Nuclear Instruments and Methods in Physics Research B 288 (2012) 23–27

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Algorithm for evaluating layer thickness based on electron average energy shift analysis

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ARTICLE INFO

Article history:
Received 19 December 2011
Received in revised form 19 July 2012
Available online 31 July 2012

Keywords:
Electron beam
Inelastic scattering
Mean free path
Electron spectrum
Solid surface

ABSTRACT

Layer thickness estimation method using the average energy shift of electrons passing through the layer is presented. The traditional approach of analyzing the signal electron is extended by using the spectral distribution of the energy shift of the electrons. In this approach, the tendency of the multiple inelastic scattering spectra to increase the average energy shift, depending on the number of inelastic interactions, is utilized to estimate the thickness of a layer. An algorithm that uses this spectral energy shift to evaluate the layer thickness was developed and validated against calculated spectrum from a known materials and thicknesses. The thickness evaluation by this algorithm is in a good agreement with the known thickness.

1. Introduction

Surface analysis of thin films is used to determine film thickness, buried layers and surface composition. This type of analysis is essential in several industrial fields such as semiconductor, microelectronics, photonics and Microsystems [1] as well as for scientific research. Film thickness measurements are performed in several methods, ranging from optical techniques [2–5], X-ray techniques [6,7], RBS and NRA [8], to electron scanning and photoelectron emission techniques [9–12]. In this paper analysis of a 10 keV electron beam spectrum emerging from a sample is performed. Typically, most electron surface analysis techniques use electrons from a few eV up to 2000 eV. In recent decades, the improved performance of third generation synchrotrons enables the use of high intensity and more energetic electrons than before [13]. Therefore, data of elastic and inelastic interactions at higher energies are available for spectrum analysis [14].

The basic type of thickness measurement, using electrons, is to measure the signal electron after it had interacted with the sample. A common technique is the X-ray photoelectron spectroscopy (XPS) [9]. In XPS an incident photon beam interacts with a reference substrate and emits photoelectrons creating the reference detected signal. Then an overlayered sample is subjected to the same procedure. When the electrons pass through the overlayer, some of the electrons lose energy and the signal intensity decrease. The overlayer thickness can then be calculated using tabulated electron inelastic mean free path (IMFP) values, and the ratio between the intensities of the reference and the overlayered samples. In order to elucidate the signal electron from the background, noises such as bulk inelastic scattering, surface excitations, X-ray satellites and intrinsic losses [12], that occur both at the signal generation in the substrate and in the overlayer, must be taken into consideration.

Extensive work was carried out over the years to eliminate these disturbances from the electron spectra measurements and to evaluate the electron IMFP [15–21]. However, there are still many assumptions in the field of electron transport. Two main methods of evaluating IMFP are the elastic peak electron spectroscopy (EPES) [22] and calculated IMFP from experimental optical data [23]. Recently, new calculated IMFP values based on optical data for energies up to 30 keV were published by Tanuma et al. [14]. When calculating layer thickness using the signal electron, as mentioned above, the reduction in the signal intensity due to inelastic collisions determines the layer thickness. Bulk inelastic scattering is one of the main contributors to the disturbance that affects the electron spectra. That is so since the majority of the energy loss occurs in the bulk material. The shortcoming using IMFP is as the electron trajectory length is dominated by the elastic scattering effect [15], the electron projection length from a given angle may differ from its actual path length. A correction to the electron projection length due to consideration of the electron elastic scattering is given by the electron effective attenuation length (EAL) [24–26].

The aim of this paper is to present a quantitative analytic algorithm to evaluate the thickness of a layer. It is based on the correlation between the electron path length and the electron average

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http://dx.doi.org/10.1016/j.nimb.2012.07.025

energy shift. This correlation is encoded in the inelastic scattering part of the electron spectra. The newly developed algorithm, presented in Section 2, is based on the analysis of multiple inelastic scattering.

Multiple inelastic scattering spectra are determined by the probability for n-fold scatterings, and the energy-loss distribution after n inelastic collisions [15,16]. The calculation of multiple inelastic scattering is used for deconvolution procedure in various electron spectroscopies, subtracting it from the electron spectrum to isolate the signal electron peak. The advantage of our new approach for evaluating layer thickness is the use of the inelastic spectrum to measure the average energy loss. The proposed algorithm converts from average energy loss to layer thickness.

Deconvolution of the bulk losses requires a calculated spectrum that considers only the electron inelastic effects. To generate these spectra, the multiple inelastic scattering effect should be considered with three possible options: the electron had no interaction in the layer; single interaction in the layer; or multiple interactions in the layer. In the first case the electron retains its original energy. In the second case, the electron energy depends on the probability to lose a certain amount of energy during that interaction. This probability is described by the differential inverse inelastic mean free path (DIIMFP) [27].

When looking at the graph of DIIMFP vs. energy [15], the probability for a collision is different for different initial electron energies. However, the energy loss probability in a collision remains nearly the same for different initial electron energies. Since the energy loss probability is independent on the initial electron energy and depends on the property of the material, the energy loss distribution for an individual collision is taken from the normalized DIIMFP. Finally, the energy loss distribution for an electron that had undergone more than one collision can be obtained by self convolution on the normalized DIIMFP. The energy loss distribution obtained from the self convolution on the normalized DIIMFP has to be multiplied by the electron probability to undergone that number of interactions. Summation on all the possible number of interactions yields the required electron spectrum.

Section 2 formulates the theory of the new proposed method. A mathematical description for the building of the inelastic scattering spectra is given in Section 3, and the resulted values are summarized in Section 4.

2. Theory

The average energy shift (E_{Av}) for electrons with initial energy E_0, which have undergone multiple inelastic scatterings in a specific layer, can be calculated from spectrum measurements. The average energy shift caused by the multiple inelastic scattering, can also be defined as

$$E_{Av} = \overline{n} \cdot \overline{T} \tag{1}$$

where $\overline{n}$ is the average number of inelastic interactions an electron undergoes in a layer with thickness x, and $\overline{T}$ is the mean energy-loss per collision. This relation is possible since the mean energy-loss is independent on the incident electron energy. As shown in Ref. [15] using this lack of dependency is adequate for the energy range of 5–10 keV. When analyzing the electron inelastic data, good approximation to the energy dependence of the IMFP is

$$\lambda(E) = \lambda(E_0) \cdot \left(\frac{E}{E_0}\right)^{\alpha} \tag{2}$$

$$E = E_0 - E_{Av} \tag{3}$$

where $\lambda(E)$ denote the energy dependent IMFP, and α is a fit coefficient. Inserting Eqs. (1) and (3) into Eq. (2), a collision dependence of the IMFP is obtained

$$\lambda(n) = \lambda_0 \cdot \left(\frac{E_0 - n \cdot \overline{T}}{E_0}\right)^{\alpha} = \lambda_0 \cdot \left(1 - \frac{\overline{T}}{E_0} \cdot n\right)^{\alpha} \tag{4}$$

From Eq. (4) it follows that $\lambda(n)$ depends only on the properties of the material, and the number of interactions an electron has undergone. For clarity, the switch between $\overline{n}$ in Eq. (1) to n in Eq. (4) is justified since Eq. (4) gives the IMFP for a given electron, and is not an average over large amount of electrons as in Eq. (1). The electron IMFP is the distance at which the electrons have undergone, on average, one inelastic collision. At distance x we can define that the electrons, on average, had undergone between $n-1$ and n inelastic collisions. Recalling that after every collision the IMFP changes (due to energy-loss), x can be defined as an interpolation between

$$\sum_{k=0}^{n-1} \lambda_k \tag{6}$$

and

$$\sum_{k=0}^{n} \lambda_k \tag{7}$$

where λ_k is the collision dependent IMFP.

The electron average energy-loss per collision for electrons with initial energy E_0 in a certain material is known [23,27]. Using Eq. (1) the average number of interactions $\overline{n}$ can be calculated. Interpolating Eqs. (7) and (8) to $\overline{n}$ will give the layer thickness estimation.

In order to illustrate the use of this algorithm, we calculated electron inelastic spectra based on multiple inelastic scattering evaluation data.

3. Spectrum calculation

The spectrum of electrons traveling through thin layers was computed using Werner's multiple inelastic scattering evaluation [15,16]. Four materials were selected (Al, Cu Au and Ag), and for each material the spectrum was calculated for four different layer thicknesses, 500, 1000, 1500 and 2000 Å. These thicknesses were chosen to cover the range in which there is limited data.

This calculation accounts only for inelastic scattering and produces the electrons energy-loss spectrum. The electron incident energy was chosen to be 10 keV and the electron beam is perpendicular to the surface. The energy-loss spectrum is always normalized to unity so it refers only to electrons that have penetrated the layer in a straight line. For the calculation of the energy-loss spectrum, the DIIMFP is essential. The DIIMFP for non-relativistic electron with energy E can be obtained from optical data as follows [27]

$$W(T,E) = \frac{1}{\pi\alpha_0 E}\int_{q-}^{q+}\frac{dq}{q} Im\frac{-1}{\varepsilon(q,T)} \tag{8}$$

where $\varepsilon(q,T)$ is the dielectric constant of the medium for momentum transfer q, and a_0 is the Bohr radius. Exchange effects are neglected. The mean energy-loss in an individual collision is given by the first moment of the normalized DIIMFP.

$$\langle T(E)\rangle = \int_0^{\infty} T\omega(T,E)dT \tag{9}$$

where $\omega(T,E)$ is the normalized DIIMFP. The probability distribution $W_n(s)$ for n-fold scattering as a function of the travelled path length is essential for evaluating the partial intensities and the energy-loss function [14]. When the interaction depends on the energy this quantity is given by [16]

$$\frac{dW_n}{dS} = -\frac{W_n}{\lambda_n} + \frac{W_{n-1}}{\lambda_{n-1}} \tag{10}$$