CIGS Processing on Flexible Polyimide Substrates

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ABSTRACT

This paper describes advances in device efficiency, absorber adhesion, monolithic integration and elimination of back contact cracking for CIGS processing on flexible polyimide (PI) substrates.

1. Introduction

Roll-to-roll production of CIGS-based PV on stainless steel or PI flexible web is commercially attractive because deposition processes can run continuously at high rates, and equipment is compact and relatively inexpensive. On PI substrate, complete monolithic integration using continuous processing at production rates can result in a flexible, lightweight product that is easily stored, transported, and assembled. Reported difficulties in producing viable PV on PI substrates at GSE and elsewhere [1] include low processing temperature required by PI, poor adhesion of CIGS to back contact/PI substrate, loss of electrical continuity due to cracking of the molybdenum back contact layer, and lack of viable methods for monolithic integration. This paper reports GSE's progress in solving many of these problems.

2. CIGS Material Quality and Device Efficiency

The most efficient CIGS devices have been made at relatively high deposition temperatures with an extrinsic Na source present. On PI, CIGS deposition temperature is limited to 400°C for extended times and 440°C for under about 15 minutes. Even at low temperatures, however, devices with relatively high efficiency can be produced. Fig. 1 shows the J-V characteristic of an 11.3% efficient CIGS device made on PI without extrinsic Na at an estimated substrate temperature of 423°C. The device was made by co-evaporation from the elements in a modified 2-stage approach on a moving web in roll-to-roll equipment. For CIGS deposition on a stationary PI substrate supported on glass, a device efficiency as high as 12.8% (with Na, but without AR) has been reported [2]. Based on these results and anticipated improvements due to process optimization and possibly Na addition, the CIGS electronic quality should be sufficient for production of reasonably efficient modules on PI despite the temperature limitations.

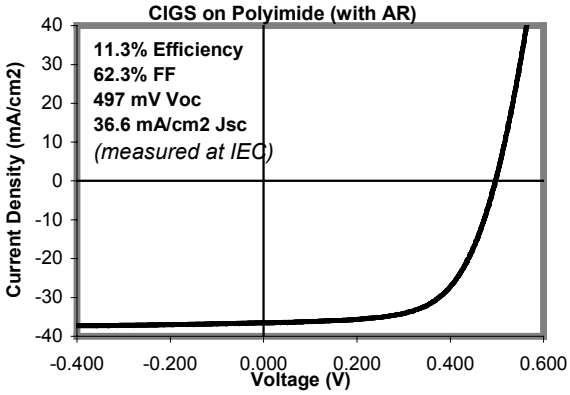

Fig 1. JV characteristics of an 11.3% efficient device

3. Back Contact Cracking and Electrical Continuity

Another difficulty reported with PI substrates is cracking of the molybdenum back contact layer [1]. We have also observed back contact cracking (Figs. 2A and 2B). Although both tensile and compressive failure have been seen to occur during CIGS deposition, disruption of electrical continuity is mainly due to tensile failure. Cracks are often parallel and vary in separation from 10 microns to a few millimeters.

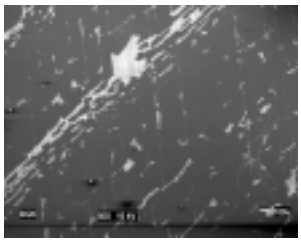

Fig 2A. SEM view of back contact Mo after removal of CIGS with adhesive shows CIGS adhering along some edges of the vertical cracks

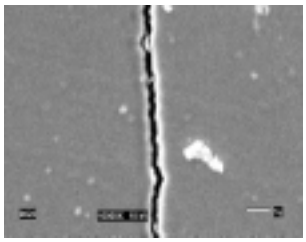

Fig 2B. Higher magnification SEM view of a crack indicates tensile failure in the Mo layer in this example

Sheet resistivity, taken with a 4-point probe in directions parallel and perpendicular to web travel, is a valid measure of the impact of back contact cracking. High variability in direction and severity of cracking is shown in electrical measurements of sheet resistivity. Cracking appears to be related to the initial stress of the as-deposited Mo and thermally induced dimensional changes of the PI during CIGS deposition. This is probably exacerbated by the brittle nature of the Mo and the large difference in coefficient of thermal expansion between Mo and PI. We have developed an alternate back contact on PI that appears to be compatible with CIGS deposition and avoids the cracking that leads to electrical discontinuity. Table 1 shows a severe example of the effect of Mo cracking on back contact sheet resistance.

Table 1. Sheet resistivity (orthogonal and parallel to the web) of a Mo back contact and a back contact of alternate construction

	Sheet Resistivity (ohms/square)	
Contact/Direction	**Mean**	**Std. Deviation**
Mo / Across Web	182.2	65.5
Mo / Down Web	19.3	15.6
Alt. / Across Web	0.338	0.018
Alt. / Down Web	0.326	0.008

The data in Table 1, taken after CIGS deposition and removal, show a significant increase in sheet resistivity, as well as significant anisotropy due to the directionality of the cracking.

For the Mo contact the sheet resistance was 1.6 ohms/sq with no variation before CIGS deposition. Data for the alternate back contact indicate that the resistivity was isotropic and unchanged from its initial value before CIGS deposition.

4. Monolithic Integration

The all-laser process at GSE uses multiple beam, selective cutting to make front and back contact and interconnect scribes at 12-in/sec, forming a monolithic interconnect on PI substrates [3, 4]. The alternate back contact required only minor changes to back contact scribing conditions, but will require re-optimization of the interconnect (via) scribe. Preliminary data using via test patterns on the newer alternate back contact show reasonable specific resistance for the via scribe, although further improvement is desirable. On Mo back contacts an interconnect resistance of 0.5 ohm-cm has been achieved. Significant improvement

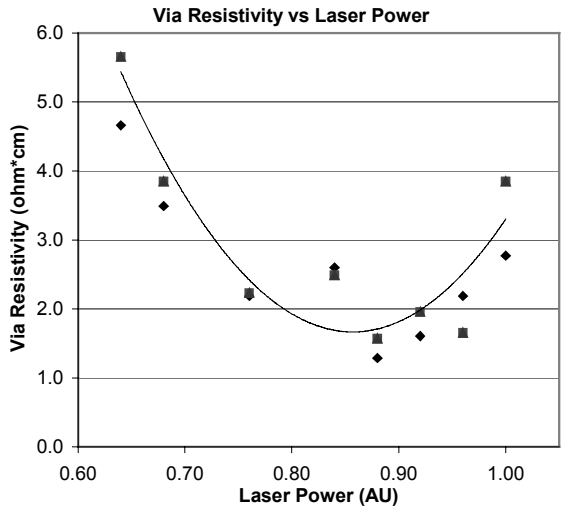

Fig. 3. Specific via resistivity as a function of laser power (in arbitrary units) for the alternate back contact

has been made in other aspects of the all-laser monolithic integration at GSE. Lines of insulating material about 100µ wide have been ink-jet printed over the back contact scribe, and total interconnect widths of about 250µ have been achieved (see Fig. 4); more work is needed to achieve those levels routinely. This monolithic interconnect technology allows narrow cell integration without imposing large losses, thus relaxing the requirements on the transparent front contact. Modules with Voc's approaching 300 volts have been made at GSE, in a 12-in by 32-in format, using 5 monolithically integrated subpanels.

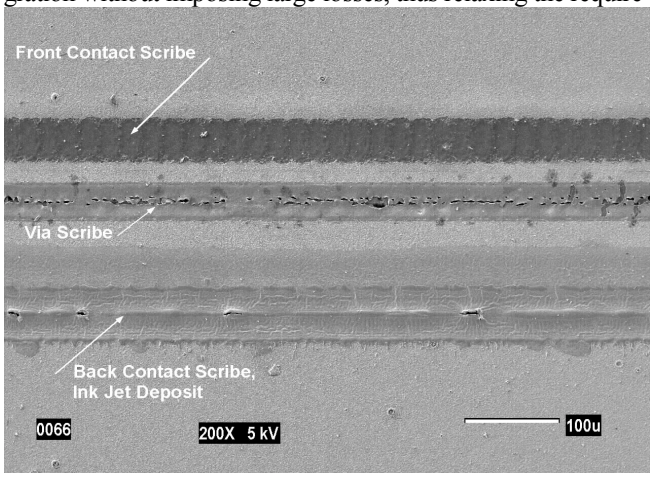

Fig 4. SEM micrograph of a monolithic interconnect made with the all-laser process; the total interconnect width is 240µ

5. Absorber Adhesion

Inadequate adhesion of the absorber layer to Mo back contacts on PI based CIGS has also been reported [1] and observed at GSE. We are testing a modification to the interface intended to improve absorber layer adhesion; so far, dramatically improved adhesion of the absorber layer has been observed, as shown in Table 2.

Table 2. Adhesion test results using 26 oz-in tape pull and calibrated film-pull tests on CIGS deposited on PI substrates with and without interface modification

Sample / Interface	Tape Pull Test CIGS Film Remaining (% of Area)	Film Pull Test Tensile Failure (PSI, Average)
#1 Standard	10	- 0 -
#2 Standard	18	- 0 -
#3 Standard	97	- 0 -
#4 Modified	50	148
#5 Modified	100	2010
#6 Modified	100	3120

6. Conclusions

GSE has demonstrated that CIGS capable of 11.3% device efficiency can be made on PI substrates in a continuous, roll-to-roll process despite the limitations imposed on processing temperature by that substrate. We have also demonstrated monolithic interconnects of less than 250µ total width on PI using a high speed, all-laser process. This is an enabling technology for the low-area-loss, high-efficiency, high-voltage modules preferable for bulk utility power generation, as well as many space applications. Significant progress has also been made to improve back contact durability and absorber layer adhesion.

7. Acknowledgements

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