

# Backscattered Electrons in the SEM

Eli Napchan, Department of Materials, Imperial College, London, UK

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## INTRODUCTION

The interaction of an electron beam with a target material, for example in a SEM, results in a large number of externally observable signals such as secondary, Auger and backscattered electrons, X-ray emission, cathodoluminescence (emission of photons from luminescent materials) and EBIC (electron beam induced current). Measurement and analysis of these signals is used to derive information about the specimen and about its behaviour under electron beam bombardment.

As the electrons travel inside the specimen it is useful to describe their interactions as consisting of either elastic or inelastic scattering events. Elastic events are broadly associated with nuclear scattering, in which the electrons change their direction of travel without a significant energy loss. Inelastic events produce excitation of atomic electrons, and are assumed to result in some energy loss but no change in direction. Some inelastic events result in the generation of secondary and Auger electrons, both characteristic and Bremsstrahlung X-rays and light emission known as cathodoluminescence.

Backscattered electrons (BSE) are those electrons from the incident electron beam that underwent a series of elastic scattering events that reverse their travel direction and cause them to be emitted from the top surface of the specimen. Some of the interesting BSE properties are: their energy and angular distributions, their depth of generation and lateral spread, the incident beam energy and tilt dependence. This article will discuss various BSE properties, present methods of electron scattering calculations applied to the study of backscattering, in particular those based on Monte Carlo simulations, and will present some of the experimental results and data available. Finally, some applications for BSE signals will be discussed.

## PROPERTIES OF BSE

Figure 1 shows the energy (relative to the incident beam energy) distribution of electrons emitted from a solid specimen. At the low end of the energy axis are the secondary electrons with energies in the tens of eV, while the BSE have energies up to the beam incident energy and show a typical peak that varies depending on the atomic number of the sample material. The increase in the fraction of faster BSE with target atomic number can be seen as linked to the general increase in BSE coefficient with increased  $Z$ , as shown in Fig. 2, and forms the basis for the common use of backscattered electrons for composition imaging.

The backscattered electron coefficient ( $\eta$ ) is a simplified parameter used to quantify the

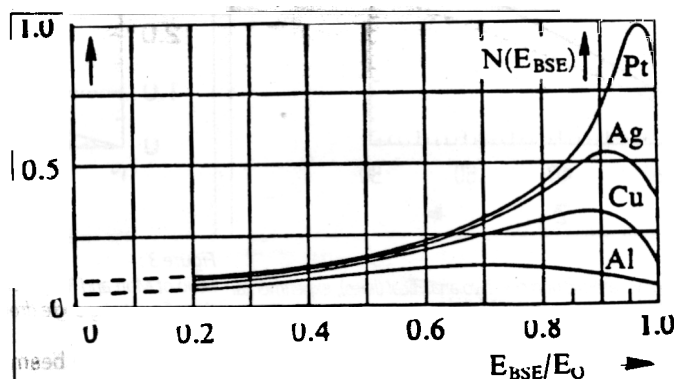


Figure 1: Energy spectrum of BSE from various materials at normal incidence and for incident beam energies in the 20-40 keV range (from [11])

number of electrons emitted from a specimen, and which usually have energies comparable to the energy of the primary beam (but the energy range is never specified). The BSE coefficient variation with primary beam energy and/or incidence angle for a specific material is also of interest, in particular for low  $Z$  numbers and low beam accelerating voltages. See for example [1] for studies of BSE emission from carbon in which an increase in BSE coefficient for low energies has been experimentally measured and calculated.

Other interesting BSE properties are their angular distribution with respect to the original beam incidence direction, their lateral spread, and the depth in the specimen from which electrons can backscatter. The angular distribution of the BSE as they emerge from the top surface of the specimen covers a 180 degree solid angle, but the amount actually detected as part of the BSE signal depends on the geometry and mechanism of collection of the detector used. The depth distribution and the lateral spread are dependent on the selection of the beam tilt and accelerating voltages, and will determine the technique's spatial resolution.

Observed BSE signals can be difficult to interpret when investigated under special conditions, such as multilayer specimens, adjacent materials, non-trivial beam accelerating voltages and tilt. The study of electron backscattering has advanced hand in hand with analytical methods based on Monte Carlo simulations, which in many cases benefit from experimental data to create more accurate models, which in turn prompt further experimental investigations.

## MONTE CARLO (MC) SIMULATION METHODS

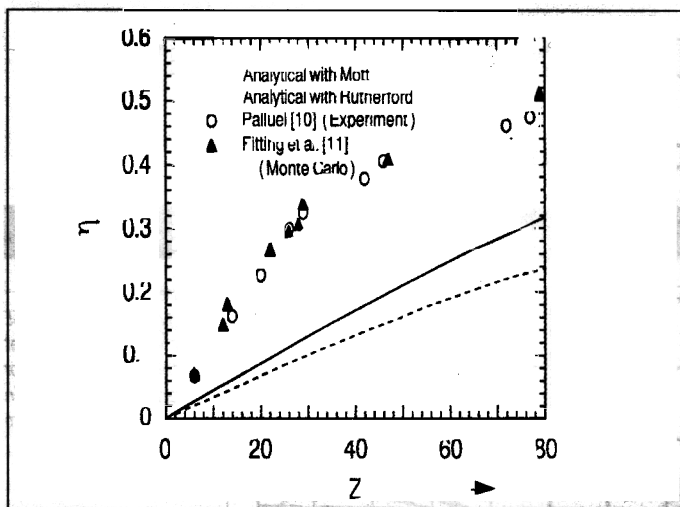
The modelling of electron scattering in a solid specimen by the Monte Carlo method is based on a detailed and stepwise calculation of electron position, direction and energy after a series of scattering events for a statistically large number of electrons representing

the primary electron beam. The trajectory and scattering calculations start from the original incidence position and continue until either the electron leaves the specimen or it reaches a sufficient low energy that does not result in significant changes to its position.

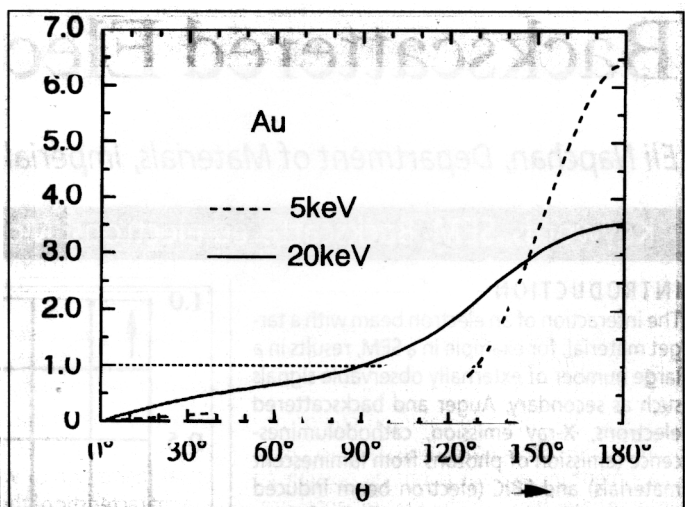
Various MC models have been used for many years for various analytical purposes. They differ in their approach to the treatment of electron elastic and inelastic scattering, and in methods used in dealing with the experimental conditions and specimens to be simulated. Ultimately, they are expected to generate data related to particular measurable signals, and to do it at a reasonable calculation speed.

Two options widely used for handling the elastic scattering process are based on the Rutherford (based on the Born approximation for the specimen atom) and the Mott (based on the exact solution of the wave equations for the electrons) cross section. The advantage of the former is its simplicity and thus computation speed, while the latter provides in general a better fit to a wider range of experimental conditions.

Figure 3 shows a comparison between the Mott and the Rutherford cross sections, normalized to the Rutherford cross section as a function of the elastic scattering angle, for a gold specimen at different beam accelerating voltages. When both cross sections are the same, the normalized value becomes 1.0. It can be seen that for high scattering angles the Mott cross section becomes many times larger than the corresponding screened Rutherford cross section; the lower the beam energy the larger the difference. It is this difference in the large scattering angles that results in increased values for the backscattering coefficient for the Mott cross section, and which in some cases dictates the physics needed in the simulation depending on the experimental conditions and materials. This can be clearly seen in Fig. 2, where along the experimental values appear results from two analytical expressions based on the two different cross sections. Other data plotted in this figure show the



**Figure 2:** Backscattered electrons coefficient vs. atomic number. Two analytical (lines), experimental and Monte Carlo (at 16 kV) results are compared (from [12])



**Figure 3:** Ratio of Mott and Rutherford cross-sections for Au at 5 and 20 kV beam voltage, as function of scattering angle (from [12]).

good agreement obtained between the reported experimental values and corresponding results from a specific Monte Carlo simulation program (references in the figure caption).

A compromise between the use of the screened Rutherford elastic cross section and the tabulated Mott cross sections in MC simulations has been proposed in [2], where empirical forms for electron/atom scattering cross sections have been prepared. Predicted BSE coefficients for low to medium incident beam voltages (0.1 to 30 kV) and high atomic number targets compare well with those calculated using the full Mott tabulations, and have the advantage that computational speed is closer to those based on the Rutherford cross section.

A fast MC simulation program has been written and modified over the years (see full description in [3] and various references there), which allows for multi-material and multilayer specimens, at varying beam tilting and voltage conditions. The calculated data can be BSE, secondary and transmitted electrons, CL and EBIC signals, and various forms of beam energy dissipation in the specimen such as depth dose and 3D energy dissipation values. For increased calculation speed and use as an almost real-time tool, the physics used in the calculation has been selected to be broadly applicable to the experimental conditions along with optimised (simplified) approaches to elastic and inelastic scattering, for particular experimental conditions, as in [1].

An example of some output produced by this simulation can be seen in Fig. 4 (a) and (b). The specimen is a flat silicon wafer, observed at a beam tilt of 70 degrees and an accelerating voltage of 10 kV (conditions used for backscattered electron diffraction work). The simulation took a few minutes to run for 3000 incident electrons, and generated data about angular, energy and positional information for each backscattered electron. The figures show statistics about the depth of generation of the backscattered electrons, and their lateral spread (exit positions) relative to a plane con-

taining the specimen normal and the beam incidence direction.

### BSE IMAGING

The strong dependence of the BSE coefficient on mean atomic number is utilised for imaging in the SEM, where resulting pixel intensity is a function of atomic number: higher atomic number materials result in brighter pixels. This has proven to be a useful method for analysing mineral distribution in bone samples [4,5] where the absolute value of the BSE coefficient is linearly related to the bone's mineral content. The light elements (primarily C, N and O) which compose the organic fraction of bone have at a beam voltage of 20 kV a much smaller coefficient ( $\eta$ ) than the mineral phase rich in Ca, allowing the derivation of relative quantitative methods for measurements of mineral content.

A further example of the application of BSE in life sciences can be found in [6]. In this work computer controlled stage movement was coupled to low magnification BSE imaging and high magnification EDX analysis to identify metal particles (from metal artificial joint or implant debris) in samples from tissues remote from the implant. The tissues selected were those likely to concentrate particles due to their normal haematological filtering roles, such as lymph nodes, liver, and splenic specimens. High atomic number particulates from implant debris (such as Ti, Cr and Co) are brightly imaged at 30 kV beam voltage when referenced to an Al standard.

Monte Carlo simulation can be used for image simulation of BSE signals, as done in [7]. The rapid increase in computer speed allows for the analysis of complicated structures in a three-dimensional approach using image simulation similar to the actual scanning procedure. The concise definition of electron trajectories and backscattering parameters allows not only the investigation of complex multi-material device structures, but also the study of a solid-state detector electrical and angular characteristics and the effect of the electron beam dimensions on the generated image.

Typical applications include automatic and accurate stage positioning for mask writing in electron beam lithography systems.

Another example of BSE imaging where the detector is taken into consideration can be found in [8]. A system of two opposite Everhart-Thornley detectors has been used at different operating conditions to obtain various combinations of BSE and secondary electrons signals. This technique was used successfully in low voltage SEM work (below 5 kV), where the decreasing information depth with decreasing beam energy allows for increased sensitivity in surface features observation, both related to material and topographic contrasts. As in the previous example, the intricate experimental technique has been combined with the simulation by MC methods of the expected signals to allow the understanding of the contrast mechanisms involved.

### EXPERIMENTAL DATA

Since the discovery of the electron and of its backscattering from solid specimens, a large number of papers have been published with experimentally measured data on the various aspects of electron-matter interaction, including backscattered electron yields. To ease the finding of such data for a particular material and experimental conditions David Joy has started an Internet-accessible database [9] containing several thousands of values of directly measured experimental results, both for elements and for compounds. These data come from many of the published reports since 1898 to about 1998, and is being extended as additional values are reported in the literature.

In this database no judgement has been made about the quality of the data leading in some cases to a wide spread in reported values. One possible reason for this could be the inherent differences in the experimental conditions used. A measurement carried out in a UHV chamber with in situ cleaning and baking facilities will be more 'reliable' than a similar experiment carried out in a typical SEM, but the later type of result is more representative

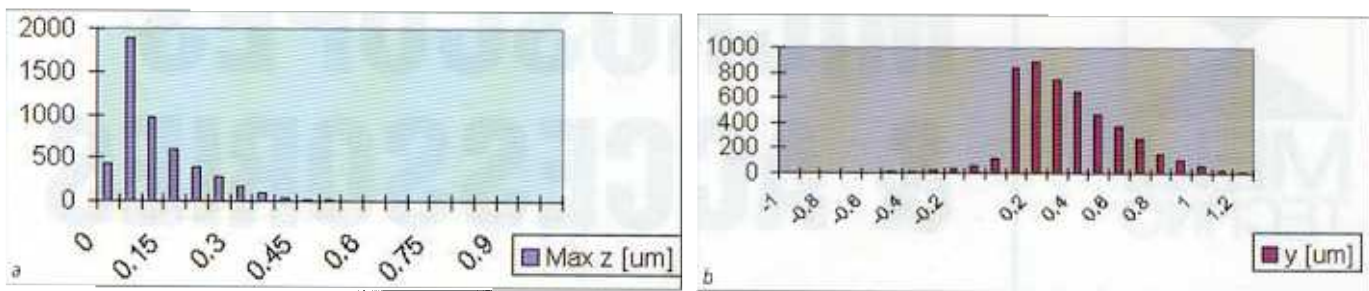


Figure 4:

Statistical distribution of backscattered electrons at 10 kV from a silicon specimen under 70 degrees beam tilt. Results obtained with the Monte Carlo simulation program described in [3]. (a) Depth generation of backscattered electrons: most BSE come from depths between 0.05 to 0.15 microns. (b) Lateral spread of exit positions of the backscattered electrons. Data are in the direction normal to the plane of beam incidence and the specimen normal.

of conditions found in common microscopy work. As the number of reported data for each experiment increases it might be possible to differentiate between the experimental procedures, and also to remove values that fall outside acceptable ranges.

An attempt to explain the reasons for the variations in the available experimental data and thus the poor fitting to MC simulation results has been done in [2]. BSE coefficients ( $\rho$ ) for ( $\eta$ ) gold under beam accelerating voltages in the 0.1 to 5.0 kV range were calculated for a perfect surface and for various 'not so ideal' surface conditions: a surface contaminated with an 'oil like material' (as a multi-layer specimen), a surface with close packed 10 nm V grooves, and a surface with 10 nm deep and wide stepped lines. Some of the results are shown in Fig.5, which is a comparison between a clean surface and one contaminated with a 2 nm layer, and between the same perfect clean surface and surfaces that have different 10 nm topographical features. The calculations show that BSE coefficients can be strongly influenced by the state of the surface, with ratios up to 2 at about 1 kV, and that the surface effects become less significant as the beam voltage approaches 5 kV.

To ease the visualisation of the data in the Joy database allowing the spread in values for each material at each accelerating voltage to be seen graphically, the author has processed the original data and produced graphical plots [10] of the backscattering (and also secondary) electrons results. These can be viewed and copied on-line.

As discussed in the previous MC simulation section, the backscattering data are of particular importance for testing the various simulation models, being in some cases both the starting point for the construction of a Monte Carlo model and for testing it. Another use for experimental elemental backscattering data is for the estimation of the BS coefficient for compounds, assuming that the yield for the compound can be calculated from the BS coefficient and the atomic fraction of the elements that form it (Castaing's rule).

## CONCLUSION

Backscattered electrons are one of the signals resulting from the interaction of an electron beam with a specimen which can be measured in a SEM, and for which analytical models can

be used to match the experimental data. They can be measured as part of clearly defined experiments, which will produce results that are characteristic of the specimen under observation interaction with the electron beam. In many cases, the ease of simulation of BSE allows the creation and verification of models, which can then be applied to the study of other SEM signals. A large and growing body of experimental data related to different materials already exists in a structured manner, which can be used for experiment design and model testing.

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Author's details: Dr Eli Napchan, Dept. of Materials, Imperial College of Science Technology and Medicine, London SW7 2BP, England. Tel: +44 (0) 973 106465, Fax: +44 (0) 780 7061102.  
Web: [www.napchan.com](http://www.napchan.com),  
Email: [eli@napchan.com](mailto:eli@napchan.com) or [eli@ic.ac.uk](mailto:eli@ic.ac.uk)  
Correspondence address: DLM Enterprises, 22 Broomsleigh St, London NW6 1QH, England

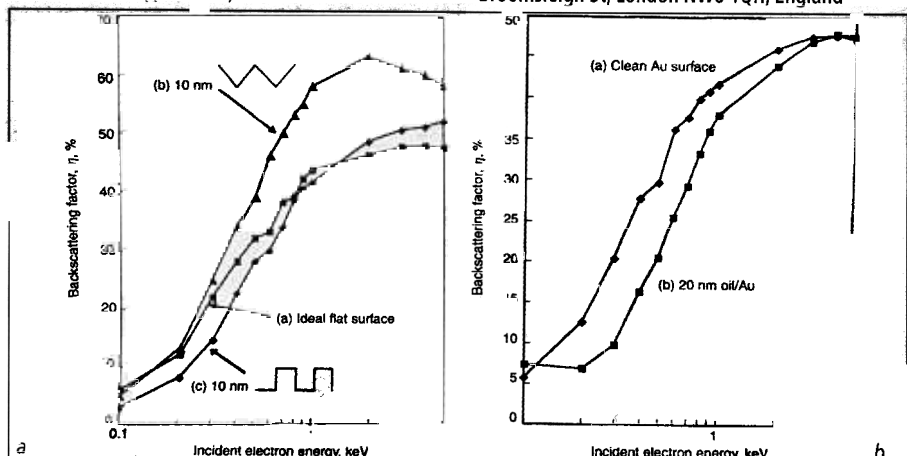


Figure 5:

Comparison of surface effects on the Monte Carlo simulation calculated values of the backscattering coefficient for gold at accelerating beam voltages in the 0.1 to 5.0 kV range (data from [2]). (a) Comparison between an ideal flat surface and surfaces with topographical features of 10 nm size. (b) Comparison between a clean surface and one with a contamination layer of 2 nm of oil-like material (possibly found in low vacuum SEMs) with average atomic weight 2, atomic number 4, and density 1 g/cm<sup>3</sup>

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