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Electrochemical Approaches to PV Busbar Application

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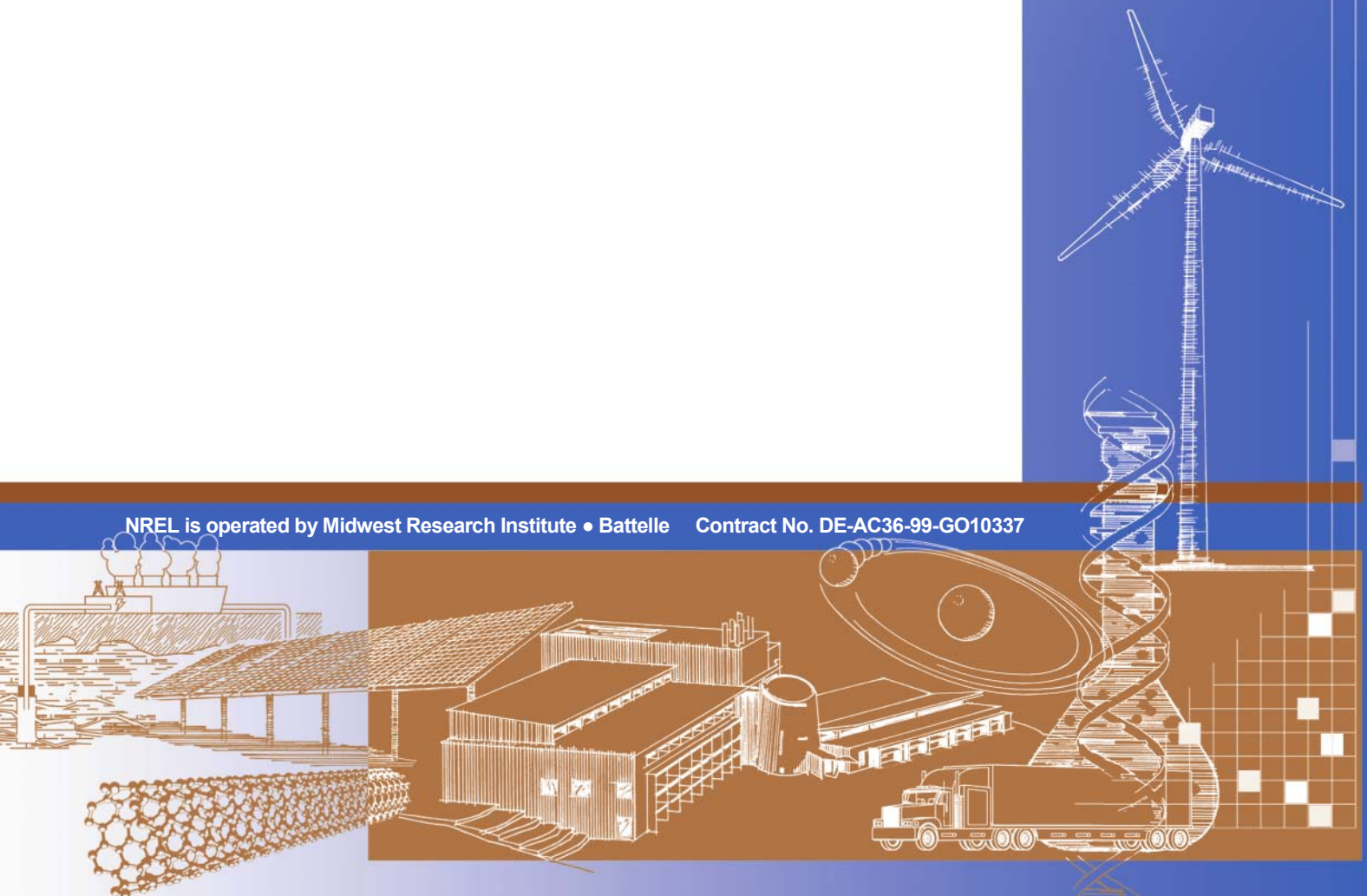

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Electrochemical Approaches to PV Busbar Application

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ABSTRACT

Busbars are an integral component of any thin-film photovoltaic module and must be easy and quick to apply by PV manufacturers, as well as provide long-term reliability in deployed modules. Potential reliability issues include loss of adhesion and delamination, chemical instability under current collection conditions (electromigration or corrosion), compatibility of material and application method with subsequent encapsulation steps. Several new and novel busbar materials and application methods have been explored, including adhering metal busbars with various one- and two-part conductive epoxies or conductive adhesive films, ultrasonic bonding of metal busbar strips, and bonding of busbar strips using low-temperature solders. The most promising approach to date has been the direct application of metal busbars via various electrochemical techniques, which offers a variety of distinct advantages.

1. Objectives

Improved PV components are required to ensure the reliability of thin-film PV modules. Achieving increased reliability through improved packaging and proper PV components is found throughout the *Solar Program Multi-Year Technical Plan* [1]. The objective of this work was to investigate new busbar materials and application methods that have not been investigated or used by manufacturers.

2. Technical Approach

Busbar materials and application methods were screened and judged according to: 1) fundamental physical criteria such as conductivity, 2) initial and long-term adhesion, 3) chemical stability under PV operational conditions, 4) any direct or indirect undesirable impact on the module caused by the application such as residual stress, and 5) projected ease of transfer of the developed technology to manufacturers. Of all the new methods investigated, electrochemical approaches have proven to be the most promising based on the requirements mentioned above. Electrochemically deposited busbars offer various distinct advantages to other approaches including: 1) electrochemical formation of chemically bonded metals to the PV substrate results in unparalleled adhesion and intimate electrical contact, 2) deposits are hard, dense, and formed with minimal residual stress, 3) deposits are chemically pure, 4) no sample heat build-up or mechanical agitation/disruption of the substrate occurs during application, 5) electrochemical approaches offer a large variety of user-controllable parameters, including voltage, current, solution concentration, temperature, and mixing, and 6) a large variety of metals can be deposited.

3. Results and Accomplishments

3.1 Selective plating (brush plating). In selective plating, the substrate is the cathode and thus serves as the site of electrochemical reduction or electron consumption. An electrochemical cell is completed by contacting an anode "pen" to the surface. Because the substrate is the cathode, it is critical that the area to be plated be conductive. Because PV modules contain some sort of exposed metallic conducting layer reserved for providing current collection, this does not pose a problem and nickel- and chrome-coated glass plates were used as substrates to evaluate the electrochemical approaches.

The anode "pen" is typically constructed using a conductive graphite rod wrapped with an absorbing material saturated with the electrolyte solution of choice. The cathodic substrate and anode pen are connected to the negative and positive leads of a power supply, respectively. When the anode pen is contacted to the cathodic substrate, a localized electrochemical cell is created, and metal deposition on the substrate only occurs at that spot (selective plating). As the pen is drawn across the surface, an electrochemical trace line appears, the width of which depends on the anode-tip diameter (brush plating). Although commercial selective plating instruments are available, an anode pen was constructed using a plastic disposable pipette with the tip plugged with cotton. The pipette was filled with the plating solution of interest and a platinum wire was inserted into the solution to serve as the anode. By adjusting the packing density of the cotton, suitable flow could be achieved at the tip of the pipette. Contact to 4"x4" metallized glass substrates was achieved using 3M 1181 single-sided adhesive conductive copper tape. For copper deposition the pipette was filled with a copper sulfate/sulfuric acid solution [2]. By briefly contacting the pipette anode to the substrate, small dots of metallic copper could be plated to establish proper plating conditions. A bright and adherent deposit was achieved using 8 to 10 volts DC resulting in about 10 to 15 mA. During deposition, evolved gas bubbles were observed at the platinum anode surface due to anodic oxidation of water to oxygen. The respective half reactions and net cell reactions for copper deposition are as follows:

$$2\,Cu^{+2} + 4\,e^- \rightarrow 2\,Cu^0 \qquad \text{CATHODE} \quad (1)$$

$$2\,H_2O \rightarrow O_2(g) + 4\,H^+ + 4\,e^- \qquad \text{ANODE} \quad (2)$$

$$2\,Cu^{+2} + 2\,H_2O \rightarrow O_2(g) + 2\,Cu^0 + 4\,H^+ \qquad \text{CELL} \quad (3)$$

Excessive voltage caused reduction of hydrogen ions to hydrogen gas to occur simultaneously with copper reduction causing a powdery deposit. Copper traces were made by

slowly drawing the anode across the metallized glass plates within the confines of 3M 470 insulating plater's tape (Fig. 1). The residual electrolyte solution was then rinsed and the plate was allowed to dry. Copper traces were found to be well adhered and passed the Scotch tape test, as well as attempts to dislodge the traces. There was minimal resistance (0.3Ω) between the trace and metallized substrate.

Figure 1: Copper traces of varying width and thickness produced by selective plating using $CuSO_4/H_2SO_4$.

For both selective and immersion plating, total coulombs can be calculated from integrated current flow and time. Faraday's Law and the corresponding redox reaction such as equation (1) can be used to calculate the total mass of metal deposited. Plating efficiencies (reduced atoms per consumed electrons) are also needed (close to 1.0 for $CuSO_4/H_2SO_4$ solutions) [2]. Calculated mass can then be used to obtain trace thickness given the deposit area and metal density. Deposit thickness can be varied according to the dwell time or rate at which the pipette anode is held or drawn across the substrate, although it can also be varied by judicious variation of the applied constant voltage or constant current. DekTak profilometry revealed thickness values of 700 to 3000 Å. Other metals judged to be suitable for busbars such as silver and tin were also deposited by this technique using commercial solutions from EPI (Electrochemical Products Inc., New Berlin, WI).

3.2 Immersion plating. Immersion or tank plating involves placement of the conductive substrate directly in the plating solution. The anode consists of a piece of the same metal intended to be electrochemically plated (e.g., silver anode for silver deposition) to alleviate solution depletion. Alternatively, a platinum anode can be used when depletion is not an issue. For these studies, ¼" x 2" strips of metallized glass were used as substrates and 3M copper tape established cathodic connection. Commercial silver- and tin-plating solutions were obtained from EPi. Once the strips were immersed into the solution, several hundred mV DC were applied resulting in 5 to 50 mA of current flow depending on the metal deposited. Copper plated directly on chromium- and nickel-metallized glass, but silver and nickel electroplates require thin "strike" layers to be electrochemically applied prior to deposition. For silver, a copper strike layer is used and for tin, a nickel strike layer is required. As discussed previously, deposit thickness is proportional to plating time. Plots of plate thickness vs. plating time were constructed, demonstrating that operational calibration plots for electroplated PV busbars could easily be accomplished. In the case of nickel, almost 2 μm were deposited in 5 minutes for the given conditions.

3.3 Electroless plating. The third type of electrochemical approach that was investigated is electroless plating. Unlike selective plating and immersion plating, electroless plating does not require any external source of voltage or current. Metal deposition is spontaneous through the use of reducing agents in solution and is autocatalytic. Electroless deposition baths are available from plating suppliers and often contain proprietary additives to ensure ease of deposit and quality. McDermid Niklad 724 (nickel sulfamate) was used to successfully deposit nickel on nickel-coated glass substrates. Electroless plating baths often require elevated temperatures for deposition, such as 85°C for this particular product.

3.4 Solderability of electroplated surfaces. An alternative to a busbar that has been exclusively electroplated on a module is to electroplate a metal strike layer or strike spots to which bare busbar foil can be soldered. Tin and bismuth form a eutectic alloy at 42%/58% that melts at 138°C, corresponding well with EVA lamination temperatures. By placing plated glass substrates on a hot plate at 150°C, bare tinned copper foil could readily be soldered to the strike layers. Adhesion to silver strike layers was fair and adhesion to tin was excellent.

4. Conclusions

Of all of the new busbar materials and application methods examined, direct electrochemical application appears to be very promising and offers unique advantages not found with current PV busbar methodology. Given electrical conductivity values for copper, silver, tin, and nickel and stipulations that the IR drop along busbars should be less than 1% of the maximum V_{oc}, it can be shown that for typical busbar dimensions the required thickness is in the range of 2 to 20 μm, which is easily and quickly achievable with electroplating techniques. Although selective plating may be the most straightforward approach for creating electrochemically applied busbars, one can also envision immersing masked ends of PV modules in an electrolytic tank and using immersion or electroless plating. Alternatively, busbar strips can be bonded to electrochemical strike layers on modules using Sn/Bi solder during the encapsulant lamination step.

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The author acknowledges M. Kempe for his prior work in demonstrating the solderability of Sn/Bi solder to tinned copper at EVA lamination conditions, which provided reason to explore Sn/Bi solderability to electrochemical strike layers. The author would also like to acknowledge J.F. Pern for his generous donation of lab space and electrochemical instrumentation required for this project.

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[1] *Solar Energy Technologies Program Multi-Year Technical Plan, 2003-2007 and Beyond,* DOE/GO-102004-1775, U.S. Department of Energy, Washington DC, January 2004.
[2] *Electroplating Engineering Handbook*, A. Kenneth Graham, ed., Van Nostrand Reinhold Co., NY, 1971.

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