applications, for instance: quantitative measurements of BSE (Faraday cages), electron channeling patterns (channeltrons in ultra high vacuum) or electron backscattering patterns (fluorescent screen).

The requirements for a suitable BSE detector in SEM include the following: good sensitivity, high gain, high signal to noise ratio (S/N), TV and slow imaging capability and small size. The semiconductor detectors satisfy most of these requirements. They can distinguish materials with mean atomic numbers that differ by less than 1, and which have a current gain of the order of a few thousand in the range of electron energy above a few keV, and have at least 5:1 signal to noise ratio (Oatley, 1981). They can also be used for both TV and slow scan imaging (Gedcke et al., 1978). They may work in a current mode as well as in the single counting mode. Finally the semiconductor detectors are very thin which makes it easy to mount them in the microscope chamber.

The solid state detectors can be constructed in different forms for various applications, for example

- a single detector with small solid angle, e.g., for measurements of angular distribution of backscattered electrons (Matsukawa et al. in 1974), or to achieve images with high resolution,
- a pair, for separation of topographic and compositional contrast (the first multiple detector system proposed for BSE by Kimoto and Hashimoto, 1966),
- a large solid angle detector, for imaging pseudo Kikuchi patterns (Wolf and Everhart, 1969), or in a multidetector system for imaging "true" topography (Hejna et al., 1985).

Technology of solid state detectors

The solid state detectors for SEM are either surface-barrier type or p-n junction diodes. The surface-barrier type diode, also called a Schottky diode, can be obtained by simple deposition of metal or forming a silicide on a semiconductor surface. In the first case, gold deposited on n-type silicon and aluminum or titanium on p-type material are most common. The thickness of the metal layer is usually about 20 to 50 nm. The silicides are formed by solid-solid metallurgical reaction after annealing of deposited metal (Ti,W,Mo) on the silicon surface. Since these interface chemical reactions are well defined and can be maintained under good control, this type of process provides reliable and reproducible Schottky barriers. The silicide thickness is usually about 2-4 nm. In a Schottky diode the barrier height is simply the difference between the metal work function and the electron affinity of the semiconductor, and the space charge region extends from the surface to the bulk of the semiconductor detector, as is schematically shown in Fig. 1a.

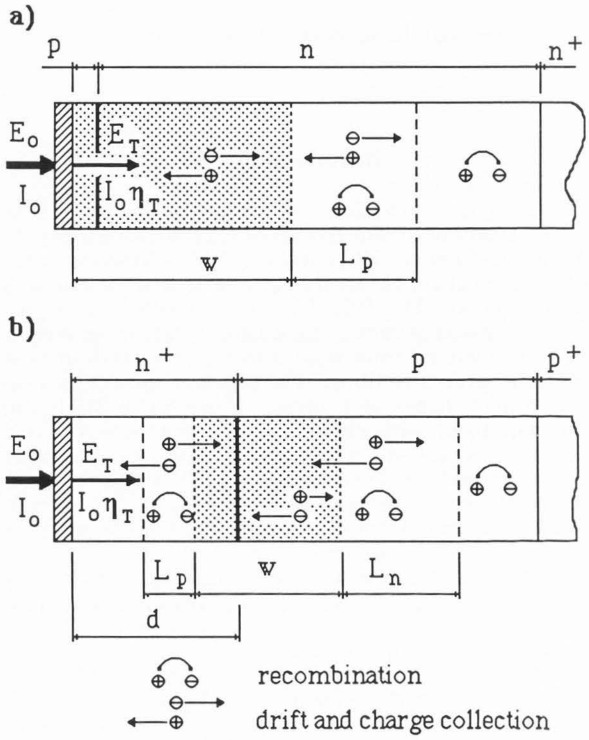

Fig.1. Schematic diagram of space charge region in a) n-type Schottky type and b) p-n junction diodes. w - space charge region width, d - junction depth, L_n, L_p - diffusion length of minority carriers, E_o - incident electron energy, E_T - energy of electrons transmitted through front layer, I_o - incident electron current, η_T - transmission coefficient of front metal layer.

The p-n junction detector can be obtained by doping a silicon substrate by diffusion or implantation, upon which an ohmic contact is deposited. Sometimes the contact is formed only as a ring outside a reactive area of detector. The junction depth can be controlled during fabrication, and it may vary from as low as 150 nm to a few micrometers depending on the technology used (Wilson, 1986). A space charge region extends in both directions from the junction (Fig. 1b), reaching a greater depth in a material with higher resistivity.

From the user point of view the main disadvantage of the classical Schottky detector is that any careless handling can induce mechanical damage and cause short-circuiting of the surface barrier. Moreover, they can also be destroyed by very high electron beam currents. Much more reliable is the silicide Schottky diode which should eventually replace the classical Schottky detectors now used in SEM. The p-n junction detector, with junction and depletion region located below the surface, is better protected against damage, since damage in the ohmic contact layer does not destroy the ohmic contact to the semiconductor.

Current gain of solid state detectors

The electrons injected into a semiconductor detector produce electron-hole pairs during inelastic scattering which can be separated before recombination, and as a consequence an external charge collection current is generated. The current gain is defined as the ratio of charge collection current to the incident electron current. The energy which should be provided to create an electron-hole pair varies for different semiconductor materials. For example for Si this energy is equal to 3.6 eV and for GaAs to 4.6 eV. If we compare these values with the electron beam energy or the average energy of BSE in SEM we can see that the gain of solid state detectors may be very high, in the order of several thousands. The collection efficiency of generated carriers will depend strongly on the type of detector and its parameters. Very important is the location and width of the depletion region in a semiconductor. To achieve the higher collection efficiency the depletion region width should be as large as possible and it should cover a wide range of electron penetration depths, consequently high resistivity materials are usually used. Moreover, the depletion region width may be extended by reverse biasing.

In the case of Schottky diodes the whole energy loss distribution of incident electrons can be included in the space charge region if the maximum penetration depth is smaller than its width, thus providing a high collection efficiency. However, part of the incident electron's energy is lost due to absorption inside the front metal coating. This layer is also called the "dead layer" of detector, causing the semiconductor detector to behave as a high pass energy filter. The minimum energy of incident electrons which can be detected is called the threshold energy and it is usually a few hundred eV to a few keV depending on the thickness and type of metal.

For the Schottky type detector, one assumes that all the generated electron-hole pairs contribute to the output detector current, the current gain (N) can be expressed as:

$$N = \eta_T E_T/\varepsilon_p \qquad (1)$$

where: η_T - transmission coefficient through the metal layer,
E_T - average residual energy of the incident electron transmitted through metal layer,
ε_p - energy per electron-hole pair.

Examples of the current gain dependence on the incident electron energy are shown in Fig. 2a for different materials with thicknesses giving the same threshold energy.

In a p-n junction detector charge collection depends on the absorption of electrons in the "dead layer" and on the junction depth. The "dead layer" of the p-n junction detector consists of the metal layer and semiconductor surface layer where all generated electron-hole pairs recombine. This surface layer can be neglected in a detector with a shallow junction. Minority carriers excited at a distance x from the junction reach the depletion layer with a probability exp(-x/L), where L is the diffusion length of the minority carriers. If the distance x is larger than the diffusion length, most of the carriers recombine on their way to the junction. Almost all carriers created in the depletion region contribute to the output detector current. The current gain of a p-n junction (N_o) detector depends on the ratio of junction depth to the electron penetration range in the following way (Siekanowicz et al., 1974):

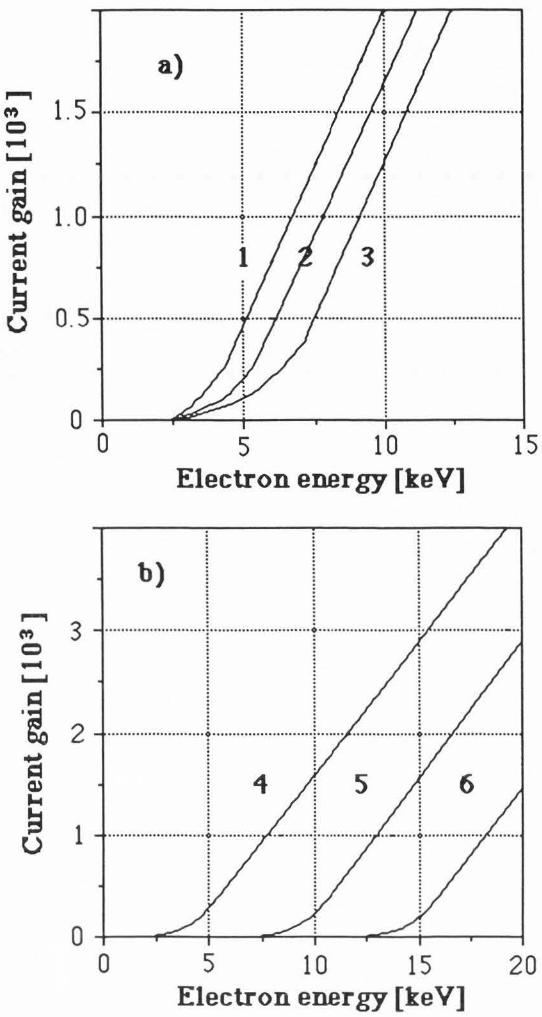

Fig. 2. Current gain vs. incident electron energy for a) Schottky type detector with different material used for front layer (1-Al, 2- Cr and 3- Au), and b) p-n junction detector with different thicknesses of front metal layer (4- detector without metal on active area, 5- with 150 nm Cu, 6- with 300 nm Cu. Figure a) from Siekanowicz et al., 1974.

$$N_o = N\left[1 - \frac{d}{2R}\right] \qquad (2)$$

where: d - junction depth,
R - maximum penetration depth of incident electrons in semiconductor.

The above equation describes the case for an electron penetration range comparable with the depletion layer width w (Fig. 3b). Examples of current gain dependence on electron beam energy for different contact layer thicknesses is shown in Fig. 2b. If the depletion region width is much smaller than the electron penetration range (Fig. 3c), a saturation effect on current gain vs. electron energy curve is observed (Fig. 3e). This saturation is due to an increase of the maximum energy dissipation depth beyond the p-n junction area, the effect being more visible in a semiconductor with low diffusion length.

The fraction of collected carriers can be increased by a reverse biasing of both the Schottky and p-n junction diodes,

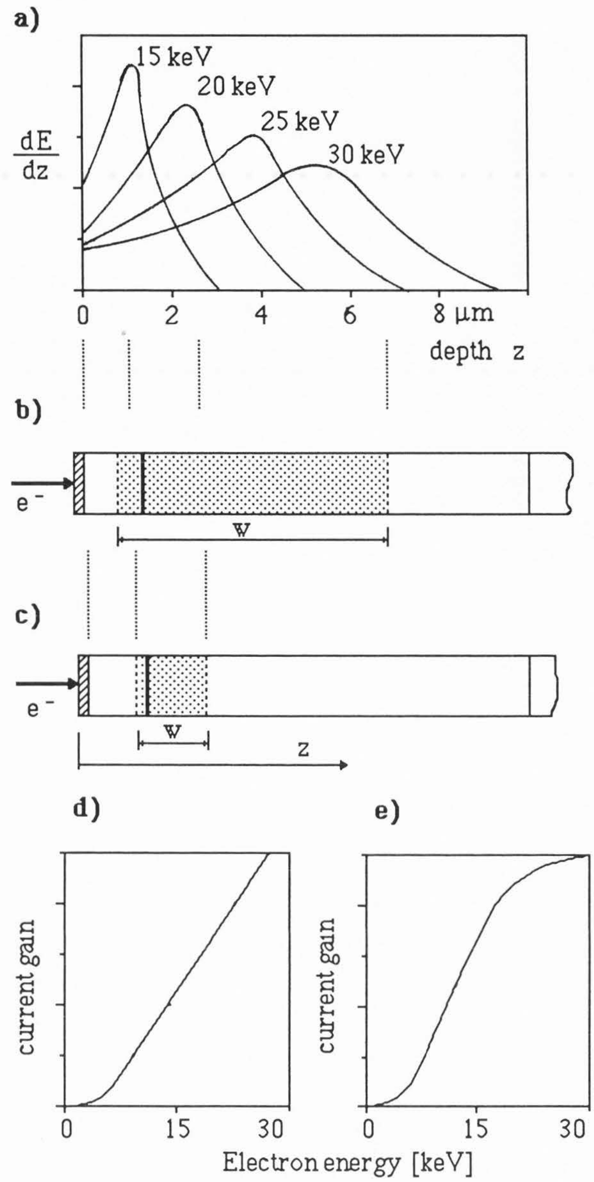

Fig. 3. The current gain vs electron energy for p-n junction detector with wide [Fig. 3d)] and narrow [Fig.3e)] space charge region. Fig.(a) shows energy loss distribution of incident electrons in Al for different primary energy (Shimizu et al, 1972).

however this also increases the dark current and substantially multiplies the effective shunt capacitance represented by the detector. By increasing the reverse external bias V_e, the width of the junction increases according to the formula:

$$w = \left[\frac{2\varepsilon}{e N_B}(V_d - V_e)\right]^{1/2} \qquad (3)$$

where: $N_B = N_D$ for an n-type Schottky and
$N_B = 1/N_D + 1/N_A$ for a p-n junction.
N_A, N_D - concentration of acceptors and donors
V_d - diffusion potential

With V_e=10 V and dopant concentration less than 10^{14} cm^{-3} it is possible to produce a space charge region width larger then 10 μm, which is the range of 30 keV electrons in silicon.

The analysis of the above factors which influence the charge collection in semiconductor detectors shows that modern technologies allow fabrication of a detector with a desirable current gain curve. As shown on Fig. 2 the slope of the current gain curve and threshold energy can be controlled. A low threshold energy of the order of a few hundreds of eV can be achieved if a silicide Schottky or shallow junction is used with a ring contact around the active area of the detector. A detector with high threshold energy, i.e., with a high pass energy filter built in, can be obtained if a thick front metal layer is used. New technologies can be utilized for fabricating a detector with an enhanced saturation effect on the current gain curve, i.e., with constant gain in a certain range of electron energies. This can be obtained if the charge collection region is limited to a narrow surface layer of the detector and the diffusion of the carriers from deeper layers is reduced. A new type of epitaxially grown silicon detector with an intentionally introduced defect plane at a certain depth may provide such behavior (Radzimski et al., 1987).

For general application in the SEM, i.e., for BSE detection, the detector should have a space charge region as wide as possible located at the surface, providing high gain and good detector sensitivity.

Bandwidth limitation

The bandwidth of a semiconductor detector or the rise time of the output signal depends strongly on the junction capacitance and the resistance of the non depleted region of the diode. Because of the large capacitance of the depletion layer the bandwidth is about 100 kHz if operating with low electron beam currents. The combination of the relatively high impedance and capacitance represented by the detector can be handled effectively by an analog amplifier with a low-current low-impedance preamplifier, to keep the RC constant small. Moreover, small R can be realized if the output current of the semiconductor detector is large due to using a sufficiently high electron probe current. For instance, the record of compositional contrast without loss of resolution and with the detection and amplifier system perfectly stable, the electron-probe current of order 10^{-10} A can be used. Small C values are obtainable by using a small detector area and by increasing the width of the depletion layer by reverse biasing. Commercial solid state detectors have a low time constant (less than 20 nanoseconds) They can be used for both TV and slow scan imaging.

Example of applications

The semiconductor detector can be utilized for all kinds of information available from backscattered electrons. In the SEM they can be used for imaging the morphology and topography of a specimen surface, and magnetic domain and channeling patterns from crystalline specimens (Stephen et al., 1975; Reimer, 1985). Moreover they can provide quantitative information about the mean atomic number of compounds (Ball and McCartney, 1981; Hermann and Reimer, 1984), and thin film thicknesses of self supporting films and thin layers on substrates with different atomic numbers (Niedrig, 1978; Hunger and Rogaschewski, 1986). They are also a very good tool for surface topography reconstruction (Lebiedzik, 1979; Carlsen, 1985).

All kinds of information are always modified by the detection system used. The variation of output signal from a backscattered electron detector is a function of three major factors, (a) the number and angular distribution of BSE; (b) the energy of backscattered electrons; and (c) the collection efficiency of the detector. The two factors results from interaction of the electron beam with the specimen and are characteristic for the investigated material. The third factor includes the solid angle and collection and the detection properties of the detector. The solid angle of detection depends on detector size (its area) and the distance from the specimen. In general two types: large and small solid angle detectors can be distinguished.

The detection properties of semiconductor detector can be described by:

- the threshold energy, i.e., the minimum energy of detected incident electrons. Because this energy is usually of the order of a few keV, it means that the detector is directly recording BSE, while secondary electrons are absorbed in the front layer.

- the current gain which is proportional to an electron energy, i.e., high-energy BSE contribute to the signal with larger gain.

Compositional contrast imaging or mean atomic number measurements are the main application of BSE in SEM. A contrast C_m, defined as the ratio of output detector signals from two different materials. is proportional to the ratio of BSE coefficients and the ratio of the mean energies of BSE for these materials.

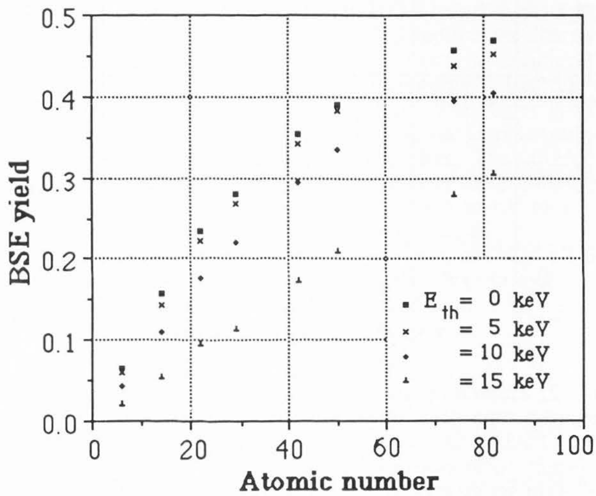

Fig.4. Monte Carlo calculation of backscattered electron yield as a function of atomic number for different threshold energy E_{th} of detection.

The BSE yield increases monotonically with an increase of atomic number of elements or mean atomic number of compounds, when topography and other effects have been eliminated. Because the energy distribution of BSE is nonuniform, the BSE detector output versus atomic number is different from the shape of the η=f(Z). An energy filtration of low energy BSE by a "dead layer" of the detector decreases the number of BSE reaching the active volume of detector. Fig. 4 shows Monte-Carlo calculation of η vs. atomic number for various threshold energies E_{th} of detection from primary electrons energy E_o = 20 keV. The curve becomes more linear for higher E_{th} and for E_{th} = 0.75 E_o BSE yield is almost proportional to Z. Atomic number contrast increases also with energy filtering. The effectiveness of material contrast improvement is compared in Table 1, which shows the ratio of η for various materials (Cu, Mo and Pb) to η from silicon for various E_{th} calculated from Fig. 4. The atomic number

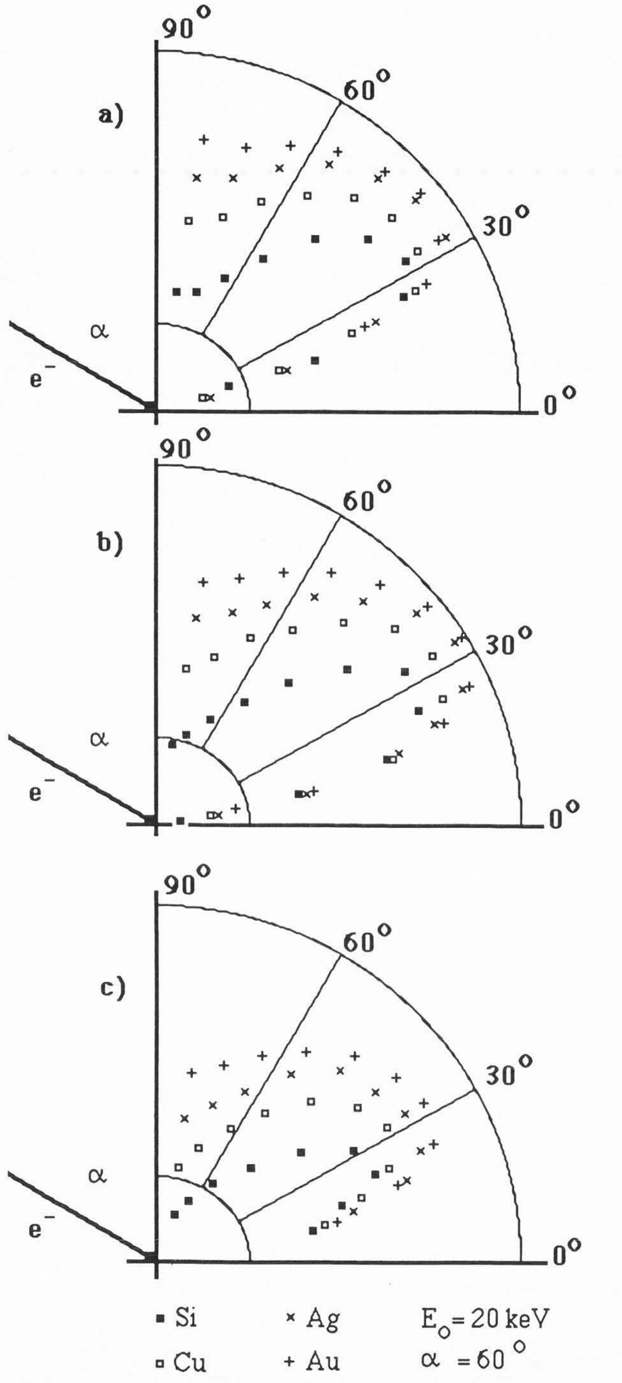

Fig.5. BSE angular distribution for different materials measured by semiconductor detector with a) 2 keV, b) 7 keV and c) 12 keV threshold energy.

contrast increases slightly for E_{th} = 5 keV, which is a typical value for SSD, and can be improved when the threshold energy will be higher than 10 keV, i.e., 0.5 E_o.

As mentioned, the output signal of a BSE semiconductor detector is proportional to a mean energy of the BSE. As shown for example by Darlington (1975) and Kulenkampf and Rüttiger (1954) the mean energy E_m and the most probable energy E_p of BSE increase with an increase in atomic number. It means that an atomic number contrast from two materials with $Z_1 > Z_2$ is enhanced by the factor E_{m1}/E_{m2} in comparison with contrast following from $\eta = f(Z)$ curve. Table 2 gives the calculated ratio of E_m from Cu, Mo and Pb to E_m from Si for different threshold energies of detection. The ratio decreases as E_{th} increases and is close to 1 for all materials at the highest threshold energy.

Table 1. The ratio of detected BSE coefficient η from Cu, Mo, and W (E_o = 20 keV).

Eth	0 keV	5 keV	10 keV	15 keV
$\eta Cu/\eta Si$	1.77	1.85	2.02	2.18
$\eta Mo/\eta Si$	2.03	2.24	2.47	3.24
$\eta Pb/\eta Si$	2.94	3.15	3.71	5.66

Table 2. The ratio of mean energy E_m of detected BSE from Cu, Mo and Pb to mean energy of detected BSE from Si for various threshold energy E_{th} of detection (E_o = 20 keV).

E_{th}	0 keV	5 keV	10 keV	15 keV
E_m(Cu/Si)	1.12	1.06	1.03	1.01
E_m(Mo/Si)	1.17	1.11	1.08	1.01
E_m(Pb/Si)	1.26	1.19	1.12	1.03

The above data assume that all BSE electrons are detected. The precise value of contrast can be calculated if the energy distribution of BSE and detection properties are known (Radzimski, 1983). The quality of information about Z contrast depends on the collection efficiency of the detector. To obtain an efficient detection the detector should cover as large a solid angle as possible. This can be achieved by placing a large detector close to the beam and specimen. For this purpose an annular detector is particularly attractive as the sensitive area surrounds the central hole through which the primary beam is directed. By standardizing the output of such a detector at two known positions, the detector output can be calibrated directly in terms of an atomic number factor.

The same requirements from the point of view of detection have to be fulfilled when a BSE detector is used for thin film thickness measurements. The linear increase of η with increasing thickness (Niedrig, 1978, 1982; Hunger and Rogaschewski, 1986) can be used to measure the latter and record thickness profiles from areas as small as defined by electron beam penetration to as large as the sample that can be mounted in the SEM chamber and scanned by the beam. The semiconductor detector, as a high pass energy filter, limits the range of measurable thicknesses but increases sensitivity, because most scattered electrons from thin films have high energy.

The other range of SSD application is topography imaging or topography reconstruction. Results pertaining to the lateral spread, energy distribution and change of topographic contrast with the energy loss of the emerging BSE and increasing electron penetration show according to George and Robinson (1976) that most of the topographic information is contained in the BSE which have lost less than 3 keV energy. These electrons comprise 30% to 60% of the total number of BSE from the specimen, depending upon beam proximity to an

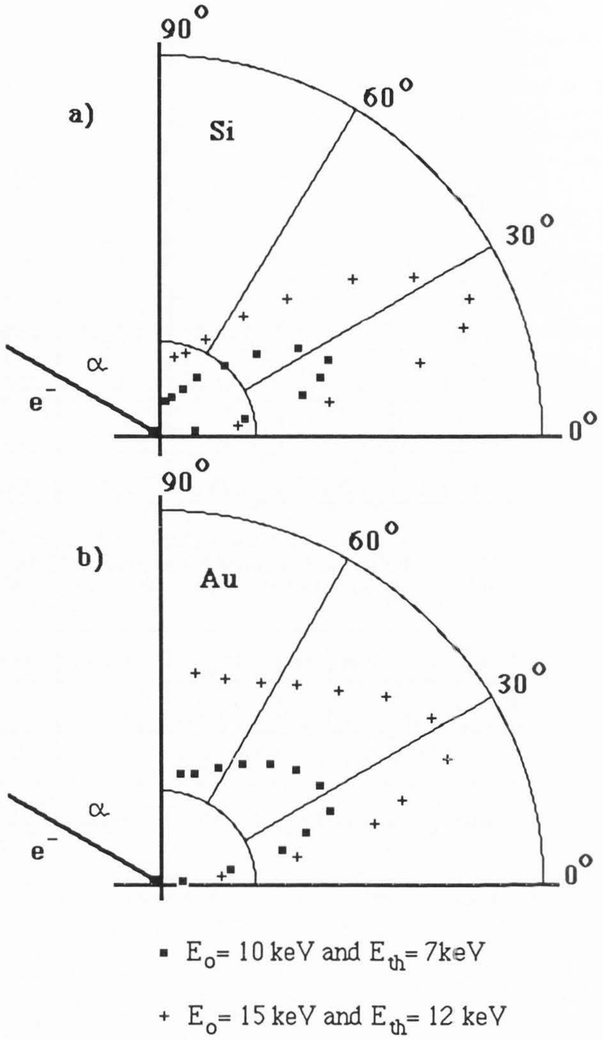

Fig.6. BSE angular distribution for a) silicon and b) gold measured by semiconductor detectors with 7 keV threshold energy for 10 keV and 12 keV threshold energy for 15 keV primary electrons.

edge. An improvement in topographic contrast could be achieved by excluding those BSE which had lost more than a few keV energy i.e., those diffusely scattered in the specimen. The SSD can be a useful tool for this purpose. The angular distributions of BSE (Fig. 5), measured by moving a small semiconductor detector with various threshold energy around the specimen, become sharper for highly deflected electrons, especially for targets with low Z, due to filtering of diffusely scattered electrons. The data presented in Fig. 5 were obtained with p-n junction detectors with current gain vs. electron energy curves as shown on Fig. 2b, i.e., with threshold energies equal to about 2, 7 and 12 keV. For a 20 keV electron beam only part of the diffusely scattered electrons in the specimen are absorbed in the front "dead" layer of the detector. The more directional distributions, also for high Z materials, were measured when the ratio E_{th}/E_o becomes higher (Fig. 6).

Topographic contrast can be obtained by using one small solid angle detector placed at the side of the electron beam for a tilted specimen. It should be pointed out that such a detector placed near the beam (i.e., at high angle above the surface) gives mostly compositional contrast (Reimer et al., 1979). Another method of surface topography imaging, the most popular in the commercial SEM, is signal subtraction with a two detector system at normal electron beam incidence (Kimoto and Hashimoto, 1966). The latter system can also be used for topography reconstruction of the surface along the line paralleled to the line connecting the detectors (Reimer, 1985). The three dimensional reconstruction requires four detectors placed above the specimen around the electron beam (Carlsen, 1985). Because SSD's can be built in various shapes and they occupy little space in the SEM chamber, that is why these detectors are so often used for this application.

The information depth of a normal BSE image is large, of the order of half the electron range. Structures at progressively greater depths below the surface are increasingly blurred due to the broadening of the primary electron beam by multiple scattering and electron diffusion. BSE scattered at greater depths travel along longer paths and hence lose more energy. Energy filtering of low-loss electrons is therefore, a method of decreasing the information depth. By using a high-pass filter which transmits only electrons with energy losses below a few hundreds of eV's, the information depth can be decreased to that of SE, namely by the order of a few nanometers (Lin and Becker, 1975). The most effective method of reducing the information depth and increasing the resolution and contrast of BSE images is the selection of low-loss electrons (LLE) with a retarding filter spectrometer. The contrast of LLE image can be even better than that of SE because SE excited by BSE are not recorded. Moreover, thanks to energy filtering the depth resolution may be improved as was confirmed experimentally (Wells, 1979).

This is also advantageous for the recording of electron channeling patterns, or for observation of type-magnetic contrast. The channeling contrast is generated inside a thin surface layer of the order of thickness equal to the absorption length. Lattice defects like the strain field of dislocations or phase shift of stacking faults influence the propagation of Bloch waves. For bulk specimens the channeling contrast is weaker owing to a strong background of multiple and diffusely scattered electrons. The BSE coefficient changes only on the order of a few percent as a result of channeling. According to Newbury et al. (1986), the energy filtration of electrons which have lost more than 100 eV of energy results in channeling contrast of 25% compared to 1.3% when the complete energy spectrum of BSE is utilized. To obtain this range of energy filtration the semiconductor detector has to be combined with an additional energy filter, for example a retarding field spectrometer (Morin et al., 1979). To obtain good contrast, the BSE detector should cover a large solid angle when rocking beam or rocking specimen methods are used. In the case of a stationary electron beam, small solid angle detectors are used. In both cases the detectors should have a threshold energy as high as possible.

The observation of type-2 magnetic contrast needs a relatively high electron probe current to reveal contrast of less than 0.5% with a good signal to noise ratio. An increase of this contrast can be obtained by employing an SSD because the signal is proportional to the BSE energy and most of the BSE contributing to contrast have lost less than 20% of their initial energy (Newbury et al., 1986).

Among other applications of SSD in electron beam devices is registration mark detection in electron beam lithography, which is somehow related to topographic imaging of a surface (Lin et al., 1982; Kaczmarek and Radzimski, 1983). The small detector shaded by a very thin wire or sharp edge can also be used for electron beam current distribution measurements or testing SEM quality parameters (Maternia et al., 1984; Reimer et al., 1979).

Conclusion

The range of presented applications shows that the semiconductor detector is a useful tool for BSE detection in SEM. In most cases the detector gives a good contrast and resolution, due to filtering of low energy electrons in their non-active surface layer and because the current gain of the detector is proportional to the energy of incident electrons. The solid state detector can also be successfully utilized to obtain quantitative information about the investigated specimen. Recent advancement in semiconductor technology allows the fabrication of detectors with controllable current gain vs. electron energy curves. This means that the detector parameters can be optimized for certain application in electron beam instruments, and can be an attractive tool for commercial SEM's.

Acknowledgements

The author wishes to thank J. Russ for the Monte Carlo simulation of backscattering and for helpful discussions.

References

Ball M D, McCartney D G. (1981). The measurement of atomic number and composition in an SEM using backscattered detectors. J. Microsc., 124, nr 1, 57-68.

Carlsen I C. (1985). Reconstruction of true surface-topographies in scanning electron microscopes using backscattered electrons. Scanning, 7, 169-177.

Darlington E H. (1975). Backscattering of 10 to 100 keV electrons from thick targets, J. Phys. D: Appl. Phys., 8, 85-93.

Gedcke D A, Ayers J B, Denee P B. (1978). A solid state backscattering electron detector capable of operating at TV scan rates. Scanning Electron Microsc. 1978; I: 581-584.

George E P, Robinson V N E. (1976). The dependence of SEM contrast upon electron penetration. Scanning Electron Microsc. 1976; II: 17-26.

Hejna J, Radzimski Z, Buczkowski A. (1985). Detection system for SEM. Scanning Electron Microsc. 1985; I: 151-156.

Hermann R, Reimer L. (1984). Backscattering coefficient of multicomponent specimens. Scanning, 6, 20-29.

Hunger H J, Rogaschewski S. (1986). A study of electron backscattering of thin films on substrates. Scanning, 8, 257-263.

Kaczmarek D, Radzimski Z. (1983). Signal detection from various shapes of registration mark in silicon. Symp. on Electron Technol. '83, Opt. Acous. Filmtech. Soc.. Budapest, 169-173. (copy available from author)

Kimoto S, Hashimoto H. (1966). Stereoscopic observation in SEM using multiple detectors, in *The Electron Microprobe*. (Eds). T. D. McKinley et al. Wiley, New York, 480-489.

Kulenkampff H, Rüttiger K. (1954). Energie und Winkelverteilung rückdiffundierter Elektronen. Z. Phys., 137, 426-436.

Lebiedzik J. (1979). An automatic topographical surface reconstruction in the SEM. Scanning, 2, 230-237.

Lin Y C, Neureuther A R, Adesida I. (1982). Alignment signals from silicon tapered steps for electron beam lithography. J. Appl. Phys., 53, nr 2, 889-911.

Lin P S D, Becker R P. (1975). Detection of backscattered electrons with high resolution. Scanning Electron Microsc. 1975: 61-70.

Maternia Z, Radzimski Z, Borkowicz Z. (1984). Method of measuring the profile of a fine-focused electron beam by using a semiconductor detector, J. Phys. E: Sci. Instr., 17, 447-450.

Matsukawa T, Shimizu R, Hashimoto H. (1974). Measurements of the energy distribution of backscattered electrons with a spherical retarding field energy analyzer. J. Phys. D: Appl. Phys., 7, 695-702.

Morin P, Pitaval M, Besnard D, Fontaine G. (1979). Electron-channeling imaging in SEM, Phil Mag., A 40, 511-517.

Newbury D E, Joy D C, Echlin P, Fiori C E, Goldstein J I. (1986). *Advanced Scanning Electron Microscopy and X-ray Microanalysis*. Plenum Press, New York and London.

Niedrig H, (1978). Backscattered electrons as a tool for film thickness determination. Scanning Electron Microsc. 1978; II: 841-858.

Niedrig H, (1982). Electron backscattering from thin films, J, Appl. Phys., 53, 15-19.

Oatley C W. (1981). Detectors for the SEM. J. Phys. E: Sci. Instrum., 14, 971-976.

Radzimski Z. (1983). The response of p-n junction detector to backscattered electrons. Scanning Electron Microsc. 1983; IV: 1547-1553.

Radzimski Z, Honeycutt J, Rozgonyi G A. (1987). Minority carrier lifetime analysis of silicon epitaxy and bulk crystal with non-uniformly distributed detects. IEEE Trans. on Electron Devices. In press.

Reimer L, Volbert B, Bracker B. (1979). STEM semiconductor detector for testing SEM quality parameters. Scanning, 2, 96-103.

Reimer L, Popper W, Brocker W. (1978). Experiments with a small solid angle detector for BSE. Scanning Electron Microsc. 1978; I: 705-710.

Reimer L. (1985). *Scanning Electron Microscopy*, Springer-Verlag, New York.

Robinson V N E, Cutmore N G, Burdon R G. (1984). Quantitative composition analysis using the backscattered electron signal in a scanning electron microscope. Scanning Electron Microsc. 1984; II: 483-492.

Shimizu R, Ikuta T, Murata K. (1972). The Monte Carlo technique as applied to fundamentals of EPMA and SEM, J. Appl. Phys., 43, 4233-4249.

Siekanowicz W W, Huang H C, Enstraom R E., Martinelli R U, Ponczak S, Olmstead J. (1974). Current gain characteristics of Schottky barrier and p-n junction electron beam semiconductor diode. IEEE Trans. on Electron Devices, ED 21, 691-702.

Stephen J, Smith B J, Marshall D C, Wittam E M. (1975). Application of a semiconductor backscattered electron detector in SEM. J. Appl. Phys., 8, 607-610.

Wells O C. (1979). Effect of collector take-off angle and energy filtering on the BSE image in the SEM. Scanning, 2, 199 -216.

Wilson S R. (1986). Present status of ion implantation and rapid thermal processing in the fabrication of integrated circuits. In *Semiconductor Silicon 1986*, (eds.) H. R. Huff, T. Abe, B. Kolbesen. The Electrochemical Society, Pennington, NJ. 621-641.

Wolf E D, Everhart T E. (1969). Annular diode detector for high angular, resolution pseudo-kikuchi patterns. Scanning Electron Microsc. 1969: 41-44.

Discussion with Reviewers

P S D Lin: What are "commercial solid state detectors"? Who sells them and what are their typical specifications?

Author: Commercial solid state detectors are the detectors especially constructed for BSE detection in SEM and are very often mounted as a standard detector in commercial SEMs (for example by JEOL, Hitachi,etc.). Some companies, such as GW Electronics (Norcross, GA) or EG & ORTEC (Oak Ridge, TN) also manufacture SSDs as optional detectors for various types of microscopes. In addition to these commercial detectors, a simple photodiode can work as BSE detector when the protective window is removed. SSDs are specified by diode structure, range of active area, range of active thickness, threshold energy and sometimes by atomic number resolution.

P S D Lin: The use of metal-silicide as contact metal for surface barrier detectors is a very interesting development. Please explain in some detail how to form and anneal the silicide. Can aluminium be used as contact metal?
Author: More than half of the elements in the periodic table react with silicon to form silicides. For example on n-type silicon Pt, Pd, Rh, Ti, Cr and Hf can be used to form silicide Schottky barriers. Silicides are formed by sintering a thin-film metal deposited on a silicon wafer surface. Depending on the metal the sintering temperature varies from 400^o to 1000^{o}C. Usually a thin metal layer is deposited over the patterned silicon oxide and then sintered. Unreacted metal on the oxide, oxide walls, as well as in the window is then etched away. A good review of silicide technology can be found in "Silicides for VLSI Applications" by S P Murarka published by Academic-Press, Inc., Orlando, 1983. Aluminium does not form silicide. It can be used only as a metal contact to the silicide.

V N E Robinson: Can you briefly describe suitable dopants and procedures to produce p-n junction silicon diodes?
Author: I understand that this question is related only to silicon diodes with shallow junctions. Ion implantation is a well established technique for forming shallow junctions. The implantation energy and dose is selected on the basis of junction depth desired. Shallow n^+-p junctions are normally formed using arsenic implantation. As an example for 0.2 µm junction depth, the implantation could be carried out at 50 keV at a dose of about 5×10^{15} cm^{-2}. Then the dopant is activated either by rapid thermal anneal (1000^o-1050^{o}C for 10-20 sec) or furnace anneal (800^o-900^{o}C for 30-60 min). Shallow p^+-n junction with ~0.2 µm depth is usually formed by implanting boron at 10 to 15 keV with dose 1×10^{15} to 2×10^{15} cm^{-2}. To form a p-n junction in an n-type substrate, boron is used as a dopant, and in p-type substrates phosphorus is often used.

K Murata: Could you describe the minimum beam current required to obtain images with reasonable quality with SSD?
L Reimer: It should be mentioned that the incident current for reducing the time-constant cannot only be increased by increasing the primary beam current but also by increasing the solid angle of collection. Optimum: small area (low C) and low distance (high solid angle).
Author: The minimum beam current as pointed out by Prof.Reimer is not the only factor which influences the image quality. Also important is the solid angle covered by SSD and the primary beam energy. For example, for 20 keV primary electrons and an annular detector placed below the polepiece near the sample, images with good atomic number resolution can be obtained for beam currents of the order of tens to hundreds pA depending on the sample.

V N E Robinson: Although increasing the threshold energy increases the sensitivity of the detector to changes in atomic number, your Table 1, it should also be pointed out that such an increase is only achieved with a lowering of the total signal to noise characteristics of the detector. As such, the detector is generally less sensitive to changes in atomic number. That has been my experience. Can you show any examples where the detector can detect smaller differences in atomic number using higher threshold energy?
P S D Lin: What is the optimum threshold energy for maximum atomic number contrast and for the best linearity?
Author: Energy filtering always decreases the total input signal and thus increases the signal to noise ratio, which at certain level may be not acceptable. Increasing the threshold energy by increasing the "dead layer" thickness decreases significantly the current gain of detector because not only the number of BSE is decreased but also their effective energy when they reach the active region of the diode. Another way of increasing the threshold energy is to use a low threshold energy (high current gain) semiconductor detector coupled with a retarding field analyzer. In such a system an increase of retarding potential cuts off the low energy BSE which slightly influence the output signal of semiconductor detector. The input from high energy BSE remains unchanged. This system will have better resolution in comparison with SSD with a wide "dead layer". I am now working on such a system, and I hope to present the experimental data, which can be compared with those in Table 3 in the near future. The theoretical data obtained using Monte-Carlo calculations show that the optimum threshold energy for maximum atomic contrast and for the best linearity is equal to about 70% of the primary beam energy. It should be mentioned however that such high threshold energy decreases the input signal of the detector to about 25 to 35% of the total BSE signal for low Z materials and about 40 to 55% for high Z materials.

K Murata: The atomic number contrast depends on detection angle as seen in Fig.5. Are the optimum detection angle, incident beam energy and detector condition established to obtain the best Z contrast?
Author: To obtain the best atomic number contrast the detection system should cover as wide a solid angle as possible. An annular detector placed below polepiece with low stage distance will be optimal for this purpose. The primary electron beam energy should be as high as possible when SSD is used. The output signal depends strongly on the energy of BSE. One should remember that below 10 keV the Z contrast due to BSE coefficient decreases, so this range of electron energy is not suitable for Z contrast even if another type of BSE detector is used.

K Murata: I understand the effect of X-ray photons on signals is very small. But when you have a thick metallic layer on the detector, is it still negligibly small from a point of view of signal to noise ratio especially for heavy element samples?
Author: Yes, it may influence the signal to noise ratio if the metallic layer is a few microns thick. As a result, the current gain of the detector will be very small. To maintain the high gain a thin metal layer, such as 200Å to 300Å of Au, is used to form the Schottky diode.