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Primary energy dependence of secondary electron polarization

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Abstract. To explain quantitatively the primary electron energy dependence of secondary electron spin polarization, we propose a simple model, where spin-dependent net mean absorption length of secondary electrons is assumed.

Secondary electron emission from a sample has been extensively studied both experimentally and theoretically in the last half century, especially in relation to the development of photomultipliers and camera tubes [1], and scanning electron microscopes [2]. The two major characteristics, energy distribution and yield dependence on primary energy are now relatively well understood. Polarization of secondary electrons from a ferromagnetic sample was first detected in 1976 by Chrobok and Hofmann [3]. The energy distribution [4–6] and primary energy dependence [7–10] of the polarization were studied experimentally by several authors. Both show significant characteristics; the polarization that is a few times larger than that of the valence electrons at the lowest secondary energy decreases with increasing secondary energy, and reaches valence polarization at several eV [4–6]; while the polarization that is smaller at lower primary energy increases with the energy and reaches a saturation value at around 1 keV [7–10]. The former characteristic is explained qualitatively by Kisker *et al* [5] and by Hopster *et al* [6], and quantitatively by Penn *et al* [11] in terms of spin-dependent mean free path. As for the latter characteristic, we have already given a qualitative explanation [10]. However, so far there is no quantitative explanation. In this paper, we present a simple model which explains quantitatively the observed primary energy dependence of secondary polarization. The polarization phenomenon of secondaries has important applications in the field of magnetic measurement, such as spin-polarized scanning electron microscopy [12–15] and spin-polarised secondary electron spectroscopy [16, 17]. Thus study of the polarization phenomenon gives a better understanding of the information obtained by those methods.

The secondary electron yield δ can be given by [18]

$$\delta = \int_0^\infty n(x, E_p) f(x) \mathrm{d}x \qquad (1)$$

where $n(x, E_p)\mathrm{d}x$ is the number of secondary electrons produced by a primary electron of energy E_p in the layer of thickness $\mathrm{d}x$ at a depth of x below the surface, and $f(x)$ is a number of secondary electrons emitted from the surface per electron produced by the primary electron beam. The function $f(x)$ is given by

$$f(x) = B \exp(-x/\lambda) \qquad (2)$$

where B is the escape probability at the surface and λ is a net mean absorption length of secondaries including cascade process.

If we assume the constant energy loss per unit path length of primary electron [19] $n(x, E_p)$ is given by

$$n(x, E_p) = \frac{1}{E_d} \frac{E_p}{R \cos\theta} \qquad (3)$$

where E_d is the average energy required to create a secondary electron, R and θ are, respectively, the range and the incident angle (measured from sample surface normal) of a primary electron. By substituting equations (2) and (3) for equation (1), one gets

$$\delta = B \frac{E_p}{E_d} \frac{\lambda}{R \cos\theta} [1 - \exp(-R \cos\theta / \lambda)]. \qquad (4)$$

The range R (cm) is given semi-empirically by various other researchers [20-22]

$$R = 1.6 \times 10^{18} (E_p^{4/3} / N Z) \qquad (5)$$

where E_p is in keV, N is the atomic density (cm^{-3}) and Z is the atomic number.

To consider the spin-polarization of secondary electrons, we assume the mutually different net mean absorption length λ_+ and λ_- for positive (majority) and negative (minority) spin electrons, respectively. The assumption is reasonable since the net mean absorption length should be ruled by elastic and inelastic mean free paths which are reported to be spin-dependent

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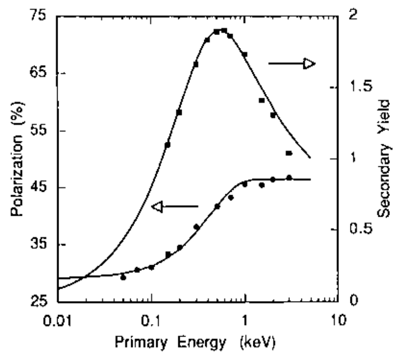

Figure 1. Polarization and total yield of secondary electrons emitted from a clean Fe(110) as a function of primary electron energy. The polarization is for 1 eV energy, and the incident angle of the primary electrons is 48° from the sample surface normal. Experimental data (solid squares and circles) are from Paul *et al* [9]. Solid lines are the calculations where the mean escape depth of $\lambda = 0.914$ nm of the secondaries is assumed for the yield curve, and spin-dependent mean escape depths of $\lambda_{\pm} = 0.914(1 \pm 0.2)$ nm are assumed for the polarization curve.

[11, 23, 24]. The secondary spin-polarization is also affected by spin-polarization P_0 of electrons created directly by primary electrons. By using these $\lambda_{\pm}$ and P_0, spin-dependent secondary yields $\delta_{\pm}$ are given by

$$\delta_{\pm} = \frac{1 \pm P_0}{2} B \frac{E_p}{E_d} \frac{\lambda_{\pm}}{R \cos\theta} [1 - \exp(-R \cos\theta / \lambda_{\pm})]. \tag{6}$$

The polarization of secondary electrons P is then given by

$$P = \frac{\delta_+ - \delta_-}{\delta_+ + \delta_-}. \tag{7}$$

Figure 1 shows the primary electron energy dependence of polarization and the total yield of secondary electrons emitted from a clean Fe(110) surface [10]. The polarization is for 1 eV energy. The incident angle θ of primary electrons is 48°. To give a quantitative explanation to the observed polarization, we first determined spin-average net mean absorption length λ

$$\lambda = (\lambda_+ + \lambda_-)/2, \tag{8}$$

as follows. In equation (4), if we define $R_{max} \cos\theta$ as $R \cos\theta$ which gives maximum yield, the relationship between λ and $R_{max} \cos\theta$ can be derived from equations (4) and (5), and is given by

$$\lambda = 0.428 R_{max} \cos\theta. \tag{9}$$

From E_p = 540 eV, which gives maximum yield in figure 1, $R_{max} \cos 48°$ is calculated to be 21.3 Å using equation (5), and λ to be 9.14 Å using equation (9). Substituting λ = 9.14 Å and B/E_d = 9.10 (keV^{-1}) with equation (4) gives the solid yield curve in figure 1, which matches well with the experimental data. Using the same λ and B/E_d but $\theta = 0$ gives maximum yield $\delta_{max} = 1.4$ at $E_p = 0.4$ keV. These values are in good agreement with $\delta_{max} = 1.1$–1.3 and $E_p = 0.4$ keV observed at normal primary incidence for an iron sample [2].

The λ = 9.14 Å can be compared with the net mean absorption length x_α presented by Ono and Kanaya [25]. Different from λ, which is defined in a one-dimensional system, x_α is defined in a three-dimensional system, where secondary electrons diffuse spherically with the radial net absorption length of x_α. The relationship between λ and x_α is easily calculated and

$$\lambda = 2/3 x_\alpha. \tag{10}$$

From the given value of x_α = 16.9 Å for iron, λ is calcurated to be 11.3 Å, which is comparable to the λ = 9.14 Å obtained above.

Here, we define asymmetry A of spin-dependent net mean absorption lengths as

$$A = \frac{\lambda_+ - \lambda_-}{\lambda_+ + \lambda_-}. \tag{11}$$

From equations (8) and (11),

$$\lambda_{\pm} = \lambda(1 \pm A). \tag{12}$$

Now, the undetermined variables in equation (6) are P_0 and A. The saturation polarization P_s at $E_p \to \infty$ is given from equation (7) by

$$P_s = \lim_{E_p \to \infty} P = \frac{A + P_0}{1 + P_0 A}. \tag{13}$$

Thus the asymmetry A is obtained from the experimental value P_s and P_0. Although P_0 should be the conduction band polarization, we choose its value so that the result calculated by equation (7) matches well with the experimental data.

Since the equations developed above are for total secondary electrons, strictly speaking, it is not correct to apply them to secondary electrons with special energy. However, since the energy distribution of secondary electrons has a maximum at around a few electron volts and rapidly decreases with increasing energy, it is not a bad approximation to represent total secondary electrons by the electrons with 1 eV energy. The best fit is obtained when $P_0 = 0.29$ and $A = 0.20$, as shown by the solid line in figure 1. The P_0 of 0.29 is in good agreement with the iron conduction band polarization of 0.27.

To confirm the validity of this model, we apply it to previously reported experimental data for a permalloy ($Ni_{78.5}Fe_{21.5}$) polycrystal [7]. The results are shown in figure 2. In this case, θ = 58° and roughly 0–4 eV secondaries are collected. R is again calculated from equation (5). The best fit is obtained for λ = 8.0 Å, $P_0 = 0.050$ and $A = 0.0623$. The value of λ is comparable to 9.9 Å calcurated by using equation (10) where x_α = 14.8 Å is obtained from [25]. Regarding the value of P_0, since we do not know the conduction-band polarization of the permalloy, we cannot say much about it. However, the conduction-band polarization of

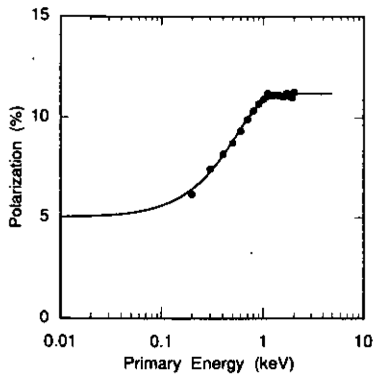

Figure 2. Polarization of secondary electrons emitted from a clean permalloy polycrystal as a function of primary electron energy. The incident angle of the primary electrons is 58° from the sample surface normal. Experimental data (solid circles) are from Hastev *et al* [6]. The solid line is the calculation where spin-dependent mean escape depths of $\lambda_{\pm} = 8.0(1 \pm 0.0623)$ Å are assumed.

nickel, which is the main constituent of the permalloy, is 0.55, which is comparable to the observed value of 0.5.

In conclusion, we have presented a simple model for explaining the primary energy dependence of the secondary polarization. In this model, the polarization is determined by the conduction-band electron polarization and spin-dependent net mean absorption lengths of the secondaries.

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