Rapid Processing of Large-Area Electronics using Intense Pulsed Light

T. Druffel, B. Lavery, G. Draper and Krishnamraju Ankireddy

Conn Center for Renewable Energy Research, University of Louisville, Room 302, Louisville, KY, USA, thad.druffel@louisville.edu

ABSTRACT

The Intense Pulsed Light (IPL) technology is well suited to continuous manufacturing platforms such as roll-to-roll due to its very large processing area and rapid processing time scales. The IPL technique delivers high energy pulses of broad spectrum light (UV-Vis-NIR) in a very short duration (ms) over a large processing area (cm^2). Photosensitive materials within depositied thin films absorb the light and this energy is immediately released and can both initiate chemical reactions and thermal processes. The deposition of the thin films and high resolution lines can simply be accomplished using traditional solution phase depositions of inks, which is aided by the use of nanomaterials. The nanomaterials are convenient for the formation of thin films of varying morphologies and are amenable to several solution phase deposition processes spanning a range of viscosities. The nanomaterials are also important as they can reduce the energy required to initiate sintering of inorganic materials. The absorption of the light is limited within the thin film and as such the high temperatures are not transferred to the underlying substrate with the IPL treatment. From the past few year, this method is playing a key role in the flexible electronic industry by sintering the printed structures such as wires, transparent conductors and RFIDs on low-temperature compatible substrates..

Keywords: Intense Pulse Light, Roll-to-roll, Advanced Manufacturing,

1 INTRODUCTION

Continuous manufacturing using roll-to-roll platforms has a strong history of economic success in a number of industries including photographic films and printed consumer products. There is a vast infrastructure and knowledge base within this industry that will play an important role for the next generation of products. The roll-to-roll platform offers an extremely low cost manufacturing that is readily available for inks incorporating nanoscaled elements. For electronic devices utilizing solution phase processing, the difficulty lies in producing electronically conducting pathways throughout the deposited films at high speed. These processes must also work on a variety of substrates that have relatively low processing temperature windows.

In the past decade, the intense pulsed light processing (IPL) technique has gained a large amount of interest within the printed electronics industry. Several groups and companies have developed solution phase inks that are processed by the IPL after deposition producing conductive traces on platsic and paper substrates. These are often included into devices such as radio frequency identification (RFID) tags, transparent conductive films and wire traces.

Our group has extended the IPL process beyond the traditional use of single metal conductors into more functional multi-metal structures, metal oxides, mixed metal oxides and complex materials containing components with low sublimation temperatures. Applications for these materials include optically transparent conductors, absorbers for electricity generation, 3-D printed ceramics and other electronic materials critical to the renewable energy devices. In this talk, the IPL technique will be described and results of the densification by IPL of nanomaterials deposited using traditional solution phase deposition techniques will be presented. The results include models of the chemical and thermal response within the film/substrate as well as morphology changes observed by XRD, SEM, TEM UV-Vis and TGA. Finally these films will be demonstrated in functional devices. The talk concludes with the discussion of how the IPL process fits into a roll-to-roll manufacturing scheme.

2 THE INTENSE PULSED LIGHT PROCESS

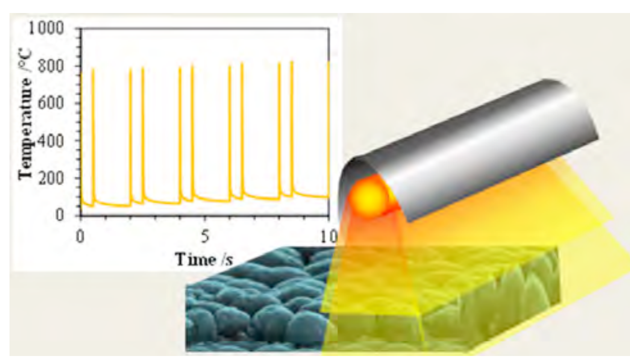

Fig. 1. Schematic of the proposed IPL process in which intense light pulses over a large area induces localized temperature rises.

The IPL technique delivers high-energy light in a very short duration over a large processing area that is absorbed by the photosensitive semiconducting thin films. The light source spans wavelengths from the ultraviolet (UV) through the visible (VIS) to the near infrared (NIR). The UV wavelengths can be used to initiate chemical reactions and the full spectrum produces heat only within the film. The method is analogous to additive manufacturing techniques utilizing infrared lasers; however, IPL uses a full spectrum of light and the processing area is considerably larger making it more economically feasible. Costs are further reduced by depositing inks composed of nanoparticles (NP)s and precursors via well known and supported printing processes. The outcome for large-scale PV manufacturing will be reduced capex and O&M costs, which are critical for achieving cost parity while returning manufacturers to profitability.

2.1 Metal Inks

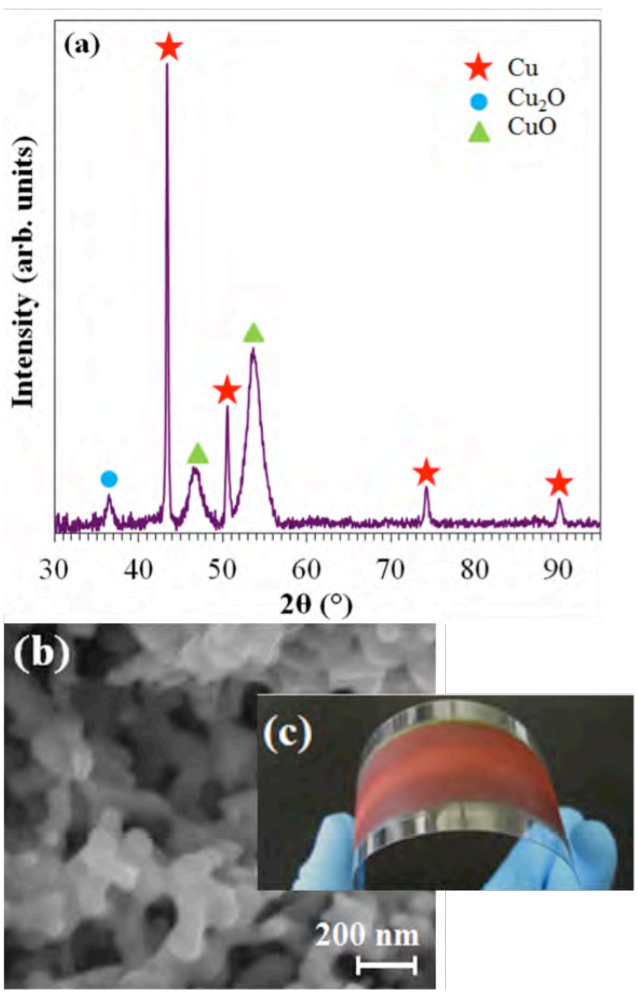

Figure 2. (a) XRD pattern, (b) SEM and (c) photograph of the IPL sintered Cu/Cu_2O film on PET using 1 pulse with an energy density (ED) of 22.4 Jcm^{-2} in air.

Solution phase inks and pastes for the direct printing of conductive lines are typically composed of metallic particles (spherical, flake and wires and may include dimensions less than 100 nm) suspended in an organic solvent or binder. Silver in the form of flakes is the most predominant material used in the direct printing of conductive lines. Inexpensive materials such as copper (Cu) that utilize the lower temperature sintering processes above would further reduce the costs associated with conductive patterns. Cu and silver have very similar electrical conductivity; however, Cu is significantly less expensive. Despite this, silver is commonly used in printed electronics primarily due to its stability in air. Cu tends to rapidly oxidize under ambient conditions, which significantly reduces conductivity and higher processing temperatures to sinter. The IPL process overcomes the oxidation due to the fast time scales of the sintering. In fact it is well documented that copper oxides can be reduced during the IPL process, which enables engineers to design more stable ink solutions. The deposition of a copper oxide ink and subsequent IPL processing on a polymer substrtae is shown in figure 2. [1] The results show that a significant reduction to a functional conductive film on plastic from a stable copper oxide ink can be accomplished using a single pulse of light. This makes the method very attractive to a roll-to-roll platform.

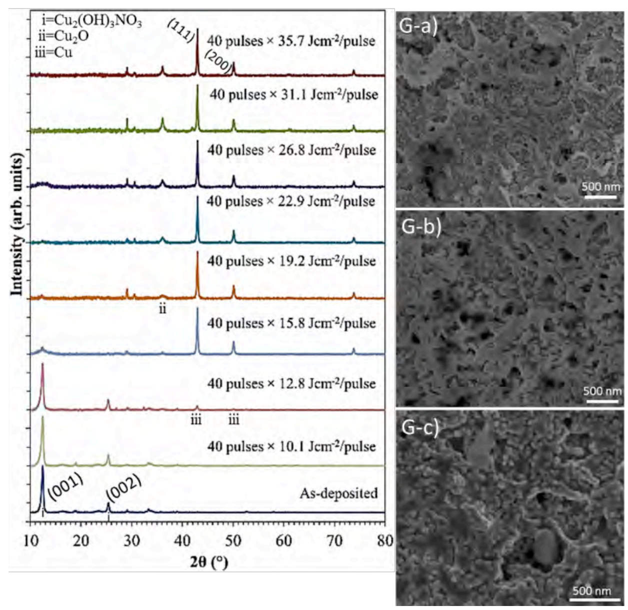

Figure 3. XRD results with IPL processing of forty pulses at increasing energy densities and SEM images of copper oxide-fructose (G-a,b,c) samples at different energy densities of IPL processing a) 12.8 Jcm^{-2} b) 15.8 Jcm^{-2} c) 35.7 Jcm^{-2}

The IPL method allows for the reduction of metal oxides via the release of a reducing environment created when organic molecules are decomposed. This was previously accomplished using traditional sodium boro-hydroxide. Alternative organic molecules available to promote this decomposition/reduction include simple sugars. Fructose is known to thermally decompose ($\Delta Hrxn=11.09$ kcal/mol) into glyceraldehyde and 1,3-dihydroxyacetone while glucose ($\Delta Hrxn=12.06$ kcal/mol) decomposes into erythrose and glycolaldehyde. Figure 3 shows the fast decomposition and reduction of a copper oxide ink during IPL using glucose. Similar results were obtained using fructose. [2]

2.2 Beyond Metal Inks

The IPL technique has received a lot of attention in the printed electronics industry primarily using low melt metals such as silver and copper. However, industry has not yet implemented the manufacturing method for more complex compounds, because the morphological changes to these materials at these fast time scales (~ 1 ms) have not been characterized. The challenge to the implementation of the IPL technique at the industrial scale is to maintain the stoichiometry of multi-component materials with a predictable understanding of the process tolerance. For example, many absorber materials are multi-compound crystals with vastly different thermodynamic properties. Simply heating the absorber can result not only in phase changes, but also decompositions initiated by sublimation. Thus, a successful process needs to establish secure crystal growth without destroying the integrity of absorber

CdS is a very important semiconductor often used as a window film for thin film solar cells. In this case the sulfur has a low sublimation temperature that when exceeded often results in a Cd rich product. In our work, we electrodeposited a CdS layer and then subsequently processesed with IPL. The initial layer did not have the correct bandgap, (as shown by the color of the sample) but the IPL was able to adjust the bandgap. The results of multiple pulses is shown in figure 4 along with the temperature rise at the surface of the film. [3]

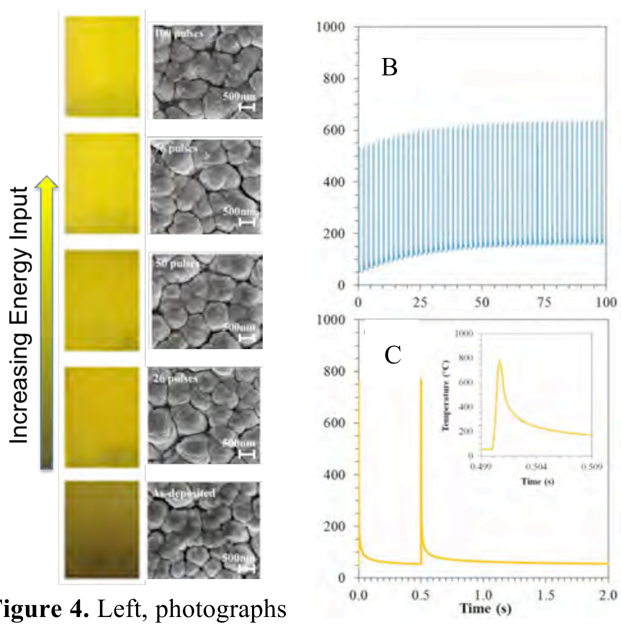

Figure 4. Left, photographs of the color change and corresponding change in morphology of the films. B and C are the changes in computed temperature.

Cadmium teluride (CdTe) is a strong absorbing semiconductor with applications in photovoltaics. In this case the industry regularly utilizes a heat treatment to improve the crystallinity of the device. This is often done in the presence of $CdCl_2$ and often results in improved performance. We attempted the IPL of an electrodeposited CdTe thin film in the presence of $CdCl_2$. Interestingly enough, we were able to improve the grain size and crystallinity of the films. However, the reorientation of the grains in the 220 direction were much more pronounced in the presence of $CdCl_2$. [4]

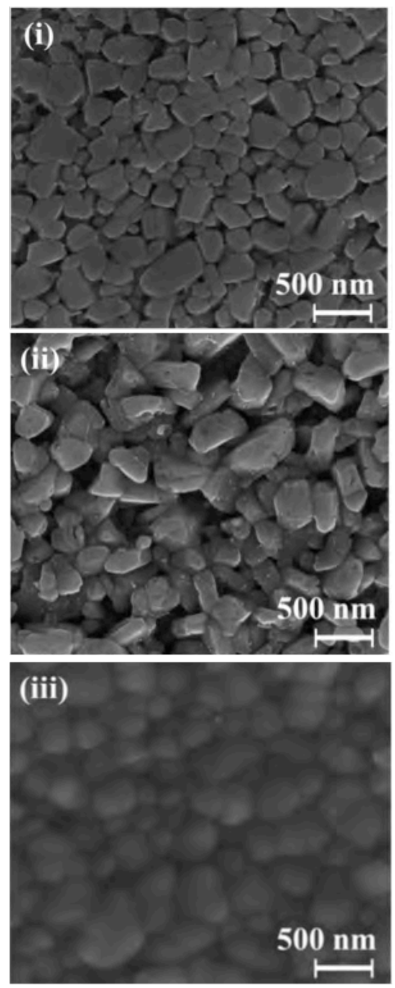

Figure 5. SEM topographical images of IPL processed CdTe films treated with $CdCl_2$ for 100 pulses at varying ED of (i) 17.6 Jcm^{-2}, (ii) 21.6 Jcm^{-2} and (iii) 25.9 Jcm^{-2}.

2.3 IPL Processing for Printed RFID Tags on a Photo Paper

We recently developed aqeuous based copper nanoparticle synthesis and formuated ink for printing various patterns with a Dimatix printer from FujiFilms. The RFID antenna was printed on a photopaper. The IPL treatment on the printed patterns is being conducted to turn them electrically conductive.

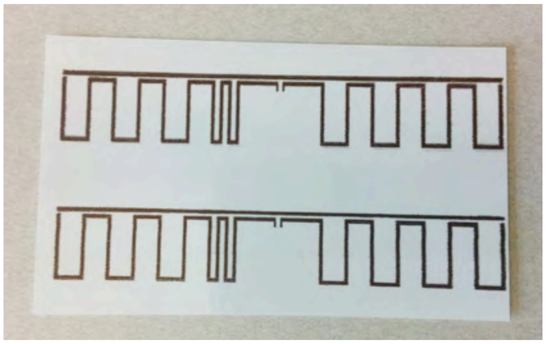

Figure 6. Inkjet printed RFID antennas using copper nanoparticulate ink.

3 CONCLUSION

In this paper, we have demonstrated the utility of the IPL process on varying thin films. The process has been used to successfully sinter metal oxide nanoinks on polymer substrates very rapidly, on the order of 1 ms. The technique has also been demonstrated on semiconducting materials which are important to the photovoltaic industry. This includes a material with a moderatley low sublimation temperature, as well as a the use of a fluxing agent to reorient crystals. All of the processing is very rapid and is accomplished over lareg areas, making it amenable to roll-to-roll manufacturing.

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