Microelectronic Engineering 88 (2011) 844–847

Contents lists available at ScienceDirect

Microelectronic Engineering

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

Mechanical characterization of aluminium nanofilms

G. Guisbiers [a,b,*], E. Herth [a], L. Buchaillot [a]

[a] IEMN, CNRS-UMR8520, Scientific City, Avenue Henri Poincaré BP60069, Villeneuve d'Ascq 59652, France
[b] UCL, Institute of Mechanics, Materials and Civil Engineering, 2 Place Sainte Barbe, 1348 Louvain-La-Neuve, Belgium

ARTICLE INFO

Article history:
Available online 23 June 2010

Keywords:
Nanofilm
Mechanics
Nanoindentation
Aluminium
Hall–Petch

ABSTRACT

The mechanical properties (Young's modulus, hardness, wear resistance) of aluminium nanofilms on silicon substrate are studied. Size effect on these mechanical properties are exhibited. Young's modulus, hardness and wear resistance increases when the thickness is reduced. Experimental investigations have been led by atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and nanoindentation. Compared to the bulk values, hardness and wear resistance of one aluminium nanofilm (thickness = 100 nm) have increased by a factor ∼7 whereas the Young's modulus only increased by a term ∼15%. By comparing mechanical properties between high and low melting point materials, we conclude that high melting point materials have a decreasing behaviour of the Young's modulus with size whereas low melting point materials have an increasing one.

1. Introduction

Aluminium is the third most abundant element in the Earth's crust after oxygen and silicon [1]. It is therefore a metal widely used, especially in nano/micro-electronics [2] due to its low melting temperature and high electrical conductivity for metallization, a fabrication step which properly interconnect circuits elements at the surface of non-metallic substrates. It is well established now that by shrinking the size of a material, its materials properties are modified [3]. Size dependence of material properties in the nanometer regime arises primarily due to the high surface to volume ratio and quantum confinement effects [4]. Focusing our investigation on the size-dependent mechanical properties, Young's modulus (E), hardness (H) and wear resistance (H/E) values of aluminium nanofilms are determined. Microscopic and mechanical characterization have been led on these films by atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM) and nanoindentation which is a popular and powerful method to provide quantitative informations on the mechanical properties of materials at the nanoscale.

2. Experimental

Aluminium nanofilms have been deposited by e-beam evaporation on silicon substrates [5]. The residual stress state had been measured previously by laser deflection in Ref. [5]. The nanofilms have now been investigated by AFM (Nanoscope IIIa from Veeco), SEM (Ultra 55 from Zeiss), TEM (CM200, Philips) and Nanoindenter (XP from MTS). AFM measurement allows the grain size to be obtained and allows a three-dimensional cartography of the surface (Fig. 1) whereas SEM measurement allows a two-dimensional cartography of the surface (Fig. 2). TEM gives cross-sectional view of the films and then reveals the shape of the grains (Fig. 3). Nanoindentation measurements (using a Berkovich indenter) allows the Young's modulus, hardness and wear resistance to be determined [6,7]. A typical load–displacement curve is indicated in Fig. 4. The profile include three segments: loading to peak load, holding at the peak load, and unloading back to zero load. A holding period of 10 s has been applied to diminish time-dependent effects.

3. Results and discussion

3.1. Nanoindentation results

From nanoindentation, hardness and Young's modulus can be extracted with the Oliver and Pharr method [6]. From the scan indent, hardness, H, can be determined and is defined by:

$$H = P_{\max}/A \qquad (1)$$

where $P_{\max}$ is the peak indentation load and A is the projected area of the hardness impression.

From the load–displacement curve, the Young's modulus, E, can be determined and is defined by:

$$E = (1-\nu^2)\left[\sqrt{\frac{A}{\pi}}\frac{2}{S}\beta - \frac{(1-\nu_i^2)}{E_i}\right]^{-1} \qquad (2)$$

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* Corresponding author at: UCL, Institute of Mechanics, Materials and Civil Engineering, 2 Place Sainte Barbe, Louvain-La-Neuve 1348, Belgium. Tel.: +32 10 47 30 59; fax: +32 10 47 40 28.
E-mail address: gregory.guisbiers@physics.org (G. Guisbiers).

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doi:10.1016/j.mee.2010.06.028

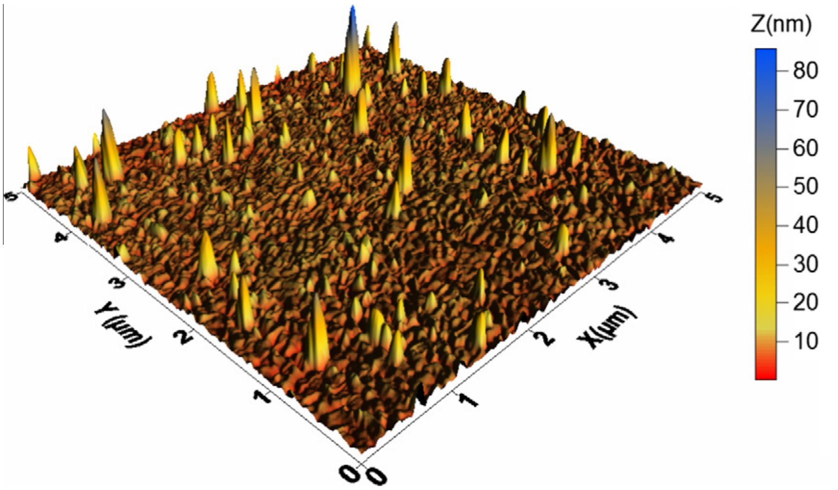

Fig. 1. AFM image of an aluminium nanofilm with a thickness equal to 200 nm (done in tapping mode with a cantilever frequency of 300 kHz).

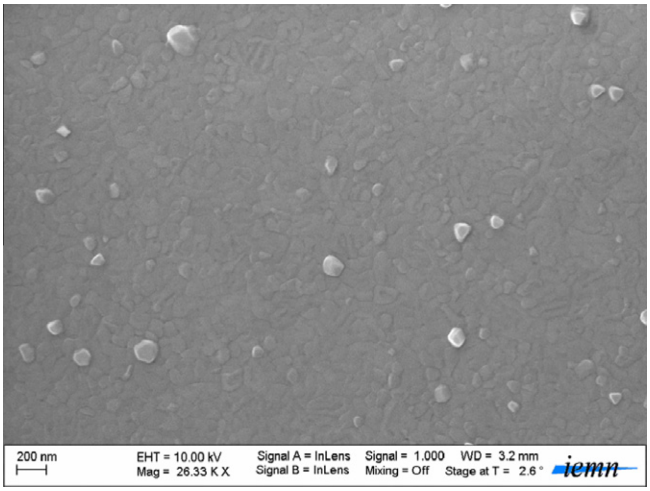

Fig. 2. SEM image of an aluminium nanofilm with a thickness equal to 200 nm.

where v is the Poisson's ratio of the investigated material and E_i and v_i are the same parameters for the indenter. S is the stiffness obtained as the tangent slope of the unloading part at the peak indentation load in the load–displacement curve.

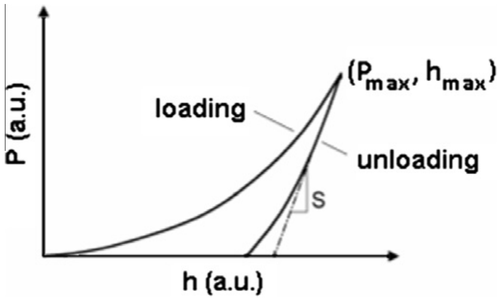

Fig. 4. Typical load–displacement curve obtained from nanoindentation.

For a Berkovitch indenter (three sided pyramid) as used in this paper, $\beta = 1.034$ and the area is given by $A = 3\sqrt{3}h_f^2\tan^2\theta$, where h_f is the final depth of the contact impression after unloading and $\theta = 65.27°$ is the face angle with the central axis of the indenter [8]. It has been reported that the usual indentation size effect (measured hardness usually increases with decreasing depth of penetration) is observed for indents with depth to thickness ratio of up to ~0.2 [9]. Therefore, indentations were realized with depth values higher than 20 nm, 40 nm and 80 nm for film thickness equal to 100 nm, 200 nm and 400 nm, respectively.

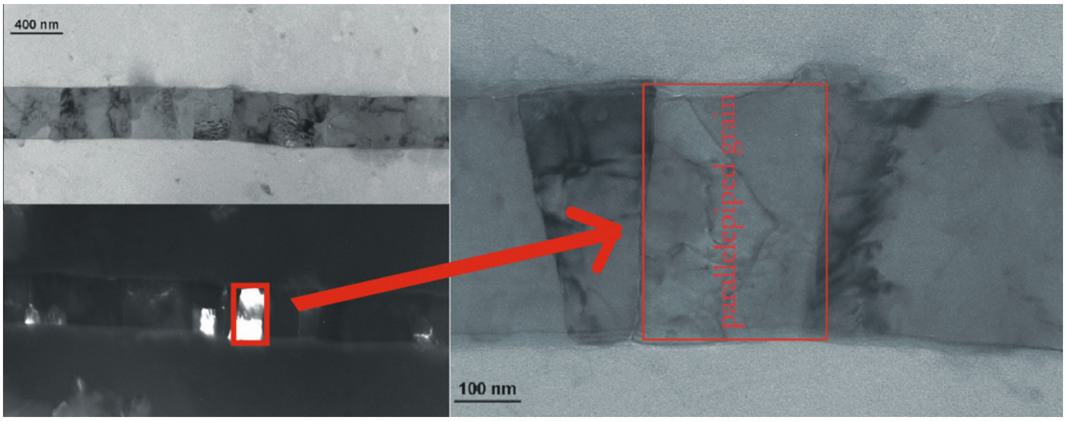

Fig. 3. TEM image of an aluminium nanofilm with a thickness equal to 200 nm. The grain shape is a parallelepiped in agreement with the structure zone model of evaporated thin films.