Nuclear Instruments and Methods in Physics Research B 392 (2017) 102–105

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Determination of the area density and composition of alloy film using dual alpha particle energy loss

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ARTICLE INFO

Article history:
Received 30 August 2016
Received in revised form 20 November 2016
Accepted 9 December 2016
Available online 22 December 2016

Keywords:
Dual alpha particle energy loss
Area density and composition
Binary alloy film
Inertial confinement fusion

ABSTRACT

A novel method based on dual α-particles energy loss (DAEL) is proposed for measuring the area density and composition of binary alloy films. In order to obtain a dual-energy α-particles source, an ingenious design that utilizes the transmitted α-particles traveling the thin film as a new α-particles source is presented. Using the DAEL technique, the area density and composition of Au/Cu film are determined accurately with an uncertainty of better than 10%. Finally, some measures for improving the combined uncertainty are discussed.

1. Introduction

In laser inertial confinement fusion (ICF) experiments, alloy films is one of the key target components, which is used extensively to control the X-ray spectrum produced from the interaction of high power laser and matter and improve the radiative opacity of material. To obtain quantitative spectral information and opacity data, the area density and composition of the alloy films need to be characterized accurately [1]. A variety of techniques have been applied to measure the composition of alloy film, including X-ray fluorescence spectrometer (XRF), proton induced X-ray emission (PIXE), Rutherford backscattering spectrometry(RBS) and atomic emission spectrometry(AES) [2,3]. In addition, an electronic balance has been used to determine the area density of thin films with known dimensions. Each of techniques has its limitations. The accuracy of XRF and PIXE depends on standards with known density and composition. RBS needs complex equipments and AES is a destructive testing method. More importantly, most of these techniques cannot measure the area density and composition simultaneously.

Owing to the many advantages of α-particles energy loss (AEL) method, such as simple physical model and concise measuring system, no standards for quantitation and nondestructive testing, it has been widely used in various fields. M. Beaudoin has demonstrated that AEL method could be applied in situ to monitor the thickness, and the specific elemental concentration can be inferred from the ratio of average energy loss rates in different layers such as GaAs, AlGaAs and InGaAs [4]. M.C. Fujiwara utilized AEL technique to determine the thickness and uniformity of thin films with a relative accuracy of better than 1% [5]. Patrick G. Grant measured the mass of biomolecules using a commercially available α-particle spectrometer [6]. Y Levy measured the etch rate of films via AEL technique[7]. Moreover, some non-planar samples and textured membranes were determined using AEL method [8–9]. However, there is no report about the determination of area density and composition simultaneously using AEL technique. In this letter, a simple and novel method based on AEL is proposed that can determinate the area density and composition of the binary alloy film in a measurement.

2. Theoretical analysis

When α-particles with initial energy E_1 passes through a pure metal film, the thickness of metal film can be given by

$$h = \int_{E_2}^{E_1} \frac{dE}{N\varepsilon(E)} \tag{1}$$

where $\varepsilon(E)$ is the stopping cross-section of film material; N is the atom density; E_2 is the energy of transmitted α-particles.

In numerical calculation, Eq. (1) can be rewritten as

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http://dx.doi.org/10.1016/j.nimb.2016.12.021
0168-583X/

$$\sum_{i=1}^{n}\Delta x_i = \sum_{i=1}^{n}\frac{\Delta E}{nN\varepsilon(E_i)} \quad (2)$$

where n is the number of sub-layers, Δx_i is the thickness of sub-layers, ΔE is the energy loss.

As for the alloy film composed of elements a and b, according to Bragg rule, the energies loss of α-particles with dual initial energy E_1 and E_3 traveling the film can be written as

$$\begin{aligned}\sum_{i=1}^{n}\Delta x_i &= \sum_{i=1}^{n}\frac{\Delta E}{n(N_a\varepsilon_a(E_i)+N_b\varepsilon_b(E_i))}\\ \sum_{i=1}^{n}\Delta x_i' &= \sum_{i=1}^{n}\frac{\Delta E'}{n(N_a\varepsilon_a(E_i')+N_b\varepsilon_b(E_i'))}\end{aligned} \quad (3)$$

where $\varepsilon_a(E_i)$ and $\varepsilon_b(E_i)$ are the stopping cross-section of elements a and b, respectively. N_a and N_b are the atomic area density of elements a and b, respectively. $\Delta E'$ are the energy loss of E_3 traveling the film.

Utilizing Eq. (3), the ratio y of N_b/N_a can be rewritten as

$$\frac{\Delta E}{\Delta E'} = \frac{\sum_{i=1}^{n}(\varepsilon_a(E_i)+y\varepsilon_b(E_i))}{\sum_{i=1}^{n}(\varepsilon_a(E_i')+y\varepsilon_b(E_i'))} \quad (4)$$

According to linear Eq. (4), the composition of alloy film can be calculated conveniently, and the area density can be easily inferred from the Eq. (3). In principle, when the α-particles with initial energy $E_i(i = 1 - n)$ pass through the alloy thin film composed of elements $m_j(i = 1 - m)$, different energy losses can be obtained. In the case of $n > m$, the area density and composition of the film can be calculated conveniently from the measured energy losses. It is noted that the stopping cross section depends on the film composition and incident α-particles initial energy, and the difference between incident initial energies of α-particles need to be considered carefully to ensure this method works perfectly and improve the accuracy of measured results.

3. Experimental apparatus

To utilize DAEL technique for determining the area density and composition of thin films simultaneously, a key issue is how to obtain dual-energy or multi-energy α-particles source in the experiment. In general, there are three ways to get α-particles sources with dual-energy or multi-energy. The first configuration is to construct a combined source consisting of the different α-particles sources and the measurements can be performed in a measurement. The second arrangement is to measure the sample using different α-particles sources successively, that is, the measurement needs to be accomplished in two measurements. The last one is to use the isotopes sources with more than one alpha line such as ^{239}Pu. However, the three ways have their disadvantages. The first one is costly and not suitable for small sample analysis due to the large geometric structure. The second one is also costly and time-consuming. The third one has only specific and changeless discrete energies and intensity distribution that may not be suitable for some thin films. In order to obtain a α-particle with specific initial energy, we can take advantage of the transmitted α-particles traveling the thin film as a new α-particles source. Because the thickness and composition of thin films can be designed and fabricated according to the specific requirements, the corresponding transmitted α-particles energy is also controllable.

The schematic diagram of experimental apparatus is shown in Fig. 1. A ^{241}Am source is chosen due to its long half-life of 432.6 years, which implies high stability, and almost single energy of 5.486 MeV, which means no the transmitted peak overlapping. A Au-Si detector was used to measure the α-particles energy and the data were collected with a multi channel analyzer (MCA). All equipments were installed in a vacuum chamber to minimize the influence of air on determination of the α-particles energy. The thin film with a hole is placed in the middle of the collimator, and the corresponding transmitted α-particles are used as the new radiative source. In this arrangement, a typical spectrum obtained from the Au-Si detector in a measurement has four characteristic peaks, which can be used to calculate the area density and composition of films.

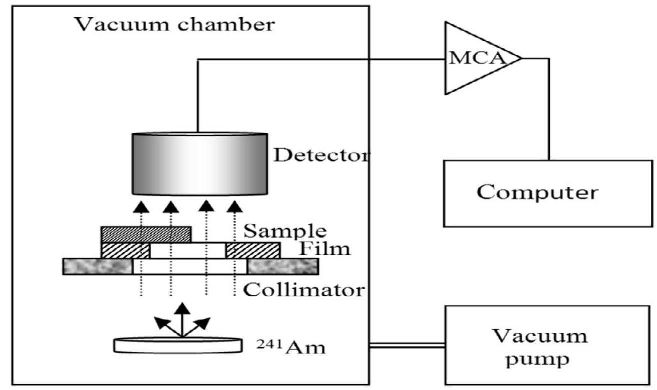

Fig. 1. The schematic diagram of experimental arrangement.

4. Results and discussions

To verify the feasibility and reliability of DAEL method for determining the area density and composition of alloy films simultaneously, experimental measurements are performed on a Au/Cu alloy thin film. In this work, the transmitted α-particles energy through a uniform gold film of about 1 μm thickness is used as the new α-particles source. An electronic pulser is applied to measure directly the electronic offset of the MCA, then, the ^{241}Am source is devoted to calibrate the energy scale of MCA by calculating the ratio of the characteristic energy of the ^{241}Am source to the

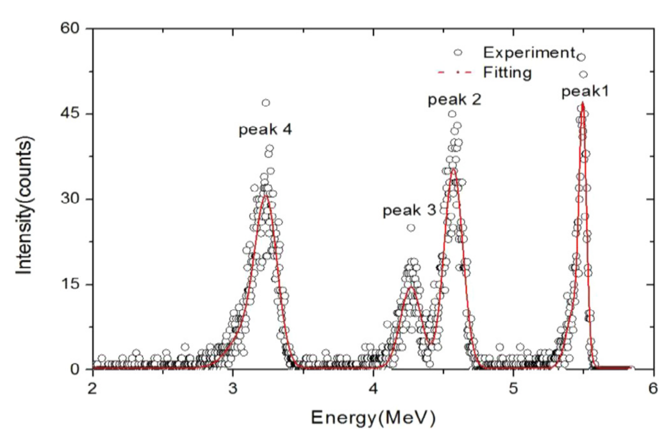

Fig. 2. A typical spectrum of Au/Cu thin film. The closed circles is the signal obtained from the Au-Si detector and the solid line shows fitting peaks. The weighted average energies of the peaks labeled 1–4 are 5.477 MeV,4.5665 - MeV,4.2608 MeV and 3.2062 MeV, respectively. The peaks labeled 2–4 represent the α-particles traveling from Au, Au/Cu alloy and their superposition films, respectively. The differences between peak 1 and peak 3, peak 2 and peak 4 are used to determine the area density and composition of the film according to Eqs. (2) and (3).