J Solid State Electrochem (2010) 14:1013–1020
DOI 10.1007/s10008-009-0909-z

ORIGINAL PAPER

$CuInSe_2$ thin-film deposition on flexible plastic substrate: electrolyte recirculation rate and deposition potential effects

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Received: 10 June 2009 / Revised: 14 July 2009 / Accepted: 16 July 2009 / Published online: 11 August 2009

Abstract Copper indium diselenide ($CuInSe_2$; CIS) layer was electrolytically plated from an aqueous medium at room temperature onto electroless nickel deposited on flexible plastic (Kapton). The CIS depositions were carried out under constant deposition potentials (−0.5 to −1.1 V vs. Ag/AgCl) and at various electrolyte flow rates (0.3 to 1.5 ml/s) under constant applied current. The resulting thin films were characterized using atomic force microscopy, energy-dispersive X-ray spectroscopy, environmental scanning electron microscopy, and X-ray diffraction. The surface morphology and the atomic composition of the deposited CIS film were found to be influenced by the deposition potential under potential control and the electrolyte recirculation rate under current control. Low electrolyte flow rates under constant current control and high cathodic deposition potential under voltage control favor the deposition of indium. CIS films of uniform deposit, smoother surfaces, and with better adhesion properties are favored by moderate electrolyte recirculation rate. At a current density of 0.6 mA/cm^2, the electrolyte recirculation rate required to achieve ideal CIS atomic composition was found to be 1.0 ml/s in such a setting. The crystallinity of the film improved after annealing for 2 h at 390 °C under argon atmosphere.

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Keywords Electrodeposition · Solar cell · $CuInSe_2$ (CIS) · Thin film · Roll to roll · Deposition potential · Electrolyte flow

Introduction

Despite the significant advancement made in solar cell technology in the past decade, the purchase and installation cost of solar energy system is still not competitive in the energy industry. Ideally, mass-produced solar cells that cost $0.06 per kilowatt-hour or less are required for solar energy to be as competitive as energy from hydrocarbon sources [1]. Because of its favorable electrical, optical, and semiconducting properties and its feasibility of large-scale fabrication, $CuInSe_2$ (CIS) or Cu (In, Ga) Se_2-based thin films have attracted many research interests [2]. The energy bandwidth of about 1.1 eV and absorption coefficient of 3×10^4 cm^{-1} make CIS most suitable for photovoltaic applications [3]. Recent CIS research efforts are mostly devoted to the improvement of the thin-film fabrication methods [3–8]. The different growth methods studied include metalorganic chemical vapor-phase deposition, radio frequency sputtering, chemical spray pyrolysis, chemical bath deposition, and electrodeposition (ED) [5].

The utilization of the ED method to produce CIS thin film offers great economic advantages since ED does not require complicated facilities such as vacuum chamber or elevated temperature operation [8]. Although several works have been published on CIS thin-film electrodeposition, several aspects of the thin-film ED technology remain unclear on how to directly produce low-cost CIS solar cells with highest conversion efficiency using ED alone. Published works demonstrate that, like other deposition methods, ED is sensitive to many deposition parameters that affect the atomic composition of the film including bath composition,

buffer agent, deposition potentials, and back contact (BC) materials [8–11]. Composition of electrodeposited Cu–In precursor film, observed as the In/Cu ratio, was found to be sensitive to the additives (triethanolamine (TEA) and Na-citrate) in the bath [8] and the additives in turn influence the film morphology and efficiency [9, 10]. In [9], the relationship between In/Cu and Se/Cu in the bath and in the deposit was used to obtain mass transfer coefficient for the species. These data were further used to show that stirring improved the In/Cu ratio in the films of ED $CuInSe_2$. In addition, through changes made in the In/Cu ratio in a bath containing only $CuCl_2$ and $InCl_3$, Nakamura and Yamamoto [10] improved the crystallinity of the electrodeposited thin film by first annealing the as-deposited Cu–In precursor film in sulfur vapor at 500 °C for 1 h to obtain solid $CuInS_2$.

Despite the efforts and progress made in CIS ED research, many aspects of the thin-film ED fundamentals still remain unclear including the relationship between electrolyte transport properties, BC (other than Mo), to the surface morphology and atomic composition of the film. Also, the variation and dependency of the CIS deposition potential on the solution composition, acidity, buffer agent, temperature, and substrate prevent the establishment of a prescribed value for deposition of the compound. Thus, for any ED studies of CIS, an outline of the deposition potentials and other conditions used must be provided.

A low-cost fabrication concept for the production of CIS thin film on flexible substrate can be carried out by the utilization of a combination of electroless method (for the deposition of the BC) and electrolytic deposition routes (for the deposition of the CIS thin film) to produce solar cells in a single continuous line. Such a concept presents enormous economical advantage with ED and improved manufacturability [12, 13]. In addition, the electroless substrate such as Ni or Ni–Mo alloy on which the CIS is grown will provide improved corrosion advantage compared to the use of Mo only. The concept will also offer flexibility. If desired, the materials are interchangeable, and other deposition techniques such as sputtering can still be integrated into the approach. The low-cost idea precludes the use of expensive vacuum equipments. For the proposed concept, several technical questions remain open about feasibility. The effects of various deposition parameters on the deposits and substrates need to be known for the design of appropriate combined electrochemical and electroless reactors.

The purpose of this paper is to explore the effects of various ED parameters on $CuInSe_2$ thin film electrodeposited on electroless BC material on a flexible plastic substrate that can possibly be used for a low-production concept of CIS as outlined above. The influence of the electrodeposition parameters on the microstructural features of ED $CuInSe_2$ thin film is examined. For the present evaluation, electroless Ni is used as the BC. The effects of ED parameters presented in this paper will focus on the deposition potentials and electrolyte recirculation rate. Since most commercially viable electrochemical or electrodeposition processes are often carried out at constant current with electrolyte flow or recirculation, the present analysis on the effects of electrolyte recirculation is therefore only considered for the constant current (galvanostatic) electrodeposition case.

Experimental

Kapton® (300HN) was first cleaned in acetone, rinsed in deionized water, and blown dry with nitrogen gas. A thin layer of palladium-based catalyst, prepared as described in [13], was applied on the Kapton® using a draw-blade. The coated film was air-dried and then activated in a furnace at 180 °C for 2 h under airflow. Ni was then plated electrolessly onto the catalyzed Kapton® from aqueous electroless Ni solution [12] at 80 °C for different time durations. The electroless metallized area of Kapton was only limited by the size of available electroless bath. In the present work, catalyzed and electroless metallized surface area of Kapton ranged between 25 and 100 cm^2.

To observe the effects of deposition potential, CIS was deposited onto Ni-metallized Kapton® (area$\leq$15 cm^2) at various deposition potentials utilizing a standard three-electrode setup. Ag/AgCl served as the reference electrode while platinum flag electrode was used as the counter electrode. All depositions were conducted at room temperature from an aqueous solution containing 5 mM Cu^{2+}, 10 mM In^{3+}, and 10 mM Se^{4+}. The solution pH was adjusted to pH 2.0 with dilute HCl (0.1 M) and was deaerated by passing nitrogen gas for upwards of 15–30 min prior to deposition. Previous work in our laboratory [12, 14] has identified the probable range for CIS deposition potentials to be between −0.5 V and −1.1 V (vs. Ag/AgCl). For the present work, special interest was focused on −0.5 V, −0.7 V, and −1.1 V, where significant potential drops occurred in the cyclic voltammetry. Hence, CIS deposition was investigated in the potential range from −0.5 V to −1.1 V in steps of −0.1 V, each deposition was for 5-min duration. During the deposition, nitrogen gas was kept flowing on top of the solution. Upon the completion of the thin-film deposition, the films were rinsed with deionized water, blown dry with nitrogen gas, and annealed or stored in environmental chamber for further analysis.

To study the effects of electrolyte recirculation rate, galvanostatic (constant current) depositions were carried out in a continuous undivided "flow-by" parallel plate single-cell electrochemical reactor. A line diagram of the

setup is shown in Fig. 1a. The parallel plate reactor consisted of a Ni metal anode plate and electroless Ni plated Kapton® cathode plate. Flat neoprene gaskets were used to define the reaction chamber, and the cell was held between bolted steel channels to contain internal pressures up to 1.5 atm. Both the cathode and anode chambers were 2 cm high×1 cm wide×3 mm thick, yielding active deposition area of 2 cm^2. A sketch of the electrode and neoprene arrangement is shown in Fig. 1b. The CIS electrolyte was prepared using the same procedures described in the potentiostatic deposition. The electrolyte was stored in the tank where the pH was monitored and controlled at pH 2. Nitrogen gas was also sparged into the tank at a constant rate to deaerate the solution. A peristaltic pump (Chem-Tech Pulsafeeder, model CTPD4HSA-PAP1) was used to meter and recycle the electrolyte through the reactor. Depositions were carried out galvanostatically at 0.6 mA/cm^2 for durations of 5 min at four different flow rates—1.5, 1, 0.6, and 0.3 ml/s. Substrates generated from each flow conditions were then cleaned with deionized water, blown dry with nitrogen gas, and annealed or stored in environmental sachet for further analysis.

Thin films generated at various potentials and flow conditions were examined using atomic force microscopy (AFM, JEOL JSPM-4200, AC mode), environmental scanning electron microscopy, and energy-dispersive X-ray spectroscopy (EDS, Electroscan E-3). Successfully deposited CIS thin films were annealed in a furnace under argon atmosphere at 390 °C for up to 2 h, and X-ray diffraction (XRD) data were obtained using Philips X'Pert X-ray diffractometer with Cu Kα radiation (1.54 Å) at an operating voltage of 45 kV and a current of 40 mA. The activation and annealing temperatures were chosen to fall within a range where the plastic substrate material performance remained viable but at the same time was able to yield crystalline-deposited thin films.

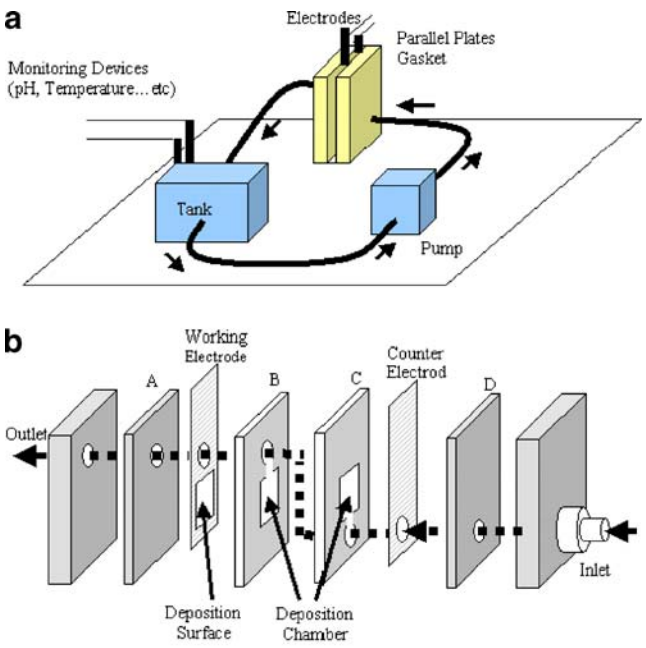

Fig. 1 **a** Schematic of the recirculating cells. **b** Schematic of the electrochemical reactor

Results and discussion

CIS was successfully deposited onto electroless Ni BC under both potentiostatic and galvanostatic (with electrolyte recirculation) methods. Results of film characteristics show sensitivity to both applied potential and electrolyte recirculation rate. Details are discussed in subsequent paragraphs.

Physical characteristics of the film

In the second column of Table 1, the physical characteristics of films deposited under potentiostatic control at −0.5, −0.7, and −1.1 V are shown. From the results, it is concluded that the surface of the films transited from bluish fine powdery, nonreflective surface at −0.5 V, to light blue, shiny, reflective surface at −0.7 V, then finally, to thick, black, powdery, nonreflective surface at −1.1 V. All films adhere to substrate well with no blistering or peeling. No direct correlation between film color and deposition potential was identified.

The second column of Table 2 corresponds to the results from galvanostatic depositions. The influence of electrolyte flow rate was studied at four different flow rates—1.5, 1, 0.6, and 0.3 ml/s. Films generated from 1.5-ml/s flow has dark bluish, nonreflective, powdery, slightly nonuniform surface, with small number of blisters and random peeling. Prior work from this laboratory indicates that the blisters and peeling resulted from high electrolyte recirculation rate—only observed when a certain level of recirculation rate is exceeded. As electrolyte flow rate decreased to 1.0 ml/s, the film quality substantially improved. The surface color turned more blackish. Although still nonreflective, the film surface became smoother and more consistent and adhered to the back contact well. Peelings and blisters were not observed under this condition. Similar to the films deposited at 1.0-ml/s electrolyte flow rates, films generated at 0.6-ml/s recirculation rate had surfaces that were uniform, smooth, and nonreflective with minimal defects. The film color was dark or solid black. No defects were observed. Finally, at the lowest flow rate of 0.3 ml/s, films produced were mostly silver in color. Very slight traces of light blue shades were observed at random regions. The result indicates that electroless Ni was responsible for mostly the silver surfaces observed. CIS was merely plated onto the substrate. Overall, the surface color turns from darker blue to black as flow rate decreases.

Table 1 A comparison of CIS thin films deposited under different deposition potentials

Deposition potential (V)	Film surface	Composition	AFM
−0.5	Dark blue Powdery (Fine)	$CuIn_{0.04}Se_{0.1}$	d=16 nm
	Smooth Uniform		Z_{RMS}=1.86 nm (see Fig. 2a)
−0.7	Light blue Shiny	$CuIn_{0.1}Se_{0.4}$	d=19 nm
	Reflective Smooth		Z_{RMS}=0.68 nm (see Fig. 2b)
	Uniform		
−1.1	Blackish Rough	$CuIn_{1.6}Se_{0.9}$	d=25 nm
	Powdery (coarse) Nonreflective		Z_{RMS}=5 nm (see Fig. 2c)
	Nonuniform		

d average particle size, Z_{RMS} roughness

From these physical characteristics, it can be concluded that although electrolyte motion promotes CIS deposition, high electrolyte recirculation rate produces poor-quality films. The film adhesion property improves as the flow rate decreases. The ideal rate to produce usable film for the configured setting used in the present work should be higher than 0.3 ml/s but lower than 1.5 ml/s. The identification of optimal flow rate was not pursued in this work.

Surface morphology of the film

The high magnification images from AFM analysis provided nanoscale examination of the substrate morphology. The 2D AFM images of the surface of potentiostatically deposited thin films of CIS are shown in Fig. 2a–c. The AFM images as shown in Fig. 2 indicate that all the films' surfaces are composed of spherical particles. For the potentiostatically deposited films, the average size of the spherical particle is approximately 20 nm. At different deposition potentials, the particles agglomerated differently to form different shapes of clusters. Particles deposited at −0.5 V (Fig. 2a) formed long and narrow clusters that layer unevenly. Numerous voids were produced from this random packing. Particles deposited at −0.7 V (Fig. 2b) packed in patterned spherical clusters, with low number of voids. The particles deposited at −1.1 V (Fig. 2c) were neatly arranged into long, oval, and corn-like clusters. Although the shapes of the clusters at −1.1 V were nearly identical, they do not have the well-distributed

Table 2 A comparison of CIS thin films deposited under different electrolyte recirculation rates at a constant current density of 0.6 mA cm^{-2}

Flow rate (ml/s)	Film surface	Adhesion	Composition	AFM
1.5	Semiuniform Dark bluish	Poor	$Cu\ In_{0.5}Se_{1.7}$	d=10 nm
	Powdery			
	Rough Nonreflective			Z_{RMS}=5.14 nm (see Fig. 3a)
	Random peeling			
1.0	Uniform Blackish	Good	$Cu\ In_{1.2}Se_{2.0}$	d=17 nm
	Powdery Rough			Z_{RMS}=9.70 nm (see Fig. 3b)
	Nonreflective			
0.6	Uniform Blackish	Good	$Cu\ In_{1.6}Se_{2.1}$	d=9 nm
	Powdery Rough			Z_{RMS}=8.20 nm (see Fig. 3c)
	Nonreflective			
0.3	Nonuniform Silver-colored	N/A	Ni and P	d=13 nm
	Shiny Reflective			Z_{RMS}=1.71 nm (see Fig. 3d)

d average particle size, Z_{RMS} roughness

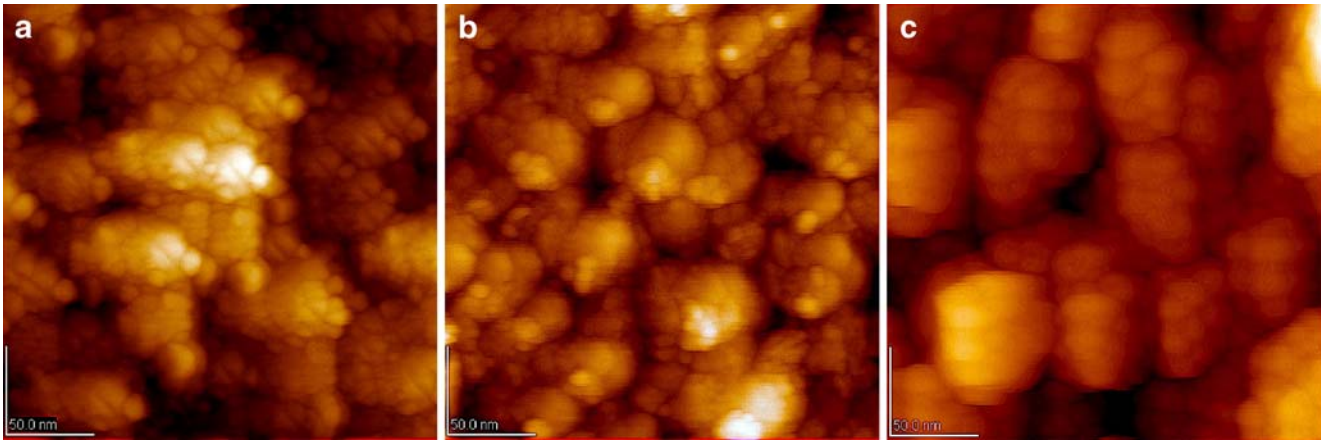

Fig. 2 AFM images of CIS thin films deposited on electroless Ni substrate at **a** −0.5 V; **b** −0.7 V; **c** −1.1 V

packing pattern as seen on the −0.7-V film. The irregular voids led to a rough film. The roughness of the film that is obtained from the analysis of the AFM images and listed in the fourth column of Table 1 corresponds to the film's packing cluster. Smoothest film was obtained from −0.7 V deposits while the roughest film corresponded to the films deposited at −1.1 V. This was also reflected at the physical properties discussed earlier. Smooth and reflective surfaces were obtained at −0.7 V while rough and powdery surfaces were obtained at −1.1 V. Above −0.7 V, rough deposits are obtained suggesting that deposition potential affects the film roughness. While the roughness at −1.1 V is speculated to be due to a possible competition from hydrogen evolution, the reason for the roughness at −0.5 V being higher than at −0.7 V is not clear. However, the film with less voids may offer better conductive property, and hence a better candidate of photovoltaic material. Qualitative multi-ammeter check on the conductivity of each sample of the CIS deposit was carried out.

Analysis of the AFM pictures obtained from the galvanostatically deposited films show the surface of the deposits as nanoscale spherical particles (Fig. 3a–d). The particle sizes averaged approximately 12 nm (excluding 0.3 ml/s). Particles produced by the 1.5-ml/s electrolyte recirculation rate (Fig. 3a) agglomerated into oval-shaped clusters with approximate size of 50 nm. The clusters spread over the substrate evenly. As the flow rate decreased to 1.0 ml/s (Fig. 3b), the clusters grew spherically in shape to about 120 nm. As the flow further decreased to 0.6 ml/s (Fig. 3c), the particles agglomerated to long, oval, and corn-like clusters, approximating 60 nm in length and 30 nm in width and stacked in single direction. The agglomeration at this flow rate is similar to the films obtained at constant potential of −1.1 V (Fig. 2c). Finally, at 0.3 ml/s (Fig. 3d), the deposited films produced particles of about 13 nm in size. Unlike the other films, the nanoscale particles were spread out evenly. Cluster structure was not found suggesting a lack of CIS content in the film. The film's roughness obtained from the analysis of the AFM pictures is listed in the fifth column of Table 2. Based on the AFM roughness values, the films generated at electrolyte recirculation rate of 1.5 ml/s yielded the smoothest films while those deposited at the flow rate of 1.0 ml/s yielded the roughest films. For the limited data studied, the roughness appears to increase with the flow rate to a maximum around 1 ml/s after which the film roughness decreases with increase in electrolyte recirculation rate. While both potentiostatic and galvanostatic depositions affect the roughness of the film, the directions in which the flow rate and deposition potential affect the film roughness are different. While decreasing deposition potential yielded a convex relationship with the roughness, an increasing recirculation rate yields a concave relationship with the roughness. The foregoing is limited to the range of variables investigated for the present work. It can only be concluded therefore that roughness is related to the physical characteristics of the film. The smoother film possess finer surface while the rough films hold powdery nonreflective features.

Film composition

Ideally, CIS films for photovoltaic applications should comprise a stoichiometric 1:1:2 proportion of Cu/In/Se components. The potentiostatic deposition results were analyzed with EDS, and the results are presented in the third column of Table 1. As the potential decreased from −0.5 V to −1.1 V, the amount of indium present in the film increased (composition is normalized with Cu=1). Indium and selenium contents for both films deposited at −0.5 and −0.7 V were significantly below the desired ratio for an ideal CIS. As the potential became more negative and approaches −1.1 V, the indium content jumped to 1.6 parts per mole of Cu in the CIS while Se content remained insufficiently below the fraction required in ideal CIS. Corresponding to the physical characteristics, the film with

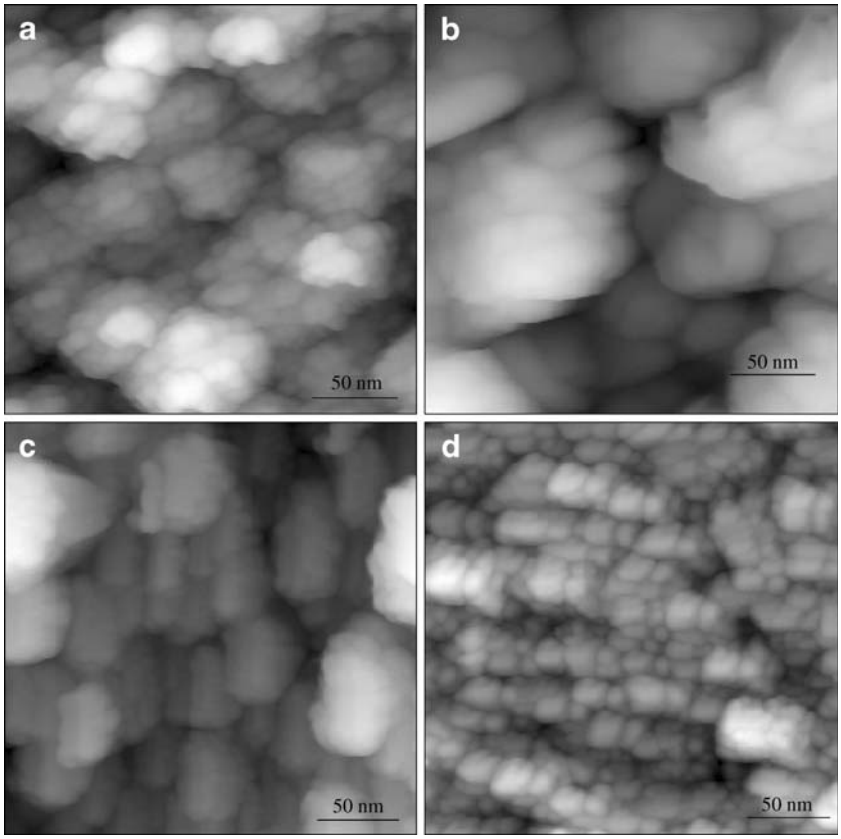

Fig. 3 AFM images of CIS thin films deposited at 0.6 mA/cm^2 at electrolyte recirculation rate of **a** 1.5 ml/s; **b** 1 ml/s; **c** 0.6 ml/s; **d** 0.3 ml/s

high indium content has darker or black surface appearance while copper-rich films have light-bluish-colored surfaces. The ideal deposition potential required to achieve $CuInSe_2$ was not identified. However, it is possible to achieve the ideal composition by altering bath composition, its buffer agent, or even the identity and composition of the back contact. Nevertheless, this work demonstrates that it is possible to electrodeposit CIS in a setting as proposed in Fig. 1 with electroless BC. The electrodeposition of CIS on electroless Ni is sensitive to the applied potential as other works in the literature have indicated for other BCs. Recently, we showed that electroless Ni–Mo alloy BC favors the electrodeposition of CIS over the performance of electroless Ni BC [15].

The EDS analysis of galvanostatic deposition results is presented in the fourth column of Table 2. The result indicated that the ratio of indium and selenium present in the film increases as the electrolyte recirculation rate decreases. At electrolyte recirculation rate of 1.5 ml/s, the indium and selenium contents of the films were below the desired ratio for CIS. As the recirculation flow rate decreased to 1.0 ml/s, the CIS component (Cu/In/Se) composition ratio increased to approximately the ideal ratio of 1:1:2. At a recirculation rate of 0.6 ml/s, the film composition was found to be too rich in indium. That is, the ratio of indium was in excess of what is expected of an ideal CIS indium composition. Once again, the film color turns darker black as the indium content increases. EDS results indicated that the film produced at a recirculation rate of 0.3 ml/s was mostly nickel and phosphorus. The CIS content was insignificant in such films. This lack-of-CIS-content results agreed with our previous observations [12]. From the EDS analysis and for the setup studied, the ideal recirculation rate for the electrolyte to achieve desired composition can be further narrowed down to approximately 1 ml/s. The flow control experiment has indicated that the electrolyte recirculation rate directly impacts the surface quality of the deposited film. Higher flow rates (more than 1 ml/s) produce porous, defective, and poorly adhesive films. Films produced at highly low electrolyte recirculation rates (e.g., 0.3 ml/s) lack appropriate CIS components required for solar cell applications. CIS indium content is favored at depositions carried at moderate electrolyte recirculation rates. Most importantly, this work demonstrates the ability to control film composition with electrolyte recirculation rate and thus suggests that the ideal CIS composition can be achieved through the manipulation of both bath composition and electrolyte recirculation rate. Such will eliminate the need of using a postelectrodeposition process to further selenize the thin film. For the configuration studied in this work, electrolyte recirculation rate of 1 ml/s appears to yield an ideal CIS composition.

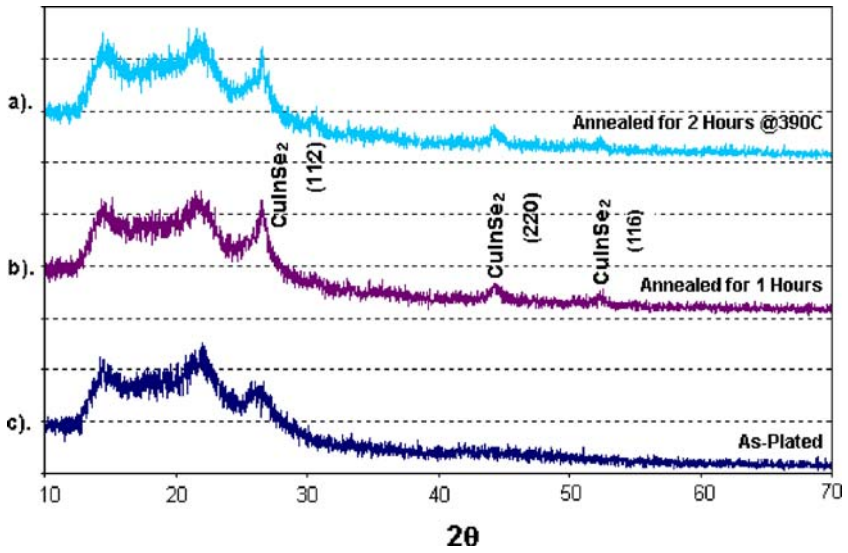

Fig. 4 XRD of CIS films electrodeposited at −0.7 V and subjected to different thermal treatments: (*a*) thermal treatment at 390 °C for 2 h; (*b*) thermal treatment at 390 °C for 1 h; (*c*) As-plated (no thermal treatment)

X-ray diffraction of $CuInSe_2$

$CuInSe_2$ has chalcopyrite structure crystals. To verify the crystallinity, XRD was performed. The XRD results in Fig. 4a–c indicate that for the As-plated sample, the Bragg peaks relative to CIS phase are not clearly recognized over the plastic substrate diffused background thereby suggesting that CIS is initially amorphous. However, they increase in intensity and become sharper in the annealed sample. No strong characteristic peaks were found in the As-plated film. Although a crest was found between 15° and 30° consistently, the crest was contributed by the plastic substrate and back contact. For the CIS thin film deposited at −0.7 V, it was observed that, after annealing for 2 h in a furnace under argon atmosphere at 390 °C, the crystallinity improved. Characteristic peaks were found at angles $2\theta = 26^{\circ}$ and 44°, which correspond to $CuInSe_2$ (112) and (220) planes, respectively. Also, a very broad and weak $CuInSe_2$ peak at angle $2\theta = 53^{\circ}$ (116) was observed. The method for deposition and annealing was not optimized in the present work. Despite not having produced ideal CIS with strong and sharp Bragg peaks in this work, the agreement of the XRD results with previous study [3, 8] shows that, through optimized electrodeposition conditions on electroless BC, $CuInSe_2$ that is polycrystalline can be produced using our approach. The crystallinity of the thin film can be improved by an appropriate heat treatment without the use of post-selenization.

For the galvanostatic depositions, XRD analysis conducted for the 1.0-ml/s sample is displayed in Fig. 5.

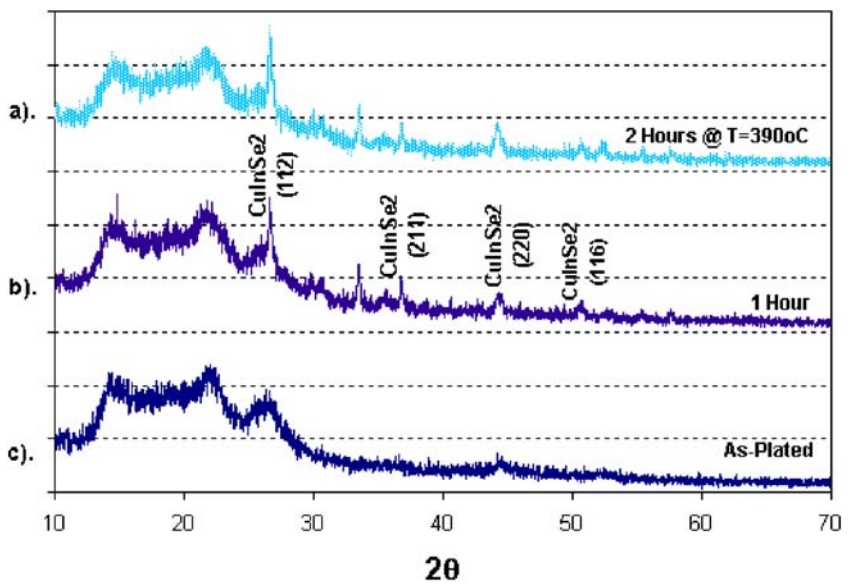

Fig. 5 XRD of CIS films electrodeposited at 0.6 mA/cm^2 with 1.0 ml/s recirculating electrolyte and subjected to different heat treatments: (*a*) 390 °C for 2 h; (*b*) 390 °C for 1 h; (*c*) As-plated (no thermal treatment)

Similar to CIS that was deposited potentiostatically, the film generated by the galvanostatic method appears to be mostly amorphous as plated. Weak peaks were found at $2\theta=26.6^{o}$ (112) and 44.3^{o} (220). After 2 h of annealing, the intensity was greatly improved. Furthermore, weak characteristic peaks appeared at $2\theta=30.6^{o}$ attributed to InO_2 (211), 36.9^{o} to $CuInSe_2$ (221), and 52.6^{o} to $CuInSe_2$ (116). The peaks ascribed to the oxides were suspected to have resulted from the reaction between residual oxygen in the system during annealing. Since the films were annealed in argon environment, it suggests that some oxygen were left present in the furnace prior to annealing process [3]. Nevertheless, the XRD confirms the crystallinity of the deposited film after an effective annealing method was employed to improve the crystallinity.

In comparing the XRD results from the two deposition methods, we find that films generated from both deposition methods were initially amorphous. The heat treatment improved the crystallinity of the deposits. Characteristic peaks were found at $2\theta=26^{o}$ and 44^{o} for all films corresponding to $CuInSe_2$ (112) and (220) planes, respectively. Both methods show weak $CuInSe_2$ (116) peaks at $2\theta=53^{o}$ after heat treatment. The calculated lattice parameters of this tetragonal chalcopyrite crystal are $a=b=$ 5.77 Å and $c=11.54$ Å yielding a ratio of $a/c=0.5$.

Conclusion

The effects of deposition potentials and electrolyte recirculation rates on $CuInSe_2$ electrodeposited on electroless Ni were studied to increase our understanding of the effects of ED parameters. Control of electrolyte recirculation rate under galvanostatic deposition was proven an effective parameter to control film's quality as well as its composition. At very high flow rates, films deposited are porous and defective and show poor adhesion, while films produced at very low flow rates lacked stoichiometric compositions. Indium deposition is favored at moderately low electrolyte recirculation rate. The ideal flow rate to achieve both ideal surface quality and desired atomic composition for the system configuration reported in the present work was found to be approximately 1 ml/s under galvanostatic control.

Overall, the experiments have demonstrated that the idea of a low-cost electrodeposition method for $CuInSe_2$ on a flexible electroless metallized plastic as conceptualized in this work is feasible. CIS was successfully deposited onto electroless Ni BC, and electroless Ni–Mo alloy was suggested as a possible BC that will yield even better results than electroless nickel. The influence of deposition conditions on the characteristics of CIS film deposited on electroless Ni was the focus of the present study. Results verified that CIS deposition on electroless Ni BC is definitely sensitive to the deposition potential.

Acknowledgments We acknowledge the support of the Partnership for Research and Education in Materials (PREM) initiative of the National Science Foundation under NSF Award 0351770, NSF Grant No. DMR-0351770, National High Magnetic Field Laboratory, and FAMU-FSU Department of Mechanical Engineering and Department of Chemical and Biomedical Engineering.

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