Summary

The conventional scanning electron microscope (LVSEM) with thermionic cathodes shows a decrease in resolution for electron energies below 5 keV, due to the decrease of gun brightness with decreasing energy. The use of field-emission or Schottky-emission electron guns in a low-voltage scanning electron microscope (LVSEM) operating with 0.5- to 30-keV electrons allows electron probe sizes of about 1-2 nm with acceleration voltages of 20-30 kV and about 10 nm with 1 kV. The probe size can be reduced for low energies only by a correction of the chromatic lens aberration using a combination of multipoles.

For the detection of secondary electrons (SE) by a scintillator-photomultiplier combination (Everhart-Thornley detector), transverse electric collection fields have to be avoided. Either a Wien filter of crossed magnetic and electrostatic quadrupoles can be used in front of the specimen, or the SE are collected by a through-lens detection system. The latter can also be used as a SE-spectrometer for the quantitative measurement of surface potentials on integrated circuits.

For the detection of low-energy backscattered electrons (BSE), these can be converted to SE at the polepiece, accelerated by about 5 kV in front of a scintillator-photomultiplier combination, or be detected by a microchannel-plate. Semiconductor detectors show a threshold energy about 1-2 keV.

The elastic and inelastic scattering is important for the discussion of electron-specimen interactions and the calculation of signal intensities. The elastic scattering cross-sections of electrons have to be calculated by solving the Pauli-Dirac equation, resulting in Mott cross-sections that show strong differences to classical Rutherford cross-sections. The inelastic scattering has to consider the electron energy-loss spectrum (EELS) of the material, which consists of the unscattered zero-loss peak, plasmon-loss maxima, Compton scattering, and inner-shell ionization edges. For example, the fine structure of the energy spectrum of BSE can only be calculated when these scattering processes are considered in detail. However, for a Monte Carlo simulation of electron trajectories it can be more convenient to use a Bethe stopping power, which has to be modified for energies below 5 keV. The slowing down of electrons by energy losses results in a practical electron range R. Measurements of R with low-energy electrons can also be described by a power law in electron energy E, but with a lower exponent n = 1.3-1.38 for E = 0.5-5 keV than n = 1.43-1.67 for 10-100 keV. For 1-keV electrons we found $R \simeq 10\ \mu g/cm^2$ in units of mass-thickness $x=\rho t$, which results in R = 100 nm and 5 nm for carbon (ρ=1 g/cm^3) and gold (ρ=19.3 g/cm^3), respectively.

The backscattering coefficient η, which is responsible for the BSE signal, increases monotonically with increasing atomic number, but is approximately independent on electron energy for 5-100 keV. However, η decreases for Z>30 and increases for Z<30 below 5 keV. As a consequence, the material (compositional) contrast of BSE is reduced below 5 keV and can even become lower for Z>40 at 0.5-1 keV. Increasing the tilt angle ϕ of the specimen, results in an increase of

η, which is weaker at low energies. For normal electron incidence and high electron energies, the angular distribution of BSE depends $\propto \cos \zeta$ on the angle ζ between exit direction and surface normal. The number of electrons with small ζ increases strongly with increasing Z and decreasing E. The BSE energy spectrum is modified in shape when decreasing the electron energy.

The secondary electron yield δ of secondary electrons (SE) increases with decreasing electron energy and shows a maximum at a few hundred volts. The strong increase of δ with increasing tilt angle ϕ, approximately $\propto \sec \phi$, which is found for high electron energies and causes the topographic contrast, is strongly reduced with increasing atomic number at low energies. At high electron energies, we can distinguish SE1, which are generated by the primary electrons inside a surface layer Λ_{SE} of about the mean-free path of SE, and SE2 generated by BSE passing through this surface layer. At low energies, Λ_{SE} becomes more comparable to the electron range R, and we cannot further distinguish between these two groups in the discussion of SE generation.

Charging of insulating specimens beyond an electron energy E_2, where the total yield $\sigma=\eta+\delta$ becomes smaller than unity, results in a strong negative charging and demands a conductive coating of the specimen. At energies below E_2, positive charging of only a few volts does not deflect the primary electrons, and the specimens can be observed without coating, although rough insulating specimens can still show negative charging, and when in holes not all SE can leave the specimen for charge neutralization. The critical energy E_2 increases with increasing tilt angle ϕ. Different methods have been reported for the measurement of E_2. When an insulating layer on a conductive substrate is penetrated with increasing electron energy, the generation of charge carriers in the insulator results in a surface voltage only a few volts different from the substrate bias. For energies below E_2, a change of the substrate bias causes a change of the surface potential of passivation layers on integrated surfaces. This results in the capacitive-coupling voltage contrast, which decreases in a short time, due to the charge neutralization by SE emission.

Specimen damage is caused by heating, radiation damage by ionization, and contamination. Damage effects are concentrated within the electron range, which means much thinner damaged surface layers at low electron energies. The reduced heating allows the investigation of substances with low melting points. The radiation damage of biological specimens results in a loss of mass and a polymerised carbon-enriched conglomerate, which, however, is also concentrated in a thinner layer at low energies. The increase of ionization probability with decreasing electron energy results in a strong increase of contamination with decreasing energy. Organic molecules deposited from the atmosphere and the vacuum are the main source of contamination. The absorbed molecules can diffuse on the surface and are cracked and cross-linked in the scanned area. The most effective methods for decreasing contamination are specimen cooling below 200 K or ultrahigh vacuum condition. A positive effect of radiation damage is the exposure of resists for submicron lithography. Thin resist layers and short electron ranges for low-energy electrons can be used for increasing the resolution and

proximity effect, or metal deposits can be formed by irradiation of adsorbed metallo-organic molecules. However, the present trend uses 30- to 50-keV electrons and multilayer resist films.

An advantage of SEM is the formation of different signals and types of contrast. The dependence of the SE yield δ on tilt angle ϕ and shadowing effects causes the most frequently used topographic contrast. However, the BSE and the SE2 excited by the BSE can leave the specimen at large distances from the electron probe and causes a diffusion contrast, which, for example, can be seen as a bright zone at edges. Decreasing electron energy decreases the electron range and the width of this zone. Therefore, better topographic contrast can be observed with 2- to 5-keV electrons, although the increase of the SE yield with increasing ϕ is decreased for low energies. Therefore, LVSEM can be better used for the metrology of integrated circuit. However, problems still exist for a quantitative metrology.

As discussed before, the dependence of the backscattering coefficient η on atomic number Z is not monotonic for low energies, and the material or compositional contrast can change for different electron energies, especially when selecting elastically reflected electrons (ERE). Thin coatings of a material with η different from the substrate can be detected with higher contrast, due to the decreased electron range at low energies. The crystal orientation contrast of BSE increases with decreasing energy, but it is disturbed by the stronger contamination.

The magnetic contrast type 1 caused by the influence of the external magnetic stray field on the SE trajectories can be observed at low energies with a better signal-to-noise ratio, due to the increased SE yield. The measurement of external magnetic stray field by the deflection of electrons passing the surface parallel at small distances can be observed with a higher sensitivity.

The lower electron energy in LVSEM allows a better use of retarding field spectrometers. This can be used for the selection of elastically reflected electrons (ERE) or a broader band of low-loss electrons (LLE). With a retarding grid in front of a CCD camera, a low-energy electron diffraction (LEED) pattern can be recorded in ultrahigh vacuum. Filtering the secondary electrons allows detection and measurement of local variations in work function, due to a shift of the maximum in the SE spectrum. The spectrum of Auger electrons can be recorded with a cylindrical mirror analyzer (CMA). When using increasing electron energies and a superposed ac bias at the electrodes of a retarding grid or the electrodes of a CMA, threshold appearance spectroscopies for the backscattered, secondary, Auger, or absorbed electrons, and soft x-rays can be applied. The detection of spin polarization of secondary electrons emitted from ferromagnetic specimens allows us to image and measure the surface magnetization in the uppermost layer.

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About the Author

Ludwig Reimer is Professor at the Institute of Physics of the Westfalian Wilhelms-University of Münster, Germany. He holds a Dr. habil. from the Faculty of Science at the University of Münster. Prof. Dr. Reimer has been working in the field of electron microscopy for 40 years and has written numerous papers in the area of the physics of electron-specimen interactions, interpretation of contrast in images and diffraction patterns, Monte Carlo simulations, specimen preparation methods and detector strategies. He has authored several books on transmission electron microscopy and scanning electron electron microscopy. His current research involves the physics of low-voltage scanning electron microscopy and energy-filtering transmission electron microscopy.