

Flexible Implementation of Rigid Solar Cell

Technologies

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Abstract

As a source of clean, remote energy, photovoltaic (PV) systems are an important area of research. The majority of solar cells are rigid materials with negligible flexibility. Flexible PV systems possess many advantages, such as being transportable and incorporable on diverse structures. Amorphous silicon and organic PV systems are flexible; however, they lack the efficiency and lifetime of rigid cells. There is also a need for PV systems that are light weight, especially in space and flight applications. We propose a solution to this problem by arranging rigid cells onto a flexible substrate creating efficient, light weight, and flexible devices.

Introduction

There is a need for the development of flexible PV devices which can obtain a higher power to weight ratio than is currently available¹. Amorphous silicon is an inexpensive, flexible PV material, however it possess a low efficiency² requiring a large coverage area for a given power requirement. This necessity for a larger area is detrimental in applications where low weight is needed. In addition to amorphous silicon, flexible organic materials also have a low efficiency³, as well as a shorter lifetime⁴, making them impractical for critical implementations, such as space applications. To overcome the problems associated with these flexible PV technologies, we propose the use of small, highly-efficient, and rigid solar cells arranged on a flexible material. Using photolithography, thin film deposition, and electrochemical deposition (ECD), we are able to pattern conductive interconnects onto this material allowing the routing of power to our device. In this paper we will explain how our engineering methods allow for the integration of advanced solar cell technologies, such as crystalline silicon and gallium arsenide

(GaAs), onto flexible and light weight films. We will also show how the cell size can be scaled to achieve virtually any radius of curvature while providing a high power to weight ratio.

Body

Design

The carrier substrate of our device is Kapton[®], a flexible, light weight, and structurally strong material. Kapton is a polyimide film distributed by Dupont[®] that is available in a range of thicknesses and a variety of physical parameters. We chose the HN and FPC versions of this film. These possess the key elements required for our application which are low weight, low coefficient of expansion, stability over a wide temperature range, and high tensile strength. These parameters are crucial for our processing steps and for the final device's requirements. In order to reduce the weight added from the carrier substrate, we have chosen the thinnest manufactured Kapton films of 1 and .5 mil (25 μ m and 12.5 μ m respectively).

In order to perform our processing on the Kapton, we mounted the film to a 3" (inside diameter) alumina ring using Loctite[®] solvent resistant epoxy, shown in figure 1. The alumina ring allows the film to remain flat and rigid for photolithographic processing. The photolithography techniques allow us to pattern a thin film of conductive interconnects allowing individual solar cells to be connected into a series/parallel configuration. Figure 2 shows the interconnect layout. The solar cells are arranged and mounted onto these conductive buses.

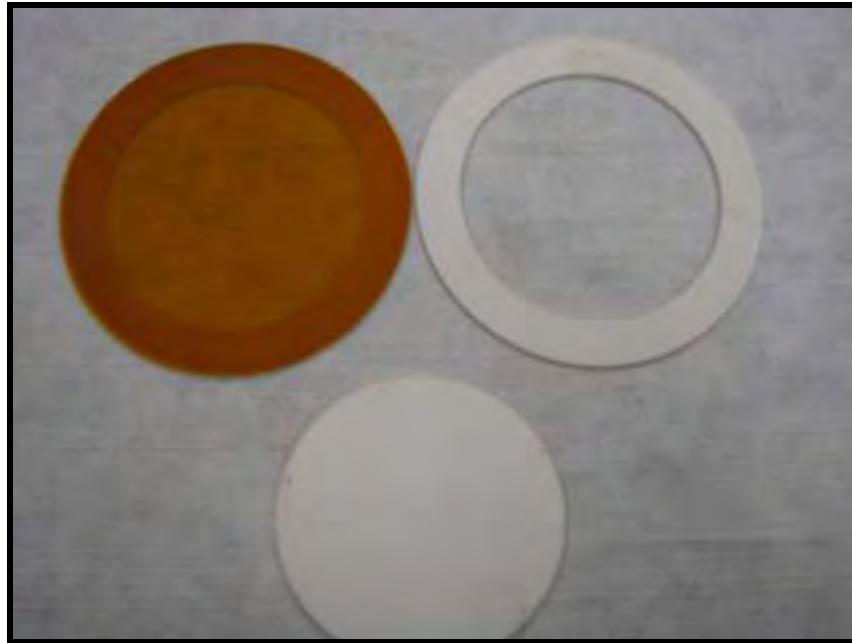


Figure 1- Kapton mounted to alumina ring, bare alumina ring, and center disc

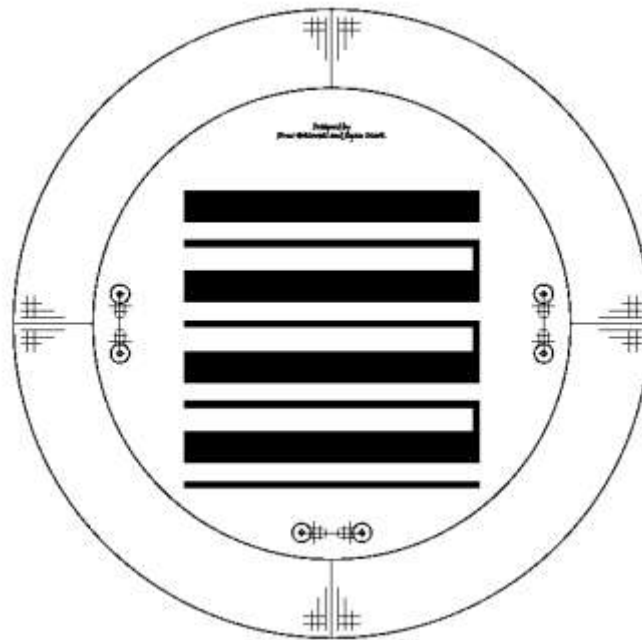


Figure 2- Interconnect layout

The larger of the interconnects is for the anode of the cell, and the smaller interconnects

are contact points for the cathode of the cell. Once mounted on the interconnects, the cells arranged horizontally are connected in parallel. This pattern allows the anodes of one row of cells to be connected to the cathode of the adjacent rows of cells creating a series connection. The photolithography masks were made on transparencies for simplicity and reduced cost as opposed to purchasing a chrome mask. Our original device was designed to incorporate cells 1.1cm by 1cm in size, thus making the resolution of the transparency masks greater than the critical dimension of our design. When our design is scaled down to achieve a smaller radius of curvature utilizing smaller solar cells, a chrome mask is necessary to accommodate the critical dimension of the design.

Fabrication

Photolithography techniques are used to pattern the conductive traces onto the Kapton⁵. In order to achieve the desired photoresist (PR) profile for thin film lift off, an image reversal process is used to reverse the polarity of the positive PR. AZ5214 PR is spun at 5000rpm for 30 seconds to achieve a thickness of approximately 1.1 μ m. The mounted Kapton then undergoes a soft bake. The substrate is heated at 110°C for 90 seconds on a hot plate with vacuum contact. A dose of 46mJ/cm² at 365nm is then used to expose the PR. After exposure, the Kapton is again heated for 45 seconds at 110 °C. Finally a flood exposure with a dose of 900mJ/cm² is used to complete the image reversal process. The substrate is submersed in MF321 developer for 90 seconds to develop out the PR, exposing Kapton in the areas where we want our patterned metal interconnects. Figure 3 is a scanning electron microscope image of the PR sidewall profile. The reentrant sidewall profile prevents the directional metal deposition from coating the sidewall of the PR, allowing a clean lift off process.

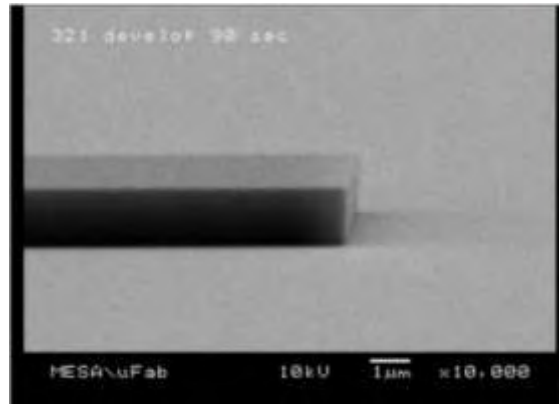


Figure 3: SEM image of reentrant sidewall profile of PR process

The substrate is then loaded into a Temescal CV8 electron beam evaporator where a titanium (Ti)/gold (Au) stack is applied. After experimenting with different thicknesses, we decided to use 200Å of Ti and 1000Å of Au. These thicknesses are used to reduce any losses due to resistance while maintaining minimal weight and cost. The 200Å of Ti is used to promote adhesion between the Kapton and the Au. The 1000Å of Au serves as our conductive base for ECD as well as a low resistance contact point for the anode of the solar cells. In addition to these properties, a Au surface is the ideal metal to use for wire bonding with gold wire. Figure 4 is an illustration of this process. The Ti/Au stack is deposited uniformly across the entire substrate. The patterned PR is then stripped, removing the metal stack from the unwanted areas on the device.

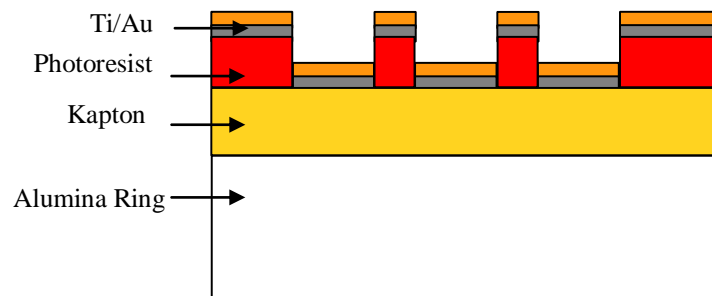


Figure 4
Illustrated cross section of processed Kapton (not to scale)

In order to remove the PR and effectively lift off the unwanted metal, the Kapton is submersed in acetone and exposed to ultrasonic agitation. Figure 5 shows our substrate after the metal deposition and lift off process is complete.

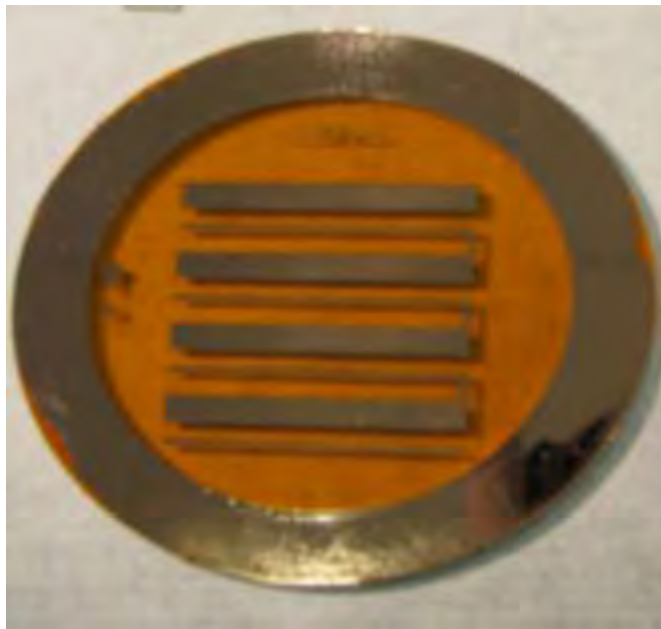


Figure 5
Patterned Ti/Au interconnects on Kapton

Once the metal is patterned on the substrate, the thickness of the Au on the thin interconnects must be increased for wire bonding purposes. 1000\AA of gold is not thick enough for sufficient adhesion of the wire bonds. In order to increase the Au thickness only in the necessary areas for wire bonding, and minimizing the weight added to the device, PR is patterned onto the substrate exposing only the thin interconnect lines. AZ4330 PR is spun at 4000rpm generating a thickness of $3\mu\text{m}$. A soft bake is performed on a hot plate with vacuum contact at 90°C for 90 seconds. The PR is then exposed at $20\text{mW}/\text{cm}^2$ for 9 seconds to generate

a dose of $180\text{mJ}/\text{cm}^2$, sufficiently exposing the PR. The substrate is submersed in MF321 developer for 3.5minutes to develop out the PR in the previously mentioned areas for ECD. Nutronex 309i Au sulfite bath from Enthone is used to electroplate Au onto the interconnects for wire bonding⁶. The plating bath is operated at 50°C with constant bath circulation from pneumatic pumping. The pneumatic pumping ensures chemical equilibrium during the plating process. Alternating current ECD is performed galvanostatically at a peak current density of $2\text{mA}/\text{cm}^2$. Electrical connection is made to the Au interconnects through a chemically isolated Au pogo pin. The pogo pin is isolated by a Viton o-ring to avoid any additive plating area from the electrical contact. The rate of uniform ECD is controlled by the pulse regime and the bath dynamics to electroplate $1\mu\text{m}$ of Au, creating a thickness sufficient for wire bonding.

Once the ECD process is complete, the solar cells are arranged and bonded to the conductive interconnects. Originally, the solar cells were bonded to the interconnects using electroplated indium because it serves as a pliable, low-temperature solder. We wanted to mount the cells using a pliable material so the cells would not delaminate during the flexing of the Kapton. After bonding the cells and testing the flexibility of the device, we discovered that indium did not have enough strength as the cells detached after repeated flexing. Our solution to this problem was to use a silver epoxy made by MG Chemicals to attach the solar cells. The cells are arranged upside down onto a silicon wafer that is patterned with PR for cell placement. The PR must be deposited at a thickness greater than 1mil ($25\mu\text{m}$) in order to sufficiently hold the cells in place. To achieve a thickness of $40\mu\text{m}$, NFR-015 negative PR is spun at 450 rpm on the substrate for 10 seconds⁶. To prevent the PR from cracking due to the thermal shock of going directly into an oven bake, the bulk of the solvent in the PR is allowed to evaporate during a relaxation period of 10 minutes at room temperature. Following the relaxation bake, the wafer

undergoes a pre-exposure soft bake at 90°C for 20 minutes and is then allowed to cool to room temperature. After the soft bake, the PR is exposed with a dose of 900mJ/cm², followed by a post exposure bake on a hot plate at 100°C for 2 minutes with vacuum contact. The unexposed PR is then developed out in MF321 for 6 minutes leaving a patterned mold for cell arrangement. Once the cells are placed upside down in the PR mold, the silver epoxy is applied to the backside of the cells. The substrate is then flipped upside down and aligned onto the array of cells, bonding the cells to the patterned Kapton substrate. Figure 6 shows the Kapton with our design consisting of a 16 cell array of 1.1cm x 1cm cells. The spacing between the cells allows the Kapton to flex while avoiding potentially destructive cell-to-cell impact.

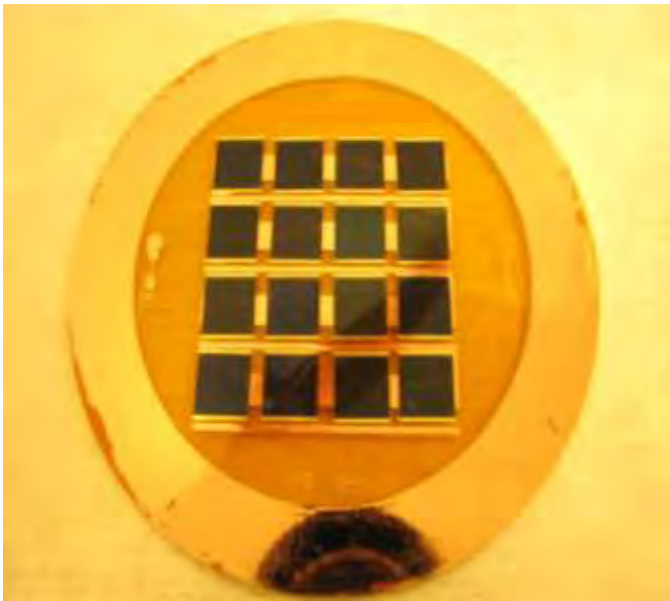


Figure 6-
Kapton with interconnects and
cells

To connect the top contact of each cell to the interconnects, we use a Westbond ultrasonic wire bonder with 1mil gold wire. The wire bonder allows for a variety of settings, which we adjusted for our application. The top contact requires a higher power for bonding than the gold interconnects, which we feel is due to the rigidity of the cells and the different thicknesses of the

metals. Our research⁷ and trial and error led us to the settings in Table I. The bonder is set up in a ball/wedge configuration, where the first bond to the solar cell is a ball and the second bond to the gold interconnect is a wedge. This allows putting a ball on a wedge to connect multiple wires if needed.

<u>Table I</u>	
Westbond Ultrasoni Wire Bonder Settings	
Bond 1 Power (Ball on solar cell)	375mW
Ball Size	9/10
Bond 1 Force	High
Bond 1 Time	20 ms
Bond 2 Power (Wedge on Au trace)	320mW
Bond 2 Force	High
Bond 2 Time	25ms

Analysis

Table II summarizes the density and volume of each component to determine a calculated weight of the device. The cells used in this design were produced by Emcore[®], and have a thickness of 200µm at a power of 31 mW at AM1.5.

Item	Density	Volume	Weight
Kapton®	1.42 g/cc	$3.81^2 \times 3.14 \times 25.4 \times 10^{-4}$	0.1645g
Titanium	4.51 g/cc	$11.4 \times 200 \times 10^{-8}$	0.0001028g
Gold	19.3 g/cc	$11.4 \times 10,000 \times 10^{-8}$	0.022g
Silver Epoxy	12.4 g/cc	$9.6 \times 100,000 \times 10^{-8}$	0.11904g
Solar Cells	.11 g/cell	16 cells	1.76g
Top laminate	1.40 g/cc	$3.81^2 \times 3.14 \times 25.4 \times 10^{-4}$	0.1621g
Total			2.2278 grams

From the above table, we can calculate a power to weight ratio of:

$$\frac{16 \text{ cells} \times 31 \frac{\text{mW}}{\text{cell}}}{2.2278 \text{ grams}} = \frac{.496 \text{ W}}{2.2278 \text{ g}} = 0.222 \text{ Watts / gram}$$

Through analysis of Table II it is easily seen that the majority of the weight of our device comes from the solar cells. The power to weight ratio of the cells alone is 0.3 Watts/g, showing that great care has been taken in reducing any additive weight from the other components of our device.

The top laminate is a low VOC conformal coating from DOW Chemicals. Its purpose is to protect the cells and to aid in providing some rigidity to the device. During application, care

must be taken to ensure that the top laminate is deposited evenly across the device so it does not cause any unwanted reflections of light, which could lower the efficiency of our device. Also seen in the table is that the bulk of the weight is in the substrate and the cells. To reduce weight further, we have used the .5mil (12.5 μ m) Kapton successfully, and no adverse side effects were noticed from this change.

The only way to reduce the weight of the device even more is to use thinner solar cells. Also, smaller cells would allow us to achieve a tighter radius of curvature. For this effort, we are attempting to use quantum dot in a well (DWELL) cells⁸. The advantage of these types of cells is their efficiency does not fall as the cells are scaled down⁹. We anticipate the ability to use 25 μ m thick, 1.41mm x 1.41mm cells. This should greatly increase our power to weight ratio, while also increasing the flexibility of the device. Appendix A demonstrates the flexing of our device using various cell sizes.

Once the device is completely assembled, the Kapton is cut out from the mounting ring, giving a 3inch circular piece of Kapton with the cells and interconnects centered on it. A design of our processing methods allows the device to be trimmed to fit a particular shape. Furthermore, if given a specific requirement, we can easily change our interconnect layout to arrange the cells in any shape or configuration desired, producing virtually any voltage or current needed. This benefit could reduce some external components normally required in a PV system for voltage up or down conversion.

Conclusion

To date, we have created a working prototype of our design using the 1.1cm x 1cm Emcore cells. We have achieved a better power to weight ratio than commercially available PowerFilm[®], which uses thin film silicon¹⁰ yielding .034W/gram. We have also tested our concept with other types of cells and verified that our methods are able to be adapted to any rigid solar cell technology. This allows us to use the highest efficiency devices despite their physical characteristics. Depending on the cell size we use, we can rival the curvature of most available flexible PV devices. We have shown how the benefits of rigid solar cells can be integrated into flexible applications, allowing performance that surpasses alternative technologies.

Appendix A

Since we are using rigid cells, the device does not completely conform to a smooth curve as the cells must remain tangential to the surface. Our device does, however, allow sharp 90° bends, which most alternative technologies will not allow. Shown below are several examples of our device in different arrangements.



Figure 7 – Side view of the 1.1 cm x 1 cm cells bending around a 4” (10.16cm) diameter object. Of interest is how the cells do not completely conform to the object, but rather approximate the curve in a Riemann sum fashion.



Figure 8 – Side view of the 1.41mm x 1.41mm cells bending around a 4” diameter object. As expected, with smaller cells, the curve of the object is followed more closely.

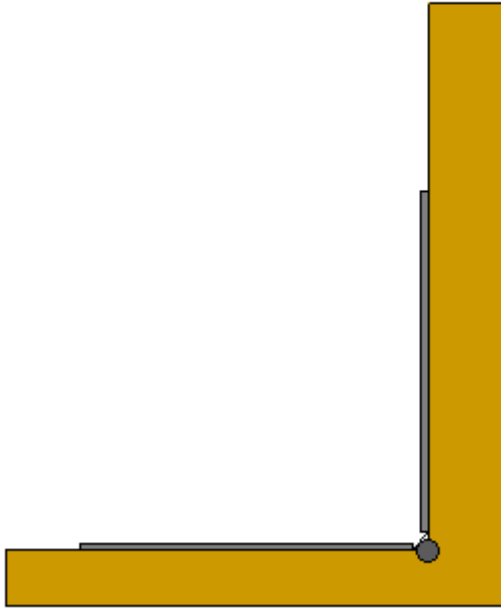


Figure 9 – Side view of our device performing a 90° bend, which may be required at a hinge point.

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