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## Signal-to-Noise Ratio Improvement in Electron Beam Testing by Using a Dispersive Analyser

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### Abstract

In conventional e-beam testers the potential of a device under test is measured by collecting the secondary electrons (SE's) faster than a certain limit, while the slower SE's are rejected. We have built an e-beam tester in which the slower SE's are also collected. In this paper we will show that this can decrease the minimum measurable voltage substantially. An additional advantage of a double channel analyser is the possible reduction of the influence of fluctuations in the primary beam and in the secondary emission coefficient.

### Introduction

The measurement of the potential of a specimen in a scanning electron microscope is based on the energy analysis of secondary electrons emitted from the surface. The secondary energy spectrum, which is known from calculations and measurements (Chung and Everhart 1974) shifts when the potential of the specimen changes. A traditional detector measures only SE's faster than a certain limit, so a shift of the spectrum due to a voltage change can be detected. The minimum measurable voltage, which is restricted by shot noise is calculated by Lin and Everhart and Gopinath, (Lin and Everhart 1980, Gopinath 1977).

In this paper we calculate the minimum measurable voltage of a new type of e-beam tester. This experimental set-up is described in a separate paper (P. Kruit and L. Dubbeldam, this volume). In this tester one detector measures the fastest part of the spectrum, while a second detector measures the rest of the spectrum.

We compare three cases: in one case the voltage is derived from the signals on both channels, in the other two cases the voltage is derived from only one of the two channels.

### Energy distribution

The energy distribution of secondary electrons emitted from metal has been calculated by Chung and Everhart (Chung and Everhart 1974). This distribution is a good fit for experimental data. The normalized equation has the form:

$$N(E)dE = 6 \frac{E-eV_s}{(E-eV_s+W_f)^4} \epsilon N_p dE \quad (1)$$

where:  $N(E)dE$  is the number of electrons with energy between  $E$  and  $E+dE$ ,  $V_s$  the potential of the sample from which the secondary electrons originate,  $W_f$  the work function of the sample,  $\epsilon$  the secondary emission coefficient and  $N_p$  the number of primary electrons. There are other relations known to approximate the energy distribution, like a Maxwellian (Lin and Everhart, 1980). The general conclusions of our paper do not depend on the exact form of the secondary energy distribution, only specific numbers change a little. The energy distribution is shown in figure 1.

**KEY WORDS:** E-beam testing, minimum measurable voltage, signal to noise ratio, double channel analyser, normalization.

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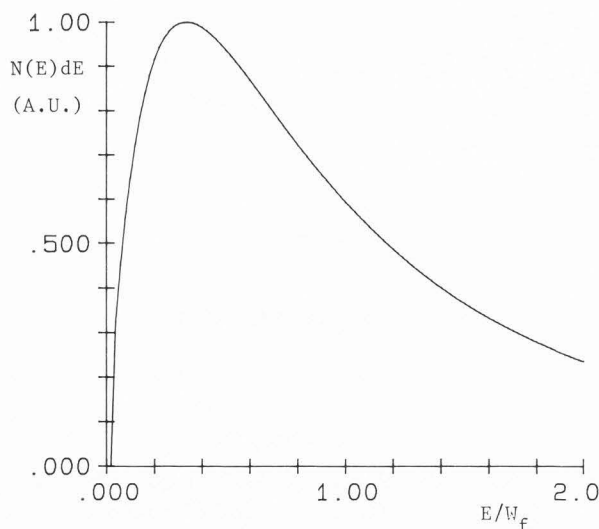


Figure 1. Energy distribution of secondary electrons emitted from a metal with work function  $W_f$ .

#### Multi-channel detector

As a theoretical exercise we will calculate in this section the number of electrons needed for a voltage measurement with an accuracy of 1 mV when a multi-channel detector is used. The most one can ever know about the spectrum, is  $N(E)dE$  in an infinite number of channels, so it seems that we should find the theoretical lower limit of the minimum detectable voltage this way. We assume there is no information about the sample potential and we will only consider statistical noise in the measured signals. We also assume in this theoretical exercise that  $W_f$  is known, although in a more practical situation it would be possible to compare  $W(E)$  with a spectrum at a sample potential  $V_S=0$ . We will calculate the minimum number of needed electrons, if only SE's with energy exceeding  $eV_R$  are detected.

If the multi-channel detector has an infinite number of channels, the output of each channel  $W(E)$  will be proportional to  $N(E)dE \pm \sqrt{N(E)dE}$ . The weighted least squares estimate of the sample potential is that particular value  $\hat{V}_S$  of  $V_S$  that minimizes:

$$J(V_S) = \int_{eV_R}^{\infty} \frac{W(E) - \frac{6(E - eV_S)\epsilon N_p}{(E - eV_S + W_f)^4}}{W(E)} dE \quad (2)$$

If the noise is statistical, the estimator  $\hat{V}_S$  converges in distribution to a normal distribution with expectation  $V_S$  and covariance  $\sigma^2$ , given by:

$$\sigma^2 = \left[ \int_{eV_R}^{\infty} \frac{\left( \frac{\partial N(E)}{\partial E} \right)^2}{N(E)} dE \right]^{-1} \quad (3)$$

This equation relates the covariance of the estimated sample potential and the number of emitted secondary electrons. The product of this number and the covariance is plotted in fig. 2 as a function of  $V_R$ . It shows that  $V_S$  can be measured with an accuracy of 1 mV (i.e.,  $\sigma^2 = 10^{-6} \text{ V}^2$ ) if  $1.4 \cdot 10^5$  electrons have been collected.

In the next section we will describe a double channel analyser. This analyser divides the secondary electrons into two parts: a small energy range at the bottom of the spectrum from which the sample potential can be estimated and the rest of the spectrum that can be used for normalization.

#### Double channel detector

In conventional retarding grid analysers all secondary electrons with energy exceeding a certain limit set by the retarding grid are collected. The slower electrons are rejected. In our experimental set-up, described by P. Kruit and L. Dubbeldam, (this volume) the slower electrons are also collected by a second detector.

The calculated output of the fast-electron analyser  $S_A$  is given by:

$$S_A = \int_{eV_R}^{\infty} N(E)dE = \frac{3(eV_R - eV_S) + 1}{\left( \frac{eV_R - eV_S}{W_f} + 1 \right)^3} \epsilon N_p \quad (4a)$$

and the calculated output of the slow-electron analyser  $S_B$  is given by:

$$S_B = \int_0^{eV_R} N(E)dE = \frac{\left( \frac{eV_R - eV_S}{W_f} \right)^2 \left( \frac{eV_R - eV_S}{W_f} + 3 \right)}{\left( \frac{eV_R - eV_S}{W_f} + 1 \right)^3} \epsilon N_p \quad (4b)$$

If the measured outputs of the two channels are  $W_A$  and  $W_B$ , the maximum likelihood estimate  $\hat{V}_S$  will minimize

$$J(V_S) = \frac{(S_A - W_A)^2}{W_A} + \frac{(S_B - W_B)^2}{W_B} \quad (5)$$

The covariance of this estimator is given by:

$$\sigma^2 = \frac{1}{\left( \frac{\partial S_A}{\partial V_S} \right)^2 \cdot \frac{1}{S_A} + \left( \frac{\partial S_B}{\partial V_S} \right)^2 \cdot \frac{1}{S_B}} = \frac{S_B(\epsilon N_p - S_B)}{\left( \frac{\partial S_B}{\partial V_S} \right)^2 \epsilon N_p} \quad (6)$$

This expression shows that the covariance is small if the signal  $S_B$  is low. This means that the energy range of the low energy detector, i.e.,  $eV_R - eV_S$ , should be chosen as small as possible. If we take the limit of this energy range down to zero, this expression shows that we need  $1.4 \cdot 10^6$  electrons for an accuracy of 1 mV. However, if the energy range is that small, that there are no electrons expected to be in this range, the denominator of (6) will drop to zero and  $V_S$  cannot be measured at all.

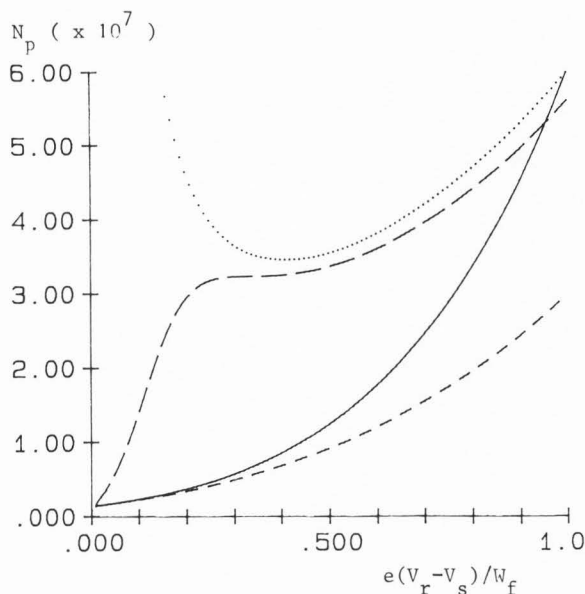


Figure 2. Number of secondary electrons needed for a voltage measurement with an accuracy of 1 mV as function of the working point.

- ..... high energy channel,  $E > eV_r$
- low energy channel,  $E < eV_r$
- - - - - both channels
- · - · - multi-channel detector,  $E > eV_r$

Now we will derive similar expressions for the case that only one channel is used for the voltage estimation. The three situations are compared in figure 2.

Single channel detectors

Expression (6) can be rewritten for a retarding grid analyser in which the slower electrons are rejected:

$$\sigma^2 = \frac{S_A}{\left(\frac{\partial S_A}{\partial V_S}\right)^2} \quad (7)$$

This formula is identical with the expression for the voltage resolution derived by Spicer (Spicer and Sackett, 1985).

Straight forward calculations show that  $\sigma^2$  reaches a minimum if:

$$\frac{e(V_r - V_s)}{W_f} = \frac{1}{6} \sqrt{6} \quad (8)$$

The working point or the retarding grid voltage should be chosen at  $eV_r = 0.4 W_f$ , if only signal to noise ratio considerations are involved.

The minimum measurable voltage as a function of the working point has been calculated earlier (Lin and Everhart, 1980). Assuming a Maxwellian energy distribution they found for "average metals" (i.e.,  $W_f = 5.3$  eV) an optimal working point at 2.6 V.

Expression (6) can also be rewritten for an estimator that only uses the slower electrons to determine  $V_S$ :

$$\sigma^2 = \frac{S_B}{\left(\frac{\partial S_B}{\partial V_S}\right)^2} \quad (9)$$

Comparison of expression (9) with (6) and (7) shows that the use of the low energy channels will give the best accuracy. Again there is a limit on the lowest  $V_r$ .

Practical restrictions

In this paper we only dealt with an ideal detection of the spectrum. We have assumed an ideal energy resolution of the spectrometer and ignored the influences of local fields.

Two types of local field effects (LFE) interfere with the voltage measurements [Menzel and Brunner 1983]. The first LFE is caused by a focussing or defocussing action of the local fields, which alters the detection efficiency and the direction of the electrons. In our analyser all secondary electrons are parallelized to the axis of the system, so neither the number of detected electrons nor their direction will be influenced by this LFE. The second LFE is caused by a potential barrier above the specimen which prevents the slowest electrons to escape. Since our signal is very sensitive for the number of slow electrons, this LFE should be suppressed as far as possible.

Thanks to the steep low energy flank of the spectrum, the minimum measurable voltage can be decreased when only a small, low energy band is detected. When the steep flank is spoiled due to a bad spectrometer resolution, the advantage of the low energy detection may disappear.

Normalization

A severe problem for voltage measurements is the change of the number of secondary electrons due to fluctuations in the primary beam or in the secondary emission coefficient.

Since our set-up is designed to collect all secondary electrons we expect to be able to normalize the signal of one channel to the total number of electrons. For example,  $S_B$  divided by  $S_A + S_B$  can be fed into a feedback loop, designed to hold this ratio equal to a preset value. This ratio should not contain topographical information and be independent of the primary beam current and the secondary emission coefficient.

Conclusions

We have calculated the number of electrons needed for a certain accuracy for three systems as a function of their working point.

We showed that if a retarding grid analyser is optimally adjusted in the working point  $eV_r - eV_s = 0.4 W_f$  there are  $3.0 \cdot 10^7$  secondary electrons needed for an accuracy of 1 mV. For a double channel detector and a single low energy detector we derived that only  $3.3 \cdot 10^6$  secondary electrons are needed for the same accuracy.

Acknowledgements

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Discussion with Reviewers

A.R. Dinnis: If secondary electrons below, say, 1 eV energy are lost because of surface field effects, will the system still give accurate voltage readings and have a worthwhile improvement in noise performance?

K. Nakamae: As the width of the electrode in IC and LSI is reduced, the formation of a potential barrier seems to be indispensable even in a high extraction field. So, to use the detected slower electron current for voltage measurements becomes difficult. Would you comment about this?

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.

The local fields that capture the slowest electrons seem to be a serious problem. Our ideas rely heavily on the secondary electrons with less energy than the mean energy i.e. for an Al track 1.3 eV. So, if the electrons below 1 eV are really trapped by local fields, our double channel analyzer will not work. In such situations the possibility remains for voltage measurements with only the higher energy detector, a mode of measurement which can be easily switched to.

A.R. Dinnis: The signals from the two detectors can presumably be fed into a circuit which will give a direct reading of the voltage at the selected point on the specimen. Can you give an indication of the bandwidth which your system might achieve when operated in this mode, i.e., without employing beam-chopping stroboscopy? As the performance must depend on operating

conditions, could you give the figure for typical conditions such as: a 5  $\mu\text{m}$  wide conductor, a 1 kV primary beam and a voltage resolution of 50 mV?

Authors: According to figure 2, the value of  $\epsilon N_p / \sigma^2$  that belongs to the working point  $eV_r = 0.5W_f$  is  $10^7$ . That means that in the situation of non-loading condition and ideal detection of secondary electrons, the number of primary electrons needed is:

$$N_p = 1.0 \cdot 10^7 \sigma^2 = 25,000 \quad (10)$$

If the primary beam current is 1 nA, this corresponds with a measurement time of 4  $\mu\text{s}$ . If the bandwidth is defined as  $1/2\pi\tau$  than the corresponding bandwidth is about 250 kHz.

Whether or not our probe system can attain this current in a spot of 1  $\mu\text{m}$  and which detection efficiency can be reached is beyond the scope of this paper. Measurement results will be published soon.

K. Nakamae: The method using a double channel detector seems to be useful, when the energy distribution of secondary electrons is known ahead of time. Is it right?

Contamination changes the energy distribution of secondary electrons. Would you comment about this?

Authors: The ratio of the two detector outputs can be fed into a feedback system that keeps that ratio constant. This feedback system will give a direct reading of the AC voltage on the specimen, even if the energy distribution is not known exactly, provided that the form remains constant, even if the secondary emission coefficient changes. However, if the energy distribution changes, this will be interpreted as a signal on the specimen.

W. Reiners: You mentioned that an additional advantage of a double channel analyser is the possible reduction of the influence of fluctuations in the primary beam and in the secondary emission coefficient. Could you distinguish between the reduction of noise caused by the primary beam or by the secondary emission coefficient?

Authors: No, since the signals on both detectors are proportional to the product of the secondary emission coefficient and the primary beam current, we cannot determine where a fluctuation occurs. And because the influence of these fluctuations are canceled out by the normalisation, we do not see the purpose of such a measurement for e-beam testing.

W. Reiners: The application of extraction field to the detectors causes an energy shift of the secondary electrons. Does the energy shift influence the noise of the measured signal?

Authors: The statistical noise in the number of electrons of a certain energy band only depends on the number of electrons. So, if the whole spectrum is shifted up or down, this will not influence the noise in the spectrum. Moreover, before the secondary electrons reach the parallelizing magnetic field, they are decelerated again.