*Applied Mechanics and Materials Vol. 606 (2014) pp 105-109* *Online: 2014-08-11*
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*doi:10.4028/www.scientific.net/AMM.606.105*

# Aluminum-Copper Bilayers Thin Films Deposited at Room Temperature by RF magnetron Sputtering

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**Keywords:** Magnetron sputtering; XRD; FE-SEM; AFM

**Abstract.** In this work, the effects of room temperature deposition on the structural properties of Al-Cu bilayers thin films were investigated. The bilayers were sputter deposited by RF magnetron sputtering on Si {100} wafers without substrate heating. The thickness of each layer is approximately 500 nm thick. Characterization were performed with grazing incidence X-ray diffraction (XRD), field emission scanning electron microscope (FE-SEM) with chemical analysis by energy dispersive X-ray (EDX) and atomic force microscope (AFM). From deposition, polycrystalline Al and Cu thin films with {111} preferred orientation were grown on the surface of the substrate. The bilayers is nanocrystalline, having very fine crystallites size of less than 20 nm. With minimal microstrain influence, each layer shows different morphologies between the columnar and non columnar structure. AFM analysis revealed that the bilayers top surface exhibits higher surface roughness ($R_a$ = 20 nm) due to low adatoms surface mobility during deposition.

## Introduction

Multilayer Aluminum-Copper thin films are frequently used as metallization in Si-based integrated circuit where intermetallic Al-Cu alloys are intentionally developed to enhance the properties (e.g. electromigration, hardness, heat resistance) [1,2,3]. Contrary, excessive growth of the intermetallic phases must be avoided as it will cause the degradation of the device [4, 5]. The fabrication of Al-Cu thin films is achieved by several different methods. One of the methods is by depositing Al-Cu alloy thin films through sputter deposition of manufactured alloy target having specific composition [6]. Another method is layer by layer deposition of Al and Cu on substrate followed by thermal diffusion [7,8]. However, the microstructure (including grain size, crystallographic orientation, lattice defects, surface morphology, and phase's composition) of sputter-deposited thin films is depending on the deposition condition during sputtering. Thin film deposition without substrate heating may pose to problems on certain aspect such as film's integrity. Furthermore, the effect of room temperature deposition on surface roughness may directly affect the resistivity [8]. In this paper, RF magnetron sputtering was chosen as a method of fabrication for the bilayer Al-Cu thin films. Instead of the common DC method, the RF method has a rather unique advantage but rarely been used to deposit conductor materials and thus become the motivation of this work. Al-Cu thin films were deposited on a Si substrate without any substrate heating to avoid unnecessary diffusion between the bilayers. Thin film microstructures were analyzed by X-ray diffraction (XRD) technique and surface morphologies were measured using field emission scanning electron microscope (FE-SEM) and atomic force microscope (AFM).

## Experimental

In this work, Al-Cu bilayers were sequentially deposited by RF magnetron sputtering using high purity (99.99%) Aluminum and Copper target. The working chamber of the sputtering system was evacuated to a base pressure below than 1 x $10^{-5}$ Torr. High purity argon (Ar) gas was induced later into the sputtering chamber with a flow rate of 30 sccm (standard cubic centimeters per minutes) while the chamber pressure was kept at 20 mTorr. Cu was firstly deposited followed by Al deposition on mirror polished {100} Si wafer at room temperature using RF power of 150 Watt and 250 Watt respectively. The distance between the target and substrate is 14 cm and substrate was rotated at 10 rpm during deposition. The deposition rate for Al and Cu is 0.07 nm/s and 0.125 nm/s, respectively and the final thickness of each layer is equal which around 500 nm.

**Characterization** Studies on the crystallographic properties of the thin films were performed by X-ray diffractometer (PANalytical X'pert Pro) using glancing angle of 0.5° to minimize the peak from Si substrate. The cross-sectional morphology of the bilayers was studied under FE-SEM (Zeiss-Supra 35VP) along with chemical mapping by energy dispersive X-ray (EDX). The surface morphology of the top layers is measured and captured using AFM (model SII NanoNavi).

## Results and Discussion

**XRD analysis** The bilayers sample is illuminated with X-rays of CuKα ($\lambda\alpha$ = 1.5406 Å) and the intensity of the reflected radiation is recorded by goniometer in the range of 30° – 90° of 2θ (Fig. 1). The diffraction peaks which correspond to Al and Cu phases were indexed according to standard JCPDS data *01-071-3760* (f.c.c Al) and *01-071-3761* (f.c.c Cu), respectively. The value of lattice spacings and lattice parameters were as listed in Table 1.

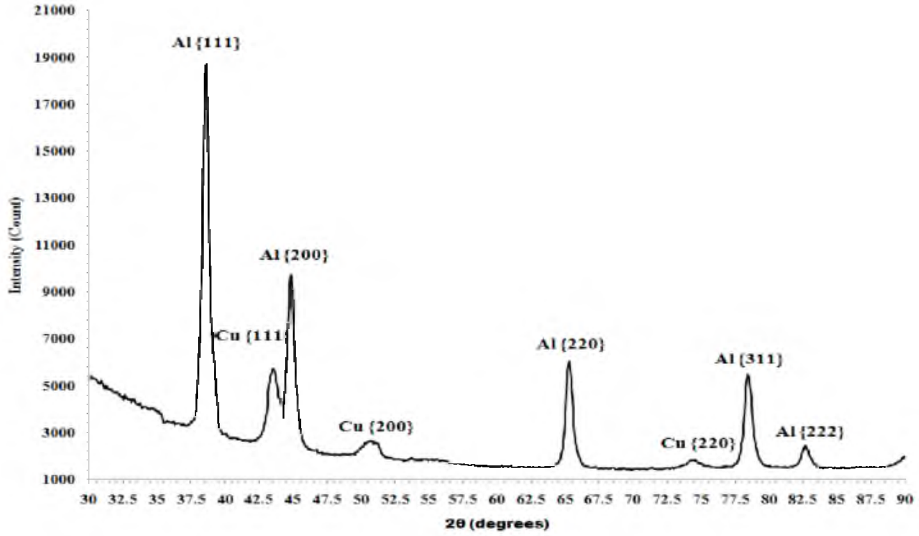


Fig. 1: XRD pattern of Al-Cu bilayers deposited at room temperature

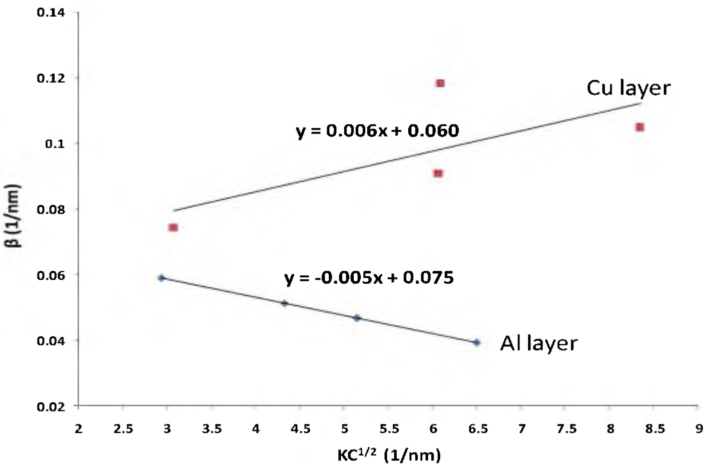
Table 1. The value of d-spacing and lattice parameter of Al and Cu layer calculated from the highest Bragg's peaks.

| **Al layer** | | | **Cu layer** | | |
|---|---|---|---|---|---|
| **Miller indices** | **D -spacings Å** | **Lattice parameter Å** | **Miller indices** | **D -spacings Å** | **Lattice parameters Å** |
| {111} | 2.332 | 4.0407 | {111} | 2.077 | 3.598 |

Various peaks are observed in the bilayers sample deposited at room temperature corresponding to low index f.c.c diffraction planes indicates that the bilayers are polycrystalline. Both Al and Cu layer shows {111} preferred orientation, which has lowest surface energy for f.c.c crystal structure. The lattice parameter "*a*" for Al and Cu layer is 4.0407 Å and 3.598 Å, respectively, which is 0.2 % and 0.44% smaller than the value from the JCPDS database.

The XRD peak broadening by lattice strain and crystallite size of polycrystalline materials can be expressed using modified Williamson-Hall method in equation (1) [9].

$$B \cos \theta/\lambda = K_s/D_v + 4K_D \sqrt{C_{hkl}}\, \varepsilon_{rms} \sin \theta/\lambda \qquad (1)$$



| Layer | Strain (%) | Crystallite size (nm) |
|---|---|---|
| Cu | 0.6 | 15 |
| Al | -0.5 | 12 |

Fig.2: Strain-size analysis of Cu film on Si substrate using modified Williamson-Hall plot as a function of $KC^{1/2}$, according to Eq. 1.

Intrinsic strain which developed during deposition may influence the film's integrity. However, data in Fig. 2 shows that the calculated strains for both deposited metallic are considerably small. The negative strain indicates that the Al layer is subjected to compressive strain. Very fine crystallite size indicates that the bilayers are nanocrystalline, between 12-15 nm.

**Scanning electron microscopy** The bilayers can be described as homogenous thin films with uniform thickness as shown in Fig. 3. The Al layer consists of dense structure which appears to be similar to the (Zone T) structure of the Thornton structure zone model [10]. Meanwhile, a columnar like structure was observed for Cu layer in the presence of voids between the columnar pillars.

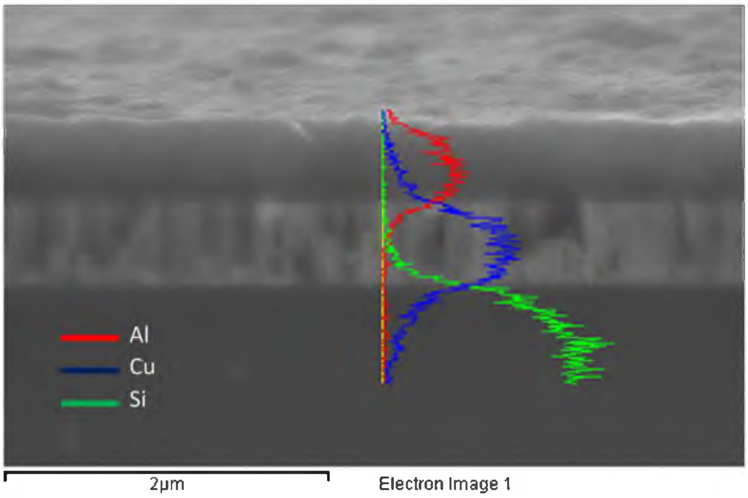
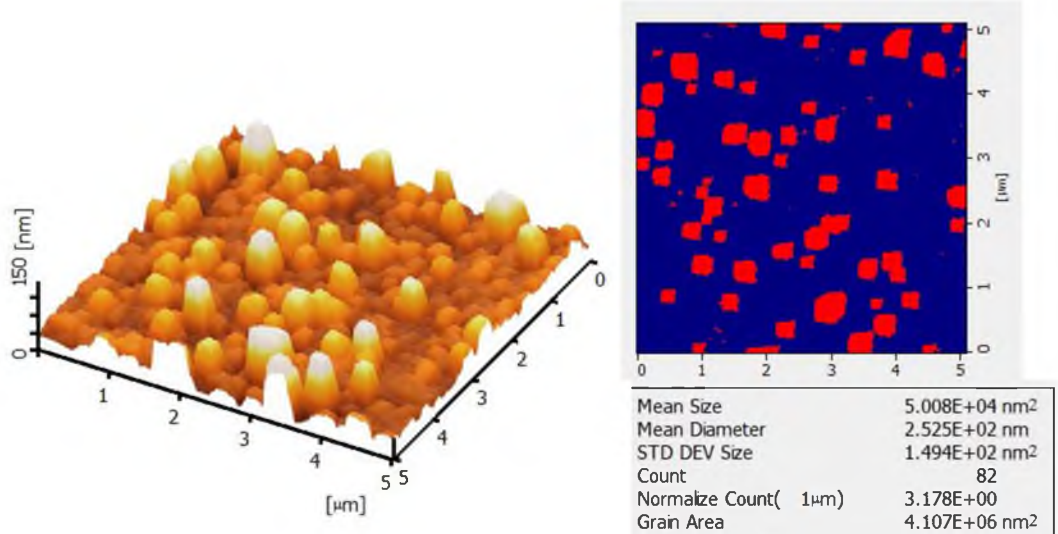


Fig. 3: Cross sectional scanning electron image of Al-Cu thin films on Si substrate

The stacking sequence of Al/Cu/Si is preferable instead of Cu/Al/Si due to the fact that pure copper lacks the properties of self passivation to protect the layer from oxidation. However, depositing pure Cu on $SiO_2$ may lead to poor film's integrity as Cu demonstrates high diffusivity into the porous oxide layer [11]. In this work, the oxide layer was removed using hydrofluoric acid. EDX analysis in Fig. 3 shows a consistency regarding the distribution of Cu element across the bilayers.

**AFM analysis.** Fig. 4 shows the three dimensional AFM (3D) image, including the grain size analysis of the Al-Cu bilayers thin film (i.e Al layer) deposited on a Si substrate at room temperature over the scan area of 5 μm x 5 μm. From the 3D image, the surface of the bilayers is non homogenous where irregular grain sizes were grown on the surface. These irregular or abnormal grains were analyzed at the selected threshold of 86.63 nm (Z value). The mean diameter of each grain is quite large which is 252 nm and therefore contribute to high surface roughness which the $R_a$ value is 20.54 nm. However, these irregular grains covers only 16% of total grain area whiles the remaining 84% are inhabited by smaller grains. Although result from XRD calculation shows that the bilayers were comprised of very small individual crystallite, the finding from AFM analysis is regarding the average grain sizes. The different between individual crystallite and individual grain is that individual grain consists of a number of same repetitive ordering of individual crystallites.



| | |
|---|---|
| Mean Size | 5.008E+04 nm2 |
| Mean Diameter | 2.525E+02 nm |
| STD DEV Size | 1.494E+02 nm2 |
| Count | 82 |
| Normalize Count( 1μm) | 3.178E+00 |
| Grain Area | 4.107E+06 nm2 |
| Ratio of Grain Area | 1.591E+01 % |

Fig. 4: AFM analysis of Al-Cu bilayers thin films deposited at room temperature.

## Conclusions

The Al-Cu bilayers thin films were deposited by RF magnetron sputtering on Si substrate without any substrate heating. The outcome result of room temperature deposition was characterized by XRD, FE-SEM and AFM. The XRD analysis revealed that the bilayers was nanocrystalline with crystallite size of smaller than 20 nm and the lattice microstrains were very small and minimal to put the bilayers under the influence of intrinsic stress. FE-SEM analysis shows that both Al and Cu layer have different morphologies despite of same deposition temperature and gas pressure. The electron images reveal that Cu layer has shown a columnar structure while Al layer demonstrate a non columnar - dense structure. The results from AFM analysis showed that the surface of the Al-Cu thin films is relatively rough as compared to standard roughness for thin films used in electronics due to formation of abnormal grains which affect the uniformity of the surface.

## Acknowledgements

The author would like to thank Universiti Teknologi Malaysia and Ministry of Higher Education (MOHE) for funding this project through the Fundamental Research Grant Scheme (FRGS) under grant no. 78702 and Research University Grant (RUG) under grant no. 04H78.

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**Materials, Industrial and Manufacturing Engineering Research Advances 1.2**
10.4028/www.scientific.net/AMM.606

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