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AN ENERGY DEPENDENT MODEL FOR TYPE I MAGNETIC CONTRAST IN THE SCANNING ELECTRON MICROSCOPE

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Abstract

The modelling of the magnetic contrast phenomenon in the scanning electron microscope (SEM) is important in understanding the physics of the contrast mechanism and the associated signal detection. In this paper, we report an improved analytical model for Type I magnetic contrast calculations using an approximate form of the Chung and Everhart secondary electron (SE) energy distribution. Previous studies have neglected this factor by assuming a mono-energetic model in order to simplify the calculations. This new model can be used to study different material specimens by appropriate choice of the work function and field-distance integral. The effect of energy filtering on the Type I magnetic contrast and quality factor can also be studied with the improved model by substituting the low and high energy limits of the filtered SE distribution into the closed-form analytical expressions obtained. Results of the above-mentioned effects and the effect of collector aperturing are reported in this paper using the new improved energy dependent model.

Key Words: Magnetic contrast, type I magnetic contrast, scanning electron microscope, secondary electrons, energy filtering, quality factor, work function, field-distance integral.

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Introduction

Magnetic contrast in the scanning electron microscope (SEM), using Lorentz deflection of electron trajectories, has been used for the characterization of magnetic materials, tapes and recording heads.

The Lorentz force, resulting from external fringing fields or internal magnetic fields, can affect the low energy secondary electrons (SEs) or the higher energy backscattered electrons (BSEs) giving rise to Type I (Banbury and Nixon (1967), Joy and Jakubovics (1968)) and Type II (Fathers et al. (1973)) contrast mechanisms respectively. Deflection of a low energy primary electron beam has also been used to map the fringing fields above the surface of a magnetic medium (Thornley and Hutchison (1969), Elsbrock and Balk (1984)). The beam deflection is measured either by observing the image distortion of a reference grid (Thornley and Hutchison (1969)) or by using a microchannel plate detector (Elsbrock and Balk (1984)). Using computer tomography reconstruction techniques, all three components of the magnetic field vector above the recording head medium can be mapped (Elsbrock et al. (1985), Matsuda et al. (1990), Steck et al. (1990)).

The modelling of the magnetic contrast phenomenon is another area of active research as it gives a better understanding of the physics of the contrast mechanism and the associated signal detection. This paper reports an improved model for Type I magnetic contrast signal and quality factor calculations by taking into account the SE energy distribution. Previous studies have neglected this component by assuming a mono-energetic model in order to simplify the calculations (Jones (1976), Dunk et al. (1975), Joy and Jakubovics (1969), Yamamoto and Tsuno (1975), Wells (1985)). Only Wardly (1971) has tried to account for this by assuming a hypothetical and simplified energy distribution for secondary electrons. However, Wardly's model is not suitable for studying the effect of energy filtering on the Type I contrast and quality factor. The model reported in this paper overcomes these limitations by using an approximate form of the Chung and Everhart SE energy distribution (Chung and Everhart (1974)) in the derivation. The use of the approximate form in the calculations is to make the solution more tractable so that analytical expressions can be derived for the contrast and quality factors. However, the model is generic as different materials can be simulated by appropriate choice of the work function and the field-distance integral. Also, by an appropriate choice of the low and high energy limits of the filtered SE emission, the effect of energy filtering on Type I magnetic contrast can be studied. This paper presents results of the above-mentioned effects together with the aperture effect of a modified collector using the new improved energy dependent model.

Derivation of Energy Dependent Model

Unmodified collector

The starting point for deriving the energy dependent model for Type I magnetic contrast calculations is the mono-energetic models described by Joy and Jakubovics (1969), Dunk et al. (1975) and Jones (1976).

Consider a primary beam travelling along the negative z direction striking the specimen at normal incidence. Assuming that the angular distribution of the emitted secondary electrons (SEs) is cosine, the number of SEs emitted into an elemental area of size $dA = \sin\Theta \, d\Theta \, d\varphi$ in the energy range W to $W + dW$ is given by

$$dN = k(W) \sin\Theta \cos\Theta \, d\Theta \, d\varphi \qquad (1)$$

where Θ is the angle in the y-z plane measured with respect to the z-axis in the clockwise direction, φ is the angle in the x-y plane measured with respect to the x-axis in the anti-clockwise direction, and $k(W)$ is the number of SEs emitted per unit energy, per unit solid angle.

Since an unmodified collector of the Everhart-Thornley type has a solid angle for collection of about π steradians (Jones (1976)), the expression for $k(W)$ is given by

$$k(W) = \frac{f(W)}{\pi} \qquad (2)$$

where $f(W)$ is the number of SEs emitted per unit energy.

Joy and Jakubovics (1969), Dunk et al. (1975) and Jones (1976) have avoided the complexity of the calculations imposed by the choice of $f(W)$ by assuming that all the emitted electrons have a peak energy of around 4eV, i.e. they have assumed an mono-energetic model with $f(W) = f_o$ = the value of $f(W)$ at W = 4eV. Our model overcomes this limitation by assuming that $f(W)$ is given by the Chung and Everhart (1974) expression as follows

$$f(W) = C_N \frac{W}{(W + \Phi)^4} \qquad (3)$$

where C_N is a constant and Φ is the work function of the specimen. Substituting eqns. (2) and (3) into eqn. (1) and integrating with the appropriate limits gives the detected signal.

Wells (1974) provided a simplified model for calculating the detected signal by considering the difference in collection angle $\delta\Theta$ between SEs emitted from two oppositely oriented magnetic fields. The value of $\delta\Theta$ (in degrees) is estimated to be

$$\delta\Theta = 17 \, BL\sqrt{W} \qquad (4)$$

where B is the peak field (in Gauss) which reverses at each distance L, i.e. BL is the field-distance integral. In some specimens, L will be approximately equal to the domain width.

Wells' model allows the origin of Type I magnetic contrast to be readily understood but involves some simplification in the estimation of the deflection $\delta\Theta$. A more sophisticated model for finding the limits of the integration is that used by Joy and Jakubovics (1969), Dunk et al. (1975) and Jones (1976). For a secondary electron emitted at right angles into a magnetic field $B_x(z)$, the relation between its initial and final directions, denoted by Θ_o and Θ_f respectively as shown in Fig. 1, is

$$\begin{aligned} \sin\Theta_o - \sin\Theta_f &= \frac{q}{mv}\int_0^\infty B_x(z) \, dz = \frac{qF}{mv} \\ &= \sqrt{\frac{q}{2mW}}F \qquad = \mu \end{aligned} \qquad (5)$$

where F is the field-distance integral, m is the free electron mass, q is the electronic charge and v is the velocity of the emitted SE. Eqn. (5) gives a more accurate determination of $\delta\Theta$ than the approximation used by Wells.

Θ_f denotes the direction of the SE as it leaves the influence of the specimen fringing field. The trajectory of the SE will be changed subsequently by the electric field of the collector. To allow for this, it is assumed that for the case of an unmodified collector, all SEs which have a positive y-component of velocity will be collected or detected (Joy and Jakubovics (1969)). The analysis for a modified collector (i.e. a collector with an aperture placed in front of it) will be treated in the next section.

Using eqn. (5), the normalised detected signals for our energy dependent model, S^+_{nor} (for $\mu > 0$) and S^-_{nor} (for $\mu < 0$), are given as follows:

$$S^{+}_{nor} = \frac{\int_{\varphi=\alpha}^{\pi-\alpha} \int_{\Theta=\beta}^{\frac{\pi}{2}} \int_{W=W_{min}}^{W_{max}} dN(W,\Theta,\varphi)}{\int_{\varphi=0}^{2\pi} \int_{\Theta=0}^{\frac{\pi}{2}} \int_{W=W_{min}}^{W_{max}} dN(W,\Theta,\varphi)} \qquad \textbf{(6a)}$$

$$S^{-}_{nor} = \frac{\int_{\varphi=\alpha}^{\pi-\alpha} \int_{\Theta=-\beta}^{\frac{\pi}{2}} \int_{W=W_{min}}^{W_{max}} dN(W,\Theta,\varphi)}{\int_{\varphi=0}^{2\pi} \int_{\Theta=0}^{\frac{\pi}{2}} \int_{W=W_{min}}^{W_{max}} dN(W,\Theta,\varphi)} + \frac{\int_{\varphi=0}^{2\pi} \int_{\Theta=0}^{-\beta} \int_{W=W_{min}}^{W_{max}} dN(W,\Theta,\varphi)}{\int_{\varphi=0}^{2\pi} \int_{\Theta=0}^{\frac{\pi}{2}} \int_{W=W_{min}}^{W_{max}} dN(W,\Theta,\varphi)} \qquad \textbf{(6b)}$$

where

$$dN(W,\Theta,\varphi) = \frac{W}{(W+\Phi)^4} \sin\Theta \cos\Theta \, d\varphi \, d\Theta \, dW \qquad \textbf{(6c)}$$

$$\beta = \sin^{-1} \mu \qquad \textbf{(6d)}$$

$$\alpha = \sin^{-1}(\mu \operatorname{cosec} \Theta) \qquad \textbf{(6e)}$$

and W_{min} and W_{max} are the low and high energy limits of the filtered SE energy spectrum.

In order to obtain analytical closed-form expressions for the normalised detected signals, the following approximation is made for the SE energy distribution $f(W)$.

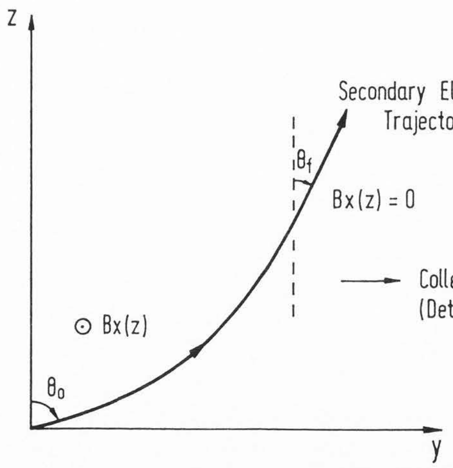

Fig. 1. Geometry of deflection for a secondary electron emitted in the y-z plane at right angles to the magnetic field $B_x(z)$. The collector is assumed to be along the positive y-direction and the region to the right of the dashed line is assumed to be field-free.

For $0 < W < \Phi$,

$$\frac{W}{(W+\Phi)^4} \approx W\,\Phi^{-4} \qquad \textbf{(7a)}$$

and for $\Phi < W < 50\text{eV}$ (where 50eV is the maximum energy of the SEs),

$$\frac{W}{(W+\Phi)^4} \approx W^{-3} \qquad \textbf{(7b)}$$

Performing the integration in eqns. (6a) and (6b) using the approximate form of the SE energy distribution in eqns. (7a) and (7b), and also assuming that $|\mu| << 1$, the normalised detected signals are given by

$$S^{+}_{nor} = \frac{1}{\pi} - \frac{4|F|}{5\pi^2}\sqrt{\frac{8q}{m}}\,\frac{[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}]}{[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}]} \qquad \textbf{(8a)}$$

$$S^{-}_{nor} = \frac{1}{\pi} + \frac{4|F|}{5\pi^2}\sqrt{\frac{8q}{m}}\,\frac{[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}]}{[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}]} \qquad \textbf{(8b)}$$

Image quality can be defined as a contrast factor C which can be expressed in terms of the normalised detected signals as follows

$$C = \frac{2\,(S^{-}_{nor} - S^{+}_{nor})}{S^{-}_{nor} + S^{+}_{nor}} \qquad \textbf{(9)}$$

Substituting eqns. (8a) and (8b) into eqn. (9), the expression for contrast C in the energy dependent model is given by

$$C = \frac{16|F|}{5\pi}\sqrt{\frac{2q}{m}}\,\frac{[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}]}{[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}]} \qquad \textbf{(10)}$$

Dunk et al. (1975) and Jones (1976) also used an alternative definition of image quality which takes into account the noise factor. This is called the quality factor Q and is defined as

$$Q = \frac{S^{-}_{nor} - S^{+}_{nor}}{\sqrt{(S^{-}_{nor} + S^{+}_{nor})}} \qquad \textbf{(11)}$$

Similarly, the expression for quality factor Q in the energy dependent model is found to be

$$Q = \frac{16|F|}{5\pi^{3/2}}\sqrt{\frac{q}{m}}\,\frac{[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}]}{[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}]} \qquad \textbf{(12)}$$

Modified collector or collector aperturing effect

Dunk et al. (1975) and Jones (1976) treated the effect of a modified collector or a collector with an aperture by defining a parameter ζ as follows

$$\zeta = \frac{v_c}{v} \tag{13}$$

where v_c is the critical velocity, v is the SE velocity and the parameter ζ is related to the actual dimension of the aperture by a simple linear relation (Jones (1976)). Only electrons with the y-component of velocity greater than a critical value v_c contribute to the detected signal. When $\zeta = 0$, all electrons with a positive y-component of velocity are collected; when $\zeta = 1$, only electrons travelling in the y-direction towards the detector are collected.

The expressions for the contrast C and quality factor Q in the energy dependent model for a modified collector can be derived by replacing μ in eqns. (6a) and (6b) by μ' where

$$\mu' = \mu + \zeta \tag{14}$$

The normalised detected signals for the modified collector are given by

$$S^{+}_{nor} = \frac{1}{\pi}\left(1 - \frac{4\zeta}{\pi}\right) - \frac{4|F|}{5\pi^2}\sqrt{\frac{8q}{m}}\,\frac{\left[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}\right]}{\left[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}\right]} \tag{15a}$$

$$S^{-}_{nor} = \frac{1}{\pi}\left(1 + \frac{4\zeta}{\pi}\right) + \frac{4|F|}{5\pi^2}\sqrt{\frac{8q}{m}}\,\frac{\left[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}\right]}{\left[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}\right]} \tag{15b}$$

With the collector aperturing effect, the new expressions for the contrast C and quality factor Q are

$$C = \frac{16|F|}{5\pi}\sqrt{\frac{2q}{m}}\,\frac{\left[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}\right]}{\left[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}\right]} + \frac{8\zeta}{\pi} \tag{16}$$

$$Q = \frac{16|F|}{5\pi^{3/2}}\sqrt{\frac{q}{m}}\,\frac{\left[\frac{8}{3}\Phi^{-5/2} - \frac{5}{3}\Phi^{-4}W_{min}^{3/2} - W_{max}^{-5/2}\right]}{\left[2\Phi^{-2} - \Phi^{-4}W_{min}^{2} - W_{max}^{-2}\right]} + \frac{4\sqrt{2}\,\zeta}{\pi^{3/2}} \tag{17}$$

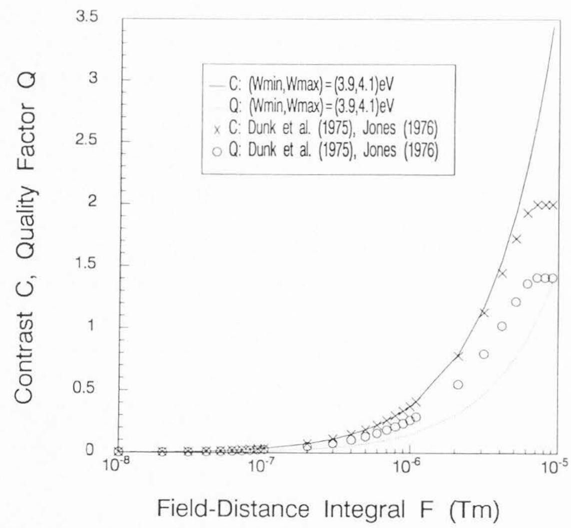

Fig. 2. Comparison of contrast C and quality factor Q of the energy dependent model (shown as solid and dotted lines respectively) to that of the monenergetic models of Dunk et al. (1975) and Jones (1976) (shown as crosses and circles respectively).

Results and Discussion

Comparison with mono-energetic models

The validity of the energy dependent model can be checked by comparing it with the mono-energetic models of Dunk et al. (1975) and Jones (1976). By setting the work function Φ = 4eV, W_{min} = 3.9eV and W_{max} = 4.1eV, our energy dependent model essentially reduces to that of a mono-energetic model with a peak SE energy of 4eV. The contrast and quality factor, calculated using the energy dependent model, are plotted in Fig. 2 as a function of the field-distance integral F and shown as lines (solid lines and dotted lines respectively). Also plotted in Fig. 2 are the contrast and quality factors calculated using the mono-energetic model of Dunk et al. (1975) and Jones (1976), and these are shown as points (crosses and circles respectively). It can be seen that the energy dependent model corresponds very closely to the monoenergetic model by appropriate choice of the work function, the low energy limit and the high energy limit of the SE energy spectrum. The agreement is especially good for the contrast C at low values of the field-distance integral F but deviates more as F increases. The reason for this deviation is because of the approximation used for μ in the derivation, where it is assumed that $|\mu| \ll 1$. In fact, this approximation is reasonably accurate for $\mu < 0.4$. The larger deviation for the quality factor Q is because of the use of different normalisation factors for the detected signals in our model and in the mono-energetic models of Dunk et al. (1975) and Jones (1976). The difference in the normalisation factor amounts to a magnitude of 2 because Dunk et al. (1975) and Jones (1976) considers only one half of the total hemispherical surface for SE emission (i.e. φ ranges from 0 to π) while our normalisation scheme considers the full hemisphere (i.e. φ ranges from 0 to 2π). If this difference is taken into account, the quality factor Q has to be scaled by a factor of $1/\sqrt{2}$ in the models of Dunk et al. (1975) and Jones (1976), and when this adjustment is made the quality factor curves match closely.

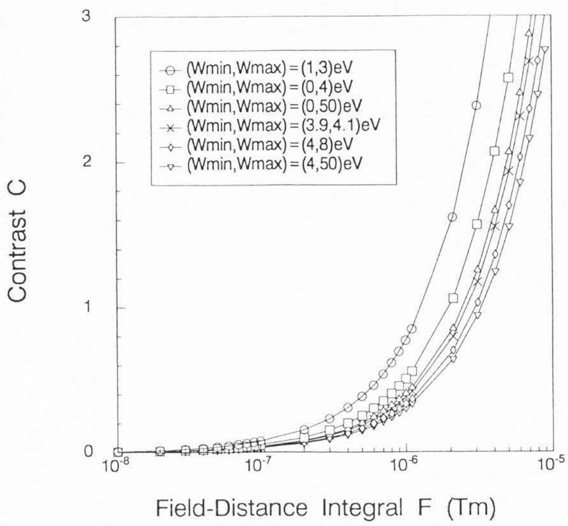

Fig. 3. Effect of energy filtering on the contrast C using the energy dependent model. The first number in the bracket represents the low energy limit of the filtered SE energy spectrum while the second number represents the high energy limit of the filtered spectrum. (0,50)eV corresponds to no energy filtering of the secondary electrons (SEs) (i.e. the whole spectrum of SEs from 0 to 50eV is admitted) while (3.9,4.1)eV represents a single filtered SE energy of about 4eV which is the peak energy of the SE spectrum. Work function Φ = 4eV.

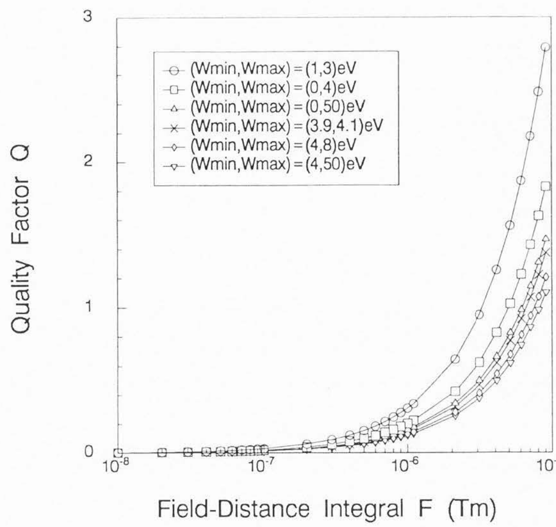

Fig. 4. Effect of energy filtering on the quality factor Q using the energy dependent model. The first number in the bracket represents the low energy limit of the filtered SE energy spectrum while the second number represents the high energy limit of the filtered spectrum. (0,50)eV corresponds to no energy filtering of the secondary electrons (SEs) (i.e. the whole spectrum of SEs from 0 to 50eV is admitted) while (3.9,4.1)eV represents a single filtered SE energy of about 4eV which is the peak energy of the SE spectrum. Work function Φ = 4eV.

Effect of energy filtering

The effect of energy filtering on the emitted secondary electrons can be studied using our energy dependent model by choosing appropriate values for the low energy and high energy limits of the filtered SE energy spectrum, i.e. W_{min} and W_{max}. Fig. 3 shows the plot of the contrast C as a function of the field-distance integral F for various types of SE energy filtering for a specimen with a work function Φ = 4eV. (W_{min},W_{max}) = (0,50)eV corresponds to the unfiltered SE energy spectrum (i.e. the whole spectrum of SEs from 0 to 50eV is admitted), (1,3)eV corresponds to bandpass filtering in the low SE energy spectrum (i.e. before the peak energy at 4eV in which only SEs of energies from 1 to 3eV are admitted), (4,8)eV corresponds to bandpass filtering in the high SE energy spectrum (i.e. only SEs of energies from 4 to 8eV are admitted), (0,4)eV corresponds to low-pass filtering (i.e. only SEs of energies from 0 to 4eV are admitted), (4,50)eV corresponds to high-pass filtering (i.e. only SEs of energies from 4 to 50eV are admitted) and (3.9,4.1)eV to a mono-energetic model with a SE energy around the peak energy at 4eV. The corresponding plot for the quality factor is shown in Fig. 4.

The results of energy filtering showed that bandpass filtering in the low SE energy spectrum or low-pass filtering (i.e. before the peak energy) gives the highest contrast and quality factor. Yamamoto and Tsuno (1975) mentioned that SEs with a peak energy of 3 to 4eV exclusively control the magnetic contrast. This corresponds to the results predicted with our energy dependent model as the contrast and quality factor of the mono-energetic case of (3.9,4.1)eV (i.e. approximately single filtered SE energy around the peak of 4eV), is very similar to that of the situation with no energy filtering, i.e. (0,50)eV. Yamamoto

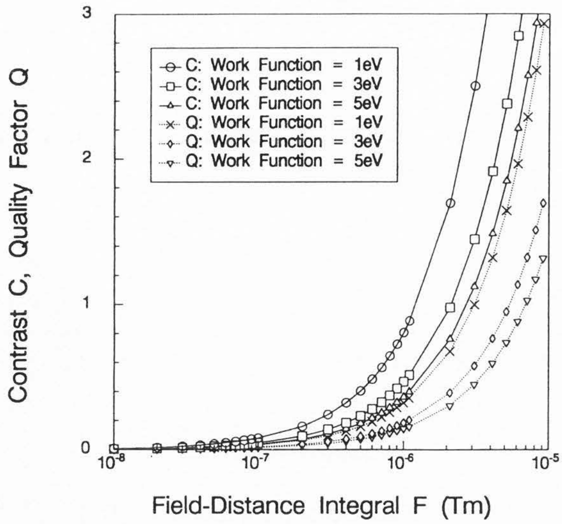

Fig. 5. Effect of work function Φ on the contrast C (shown as solid lines) and quality factor Q for an unfiltered SE energy spectrum (shown as dotted lines).

and Tsuno (1975) further mentioned that "it seems, therefore, that the energy-filtering process causes no significant improvement of the magnetic contrast". This is not correct as results from our model showed that bandpass filtering in the low SE energy spectrum or low-pass filtering (i.e. (W_{min}, W_{max}) = (1,3)eV and (0,4)eV respectively) gives a significant improvement in the contrast and quality factor when compared to the zero energy filtering situation, i.e. (0,50)eV.

The energy dependent model can also be used to study the effect of different specimens on the contrast and quality factor by appropriate choice of the work function Φ of the specimen. The results are plotted in Fig. 5 as a function of the field-distance integral for Φ = 1, 3 and 5eV. It can be observed that as Φ decreases, the contrast and quality factor increase as a result of the increased SE emission and shifting of the SE peak energy to a lower energy value.

Collector aperturing effect

The effect of additional SE filtering using an aperture placed in front of the collector can be studied using the expressions for contrast and quality factor given in eqns. (16) and (17). Fig. 6 shows that as the amount of collector aperturing or zeta (ζ) increases, the contrast and quality factor improve. The results are consistent with what was predicted in Dunk et al. (1975) and Jones (1976). In fact, the contrast and quality factor are linearly related to zeta as can be seen from eqns. (16) and (17). Hence, when energy filtering is incorporated, the lines in Fig. 6 shift vertically by a constant amount while the slope of the lines remain unchanged.

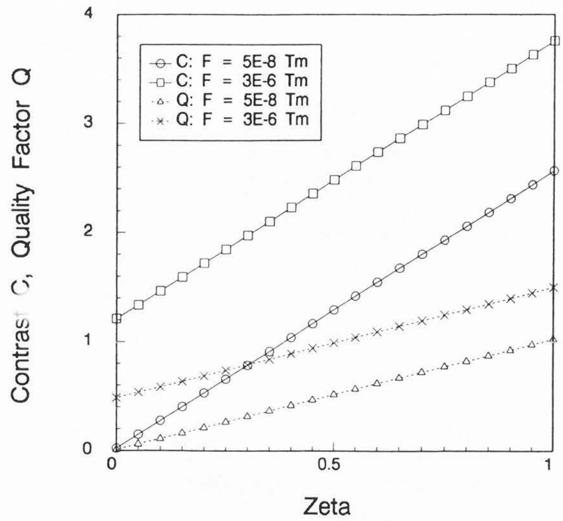

Fig. 6. Collector aperturing effect (represented by the parameter zeta (ζ)) on the contrast C (solid lines) and quality factor Q (dotted lines) for an unfiltered SE energy spectrum. Work function Φ = 4eV. Field-distance integral $F = 5 \times 10^{-8}$ Tm and 3×10^{-6} Tm.

Conclusions

An energy dependent model which includes the effect of energy filtering of the SE energy spectrum on Type I magnetic contrast was derived. Results showed that bandpass filtering or low-pass filtering in the low SE energy spectrum improves the contrast and quality factor. This model can also be used for studying the effect of different specimen materials by appropriate choice of the work function. The effect of additional SE filtering using a modified collector (i.e. a collector with an aperture placed in front of it) is also incorporated into the energy dependent model. Results are consistent with the mono-energetic models reported previously by Dunk et al. (1975) and Jones (1976).

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Discussions With Reviewers

JB Elsbrock: Is it possible to increase the contrast and quality factor by tilting the specimen?

Authors: Tilting the specimen has the effect of increasing the secondary electron (SE) yield from the specimen but does not change the angular distribution of the SEs, which essentially remains a cosine distribution. However, the detected signals in our energy dependent model are normalised quantities and thus this effect will cancel out and so will not affect the contrast and quality factor. However, the effect of tilting the specimen also increases the backscattered electron (BSE) yield and changes the angular distribution of the BSE. If the amount of BSEs collected by the detector is reduced as a result of the specimen tilt (depending on the geometry of the specimen-detector configuration), the contrast and quality factor could increase in practice. In our simplified analytical model, the effect of BSEs contributing to the d.c. background level has not been considered.

JB Elsbrock: Is it possible to get quantitative results for the magnetic peak field *B* if the specimen surface is rough?

Authors: In theory, if the surface roughness does not affect the magnetic field distribution and change the SE yield from the two domain regions substantially, it should still be possible to get some magnetic contrast results. However, quantification may be more difficult unless these effects and the effect of surface roughness on backscattered electron (BSE) yield and angular distribution can be accounted for.

JB Elsbrock: Can the contrast and the quality factor be improved by a new detector strategy (see for example L.J. Balk and J.B. Elsbrock, "A two-dimensional spatially resolving electron detection system", Proc. 10th Int. Congr. Electron Microscopy, Deutsche Ges. f. Elektronenmikroskopie, Vol. 1, 447-448, 1982)?

Authors: Some form of energy filtering in your new detector strategy could improve the contrast and quality factor. The contrast and quality factor can be further improved by using a two-detector configuration (i.e. detectors A and B) and operating it in the "A-B" mode. In theory, if the d.c. level signal collected by the two detectors are equal, one can obtain an infinitely large contrast and quality factor. However in practice, because of geometry differences between the specimen-detector configurations, material property difference in different directions, etc., the backscattered signal (which contributes to the d.c. level) collected by the two detectors are different. Hence, contrast and quality factor may not be infinitely large but still larger than operating with a single detector. We are currently working out the detailed expressions of this mode of operation for our energy dependent analytical model.

JP Jakubovics: Would it be possible to compare the results of this paper with experimental results?

Authors: We are currently carrying out some experiments on the effect of energy filtering on Type I magnetic contrast in order to verify our theoretical model. Results will be reported at a later date.

Reviewer IV: The derivation of the magnetic contrast is based on the paper by Joy and Jakubovics (the same holds for the papers by Dunk et al. and Jones). For that reason, the referee will relate to that model. In that particular model, the contrast is due to the additional SE emission from the half space opposite to the direction of the detector. With that assumption, the integration over that additional space is the only critical calculation and can be easily done if μ<<1. The integration over the half space on the detector side (having a y-component) is uncritical as the electrons will enter the detector in any case. With those considerations, Joy and Jakubovics can define the signal as $1+S_m$ (S_m is the intensity due to the Lorentz deflection). S_m, however, is directly correlated with the additional solid angle of SE emission which is accepted. Looking into eqn. (5), it is obvious that the solid angle depends inversely on the electron velocity. Thus with decreasing energy the solid angle gets larger, e.g. μ increases by a factor of 2 if the energy is lowered by a factor of 4. Hence, the contrast (i.e. the additionally accepted solid angle) increases significantly. From that consideration, the contrast should increase with decreasing SE energy which is in absolute contradiction to the results presented in Fig. 3. From the physics, the contrast should get larger or at least be constant (due to the dropping SE intensity) if the bandpass energy is lowered. It is not the task of the referee to do the calculations. Thus the reason for the wrong results is not obvious. Some reasons can be considered. It might be that the condition μ<<1 is not valid for high F values ($>10^{-6}$) for the low energy electrons. Secondly, it might be that the dependence of μ on W is not considered in the integration. Wrong results can be obtained, as well, if ß gets too large and the emission angle in μ is neglected (no longer B perpendicular to v). The last two points yield importance if the SE energy gets very small and the Lorentz force might deflect the SE out of the detector direction even in the half space on the detector side. In that particular case, the two above items are extremely important.

Authors: The reviewer mentioned that the contrast should get larger or at least be constant if the bandpass energy is lowered and said that the results presented in Fig. 3 are in contradiction to what was expected. Fig. 3 shows that the largest contrast is given by a filtered secondary electron (SE) energy range of 1-3 eV, followed by 0-4 eV, 0-50 eV, 3.9-4.1 eV (which is approximately equal to the mono-energetic case of 4eV), 4-8 eV and 4-50 eV. Although the solid angle of collection is inversely proportional to the SE energy [as given in eqn. (5)], the contrast is not only dependent on the solid angle of collection but is also weighted by the SE energy distribution and the range of the filtered SE energy considered. If the band of filtered energies is similar (e.g. take a passband of 2eV as shown in Fig. 7), then the lower energy filtering would give rise to a larger contrast as shown for the filtered energies of 4-6 eV, 8-10 eV and 18-20 eV (provided the SE energy distribution is a constant or decreasing over this range of energies considered). However, if the SE energy distribution increases with energy (and this occurs over the range of 0 to Φ, where Φ is the work function of the material which is taken to be 4 eV in the plotted figures), the situation is not so simple. From Fig. 7, it is seen that 1-3 eV gives a larger contrast than 2-4 eV and this is as expected. However, 0-2 eV has a lower contrast than 1-3 eV because the SE yield for the former range is lower than in the latter case.

The reviewer went on to suggest reasons for the "seemingly" wrong results and suggests that the condition μ<<1 is not valid for high field-distance integrals or F values. We recognise that this assumption may not be valid for high F values and we mentioned in the paper that the

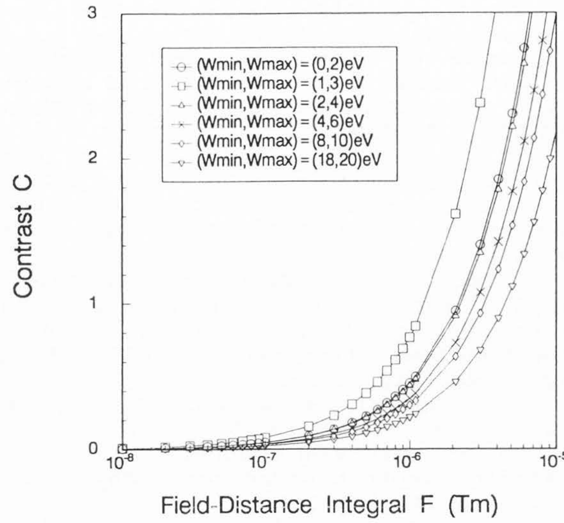

Fig. 7. Effect of energy filtering on the calculated magnetic contrast for a fixed passband of filtered energies of 2 eV. Work function Φ = 4eV.

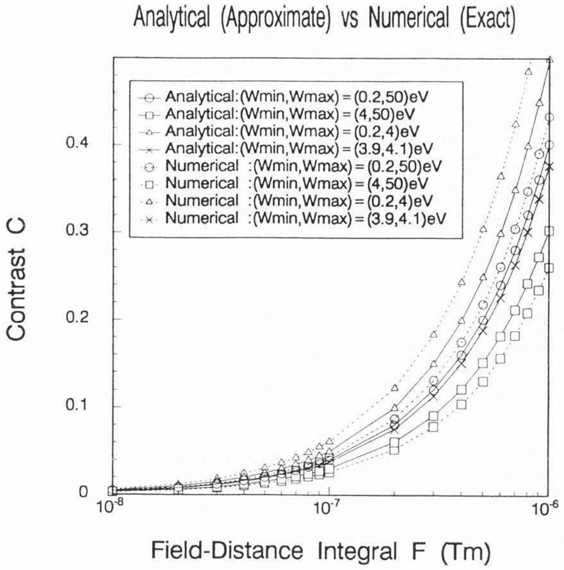

Fig. 8. Comparison of magnetic contrast calculated using the closed-form analytical (approximate) expression with that from using numerical integration based on the Cautious Adaptive Romberg Extrapolation method. The numerical solution does not assume that $|\mu|<<1$ and also uses the exact Chung and Everhart (1974) SE energy distribution without any simplifications.

approximation is reasonably accurate up to $\mu<0.4$. From the equations, it also can be seen that the model breaks down for high values of F which leads to $\mu>1$ (the particular values of F at which this occurs depend on the SE energy W through eqn. (5) in the paper), because for such situations the arc sine of μ is not defined. This, however, does not change the trend of the results for other F values as shown in Fig. 8 (which gives a comparison between the analytical (approximate) solution using the assumption of $|\mu|<<1$ in the integration and the exact (numerical) solution without invoking this assumption and which is obtained by numerical integration using the Cautious Adaptive Romberg Extrapolation Method). The exact (numerical) solution also uses the exact Chung and Everhart SE energy distribution without the simplifications described in the paper. It can be seen that the trend of the results for energy filtering is not changed in using the assumption of $|\mu|<<1$ and the simplified SE energy distribution in the closed-form analytical expressions. Our calculations also show that the error incurred in using the analytical expressions is in most cases very much less than 10% and at most not more than 20% (depending on the ranges of the filtered SE energies considered) over the range of F values ranging from 10^{-8} to 10^{-6} Tm. We have avoided carrying out calculations for values of F greater than 10^{-6} Tm because the numerical integration "blows up" when situations of $\mu>1$ occur because of the arc sine problem as mentioned above.

The reviewer also suggested a second possible reason that the dependence of μ on the SE energy W was not considered in the integration. This is incorrect because $F\sqrt{(q/2mW)}$ was actually substituted for μ (see eqn. (5) of paper) in the integration which the reviewer will discover if the calculations are carefully worked through.

The other point made by the reviewer is that wrong results can be obtained if the emission angle in μ is neglected, i.e. the magnetic field B is no longer perpendicular to the SE velocity v. In our model, the magnetic field B is pointing in the x-direction (see Fig. 1), while the velocity of the SE can be resolved into the three x, y and z components. Only the y and z components of the SE velocity will give rise to deflections and in both cases these velocity components are always perpendicular to the magnetic field B which is assumed to point in the x-direction.

Reviewer IV: The SE energy distribution calculated by Chung and Everhart is not appropriate to describe the angle dependence of SE emission. The expression derived by Chung and Everhart is an angle integrated energy distribution. Due to emission cone effects, the maximum appears at 4eV. It is not correct to divide that function by a constant factor as done in eqn. (2). If one would make an angle and energy resolved experiment, the peak appears for example near zero energy in normal emission (see for example publications about spin polarized SE emission by authors like M. Landold, J. Kirschner and H. Hopster). From that, one has to expect that the distribution gradually changes with the maximum at zero energy (normal emission) to higher energies with increasing angle. Although the solid angle argument will give the largest contribution from the large angle distribution, the wrong energy distribution could to some extent be responsible for the strange results discussed above.

Authors: It is true that the SE energy distribution by Chung and Everhart is an angle integrated distribution but the maximum does not always occur at 4eV. In fact, the maximum of the Chung and Everhart SE energy distribution occurs at an SE energy $W=\Phi/3$, where Φ is the work function of the specimen. In our simplification of the SE energy distribution to make the solution more tractable (i.e. to obtain closed form analytical expressions for the contrast and quality factor), the peak of the SE energy distribution actually occurs at an SE energy $W=\Phi$, and it so happens that we have assumed Φ to be 4eV in our calculations. The other point made is with regards to dividing the function by the constant factor of π in eqn. (2) as given by $k(W)$, which is the number of SEs emitted per unit energy, per unit solid angle. However, the exact value of the constant used does not matter because it will cancel out when the signal is normalised provided that this constant does not vary with the SE energy W. It is difficult to incorporate different constants for $k(W)$ (i.e. as a function of the SE energy W) in eqn. (2) and yet still obtain closed-form analytical expressions for the contrast factor and we are not aware of such an analytical expression for $k(W)$ if it exists at all. We do believe that this variation is small and will not affect the results greatly.