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An Electron Beam Tester with Dispersive Secondary Electron Energy Analyser

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Abstract

The design principles of a new, experimental e-beam tester are described. Using the magnetic field of an immersion objective lens the secondary electrons are guided to an energy analyser between the condenser lenses and the objective lens. The latter can now have a short working distance and small aberrations. The electron energies are analysed by a combination trochoidal motion - retarding field analyser, which enables detection of the faster secondary electrons on one detector and detection of the slower secondary electrons on a second detector. The benefit of this set up is a possibility for voltage contrast isolation, normalization with respect to primary beam current and an improved signal to noise ratio in voltage measurements. The use of a variable axis immersion lens allows a large field of view.

KEY WORDS: e-beam tester, voltage measurements, energy analysis, dispersive analyser, voltage contrast isolation, magnetic parallelizer, variable axis immersion lens, scanning electron microscope.

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Introduction

The basic measurement in an e beam tester is the determination of the shift in the energies of the secondary electrons, as the voltage of the sample changes. The original instrument was a scanning electron microscope with a retarding grid in front of the secondary electron detector, located between the integrated circuit and the objective lens. A recent trend is to guide the secondary electrons back through the last lens to a retarding field analyser between the condenser lenses and the objective lens. This has been accomplished either by a clever combination of electrostatic acceleration and magnetic focusing (Plies and Schweizer, 1987) or by the collimating action of an additional magnetic coil in the bore of the objective lens (Richardson, 1986). The advantage of through the lens detection is the possibility to use a short working distance, resulting in smaller aberrations of the objective lens and thus in a smaller probe diameter with sufficient probe current.

The use of an immersion objective lens with an additional magnetic field in the bore of the lens is instigated by the insight that slow electrons, formed in the strong magnetic field of the lens, will move to more parallel trajectories when entering a region of weaker magnetic field (Kruit and Read, 1983). The weak field can then guide the electrons towards an analyser while hardly disturbing the primary beam. This principle of parallelization was also used by Garth (Garth and Nixon, 1986) to obtain a 100% efficient detection for secondaries in a retarding field analyser, located between the original objective lens and an additional magnetic lens below the test object. Another advantage of the magnetic immersion lens is expected from a reduction of the local field effect. The influence of nearby potentials on the measurement of the point under test consists of two effects: a reduction of the number of electrons actually escaping from the surface and a disturbance of the trajectories thus possibly causing a different detection efficiency. The latter influence is expected to be absent in the magnetic parallelizer instruments. In this paper we shall describe the design of an e-beam tester in which the secondary electrons, created in an immersion objective lens, are guided through the lens to a novel kind of spectrometer in which not only the faster part of the spectrum is detected, as in a retarding field analyser, but the slower part as well. We expect, apart from the advantages of through the lens detection, two additional benefits from this set-up: normalization and better signal to noise ratio.

Several schemes to isolate voltage contrast from topographic or material contrast have been employed (Menzel and Kubalek, 1983). One method is based on comparing the detected signal to the signal obtained when there is no voltage applied, either by switching from one situation to the other at a high frequency (Oatley, 1969) possibly assisted by phase-locked detection (Gopinath and Sanger, 1971) or by frame-by-frame comparison (Fujioka et al., 1982). The second method is based on detecting a part of the secondary electrons before the energy analysis (Rau and Spivak, 1979; Tee and Gopinath, 1977).

The advantages of a dispersive analyser for the signal to noise ratio in voltage measurements are discussed in a separate paper (Dubbeldam and Kruit, this volume).

Principles of operations

Magnetic parallelizer.

Secondary electrons which exit the surface of an object inside a magnetic field B_i with an angle α_i with respect to the direction of $\vec{B}_i$ will move away from the surface in a spiral of diameter:

$$d_i \approx \frac{2mv_i \sin\alpha_i}{eB_i} \tag{1}$$

where V_i is the initial total velocity of the electron. When these electrons move out of the immersion lens into a weaker field B_f the spiral trajectory stretches so as to preserve the magnetic moment of the motion (fig. 1).

Then the angle with respect to the direction of $\vec{B}$ decreases to α_f:

$$\frac{\sin\alpha_f}{\sin\alpha_i} = \sqrt{\frac{B_f}{B_i}} \tag{2}$$

and the diameter of the spiral movement increases:

$$\frac{d_f}{d_i} = \sqrt{\frac{B_i}{B_f}} \tag{3}$$

The primary electrons are focussed on the IC by the same magnetic field which guides the secondaries away. This determines the strength of the magnetic field since, in first approximation:

$$\int B(z)dz \approx \frac{\pi m v_p}{e} \tag{4}$$

where the integral is taken from the last cross-over before the probe forming lens to the IC, and v_p is the primary electron velocity.

For the prototype instrument described later, characteristic values are: a primary beam energy of 1 keV, a $25 * 10^{-3}$ T field region of ~ 7 mm and a $1.5 * 10^{-3}$ T field region of ~ 100 mm. Then the diameter of a 5 eV energy secondary electron beam, that is twice the diameter of the spiral for $\alpha_i = 90^0$, is initially 1.2 mm and widens to 5 mm in the weak B field region.

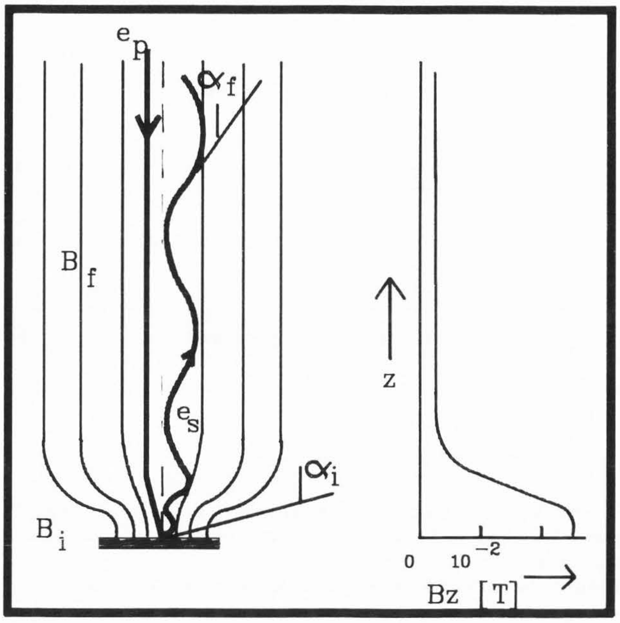

Figure 1. Schematic representation of electron trajectories in the magnetic field of the parallelizer.

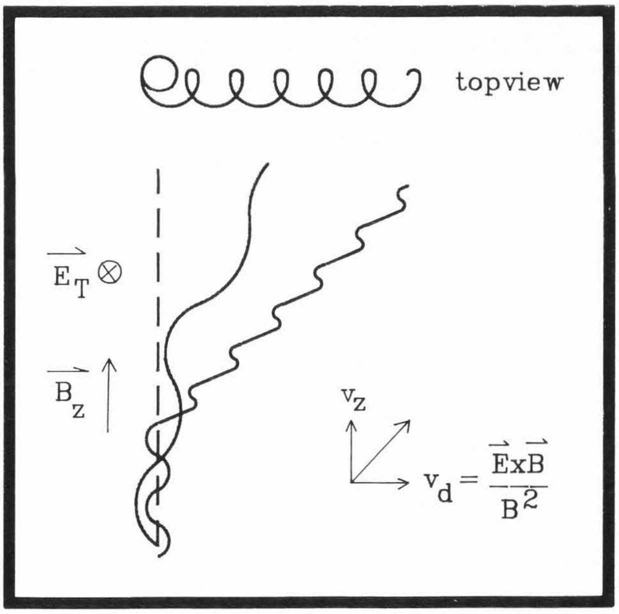

Figure 2. Schematic representation of the trochoidal motion of electrons in the analyser.

Trochoidal analyser

In a crossed magnetic and electrostatic field electrons will drift in a direction perpendicular to both fields with a drift velocity:

$$V_d = \frac{\vec{E}\times\vec{B}}{B^2} \qquad (5)$$

which is independent of the kinetic energy of the electrons. As described by Stamatovic and Schulz (1970) this phenomenon of trochoidal motion can be used as a spectrometer: the spiral in which the electrons are moving in the magnetic field bends away from the B direction with an angle β = arctg v_d/v_z that depends on the velocity v_z of the electron (fig. 2). Although our goal of one detector for the fast part of the secondaries and one detector for the slow part could now be reached by placing two detectors at the end of the crossed ExB field, this would have a disadvantage: a displacement of the secondary electron beam because of scanning would result in an undesirable shift of the energy spectrum on the detectors, thus disturbing the voltage measurement.

By adding a retarding field at the end of the crossed ExB field the slower part of the secondary electrons is reflected and can be detected with a separate detector. The special feature of the crossed ExB field is that the electrons drift in the same direction before and after being reflected (fig. 3). In a $1.5 * 10^{-3}$ T field perpendicular to a 0.5 kV/m electrostatic field, 5 eV electrons will drift away from the axis with an angle $\beta \approx 0.3$ rad. Over a distance of 50 mm the electrons will make about 2 full circles.

Variable axis immersion lens

A conventional scanning system in a system with a magnetic parallelizer has two problems: secondary electrons which are created off-axis will follow the magnetic flux lines as they bend away from axis in the region of the field gradient and may not reach the detector. Also the magnetic deflection field will disturb the trajectories and influence the voltage measurement. The scanning method of the "Variable Axis Immersion Lens" (VAIL) as described by Goto and Soma (1977) and Pfeiffer and Langner (1981) does not have these problems. Originally the VAIL was developed for a large scan field in lithography applications, because the transverse chromatic aberration is absent. It consists of small deflection coils inside the polepieces of a magnetic lens, which create magnetic fields of the same form as the perpendicular component of the lens field in the region of the gradient (fig. 4).

$$B_{defl}(z) = \frac{1}{2}\, c \, . \, \frac{\partial B_z(z)}{\partial z} \qquad (6)$$

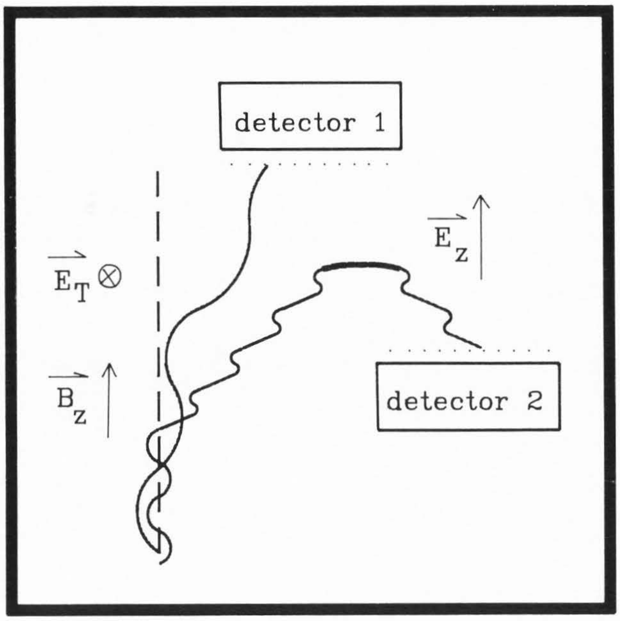

Figure 3. Schematic representation of electron trajectories in the combined retarding field - trochoidal motion analyser.

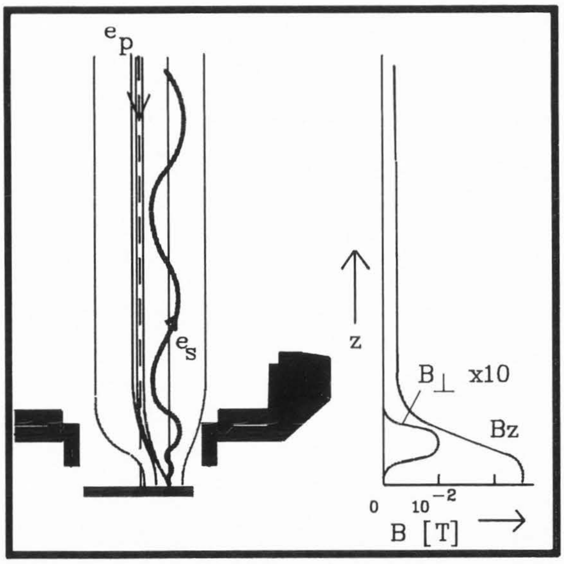

Figure 4. Schematic representation of the variable axis immersion lens (VAIL).

In this way the transverse magnetic field is zero at a distance c off-axis. The primary beam can come straight in, and the secondary electrons can come out undisturbed. Alternatively the primary beam can come in on the original axis and will be deflected to be focussed on the new axis which is now the axis of symmetry. For a lens field that drops from $25\mathrm{x}10^{-3}$ T to $1.5\mathrm{x}10^{-3}$ T over 10 mm, the necessary deflection field for a spot displacement of 1 mm is about 10^{-3} T.

Description of the prototype

In order to test the principles of the new design, a Philips SEM 500 was adapted according to fig. 5. The specimen is placed on a magnetic table (1) which can be moved together with the specimen with the original motordrive. The deflection coils for the VAIL (2) are positioned outside the vacuum in the bore of the upper pole piece (3). A computer simulation shows that this set up should have a focal length of 7.9 mm and chromatic an spherical aberration coefficients of 6.3 mm and 7.6 mm, respectively.

Additional coils (4) and (5) give the 1.5×10^{-3} T field. An extraction electrode (6) can be used in order to accelerate the electrons away from the specimen. Electrodes (7) decelerate the electrons to their original energy. In the analyser area two electrodes (8) create the cross field for the trochoidal motion. Grid (9) is the grid for the retarding field. Behind grids (9) and (10) the electrons are accelerated towards fluorescent screens and the light is detected by two photomultipliers (11) and (12). Pre-deflectors (13) can bring the primary beam on the displaced axis.

Expected performance and preliminary results

The small focal length of the probe forming lens is expected to allow larger currents in smaller spots than in traditional designs. At least as important for that aspect is a high brightness electron gun, which is not yet planned on our prototype because the aim of this work is only to test the optical principles.

The signal to noise ratio of voltage measurements, given a certain primary beam current, is maximized in the design: 100% of all secondary electrons is expected to be detected and by using the slower part of the secondary electrons as the signal instead of the faster part an increase of signal to noise ratio of a factor of 5 is expected. (Dubbeldam and Kruit, this volume). The latter improvement might not be possible if local fields on the specimen disturb the measurements. With a primary beam current of 10 nA a voltage change should be observable with a variance of 1 mV in $\approx 30\ \mu$sec. The expected field of view in the prototype set-up is 3x3 mm.

The use of two detectors is expected to give a dramatic decrease of the sensitivity of voltage measurements to:

- fluctuations of the primary beam current,
- changes in secondary emission coefficient resulting from contamination,
- differences of secondary emission coefficients in a scan,
- topography effects,
- the position of the primary beam and
- a part of the local field effects.

In preliminary experiments we have been able to measure S-curves on both detectors, while the sum of the two signals was constant. The field of view is indeed 3x3 mm although the detection efficiency seems to fall off towards the edges of the scan field.

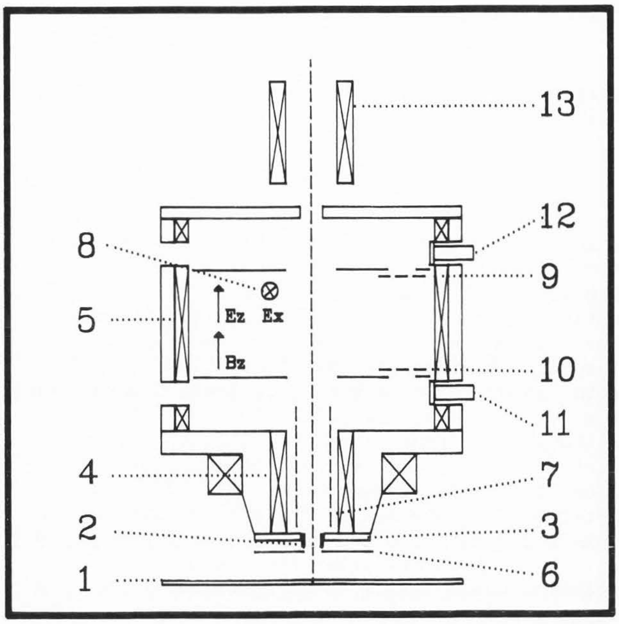

Figure 5. Prototype of the e-beam tester with dispersive secondary electron energy analyser. For description of numbered parts see text.

Acknowledgements

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Discussion with Reviewers

P. Girard: You define a field of view of 3 x 3 mm^2. Could you indicate the distortions levels within this field?
Authors: The variable axis immersion lens was originally developed as a very low aberration scanning system. For the theoretical study of the distortions we refer to the papers of Goto & Soma (1977) and of Pfeiffer & Langner (1981). We do not yet have precise measurements on our system, but the edges seem to be "square".

P. Girard: Is the combination of the various electric and magnetic fields critical for the performance optimization?
Authors: No, these fields are not as critical as in conventional dispersive analyzers.

P. Girard: What is a practical extracting field range for this type of spectrometer?
A.R. Dinnis: Over what range can the voltage on the extracting electrode be varied while still maintaining satisfactory operation of the analyzer and what value is normally used on an unpassivated specimen?
Authors: Similar to other electron beam testers an extracting field of up to a few kV per mm can be used. For low extracting fields the parallelizing magnetic field is advantageous compared to other spectrometers, because it keeps the electrons close to the axis.

P. Girard: How do you situate the performance (simulations or experiments) regarding local field effects and voltage accuracy for your equipment?
W. Reiner: In order to perform an e-beam test at passivated devices by means of capacitive coupling voltage contrast, a low extraction field (50-100 V/mm) is necessary. Such fields result in a local field effect which cannot be neglected. What about the advantages of your analyzer in this case?
Authors: Local fields can influence the SE-trajectories in two ways. Our system is expected to be insensitive for the focussing and defocussing actions of the local fields, since all secondary electrons are lead into the spectrometer and their velocity is directed into the z-direction.

However, a strong local field will result in a severely disturbed signal on the low energy detector, if the slowest electrons are really trapped in the potential barriers. That means that only the high energy detector can be used like in conventional electron beam testers. The advantages of our set-up in this situation are the high detection efficiency through the lens detection and the fact that the energy and not only the z-component, of the secondary electrons is measured.

K. Nakamae: Could you explain the focus of the primary electrons by your magnetic lens in more detail?
Authors: In a magnetic immersion lens, an electron which enters the lens parallel to the axis will perform exactly half a circle in the magnetic field (cyclotron motion) before crossing the axis in focus. Equation 4 follows from this consideration.

A.R. Dinnis: What is the maximum unobstructed working distance between the extractor electrode and the specimen and does this allow sufficient clearance for the use of some probe card so that circuits in wafer form can be examined?
Authors: The bottom plate. (figure 5, part 1) can be moved away from the extractor electrode while maintaining focus (see equation 4) to a distance of 1 cm. This increases aberrations and the parallelization is less effective.

K. Nakamae: What is the beam spot size in your system and what is the tranparency of your spectrometer? Do not some electrons attack the wall between grids 9 and 10 in figure 5?
Authors: Experimental details will be published soon.

K. Nakamae: How about the transit time effect on voltage contrast?
Authors: The influence of the detector design on this effect is totally determined by the distance between the sample and the extraction electrode and the electrode potential. These parameters are in our instrument similar to other electron beam testers.

K. Nakamae: What is the adiabaticity parameter that you have defined in the previous paper (Kruit and Read, 1983)?

Authors: We have measured the magnetic field in the lens and calculated the adiabaticity parameters from these measurements. The relative change of the field per pitch, given by parameter χ_1 is 3 for a 10 eV electron. The second adiabaticity parameter χ_2 that determines the twisting distortion is 0.1 for a 10 eV electron.