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Limitations to Depth Resolution in High-Energy, Heavy-Ion Elastic Recoil Detection Analysis

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Abstract

The depth resolution of heavy-ion elastic recoil detection analysis was examined for Al and Co thin films ranging in thickness from 100 to 400 nm. Measurements were performed with 154 MeV Au ions as the incident beam, and recoils were detected using a gas ionisation detector. Energy spectra were extracted for the Al and Co recoils and the depth resolution determined as a function of film thickness from the width of the high- and low- energy edges. These results were compared with theoretical estimates calculated using the computer program DEPTH.

Introduction

High-energy, heavy ions (1-2 MeV/AMU) offer many advantages for elastic recoil detection analysis (ERDA) of thin-film materials [1-7]. A wide range of elements can be analysed simultaneously as long as $z_2 < z_1$, where z_1 is the atomic number of the primary ion and z_2 is the atomic number of the recoil ion. The sensitivity is enhanced due to the $\sim z_1^4$ dependence of the scattering cross-section and the method has approximately equal sensitivity to all light elements [$2 \leq z_2 \leq 50$]. The depth resolution is also improved because of the high stopping power of heavy ions and the detection of scattered primary ions is reduced due to the narrow scattering cone of heavy ions scattering from light elements. These advantages have led several groups [1-7] to explore applications of heavy ion elastic recoil detection analysis (HIERDA).

A large solid-angle, position-sensitive gas-ionisation detector is well suited to HIERDA measurements [3-7]. It provides efficient recoil detection and thus minimises exposure of the sample to the ion beam. Such a detector has recently been built and installed at the 14UD accelerator laboratory of the Australian National University in Canberra [7]. This paper reports on preliminary experiments with this system which were carried out to explore the limitations of depth-profiling with HIERDA.

Experimental Details

Thin films of Co were evaporated onto Si and Ge substrates and thin films of Al were evaporated onto Ge substrates using either thermal or electron-beam evaporation. Film thicknesses varied from 100 nm to 400 nm, as indicated by a quartz crystal thickness monitor and verified for selected samples by Rutherford backscattering spectrometry. HIERDA measurements were undertaken using 154 MeV ^{197}Au ions with charge state 13^+ and a typical beam current of 1 nA. The beam had an energy spread of < 50 keV, a maximum angular spread of $0.01°$ and was collimated to produce a 1mm x 1mm square spot on the sample. Recoils were detected with a position-sensitive gas-ionisation detector located 300 mm from the sample. For these particular measurements, the detector solid angle was limited to 0.02 mSr by a 1.5 mm diameter aperture. This obviated the need for kinematic energy correction of the data. The scattering angle was fixed at $\vartheta_s = 45°$ and the incident and exit angles were $22.5°$. During analysis, the vacuum pressure inside the scattering chamber was $\sim 10^{-7}$ mbar. Further details of the experimental system are presented in a separate contribution [7].

Results and Discussion

The depth-profiling of individual elements following a HIERDA measurement requires the measured energy spectrum for each element to be transformed into a concentration versus depth profile. This requires accurate knowledge of the scattering cross-sections and stopping powers of the projectile and recoil ions. Limitations to the depth-resolution include the energy and angular spread of the incident beam, the intrinsic detector resolution, the kinematic energy spread due to the finite size of the beam and detector, the energy straggling in the sample and the detector entrance window, and energy spread due to multiple scattering.

Calculations performed with the computer code DEPTH [8-10], using Bohr straggling with Chu correction [8], and assuming an intrinsic detector resolution of 1.2%, show that the surface energy resolution of the HIERDA measurement is dominated by the intrinsic resolution of the detector and geometric effects associated with the finite beam size and detector solid angle. As the film thickness increases, the depth resolution deteriorates, largely due to the increasing contribution of multiple scattering. These results show that the energy (depth) resolution is limited by the detector configuration for film thicknesses < 100 nm but by ion-solid interaction processes for film thicknesses > 100 nm. It is also interesting to note that the main limitation comes from multiple scattering of the primary and recoiled ions, straggling is of less significance.

Energy-loss (ΔE) versus total energy (E) spectra were collected for Al and Co films of varying thicknesses from which energy spectra of Al and Co recoils were extracted. The energy width of the spectra increased with increasing film thickness, as expected. However, attempts to fit these recoil spectra with the computer program RUMP [11] highlighted discrepancies between the tabulated and actual stopping powers. For example, the thickness of Co films was overestimated by 30%. This was confirmed by calculations using stopping powers from TRIM'95 [12] and the surface energy approximation [13]. These discrepancies suggests that the tabulated stopping powers are lower than the actual values.

The depth resolution of the ERDA measurement was determined experimentally from the high- and low-energy edges of the Al and Co energy spectra. These spectra were fitted with a function of the form:

$$Y(E)=(mE+b)[\mathbf{erfc}((E-E_f)/\delta E_f) - \mathbf{erfc}((E-E_b)/\delta E_b)] \qquad (1)$$

where **erfc** is the complimentary error function, E is the recoil energy and E_f and E_b are the centroids of the high- and low-energy edges of the spectra, respectively. The factor (mE+b), with fitting parameters m and b, was used to approximate the energy dependence of the yield. The width δE_f is representative of the energy resolution for surface scattering and δE_b represents the energy resolution for recoils coming from the film-substrate interface. The depth resolution was calculated by transforming δE_f and δE_b to FWHM values, dividing by the energy width of the spectrum and multiplying by the nominal film thickness. This assumes that the energy width of the spectrum is linearly proportional to the film thickness, a reasonable approximation for the film thicknesses employed in the present study.

Fig. 1 shows the depth resolution measured for Al and Co films together with the theoretical predictions of the computer program DEPTH. For surface scattering, the measured depth resolution for Al (16 nm) and Co (12 nm) films is in excellent agreement with the calculated values. However, with increasing film thickness, the measured values consistently exceed the

predicted resolution. This suggests that either the films have some inherent roughness or inhomogeneity or that the theoretical calculations underestimate the depth resolution. Rutherford backscattering (RBS) analysis of a 200 nm thick Al film showed no evidence for roughness before or after analysis, however, similar analysis of a 200 nm Co film showed that this film had an intrinsic roughness of ~10 nm and that this increased to ~15 nm after prolonged irradiation with the Au beam. RBS analysis on and off the irradiated spot also confirmed some beam induced oxidation of the Co film. For Co, this roughness is sufficient to account for the observed discrepancy between the measured and calculated depth resolution. For Al, the situation is less clear. Stopping power uncertainties clearly affect the calculated depth resolution. However, as discussed above, the tabulated stopping powers underestimate the experimental values. Increasing the stopping powers in the DEPTH calculation reduces the calculated depth resolution, increasing the difference between experiment and theory.

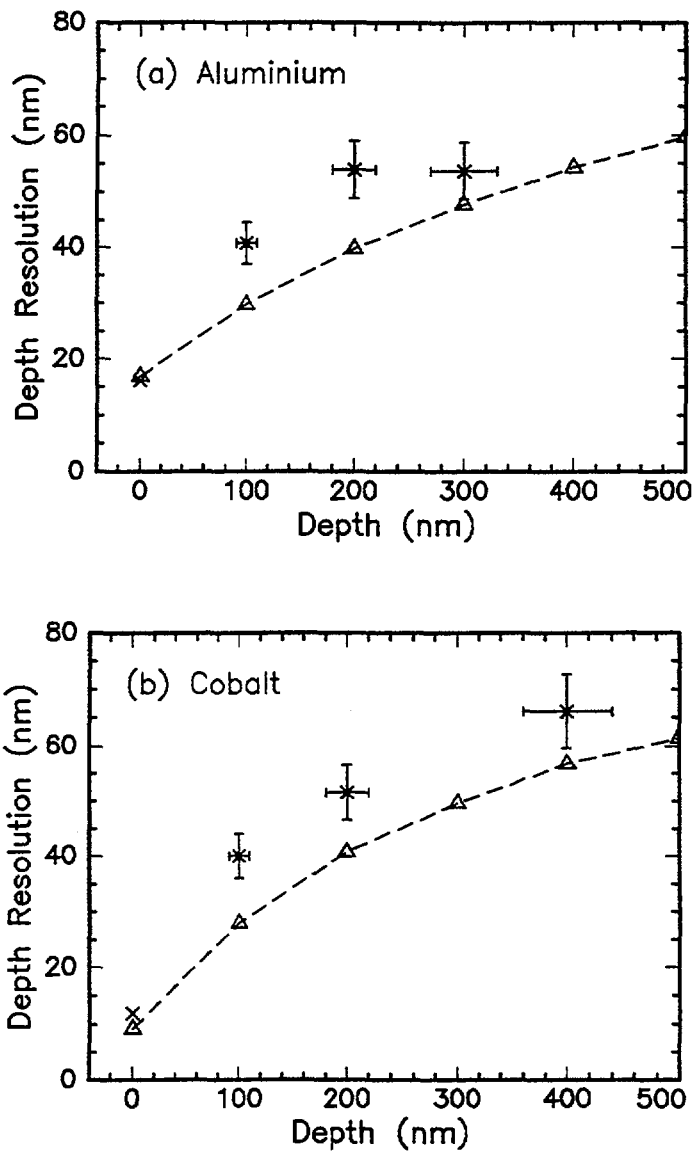

Figure 1: Comparison of measured (crosses) and calculated (triangles and dashed lines) depth resolution for a) Al and b) Co thin films.

Conclusions

HIERDA can provide high-sensitivity, composition-versus-depth analysis of materials. In this study, depth resolution measurements were performed on Al and Co films as a function of film thickness. The measured values were compared with the theoretical predictions of the computer code DEPTH [8-10]. The experimental and theoretical depth resolution showed similar trends with increasing film thickness but the experimental data consistently exceeded that predicted by DEPTH. Rutherford backscattering analysis of Co films before and after analysis showed that they were intrinsically rough and that exposure to the analysis beam caused additional beam-induced roughening and beam-induced oxidation. This accounted for the observed difference between the experimental and theoretical values. Similar analysis of Al films showed no such effects. The discrepancy between experiment and theory remains unresolved in this case.

The observation of beam-induced roughening and beam-induced oxidation of Co films highlights the importance of minimising sample exposure to the analysis beam and justifies the use of a large solid angle, position-sensitive detector for HIERDA analysis [7].

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