Creating Preliminary Specifications for Printed Photovoltaics

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The purpose of this study is to expose the traditional printing industry to an emerging field of printed electronics. With the popularity of electronic documents and the internet, the bulk of the printing industry will eventually move away from the traditional ink and paper printing and move towards more technical, functional applications that will meet the upcoming needs of society. Printed photovoltaics, or solar panels is an example of printed electronics that can be manufactured by traditional printing processes.

This study investigated if the flexography printing process was a viable way to mass manufacture printed photovoltaics. If so, what specifications and tolerance and specifications will be expected from the press and the printed output to create a successful photovoltaic. Factors such as ink film thickness, ink uniformity, and registration were explored.

The results of this study show that Flexography is a possible way to mass manufacture photovoltaics. However, press modifications and additional material developments are needed in order to successful create a functional photovoltaic.

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Chapter One: Introduction and Purpose of Study

Creating Preliminary Specifications for Printed Photovoltaics

The significance of solar power energy has been gaining media attention in recent years. The sun is a plentiful source of energy that is available just about anywhere in the world, and most importantly, it costs nothing to generate. The necessity for efficient and affordable energy is evident through the growing prevalence of the sustainability movement, the ever-present climate change, and our dependence on limited fossil fuels. These irreplaceable resources and our impact on the earth increase the need for an environmentally friendly system to harvest energy. One solution for this problem is solar panels. Currently, solar panels are an excellent way to collect energy, however, they are too costly to manufacture. One solution is to print solar panels with traditional printing presses already used to manufacture newspapers and books. By printing solar panels, high production costs would be saved and solar panels will be accessible to everyone.

Conventional solar panels, also known as photovoltaics, are manufactured by harvesting and cutting silicon wafers, which can be an extremely slow and expensive process. Printing, a high-speed process, is a logical solution to the mass manufacture needs of the photovoltaic industry. However, in order to successfully manufacture photovoltaics by a printed process, one needs to develop specifications or specific guidelines for printers to follow. Certain performance requirements will be needed from the press, substrates, and ink. These specifications will ultimately push the printing industry into new sectors and promote mass manufacture photovoltaic growth.

This research project will ask the question, is flexography a viable way to mass manufacture printed photovoltaics. If so, what specifications and tolerance and specifications will be expected from the press and the printed output to create a successful photovoltaic. The goal and outcome of this study was to find preliminary specifications and tolerances for printed photovoltaics by the flexography process. Factors such as ink film thickness, ink uniformity, and registration were explored.

The purpose of this study is to expose the traditional printing industry to an emerging field. With the popularity of electronic documents and the internet, the bulk of the printing industry will eventually move away from the traditional ink and paper printing and move towards more technical applications that will meet the upcoming needs of society. Additionally, photovoltaics are important globally as environment preservation is becoming more and more of a necessity.

Chapter Two: Literature Review

Background Information of Printed Electronics Market and Photovoltaics

History of Photovoltaics

Scientists at Bell Laboratories accidentally discovered solar cell technology in 1953. Gerald Pearson and Calvin Fuller discovered a way to control the doping, or introduction of impurities, necessary to transform silicon from a poor to superior conductor of electricity. Some of the experiments the scientists tested for conducting electricity included exposing the silicon to the sun while connecting it to a device that measured electrical flow. "The silicon that was doped had an electric output almost five times greater than the best material produced before." (Sun & Sariciftci, 2005) However, the commercial success of solar technology failed to expand at the time due to the cost of solar cells.

The first practical application of the silicon solar cell was in 1955 with the American government's intention to launch a space satellite, the Vanguard. The Vanguard was the first working satellite equipped with solar cells. (Sun & Sariciftci, 2005) The preceding satellites were powered by batteries and lost all stored power within in a week's time. The millions of dollars invested into a satellite that only functioned for a week on batteries was not cost effective. The Vanguard was installed with silicon solar cells for power because there was a need for a reliable, long lasting energy source for the satellite. (Sun and Sariciftci)

While the practical application of solar cells boosted the morale of advocates for the technology, the expensive production cost still kept it from commercial success. Research concentration went into materials and making lower grade, less expensive silicon. The first major buyers of solar cells were oil companies. The oilrigs in the Gulf of Mexico were fitted with warning lights and horns for safety that relied on batteries to power the system. These batteries needed maintenance and had to be replaced approximately every nine months. Due to the oilrig structure and placement of the battery, a large expense was required for a routine procedure. Solar modules would help save tremendous cost by eliminating the need for the expensive equipment. By 1980, photovoltaics were the standard power source for warning lights and horns for the oilrigs on the Gulf of Mexico. (Sun & Sariciftci, 2005)

Fast tracking to the present, the photovoltaics industry has experienced a tremendous growth rate of 20 percent annually in the last decade. (Kahn and Das) The solar technology has been gaining tremendous attention for its “green” purposes. With the increased concern over climate change and greenhouses gasses that effect our environment, photovoltaics are receiving great interest. Solar electricity generation has no noise, harmful emissions, or polluting gasses. There are no moving parts and it requires very low maintenance to keep the systems running. (Krebs) “It is estimated that the global solar energy market will reach $34 billion in 2010 and $100 billion in 2050.” (Kahn & Das, 2007)

How Solar Panels Work

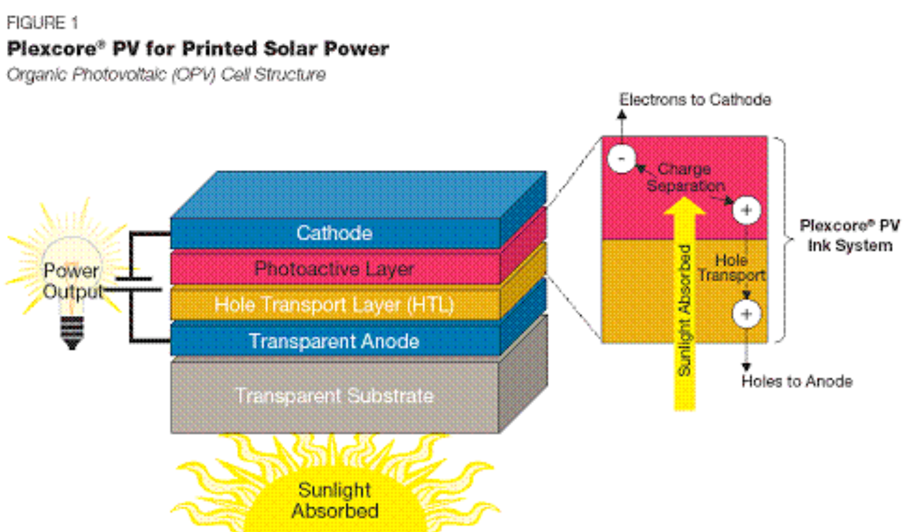
Solar panels work by converting sunlight into electricity, or photons into electrons. This is possible by the structure and materials in photovoltaic cells, "photo" meaning light, and "voltaic" meaning electricity. The photovoltaic cells are packed into modules, which are simply groups of cells electrically connected and packaged into one frame or a solar panel. (Aldus, 2000)

How the photovoltaic cell makes this conversion possible is in the unique semiconductor material, or the active layer in the photovoltaic structure. When the photon from the sun hits the solar panel, either one of three things can happen:

1. The photon passes straight through the solar panel. This is due to the low energy photon not being able to excite any electrons and serve any function for the solar cells.
2. The photons reflect off the surface of the solar panel and are unable to be used.
3. The photon is absorbed by the solar cell. This is what needs to happen to be able to create a current. When the photon is actually absorbed, the energy from the sun is then transferred to the semiconductor material. The photon excites the electron from one energy stage to another, allowing it to freely move around in the semiconductor material. These freely moving electrons are called free carriers. The electrons then flow in a certain direction, generating the current.

The current and voltage from the electrons make the power called electricity. (Aldus, 2000)

To create a photovoltaic there are multiple layers of materials that serve different functions to make a working system (see figure 1). Conventional photovoltaics are manufactured by hand using very expensive, highly sensitive materials and that need specialized tools to produce them. (NanoMarkets) New developments in the market have evaluated printing as a possible means of production in the future. Various layers would be patterned onto a transparent substrate and with the correct specifications and tolerances, create working photovoltaics.

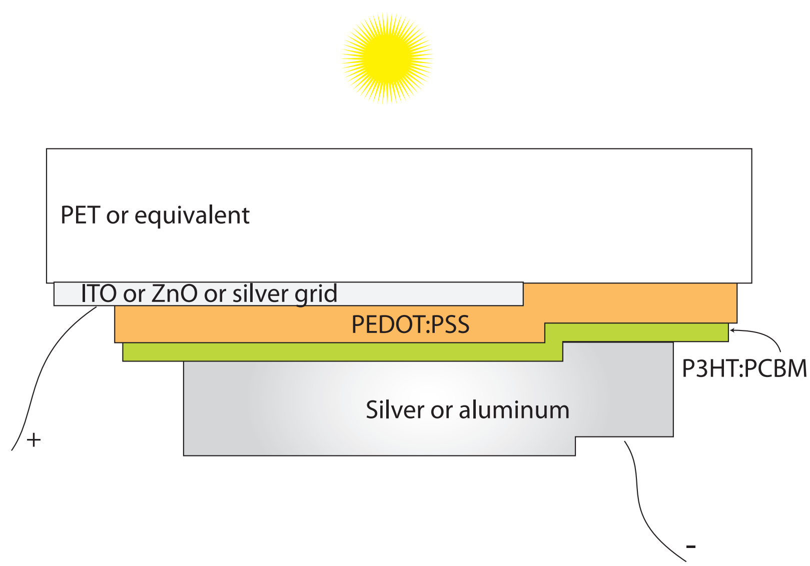


(figure 1) NanoMarkets 2009

Flexography Process

Flexography is a printing process where ink is transferred from the ink tray by an anilox roll, to a raised image area called a blanket, and eventually to a substrate. The anilox roll is a patterned roll, which functions to transfer ink from the ink tray to the blanket. The anilox roll then transfers the ink to the printing plate and then to the substrate. Flexography is one possible printing method to produce photovoltaics.

In order to determine if flexography is a viable way to produce photovoltaics, specifications and tolerances need to be determined first and evaluated against existing flexography presses to determine if it is possible to mass-produce photovoltaics by this method. For this particular study, focus was on creating an organic photovoltaic with conventional materials. (see figure 2)



(figure 2) A sample of the device architecture that was used for this study. Illustration by Malcolm Keif.

Chapter Three: Research Methods

Deriving Specifications of Printed Photovoltaics

The key to making photovoltaics widely used is with less expensive production, enabling the distribution to a wider audience. Interest is being gained in printing as a means of manufacturing because of the roll-to-roll capabilities of production. However, in order to print photovoltaics successfully, specifications such as those developed by ASTM and ISO need to be established. To gain specifications for printing photovoltaics, elite and specialized interviewing was used to gather research. The premise behind of this research approach to this project was that the subject of photovoltaics is so innovative that a great deal of knowledge was not published yet, but rather being discovered currently. The specifications for printed photovolatics are the start to the high volume distribution of renewable energy.

According to Harvey Levenson in Some Ideas About Doing Research in Graphic Communication, "Elite and specialized interviewing is where each and every interviewee is treated as a special and important individual. In this particular type of interview, the interviewer will ask precise, open-ended questions that are open to refinement as the research and interview continues." He continues on to explain, "what is sought in Elite and Specialized Interviewing is comprehensibility, plausibility, and consistency, not duplication of responses." Furthermore, the interviewee becomes part of the research “team” rather than a subject. (Levenson) Discussions with interviewees were to learn how a photovoltaic system works and ask them to help fill out a table of specifications. The specifications and tolerances are the range of particular variables that are required in order to have a working photovoltaic cell such ask ink film thickness, annealing time, and oxygen trapping specifications. The specifications were then compiled into a spreadsheet.

Various experts in the industry that have experience and knowledge in manufacturing photovoltaics were interviewed. The first interviewee was Sarah Mednick, a former California Polytechnic State University graduate and current University of California, Santa Barbara graduate student in the Heeger Research Group. Her focus of study is on photovoltaics. The purpose for interviewing her was to gain knowledge on how photovoltaics fundamentally work and have her fill out a table of specifications that was created.

The second contact was Dr. David Sime, director of technology transfer at Soligie, a privately held photovoltaic company. Their company incorporates flexographic process to print photovoltaics. He helped with the specifications sheet and developed tolerances.

The third contact was Mary Boone, a market development director at Plextronics, a privately held photovoltaic company. She evaluated the spreadsheet and gave comments on the various sections.

The final interview conducted was with Eitan Zeira, the vice president of printed photovoltaics at Konarka, a privately held photovoltaic company. He looked at the spreadsheet as a whole and gave feedback on specific questions and overall printing problems for printable electronics.

The following information was pursued during the elite and specialized interview:

1. What is the relation of band gap to the efficiency of the solar cell?
2. What is the difference between polymer photovoltaics and organic photovoltaics?
3. What defines the generation of a photovoltaic cell?
4. What factors affect the efficiency of a photovoltaic cell?
5. To what extent does ink film thickness, adhesion specification, and oxygen trapping specifications have an affect on the efficiency of a photovoltaic? If so, how critical is it to keep the materials and processing under the tolerances?
6. What is the most important tolerance to keep in a photovoltaic cell?
7. What role does flexography have in the printed electronics industry?

Chapter Four: Results

Results of Elite and Specialized Interviewing

After interviewing experts in this industry, specifications and tolerances necessary for a successful, functioning photovoltaic were derived. Due to the proprietary nature of the industry, there were varying opinions on what specifications were crucial and on the numbers themselves. Four interviews were administered by elite and specialized interviewing process.

The first interview was with Sarah Mednick, a graduate student at University of California, Santa Barbara and fellow of the Heeger Research Group. Sarah provided a site tour of her laboratory as well as a detailed explanation of how photovoltaics were processed at the university. Sarah's expertise was in lab testing photovoltaics so some of the specifications she gave were a little unreasonable for printed photovoltaics. The interview with her was considered as a starting point to understand how photovoltaics actually function and how they are traditionally fabricated. She pointed out the importance of properly drying or annealing materials to make the circuit function.

The second interview was with David Sime, director of technology transfer at Soligie, a privately held photovoltaic company. Their company incorporates the flexographic process to print photovoltics, so his knowledge was valuable for this particular paper. An in-person interview was conducted at the Printed Electronics USA conference in San Jose, California on December 3rd. Dr. Sime was able to look at the spreadsheet with the different categories that were deemed important by Sarah Mednick. He pointed out that the substrate thickness would be considerably thinner for a printed photovoltaic than one spin-coated onto glass, typical to the lab work Sarah did at UCSB. He was also able to give transparency and surface uniformity specifications while pointing out the importance of properly drying, or annealing a material. Dr. Sime further expanded the spreadsheet from what was derived with Sarah. The majority of the spreadsheet was built upon the information Dr. Sime gave.

The third interview was with Mary Boone, a market development director at Plextronics. She was able to look over the specifications that Dr. Sime gave by email and was able to give input of surface uniformity and oxygen trapping. Mary's feedback was somewhat limited.

The final phone interview conducted was with Eitan Zeira, the vice president of printed photovoltaics at Konarka, a privately held photovoltaic company. He was able to answer specific questions pertaining to the spreadsheet and overall questions with printing trends. Many of the conclusions based on printing press capabilities such as pinhole free layers were developed while interviewing Eitan.

Chapter Five: Conclusions

Conclusions of Derived Specifications

The content attained during the interviews was processed and then complied into a spreadsheet. (see table 1) The spreadsheet contains the determined critical factors necessary for a flexible photovoltaic printed on a flexographic press. Ink layer thickness, surface uniformity, contact angle, registration, annealing, conductivity, oxygen trapping, optical transparency, and adhesion were concluded to be the most important specifications to ahead to. These specifications were determined for a conventional, organic polymer photovoltaic.

Layer thickness was determined to be one of the most critical specifications for efficiency of the photovoltaic. The materials would function at optimal conductance with correct thicknesses. Ideally, the semiconductor layer should be around 150 nanometers.

Surface uniformity was deemed of upmost importance due to the potential pin holing that could be caused by the printing press. Any pinholes present would cause a short in the circuit, causing it to become inactive. The film substrate should be at 3-5 Rs whereas the semiconductor layer will be solvent dependant. While the uniformity of all layers is not necessarily critical, they must be pin hole free.

Table 1 : Preliminary Specifications for Printed Photovoltaics

Material	Layer thickness spec	Tolerance/Criticality	Surface uniformity spec	Tolerance/Criticality
Film Substrate	~ 50 micron	Doesn't matter unless transparency or dimensional stability are sacrificed	Rs~3-5 nm	Not too critical
ITO (alt. silver grid)	~150 nm	Critical parameters here are conductivity and transparency (both should be high)	Rs~10-15 nm	Not too critical but must be pin-hole free
PEDOT:PSS	300-350 nm	± 5 nm	Rs~10-15 nm	Not too critical but must be pin-hole free
P3HT:PCBM*	100-150 nm	Ideal thickness varies based on material properties (these can vary from batch to batch), and on the heat treatments and solvent annealing used post-deposition.	Solvent dependant	Not too critical but must be pin-hole free
Aluminum/silver	>1 micron	Not critical. Additional thickness makes contacts more robust.	Smooth, even layer for first 50 nm, then not so critical but should be pin-hole free	

Material	Contact Angle/wetting spec	Tolerance/Criticality	Registration spec	Tolerance/Criticality
Film Substrate	N/A		N/A	
ITO (alt. silver grid)	30 degrees, Surface tension 40	+10 degrees	Very loose for PVs	±0.25"
PEDOT:PSS	30 degrees, Surface tension 35	+10 degrees	Very loose for PVs	±0.25" - only critical if edge bleeds onto another layer
P3HT:PCBM*	30 degrees, Surface tension 30	+10 degrees	Very loose for PVs	±0.25" - only critical if edge bleeds onto another layer
Aluminum/silver	30 degrees, Surface tension 25	+10 degrees	Very loose for PVs	±0.25" - only critical if edge bleeds onto another layer

Material	Drying/Annealing spec	Tolerance/Criticality	Conductivity/ Mobility spec	Tolerance/Criticality
Film Substrate	<= 140°C	Based on dimensional stability of substrate	N/A	
ITO (alt. silver grid)	Evap temp of solvent	Must evap solvent - no max time	< 20 ohms	Critical for device permformance
PEDOT:PSS	140ºC - longer the better	Must evap water - no max time	N/A	Used as a hole transfer layer only
P3HT:PCBM*	(phase transformation rest period) 70ºC - longer the better	Must evap solvent - no max. Efficiency is improved with phase seperation rest period	10^-3 cm2 Vs	Critical for device permformance
Aluminum/silver	Evap temp of solvent	Annealing will improve conduction	< 20 ohms	Critical for device permformance

Material	Oxygen trapping spec	Tolerance/Criticality	Optical transparency spec	Tolerance/Criticality
Film Substrate	N/A		95% transparent	±2%
ITO (alt. silver grid)	N/A		80-90% transparent	±10%
PEDOT:PSS	N/A		N/A	
P3HT:PCBM*	Nitrogren chamber required	<100 PPM oxygen/water	N/A	
Aluminum/silver	N/A		N/A	

Material	Adhesion spec	Tolerance/Criticality		
Film Substrate	N/A			*PCDTBT - alternative
ITO (alt. silver grid)		ASTM test for cross hatch tape test		*PSBTBT - alternative
PEDOT:PSS		ASTM F1842 - 09		
P3HT:PCBM*				
Aluminum/silver				

Contact angle is determined by how resistant the ink is to beading up on the substrate. This in turn also creates pinholes. Having the correct surface energy helps the inks to wet out properly. Contact angles should be 30 degrees or less. The surface energy of the fluid has to be higher with each layer that is added. A minimum of 5 dyne differences should be between the different layers.

Registration was found to be not as important with photovoltaics compared to transistors or any other printed electronic device. The electrode does not short with bleeding beyond the active layer.

Drying and annealing is a considerable challenge for printing. The majority of the materials require extremely high temperatures to anneal the ink. Additionally, to properly anneal, the inks need a certain period of time, which may prove difficult for a printing press running at top speed. It was discovered that some printers modify their presses to have enhanced dryers or offline processes that will anneal the material. Additional problems included the limit on substrates that could be used. If the ink needs 140° C to dry, many paper and polymer substrate would lose stability.

Conductivity is one of the most important specifications because it determines efficiency of the electrode. When the material is deposited onto the substrate, it should be in a manner where the ink will function at optimal conditions. The mobility of the P3HT:PCBM should be 10^-3 cm2/ Vs.

Oxygen trapping is needed with certain materials to properly adhere to the substrate and dry correctly. The material P3HT: PCBM is best applied in a nitrogen environment. It may be necessary to use a nitrogen air knife and chamber to apply the ink.

Both the cathode and substrate have to be highly transparent to allow sun into the circuit. The substrate should be above 95% transparent and the cathode as transparent as possible, around 80%.

Ink adhesion determines how well the ink sticks to the substrate. This will determine the integrity and stability of the photovoltaic over time. Adhesion can be determined by the ASTM cross hatch tape test.

Initially, registration and surface uniformity was thought of as the most important specifications a printing press had to meet. However, after all the interviews, it was apparent that drying and annealing as well as surface uniformity would be the greatest challenge for a traditional flexography press.

The hardest challenge for print would be able to create a thin, pin hole free layer. Ideally, there would be some sort of system to evaluate the layers as it is being in production. The resolution levels of traditional presses need to be increased to avoid pin holing. Micro flexography or micro gravure can be researched for these purposes.

Taking the specifications into account, is it feasible for flexography to be a means of mass production for printed photovoltaics? It is possible, however from interviewing experts in the industry, it is common to have hybrid technologies to take the strengths from each individual printing process. Additionally, press modifications such as extended dryers and oxygen trapping chambers are needed. The flexography industry should focus on building strengths to manufacture functional printing products. Research in new methods to increase ink film thickness control and improving drying capabilities is needed.

Printed photovoltaics will eventually change the entire energy market and help with the affordability of solar power. Flexography can be a huge leader in this upcoming change. The first step is to discover and understand the important variables in a photovoltaic and build equipment that can manufacture a quality product at a low cost. This in turn, will revolutionize the industry.

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Figure 1. Diagram. Glen Allen, VA: NanoMarkets, 2009. Internet.