Electrodeposition of Paramagnetic Copper Film under Magnetic Field on Paramagnetic Aluminum Alloy Substrates

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Received: 10 July, 2020; Accepted: 14 September, 2020; Published: 1 October, 2020

Electrodeposition of paramagnetic copper (Cu) from a sulfate solution was investigated under magnetic fields and two different current densities. Static magnetic fields have been used during electrodeposition of paramagnetic Cu onto paramagnetic aluminum (Al) substrate to enhance the deposition rate and to alter crystallographic orientation and morphology of the film. The magnetic field might be attributed to the field-induced convection that disrupts the depletion layer near the electrode and that might also be correlated to Cu, Al, and oxygen dissolved in the solution as paramagnetic materials. An X-ray diffractometry, a scanning electron microscope with energy dispersive spectrometry, a potentiostat, and a digital camera were used for characterizing the crystal structure, morphology, the electrochemical behavior, and wettability, respectively. The results show that, at the current density of 10 mA cm^{-2} , raising the magnetic field from 800 to 1400 G increases the cathode current efficiency and alters the electrochemical behavior, the crystal growth, and the crystallite size. At the current density of 30 mA cm^{-2} , the magnetic field alters the growth and crystallographic orientation. The static magnetic field exposed during electrodeposition of Cu onto the Al alloy can control the film properties, especially crystallographic orientation and the oxygen content.

Keywords Cu Films; Al alloy; Magnetic field; Paramagnetic

I. INTRODUCTION

In recent years, paramagnetic Cu has replaced Al as a metal for interconnects material for the microelectronics industry due to its high thermal and electrical conductivity compared with Al [1, 2]. Cu metal can be deposited by several methods, such as physical vapor deposition, chemical vapor deposition, electroless deposition, and electrodeposition [3]. Electrodeposition is an established production method for thin metal films and for surface finishing [4]. In the last few decades, the influence of magnetic fields on

electrochemical deposition processes has been widely studied. Several studies have carried out to assess the effect of magnetic positions, such as perpendicular [5], parallel [6], and rotating [7] positions. Electrodeposition in the magnetic field produces different deposition rates [8], morphology [9], structures [10], corrosion currents [11], and corrosion potentials [12].

A previous research [13] has shown that various constant current plating produces difference corrosion potentials and X-ray diffraction (XRD) peak intensities of the crystal planes. A magnetic field imposed parallel to the substrate

resulted in the shift of the corrosion potential to the negative value, whereas a field perpendicular to the substrate produced the corrosion potential shifting to the positive value [5]. Rotating magnets with various field strengths and spinning rates resulted in different morphology and XRD peak intensities [7]. A magnet placed behind the substrate resulted in larger grain sizes and lower plating thicknesses [14]. Furthermore, the magnetic field with different strengths produced different XRD peak intensities for (111), (002), and (022) crystal planes [15].

Electroplating under the static magnetic field is an exciting interdisciplinary (electrochemistry and magnetism) area. It is good opportunities for developing and producing nanostructure materials and for expanding the magnetic field's application in the industry. In some respects, magnetic effects are not yet well understood.

If the magnetic field is exerted during the electrodeposition process, several forces may exist [16]. The first magnetic field effect is the Lorentz force;

$$\mathbf{F}_L = \mathbf{J} \times \mathbf{B},$$

where $\mathbf{B}$ is the applied magnetic field, $\mathbf{J}$ is the current density and $\mathbf{F}_L$ is the Lorentz force per unit volume. This force acts on moving ions in the solution, resulting in the convection flow of the entire solution [17]. It has the maximum value when the magnetic field is perpendicular to the current density.

The second force is a paramagnetic force.

$$\mathbf{F}_p = \frac{\chi_m B^2 \nabla C}{2\mu_0}$$

Here, $\mathbf{F}_p$ is the paramagnetic force, χ_m is the molar susceptibility of the ions, μ_0 is the permeability of free space, and C is the concentration. A uniform magnetic field affects the susceptibility of magnetic ions, creating a local energy density. When C has a gradient in different layer near the cathode, this leads to the paramagnetic force [18].

The third force is the electrokinetic magneto-hydrodynamic proposed by Olivier *et al.* [19];

$$\mathbf{F}_{EK} = \sigma_d \mathbf{E}_{||} / \delta,$$

where σ_d is charge density of diffusion layer, δ is the thickness of the boundary layer, $\mathbf{E}_{||}$ is an induced nonelectrostatic field. This force acts only on the diffusion double layer near the cathode

The fourth possible force is a magnetic gradient force, which has been studied by Ragadale *et al.* [20] and Tanimoto *et al.* [21]. This force follows the equation;

$$\mathbf{F}_{\nabla B} = \chi_m C \nabla B / \mu_0.$$

This force acts on paramagnetic and diamagnetic ions in different directions according to the gradient of the magnetic field.

The objective of the present research is to investigate effects of the magnetic field and the current density on electrodeposition of a nonmagnetic metal (paramagnetic) Cu

on the Al (paramagnetic) alloy as a substrate. The magnetic fields might influence the deposition rate, the structure, morphology of the Cu electrodeposits, and the corrosion behavior. The static magnetic fields of 800 and 1400 G perpendicular to the sample surface and current densities of 10 and 30 mA cm⁻² were used during the electrodeposition process. Surface morphology, the structure, the corrosion behavior, and wettability were examined by scanning electron microscope (SEM) with energy dispersive spectrometry (EDS), XRD, linear sweep voltammetry (LSV), and a digitally camera, respectively.

II. EXPERIMENTAL

A direct current electrodeposition process of the Cu films was performed at room temperature on the Al alloy (Fe; 1.63 wt%, Mg; 1.49 wt%, and Al; balance) substrate with a diameter $\varnothing 2.33$ cm. A virgin make-up solution (VMS) consisting of 0.25 mol L⁻¹ CuSO₄·5H₂O was used for electrodeposition.

Cu films were electrodeposited under the galvanostatic control with a constant current density of 10 mA cm⁻² and 30 mA cm⁻². The constant magnetic fields of 800 and 1400 G and perpendicular to the surface of the samples were used for an experiment during the electrodeposition process (Figure 1).

Before electrodeposition, the substrates were mechanically polished with a sandpaper and cleaned in an ultrasonic cleaner with distilled water. The samples with the current density 10 mA cm⁻² and the magnetic fields of 0, 800, and 1400 G are designated as Cu 10, Cu 10-8, and Cu 10-14, respectively. The samples Cu 30, Cu 30-8, and Cu 30-14 are the ones with the current density of 30 mA cm⁻² and the magnetic fields of 0, 800, and 1400 G, respectively.

FE-SEMFEI INSPECT F50 energy dispersive analysis of X-rays (EDAX) EDS analyzer was used for the morphology observation. Rigaku RINT 2000 (CuK α radiation) was used to identify the crystal structure, and HighScore Plus software was used to refine the XRD pattern using a Rietveld refinement method. For the LSV investigation, Digi-Ivy DY 2311 with a three-electrode cell system (a

Figure 1: Schematic diagram of electrodeposition of Cu onto the Al alloy substrate with various current densities and magnetic fields.

potentiostat), whose working, counter, and reference electrodes were Al, a Pt wire, and Ag/AgCl, respectively, was used. The LSV investigation was conducted with a scan rate of 10 mV s^{-1} in 3.5% NaCl. The water contact angles were taken using a digital camera.

III. RESULTS AND DISCUSSION

A. Cathode current efficiency and deposition rate

In the electroplating process, the oxidation process ($\text{Cu} \rightarrow \text{Cu}^{2+} + 2\text{e}^-$) occurs at the anode, and a reduction process ($\text{Cu}^{2+} + 2\text{e}^- \rightarrow \text{Cu}$) occurs at the cathode. A material to be coated is, thus, placed at the cathode. When the current is applied, the Cu^{2+} ions are depleted in the surroundings of the cathode. This makes a diffusion layer around the cathode. A hydrogen evolution is a secondary possible reaction at the cathode during electrodeposition from aqueous solutions. It can be neglected in many cases. Hydrogen is absorbed as H atoms, not H_2 molecules, but the H atoms may also form molecular H_2 , which is trapped in voids or vacancies to induce hydrogen embrittlement [22]. The current efficiency of copper deposition is less than 100% since some portion of the current is used to discharge hydrogen ions from water [23].

The current efficiency and the deposition rate are important properties for industrial plating. The current efficiency of electrodeposition is a ratio between the mass of the deposited Cu film and the mass of Cu calculated according to the Faraday's law below:

$$m = \frac{QM}{nF} = \frac{itM}{nF}$$

Here, m is a mass of Cu deposits, Q is electric charge, i is current, t is time, F is termed the Faraday constant, M is a molar mass of the Cu species, and n is a number of electrons involved in the reaction and equals 2 in the present case.

Current efficiency curves of electrodeposited Cu onto the

Figure 2: Cathode current efficiency of electrodeposited Cu onto the Al alloy substrate with various current densities and magnetic fields.

Al alloy substrates are presented in Figure 2. The current efficiency is affected by the current density and the magnetic field. At the low current density (10 mA cm^{-2}), the magnetic field affects the current efficiency more than at the high current density (30 mA cm^{-2}). This is probably due to the magnetic attraction of the paramagnetic Cu^{2+} ion in the solution. Increasing the magnetic field would cause Cu^{2+} to move faster and, hence, the current efficiency increases. The higher current density causes a higher evolution of the hydrogen gas at the stronger magnetic field. The secondary reaction of hydrogen evolution during electrodeposition occurs at the cathode, which could disturb the cathode current efficiency. This is the reason why the current efficiency for Cu 10-8 is higher than that for Cu 10-14. It also happens to the samples Cu 30-8 and Cu 30-14 [24].

The deposition rate is the amount of deposited copper divided by the time required to deposit. Deposition rate curves of electrodeposited Cu onto the Al alloy substrates are presented in Figure 3. The deposition rate increases as the current density increases [25]. Park *et al.* found that, by rising the magnetic field from 0 to 600 G, there was a significant increase in the deposition rate [15]. The deposition rate of the sample with the current density of 30 mA cm^{-2} is higher by approximately $25 \mu\text{m h}^{-1}$ than the sample with 10 mA cm^{-2} . The effect of the magnetic field on the deposition rate is similar to the effect of the magnetic field on the current efficiency. The Cu 10-8 sample has the highest deposition rate among three other samples. The deposition rate of Cu 30-8 is higher than that of Cu 30-14.

B. Scanning electron microscope (SEM)

SEM images of electrodeposited Cu onto the Al alloy substrates are presented in Figure 4. By raising the magnetic field, the grain of the Cu films become smaller [26, 27]. Figure 4(a, d) shows different morphology due to different current densities (10 and 30 mA cm^{-2}) in the absence of a magnetic field. Figure 4(a–c) shows an influence of the magnetic field (0 , 800 , and 1400 G) with a constant current

Figure 3: Deposition rate of electrodeposited Cu onto the Al alloy substrate with various current densities and magnetic fields.

density (10 mA cm^{-2}) on morphology of the samples. Cu 10 shows a dendrite-like structure [Figure 4(a)], but a similar structure is not seen in other samples. It seems that the magnetic field may inhibit the dendrite formation. It is seen that the current density and the magnetic field affect surface morphology of the Cu film. Surface morphology is classified into three groups based on the over-potential dependence on the electrolyte composition. These are a faceted structure, columned or spheroidal dendrites, and springy dendrites [28]. Cu 10, Cu 10-8, Cu 30, and Cu 30-8 are closely related to the faceted structure [Figure 4(a, b, d, e)], whereas Cu 10-14 and Cu 30-14 are close to the springy dendrites [Figure 4(c, f)].

By an observation with the lower magnification, Cu 10-14 shows a compact surface without a porous structure [Figure 4(c)], whereas Cu 30-14 shows as a compact but porous surface. At the higher magnification, however, small nodules are recognized on both Cu 10-14 and Cu 30-14 samples. Such morphology is probably affected by a decrease in the amount of deposited copper on the substrate by increasing the magnetic field [29]. It is seen in Cu 30-14. These

Figure 4: SEM images of electrodeposited Cu onto the Al alloy substrate with various current densities and magnetic fields: (a) Cu 10, (b) Cu 10-8, (c) Cu 10-14, (d) Cu 30, (e) Cu 30-8, and (f) Cu 30-14.

phenomena are likely similar to the results reported by Fukukana *et al.* [28].

C. Energy dispersive spectroscopy (EDS)

EDS patterns of electrodeposited Cu onto the Al alloy substrate are presented in Figure 5. The EDS analysis of the Cu films shows only a significant peak of Cu and a slight peak of oxygen (O) [30]. Other studies also found Cu and O before and after the treatment of the sample. The other research found the sulfur atoms on copper. This was caused by adsorption of inhibitors on the copper surface [31].

Based on Figure 5, the percentage of elements Cu and O₂ was evaluated and is listed in Table 1. The magnetic field

Figure 5: EDS of electrodeposited Cu onto the Al alloy substrate with various current densities and magnetic fields: (a) Cu 10, (b) Cu 10-8, (c) Cu 10-14, (d) Cu 30, (e) Cu 30-8, and (f) Cu 30-14.

Table 1: Oxygen and Cu contents on the electrodeposited Cu film with various current densities and magnetic fields.

Sample	O ₂ (wt%)	Cu (wt%)
Cu 10	1.4	98.60
Cu 10-8	2.30	97.70
Cu 10-14	3.08	96.92
Cu 30	3.02	96.98
Cu 30-8	4.22	95.78
Cu 30-14	5.02	94.98

and the current density affect the content of oxygen on the surface of the deposited copper film. Since the applied static magnetic field was perpendicular to the cathode surface, the Lorentz's force and the electrokinetic magneto-hydrodynamic were negligible. Therefore, the magnetic gradient force and the paramagnetic force are possible additional forces which affect the copper ions to be electrodeposited.

Molecular oxygen (O_2) is paramagnetic, and the magnet attracts the paramagnetic materials. During electrodeposition, O_2 is also produced as a product of a secondary reaction at the anode. O_2 can also diffuses from the air to the solution. The hydroxylation process is not possible, since the plating bath does not contain organic compounds and, from the EDS observation, carbon atoms are not detected. The magnetic field may attract O_2 and, hence, the concentration of O_2 on the surface increases as the magnetic field increases. O_2 could form a copper oxide, but the oxide was not detected by XRD as shown below.

D. X-ray diffractometry (XRD)

The XRD patterns of the samples are presented in Figure 6. Rietveld refinement on the XRD pattern was conducted using the HighScore Plus software.

All the samples are polycrystalline, and the crystals have a face-centered cubic (FCC) structure, which shows three significant peaks for the (111), (002) and (022) planes. There is a single phase of copper and no other phase is present on the surfaces of the Cu films. The suspected Cu oxide is not detected from the XRD pattern, even though oxygen was detected from EDS spectra (Figure 5). This is probably due to a small amount of the oxide on the copper film surfaces.

The three significant peaks have different peak intensities, whereas the intensities of the (111) and (022) planes are more predominant than those of other peaks. The peak intensities of all hkl planes is listed in Table 2. The increase shows different electrochemical behavior. This is probably due to the different atomic surface density for each crystal plane.

To assess how the current density and the magnetic field affect crystal orientation, the orientation index, M , is calculated using the following equation [32], and the results are shown in Table 2.

$$M(hkl) = \frac{I(hkl)/I_0(hkl)}{\frac{1}{n} \sum I(h'k'l')/I_0(h'k'l')}$$

$M(hkl)$ is the calculated orientation index, $I(hkl)$ is the XRD peak intensity of each plane in the experimental data, $I_0(hkl)$ the peak intensity in the Inorganic Crystal Structure Database (ICSD), and $I(h'k'l')$ and $I_0(h'k'l')$ are the sums of three independent peak intensities of the experimental data and the ICSD data, respectively. The index value larger than 1 [$M(hkl) \geq 1$] indicates that the (hkl) plane is preferentially

Figure 6: XRD patterns of electrodeposited Cu onto the Al alloy substrate with varies current densities and magnetic fields: (a) 10 $mA\ cm^{-2}$ and (b) 30 $mA\ cm^{-2}$ with and without magnetic fields.

Table 2: Peaks intensities of various hkl and the orientation index, $M(hkl)$, for electrodeposited Cu onto the Al alloy substrate with different current densities and magnetic fields.

Sample	hkl (a.u.)			$M(hkl)$		
	111	002	022	111	002	022
Cu 10	8904	3060	1944	1.098	0.809	1.092
Cu 10-8	9883	3068	14485	0.321	0.190	2.486
Cu 10-14	10246	4345	19652	0.286	0.185	2.528
Cu 30	12221	5320	21516	0.314	0.180	2.505
Cu 30-8	27612	6362	7791	1.014	0.548	1.438
Cu 30-14	24730	5302	7276	1.054	0.779	1.383

grown, while the index smaller than 1 [$M(hkl) < 1$] means that the growth of the (hkl) plane is suppressed.

At 10 mA cm⁻², the magnetic field affects the growth of the (022) plane. The peak height of the (022) plane increases faster than those of two other peaks of the (111) and (002) planes. At 30 mA cm⁻², increasing the magnetic field results in suppression of the (022) plane and an enhanced growth of the (111) plane. The (111) peak surpasses the other two peaks. This alteration of the peak orientation is due to the magnetic field. The (111) plane has a higher surface atomic density than the two other planes.

The magnetic field affects the growth of certain planes in a sufficient field strength. The crystal plane with a higher surface atomic density has the first probability to be created or deposited. This is due to attraction of Cu²⁺ to the magnet. Hence, the concentration of Cu²⁺ on the proximity of the surface becomes greater. Preferred orientation to the (111) plane for copper offers additional benefits such as better corrosion resistance, increase electrical conductivity, and improve mechanical properties [33].

Table 3 presents the crystal parameters of the samples after Rietveld refinement by using the HighScore Plus software. Rietveld refinement was conducted until the good of fitness of less than 2.5% and R -weighted pattern of less than 10%. The crystallite size was determined by measuring a full width at half of its maximum intensity (FWHM) (rad) [34]. The FWHM of the peak (β_0) is composed of both instrumental FWHM (β_i) and the FWHM of the sample (β). β is calculated by the Warren-Averbach equation [35]; $\beta^2 = \beta_0^2 - \beta_i^2$, where, β_i was calculated from the FWHM of silicon as a standard material. In this study, the Williamson-Hall equation was taken to estimate the crystallite size of the samples [36].

$$\beta \cos \theta = \frac{0.9\lambda}{D} + \varepsilon \sin \theta$$

Here, D is the average crystallite size, ε is an internal microstrain, λ is the wavelength and equals 0.1541 nm, and

θ is the Bragg angle of the X-ray diffraction. By plotting the Williamson-Hall equation with the y -axis being $\beta \cos \theta$ and the x -axis being $\sin \theta$, D is obtained from the cross point and ε is determined from the slope of the plotted line. The positive slope indicates a tensile residual stress, while the negative slope suggests a compressive residual stress. It is found that the crystallite size is less than 100 nm. The internal strain is positive for the sample with the current density of 10 mA cm⁻². An atomic position and the site occupancy were also refined, and they are not changed.

E. Linear sweep voltammetry (LSV)

LSV is one of voltammetry methods in which the current at the working electrode is measured while the potential between the working electrode and the reference electrode is swept linearly over time. The curve of LSV is composed of two parts; an anodic part resulting from the anodic dissolution of Cu and a cathodic part corresponding to the cathodic reaction which is an oxygen reduction reaction in the present case.

The LSV curves of electrodeposited Cu onto the Al alloy substrates are presented in Figure 7. It can be seen that the anodic parts of the polarization curves for all Cu samples which were formed with and without the magnetic field are a little bit different. Before copper metal dissolution, the anodic part of the LSV curve is related to CuCl⁻ which adsorbs on the film surface. Due to Cu dissolution, the current density rises with a rise of the potential by a direct formation of CuCl [Eq. (1)] or by Cu⁺ dissolution to form CuCl [Eqs. (2) and (3)] [25].

Formation of CuCl₂⁻ is observed at a greater concentration of chloride; $\text{CuCl} + \text{Cl}^- \rightarrow \text{CuCl}_2^-$. Corrosion of Cu in the chloride environments takes place through the cathodic

Table 3: Crystal parameters of the Cu films at the current densities of 10 and 30 mA cm⁻² with the magnetic fields of 0, 800, and 1400 G.

	Cu 10	Cu 10-8	Cu 10-14	Cu 30	Cu 30-8	Cu 30-14
Lattice constant (Å)	3.6113	3.6135	3.6168	3.6237	3.6144	3.6147
Volume (Å ³)	47.09	47.18	47.31	47.59	47.21	47.23
Crystal system	Cubic	Cubic	Cubic	Cubic	Cubic	Cubic
Crystallite size (nm)	41	60	52	69	18	36
Strain	0.0004	0.0007	0.0017	-0.0011	-0.0127	0.0011
Atomic position	x	0	0	0	0	0
	y	0	0	0	0	0
	z	0	0	0	0	0
	Occupancy	1	1	1	1	1
R -weighted pattern	8	5.37	6.02	8.84	7.61	7.2
Goodness of fit	1.05	1	1.48	2.42	2.35	2.11

Figure 7: LSV measurements of electrodeposited Cu on the Al alloy substrate with various current densities and magnetic fields: (a) 10 mA cm^{-2} and (b) 30 mA cm^{-2} with and without the magnetic field.

reaction, $\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^-$, and the anodic reactions as shown in Eqs. (1) and (2) [25].

Figure 7(a) shows that, for 10 mA cm^{-2} , the corrosion potential (E_{corr}) shifts to a more positive side in the stronger magnetic field. A similar phenomenon is also found for the sample with the current density of 30 mA cm^{-2} [Figure 7(b)]. Elias *et al.* found in the Ni-W coating [5] that the perpendicular magnetic field resulted in the shift of E_{corr} to a more positive side. To evaluate a corrosion resistance, E_{corr} and a corrosion current density (i_{corr}) were determined by the Tafel extrapolation. The corrosion resistance is defined by the following equation [37].

$$Cr = C \frac{M i_{\text{corr}}}{n \rho}$$

Cr is the corrosion rate (mmpy; mm years^{-1}), C is a constant for the corrosion rate calculation and is 3.27 mmpy [38], M is the atomic weight (g mol^{-1}), i_{corr} is corrosion current density (A cm^{-2}), n is the number of electrons involve, and ρ is the density of Cu (g cm^{-3}). The summary of the calculation for the corrosion rates is tabulated in Table 4.

As the magnetic field increases, E_{corr} shifts to a higher potential. This is probably due to the increased oxygen content on the sample surface to form an oxide with copper. As the current density increases from 10 to 30 mA cm^{-2} , E_{corr} shifts to the lower potential. The change of i_{corr} does not seem to depend only on the magnetic field, but other factors could also contribute. The corrosion rate of the FCC

Table 4: LSV measurements of electrodeposited Cu on the Al alloy substrate with various current densities and magnetic fields.

Sample	$i_{\text{corr}} (\text{A cm}^{-2})$	$E_{\text{corr}} (\text{V})^a$	$Cr (\text{mmpy})$
Cu 10	6.57×10^{-6}	-0.781	0.0716
Cu 10-8	1.36×10^{-4}	-0.707	1.48
Cu 10-14	1.05×10^{-4}	-0.623	1.14
Cu 30	2.70×10^{-4}	-0.870	2.94
Cu 30-8	9.08×10^{-6}	-0.668	0.0989
Cu 30-14	1.37×10^{-5}	-0.596	0.149

^a Values with respect to the Ag/AgCl reference electrode.

materials depends on orientation of the crystallographic plane on the sample surface. The (111) plane of the FCC materials, which has the highest surface atomic density, is more resistant to corrosion than the (002) and (022) planes. The crystallite size, the strain, and other defects could also influence the corrosion rate. Al Kharafi *et al.* have found that Cu in the 3.5% NaCl solution has a corrosion potential $E_{\text{corr}} = -0.187 \text{ V}$ (vs. Ag/AgCl) [39]. The corrosion potential of the Cu films in the present study is less negative than that reported by Al Kharafi *et al.*

F. Water contact angle

The water contact angles (wettability) on the electrodeposited Cu films onto the Al alloy substrate are presented in Figure 8. The oxygen content on the surface increases as the magnetic field and the current density increase. Oxygen and copper form an oxide, and more oxide are formed on the surface as the magnetic field becomes stronger. An increase in the contact angle with the magnetic field means that the surface becomes more hydrophobic. Water is a polar

Figure 8: Water contact angle measurements of electrodeposited Cu on the Al alloy substrate with various current densities and magnetic fields: (a) Cu 10, (b) Cu 10-8, (c) Cu 10-14, (d) Cu 30, (e) Cu 30-8 and (f) Cu 30-14.

molecule, whereas the copper oxide is not a polar molecule. Therefore, the contact angle increases as the magnetic field and the current density increase. The contact angle of all samples is more than 90° . Namely, all samples meet the hydrophobic criteria, $150^\circ > \theta \geq 90^\circ$ [40]

IV. CONCLUSION

Presence of the magnetic field during electrodeposition of Cu on the Al alloy with various current densities affects the cathode current efficiency, the deposition rate, surface morphology, the oxygen content, crystallographic plane orientation, the corrosion potential, the corrosion rate, and wettability. The oxygen content on the surface of the Cu film increases as the magnetic field and the current density increase. It is not doubted that the magnetic field can be used to control the properties needed of the Cu film for a certain application.

Acknowledgments

The author thanks Ministry of Research, Technology and Higher Education of the Republic of Indonesia for financial support Hibah Penelitian Disertasi Doktor No: NKB-2999/UN2.RST/HKP.05.00 /2020.

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