Improved hydrogen and deuterium depth profiling in polymers using low energy forward recoil spectrometry

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We demonstrate that the hydrogen and deuterium depth resolution of forward recoil spectrometry (FRES) is greatly improved by utilizing 1.3 MeV $^4$He ions and sample tilting. The near-surface depth resolution is measured on samples of alternating deuterated and protonated polystyrene layers, each ca 250 Å thick. The depth resolution at the surface is dramatically improved (from 800 Å to 250 Å) as the incident beam energy decreases from 3.0 to 1.3 MeV. We call this technique low-energy FRES (LE-FRES) to differentiate it from standard FRES, which uses 3 MeV $^4$He ions incident at $\theta = 75^\circ$. Furthermore, by using a glancing incident or exit geometry, the LE-FRES depth resolution is improved to ca 125 Å, which is comparable to the resolution of secondary ion mass spectrometry and nuclear reaction analysis. Measurements of the energy and glancing angle dependence of the depth resolution are in quantitative agreement with theoretical predictions. The probing depth of LE-FRES is found to have a maximum at $\theta = 71^\circ$ and decreases at glancing exit and incident angles. A contour plot illustrates the relationship between depth resolution and probing depth and provides guidance for future users of LE-FRES.

1. Introduction

In polymer physics, theoretical predictions of surface and interface phenomena have driven experimentalists to develop depth profiling techniques with the requisite spatial resolution. For example, forward recoil spectrometry (FRES) studies of polymer melts provided early evidence that reptation is the dominant diffusion mechanism for highly entangled polymers [1]. Following its development for diffusion studies, FRES proved invaluable as a tool for studying tracer and mutual diffusion in miscible polymer blends [2], small molecule diffusion in polymer glasses [3], surface segregation in polymer blends [4], and interface segregation of diblock copolymers [5]. However, conventional FRES lacks the depth resolution required for studying narrow (ca 100 Å) interfaces because a thick (typically 10 μm) stopper foil limits the depth resolution to ca 800 Å. Sokolov et al. [6] achieved a significant improvement in resolution, ca 300 Å, by replacing the stopper foil with a time-of-flight (TOF) apparatus. However, compared with standard FRES, TOF-FRES requires a more complicated and expensive detection system and has a lower sensitivity for detecting hydrogen and deuterium. In this manuscript we will describe a novel application of FRES, called low-energy FRES (LE-FRES), which retains the simplicity of FRES while providing excellent depth resolution (ca 150 Å).

The major thrust of this work is to improve the depth resolution of FRES. In section 2, a brief review of the principles of the FRES technique is presented. In section 3, the depth resolution is defined in terms of the energy resolution and the effective stopping powers. The various contributions to the energy resolution are discussed here and later calculated in section 5.3. Section 4 outlines the sample design and experimental setup. The dependence of FRES (LE-FRES) spectra on incident beam energy and sample tilting is presented in sections 5.1 and 5.2, respectively. In section 5.3, the experimental values of the energy and depth resolutions are compared with theoretical calculations. Section 5.4 introduces the concept of probing depth and demonstrates the influence of glancing angle geometry and stopper foil thickness on the probing depth. The contour maps shown in section 5.5 summarize the relationship between probing depth and depth resolution.

2. Basics of the FRES experiment

A schematic representation of the LE-FRES geometry is shown in Fig. 1. A monoenergetic beam of $^3$He $^+$. 

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ions with an initial energy $E_o = 1.3$ MeV impinges on a sample at an angle $\theta$ with respect to the target normal. These He ions collide with hydrogen (H), deuterium (D), and other nuclei. Being lighter than He, the H and D recoil from the sample surface and near surface. At the sample surface, the energy $E_{\text{out}}$ of the recoiled nucleus is given by

$$E_{\text{out}} = kE_o,$$

where $k$ is the kinematic factor for elastic scattering,

$$k = \frac{4M_e M_p}{(M_e + M_p)^2} \cos^2(180 - \phi).$$

Here $M_e$ and $M_p$ are the masses of the recoiling nucleus and projectile, and $\phi$ is the angle between the incident beam and detector. If the recoil collision between the He and target nuclei is sub-surface, the energy of the H or D originating from a depth $x$ is

$$E_{\text{out}} = kE_o - [S]x,$$

where

$$[S] = \frac{kS_{\text{in}}}{\sin(90 - \theta)} + \frac{S_{\text{out}}}{\sin(90 + \theta - \phi)}$$

is called the energy loss factor. The stopping powers or energy losses of the particles along their inward and outward paths are $S_{\text{in}} = (dE_{\text{in}}/dx)$ and $S_{\text{out}} = (dE_{\text{out}}/dx)$, respectively. Using Eqs. (2)–(4), the energy of H and D nuclei can be related to the depth from which they originated.

In addition to the recoiling D and H nuclei, helium ions are forward scattered from the carbon and silicon nuclei in the polymer and substrate, respectively. To prevent the detection of helium ions from masking the hydrogen and deuterium signals, a stopper foil is placed in front of the energy-sensitive surface-barrier detector (see Fig. 1). For incident $^4$He at 3 MeV, a thick (ca 11 $\mu$m) Mylar [7] foil is typically used. Because of energy straggling of D and H within the foil, the D and H energy resolutions are limited by the foil thickness. Because thinner foils cause less straggling, the resolution can be improved by using lower incident beam energies, as in LE-FRES. The H and D also lose energy $\Delta E_{\text{foil}}$ in the stopper foil,

$$E_{\text{det}} = kE_o - [S]x \cdot \Delta E_{\text{foil}},$$

so that the energy of the detected recoils is $E_{\text{det}}$. Using Eqs. (1)–(5), the detected energy can be converted to a depth scale for the H and D in the sample.

The yield of the FRES energy spectrum depends on the atomic concentration of H and/or D in the sample. The recoil yield for a singly charged projectile is [8]

$$Y(E_{\text{det}}) = \frac{(Q/e) N(x) \sigma(E_i, \phi) \Omega \delta E_{\text{det}}}{\cos(90 - \theta) dE_{\text{det}}/dx},$$

where $Q$ is the integrated charge, $e$ is the electron charge, $N(x)$ represents the atomic concentration of nuclei at a depth $x$, $\sigma(E_i, \phi)$ is the scattering cross-section evaluated at the energy $E_i$ of the incident projectile just before collision. $\Omega$ is the detector solid angle, $\delta E_{\text{det}}$ defines the energy width of a channel in the multichannel analyzer, and $dE_{\text{det}}/dx$ is the effective stopping power of the recoiled particles [8,9]. Using Eqs. (1)–(6), the FRES spectrum of recoil yield versus $E_{\text{det}}$ can be converted to a depth profile for the D and H nuclei in the sample.

3. Depth resolution

Depth resolution is a key factor to consider when choosing a technique for interfacial studies. For ion beam analysis, the depth resolution is defined as

$$\delta x = \frac{\Delta E_{\text{tot}}}{dE_{\text{det}}/dx},$$

where $\Delta E_{\text{tot}}$ is the total energy resolution [10]. This expression shows that the best depth resolution is achieved when the energy resolution is a minimum and the effective stopping power a maximum. In the LE FRES technique, $\Delta E_{\text{tot}}$ is decreased and $dE_{\text{det}}/dx$ increased by using a thin stopper foil and glancing angle geometry, respectively.

To evaluate Eq. (7), the contributions to $\Delta E_{\text{tot}}$ must be identified and determined. These are:

i) $\Delta E_d$, the detector energy resolution [11];

ii) $\Delta E_m$, the energy broadening due to multiple scattering;

iii) $\Delta E_s$, the energy straggling in the sample;

iv) $\Delta E_f$, the energy straggling in the stopper foil; and

v) $\Delta E_g$, the geometrical broadening due to beam divergence and the finite acceptance angle of detector.

Following convention, these contributions add in quadrature [12]:

$$\Delta E_{\text{tot}}^2 = \Delta E_d^2 + \Delta E_m^2 + \Delta E_s^2 + \Delta E_f^2 + \Delta E_g^2.$$
For our experimental conditions, the energy resolution of the detector is constant [13]. However, factors ii–v depend on the experimental setup and, therefore, must be calculated [12,14]. We have developed a computer program [15] that evaluates the contributions to the total energy resolution (section 5.3), calculates the theoretical FRES spectrum.

Straggling results from the statistical nature of the interactions between the incident particle and the sample. Moreover, as the incident ion beam traverses the sample, the diameter of the beam broadens because the ions make multiple small-angle collisions with the nuclei in the sample. The lateral and angular spread, including path length fluctuations, of the incoming and outgoing particles have been estimated from theories of multiple scattering [16,17]. As shown in section 5.3, multiple scattering is particularly important for glancing angle geometry and recoil collisions below the surface. Energy straggling is similar to multiple scattering in that an energetic particle loses energy via many individual encounters with electrons in the sample and stopper foil. Because of the statistical nature of these interactions, the energy loss by the ions has a Gaussian distribution with a width corresponding to the energy straggling. The essential result of the Bohr theory is that straggling is independent of energy and increases as the square root of the film (i.e., sample or foil) thickness [18]. Whereas \( \Delta E_t \) limits the resolution of conventional FRES, we will show that foil straggling decreases by a factor of ca 1.5 when the foil thickness is reduced from 11 to 3 \( \mu \)m. Geometric broadening is calculated following the procedure of Turos and Mayer [12]. Generally, it is due to two main contributions. The first one comes from the strong dependence of the kinematic factor \( k \) on \( \phi \) as can be seen in Eq. (1), the second mechanism reflects a distribution of path lengths as well as distribution of energy losses in the material. Because of the excellent collimation of the incident beam, only geometric broadening attributed to the beam width and finite detector acceptance angle is important. As shown by Turos and Mayer, kinematical spread and path length difference compensate each other near \( \theta = 87.5^\circ \) and therefore, geometric broadening is minimized near this angle. However, at lower values of \( \theta \), this broadening makes a significant contribution to the overall resolution. A detailed discussion of geometric broadening is given in refs. [8] and [12]. Note that lateral inhomogeneities, such as surface roughness, in the sample and stopper foil are ignored in the calculation of the total energy resolution. As shown in section 5.3, the measured and predicted energy resolutions are in excellent agreement, suggesting that sample roughness is not important for our experimental conditions.

Knowing the energy resolution, the depth resolution can be calculated if \( [S] \), and thus \( dE_{\text{det}}/dx \), is determined (see Eq. (7)). Recall that the best depth resolution requires a small energy resolution and a large energy loss factor. At high energies, the stopping power is mainly electronic and therefore increases as the particle energy decreases [19,20]. In the case of poly styrene, \( [S] \) increases by a factor of two as the incident helium energy decreases from 3 to 1.3 MeV [20]. Additionally, \( [S] \) can be magnified by increasing the total path length that a particle travels through the sample. As shown by Eq. (4), a geometrical increase in path length is achieved by using a glancing incident or exit geometry [12]. In section 5, we will show that LE-FRES makes use of both a low energy incident beam and glancing angle geometry to dramatically improve the depth resolution.

4. Experimental

4.1. Sample preparation

To determine the depth resolution as a function of probing depth, samples of alternating layers of polystyrene (hPS) and deuterated polystyrene (dPS) were prepared. The hPS and dPS characteristics are listed in Table 1. The bottom layer was formed by spin-coating a toluene solution of hPS onto a glass slide, floating the dried hPS film onto a bath of deionized water, and picking the hPS up with a clean silicon wafer. This film was dried under vacuum for 1 d at 96°C to remove residual solvent. The next layer was spin-coated onto glass from a toluene solution of dPS, floated off on deionized water, and picked up with the hPS/silicon sample. This sample was then dried under vacuum. The spin-coating and floating procedure was repeated until four layers, dPS/hPS/dPS/hPS/silicon, were deposited on the silicon substrate. This multilayer sandwich, dPS/hPS/dPS/hPS/silicon, will be called sample A whereas the complementary sample, hPS/dPS/hPS/dPS/silicon, will be denoted as sample B. To minimize the number of fitting parameters in the FRES data analysis [21], the film thickness of each layer was measured by ellipsometry. The layer thickness ranged from 180 to 330 \( \AA \).

4.2. Experimental setup

The LE-FRES measurements were performed on a model SSDH Pelletron tandem accelerator (National
Electrostatics Corporation, WI), interfaced with a custom-designed scattering chamber. Sample position was precisely controlled using a goniometer with four degrees of freedom. The scattering angle $\theta$ was adjusted in 0.5° increments [23], whereas the angle $\phi$ between the incident beam and detector was fixed at 150° [24]. The LE-FRES geometry is shown in Fig. 1. After leaving the sample, the elastically scattered particles pass through a stopper foil placed in front of a surface barrier detector. A unique feature of our scattering chamber is that the type and thickness of the stopper foil are easily varied via a rotating turret which is externally controlled and holds up to four stopper foils.

5. Results

5.1. Effect of incident beam energy on the depth resolution

The depth resolution of conventional FRES can be greatly improved by decreasing the energy of the incident helium particles from 3.0 to 1.3 MeV. Fig. 2a shows the FRES spectrum of sample A analyzed with 3.0 MeV $^4\text{He}^+$ at $\theta = 75^\circ$. An aluminum stopper foil, 10.35 µm thick, is used. Because of straggling in the stopper foil, the deuterium yields from the two dPS layers overlap, suggesting that the near-surface spatial resolution is greater than the thickness (250 Å) of the hPS spacer. Likewise, the two hPS layers cannot be resolved. Knowing the stopping power of He, D and H in polystyrene [19,20] and cross-sections for D and H [25], a theoretical yield (solid line) can be computed by convoluting the D and H concentration profiles with the instrumental resolution functions for D and H, Gaussians with full width at half-maximum of 750 Å and 780 Å, respectively. These surface resolutions are in good agreement with published values [1].

By decreasing the incident beam energy to 1.3 MeV, the depth resolution improves dramatically, as demonstrated by the two distinguishable deuterium maxima shown in Fig. 2b. Qualitatively, this observation indicates that the D resolution is comparable to the thickness (ca 250 Å) of the hPS spacer. The solid line in Fig. 2b corresponds to the concentration profile convoluted with the instrumental resolution function. The FWHMs corresponding to the first (dPS) and second (hPS) layers are 250 and 300 Å, respectively. This three-fold improvement in depth resolution results from two factors. First, at low incident beam energies, a thin (4.5 µm) Mylar stopper foil is sufficient to stop the forward scattered He and, as a result, the energy straggling of H and D in the foil is reduced. Second, the stopping powers for He, H, and D in polystyrene are increased by nearly a factor of 2 because of the decrease in the incident beam energy from 3 to 1.3 MeV [20]. Correspondingly, the depth resolution decreases by a factor of 2 (see Eq. (7)). We call this technique low-energy forward recoil spectrometry (or LE-FRES) in order to distinguish it from conventional FRES.

5.2. Depth resolution at glancing incident and exit angles

The depth resolution can be further improved by varying the angle, $\theta$, between the incoming He beam and the sample normal. For the standard FRES geometry ($\theta = 75^\circ$) the path lengths of the incoming and outgoing ions are the same. However, in the glancing exit geometry ($\theta < 75^\circ$) the path length of the outgoing particle is longer than the incident particle. Corre-
Fig. 3. Sample tilt for glancing (a) exit and (b) incident angles.

The conventional FRES geometry is $\theta = 75^\circ$.

...consequently, at glancing incident angles ($\theta > 75^\circ$), the incoming He particle travels a longer path in the sample than the outgoing particles. The main disadvantage of the glancing incident angle geometry is the increase in the beam footprint on the sample. Both geometries are shown in Fig. 3.

Fig. 4a shows the LE-FRES spectra of sample B as $\theta$ decreases from 70° to 62.5°. Because of the glancing exit geometry, a 3.0 $\mu$m thick Mylar foil is sufficient to prevent the forward scattered He signal (at energies less than 390 keV) from masking the D and H yields. A comparison of Figs. 4a and 2b ($\theta = 75^\circ$) shows that the energy separation between the D (and H) maxima is larger at glancing angles. As $\theta$ decreases from 70° to 62.5°, the energy separation between maxima increases because the path length of the recoiling particle increases. For the $\theta = 62.5^\circ$ spectrum, the H and D yields are significantly less than their values in the $\theta = 65^\circ$ and $\theta = 75^\circ$ spectra. Several factors contribute to the decrease in yield at the extreme glancing exit angle. First, the H and D peaks broaden because the number of detected recoils is spread over more channels. Also, the yield can be lowered if the detector solid angle (0.44 msr) is overestimated due to the detector being eclipsed by the sample holder or by the sample itself. Moreover, because of their low energy and proximity to the sample surface, the recoiled particles can be deflected by the sample bias (300 V). This bias related deflection would decrease the H yield more than D as observed in Fig. 4a.

The depth resolution is also improved by increasing the path length of the incident He ions in the polystyrene. Fig. 4b shows the LE-FRES spectra of sample A as a function of increasing incident angle, $\theta = 80^\circ$, 82.5° and 85°. Here a 4.5 $\mu$m thick Mylar foil is used. Again, using Fig. 2b as a guide, the depth resolu-
tion has improved, as demonstrated by the two distinguishable D (and H) maxima in Fig. 4b. At $\theta = 82.5^\circ$ and $85^\circ$, a small H peak near the recoil energy of 350 keV is observed. This surface contamination is likely due to the hydrocarbon and water vapor present in the scattering chamber which is at a pressure of 1 to $5 \times 10^{-7}$ Torr. Upon trapping the turbomolecular pump with liquid nitrogen, the chamber pressure decreases to $5 \times 10^{-8}$ Torr and the H signal decreases significantly. Note that this H layer is not observed in Fig. 2a, demonstrating the superior resolution of LE-FRES over conventional FRES.

Given the yield versus energy spectra, the concentration profile of the H or D species can be calculated using Eq. (6). Fig. 4c shows the D concentration profile for sample A analyzed at two angles, $\theta = 75^\circ$ and $\theta = 85^\circ$. The raw spectra are shown in Figs. 2b and 4b. Qualitatively, the two D signals are distinguishable at $\theta = 85^\circ$ (glancing incident geometry) whereas the signals overlap at $\theta = 75^\circ$ (standard FRES geometry). The depth resolutions at the surface are 145 Å for $\theta = 85^\circ$ and 250 Å for $\theta = 75^\circ$. As mentioned previously, the improvement in resolution is due to the increased path length at glancing angle. In the next section, the depth resolution will be calculated and compared with experimental values such as those given by Fig. 4c.

### 5.3. Energy and depth resolution

Fig. 5 shows the total and individual energy resolutions calculated for D in polystyrene using 1.3 MeV $^4$He$^+$ at $\theta = 70^\circ$, $65^\circ$ and $62.5^\circ$. The Mylar foil thick-

![Diagram](image)

Fig. 5. Theoretical energy resolution of deuterium in polystyrene as a function of depth. The experimental parameters are $E_0 = 1.3$ MeV, a 3.0 μm thick Mylar stopper foil and (a) $\theta = 70^\circ$, (b) $65^\circ$ and (c) $62.5^\circ$. The calculated curves correspond to the detector resolution (thin solid line), energy straggling in the stopper foil (long-dashed line), energy straggling in the sample (long-short dashed line), geometrical broadening (short dashed line), multiple scattering (dotted line) and total energy resolution (thick solid line).
ness is 3.0 μm. At the highest angle, 70°, the energy resolution is ca 20 keV at the surface and slowly increases to ca 32 keV at a depth of 1000 Å. At the lower angles, the resolution degrades more rapidly with increasing depth. For example, at θ = 62.5°, the energy resolution increases from 20 keV at the surface to 60 keV at a depth of 650 Å. Examination of the individual contributions shows that near the surface (< 200 Å), the total energy resolution is dominated by straggling in the stopper foil, the detector resolution, and geometry. However, beneath the surface (> 400 Å), multiple scattering dominates and drives the total energy resolution to larger values. The increase in multiple scattering at glancing angles results from the increase in the total path length in the sample.

Fig. 6 shows the energy and depth resolutions for D and H in polystyrene analyzed by 1.3 MeV 4He+ at θ = 70°, 65°, and 62.5°. The Mylar foil thickness is 3.0 μm. The experimental energy resolutions for D (solid squares) and H (solid triangles) [26] are determined by fitting the LE-FRES spectra with simulations based on step-function concentration profiles convoluted with the instrumental resolution functions. Because the energy resolution deteriorates with depth, the FWHM of the resolution function corresponding to each layer was allowed to vary. For example, the LE-FRES spectrum from sample A is used to determine the D energy resolution at the surface and at a depth of 450 Å; for the same sample, the H energy resolution is determined at depths of 200 and 600 Å. Note that the energy resolutions are the only fitting parameters required to simulate the LE-FRES spectra. The agreement between the experimental energy resolution and that predicted by Eq. (8) is excellent. The H and D depth resolutions can be calculated from Eq. (7) and their values are given on the right hand axis in Fig. 6. At 70°, the D and H depth resolutions are ca 250 Å and ca 325 Å at a depth of 700 Å. This resolution is at

![Fig. 6. Energy resolution (left scale) and depth resolution (right scale) for deuterium (■) and hydrogen (▲) in polystyrene for 1.3 MeV 4He+ ions incident at (a) θ = 70°, (b) 65° and (c) 62.5°. The solid and dashed lines are calculated from Eqs. (7) and (8). A 3.0 μm thick Mylar stopper foil is used. For clarity the surface resolution values are shifted by 50 Å.](image)
least 3 times better than measurements taken with the standard FRES setup. The depth resolution can be further improved by tilting the target. For example, Fig. 6c shows that the D and H surface resolutions are ca 125 Å, a resolution equivalent to secondary ion mass spectrometry [27] and nuclear reaction analysis [28] and 6 times better than FRES. Although D and H have similar energy resolutions, the depth resolution of D is always better than H because D has a larger kinematic factor (see Eq. 2). The agreement between the experimental and calculated depth resolutions is very good.

In this section, the near-surface depth resolution is shown to be greatly improved by using glancing angle geometry. In the next section, the effect of glancing angle geometry on the probing depth is discussed.

5.4. Probing depth

The probing depth is the maximum distance beneath the surface that can be investigated for a particular energy, material, and experimental geometry. Fig. 7 shows the calculated probing depths for D and H in polystyrene as a function of θ for an incident He
energy of 1.3 MeV and stopper foil thicknesses of (a) 3.0 μm and (b) 4.5 μm. When using the 3.0 μm foil, the probing depth is limited by the overlap in yield between the forward scattered helium ions and the D or H signal. Note that the maximum probing depth is shifted towards lower angles because the glancing incident geometry enhances the energy loss of the incoming He [19,20]. For samples with both D and H at the surface (e.g., a blend of dPS and hPS), the probing depth for D is limited by the energy overlap between the surface H and buried D as demonstrated in Fig. 4b. In this case, the deuterium probing depth is the difference between the solid and dashed lines in Fig. 7. When a 4.5 μm Mylar foil is used, the overall probing depth is only limited by the electronic noise at ca 50 keV. Fig. 7b shows that the probing depths for H and D increase by 1000 Å when the foil thickness increases from 3.0 to 4.5 μm. In the next section, we will show that this improvement in probing depth occurs with a negligible loss in depth resolution.

5.5. Contour map of the depth resolution and probing depth

Contour plots of the deuterium depth resolution and probing depth as a function of target tilting are shown in Fig. 8. The contour lines correspond to a constant depth resolution and serve as a guide for choosing the experimental geometry for a particular application. Calculations for Mylar stopper foils of 3.0 and 4.5 μm are shown in Figs. 8a and 8b, respectively. Both figures quantitatively illustrate the tradeoff between depth resolution and probing depth. For example, in Fig. 8a the probing depth is only 1500 Å at θ = 85°; however, the near-surface depth resolution (ca 140 Å) makes this setup ideal for measuring surface segregation in polymer blends. As discussed in section 5.3 and reiterated in Fig. 8, the depth resolution of LE-FRES is better at glancing incident angles (θ > 75°).

Whereas the probing depth increases by 1000 Å, the depth resolution remains relatively constant as the foil thickness increases from 3.0 to 4.5 μm. This result follows from Bohr theory [18] which predicts that the energy straggling in the foil, ΔE_f, varies as the square root of the foil thickness. Therefore, as the foil thickness increases from 3.0 to 4.5 μm, ΔE_f increases by only ca 3 keV. Although the decrease in total energy resolution, Eq. (8), is quite small, the probing depth is dramatically improved (by ca 35%) as the foil thickness increases.

6. Conclusion

In this paper, LE-FRES is introduced as a novel ion beam technique for depth profiling H and D in materials. The depth resolution at the surface is dramatically improved (from 800 to 250 Å) as the incident beam energy decreases from 3.0 to 1.3 MeV. In LE-FRES, the use of a 1.3 MeV 4He beam improves the depth resolution because the stopping powers are enhanced and the stopper foil thickness reduced as compared to standard FRES which uses 3.0 MeV He ions. By using a glancing incident or exit geometry, the LE-FRES depth resolution is improved to ca 125 Å, which is comparable to the resolution of secondary ion mass spectrometry and nuclear reaction analysis. This additional improvement in resolution is a consequence of the angular dependence of the stopping power values.

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References


[13] Canberra Industries PIP detector, FWHM 12 keV, 100 μm depletion depth, area 25 mm².


[20] The version 92.02 of TRIM (TRansport of Ions in Matter) computer code written by J.F. Ziegler and J.P. Biersack was used to generate tables of stopping powers of ions in polystyrene.

[21] Data analysis was performed using the program RUMP [22] and checked using our computation package [15].


[23] The smallest angular increment for our goniometer is 0.01°.

[24] In ref. [12], Turos and Mayer show that the optimum angle for the analysis of the forward recoiled particles is at φ ~ 150°.


[26] Each symbol represents the average of three measurements taken from the same sample type.
