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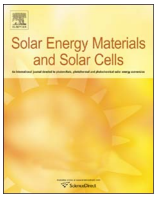

Degradation of multijunction photovoltaic gridlines induced via thermal cycling

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ABSTRACT

A well-known but heretofore uncharacterized failure mechanism in multijunction photovoltaic cells involves the development of cracks in the top cell directly adjacent to metal gridline structures. In this study, we systematically explore the potential evolution of stress, grain size, roughness, and hardness of metal gridlines during thermal cycling as it pertains to top cell cracking behavior. We discover that although top cells are found to crack after many cycles, this is not due to an accumulation of stress or damage, but rather a progression of strain hardening within the metal gridlines due to cyclic plastic deformations, quantified as an increase in hardness of as much as 57%. Furthermore, optical and topological characterization reveals morphology changes at the gridlines' top surfaces, lending some insight to commonly observed bus bar wire-bonding issues. Ultimately this suite of characterization techniques not only reveals the underlying behavior leading to gridline-induced top cell cracking failures in multijunction photovoltaics, but also suggests a route forward for the development of improved gridline materials.

1. Introduction

Rapid improvement and cost reduction of concentrator systems has led to increased interest in the development of terrestrial installations using high-efficiency multijunction photovoltaic (PV) cells in recent years [1–3]. While concentrator photovoltaic (CPV) systems have held a clear advantage in conversion efficiency over traditional silicon PV, with efficiencies that have long exceeded 40% and even recently reaching as high as 46% [1,4,5], questions regarding long term reliability remain as availability of field use data is limited [1,6]. Furthermore, environmental degradation is of greater concern as cells are subjected to higher incident flux of UV light and larger temperature cycles.

The application of multijunction PV cells, with their complex layered structures, in terrestrial applications requires an improved understanding of thermomechanical reliability and testing metrologies as the basis for improved lifetime predictions [7]. The ability to establish bankability via accelerated life testing stands as a key hurdle to any new solar technology if it hopes to overcome the relative safety provided by silicon panels [3,8–11].

While there have been studies of performance degradation [12–16], little has been done to understand and quantify the underlying materials properties that lead to degradation. Of particular concern are the effects of thermal cycling, given the large variance in coefficient of thermal expansion between the many individual layers within a multijunction cell [17–19]. A well-known but heretofore uncharacterized failure mechanism involves the development of cracks in the top cell directly adjacent to metal gridline structures [17,18,20]. As shown in Fig. 1, after many thermal cycles, cracks form at the corner of the semiconductor cap, and cells fail due to metal diffusion into these cracks. These cracks only form following multiple thermal cycles (has not been observed following a singular temperature cycle). This implies that cracking is caused by the cycle-by-cycle accumulation of damage within the brittle device layers and substrate. However, as this is unlikely to be the case in a brittle, defect-free material, it follows that there must be a cycle-by-cycle change in stress state of the gridline structure leading to these mechanical failures [21]. Previous work has investigated these failures as a function of current density within CPV cells, implying that there may be a synergistic effect between multiple stressing parameters, but in this case, we will focus on cracks induced by mechanical stress [16].

In this study, we systematically explore the potential evolution of stress, grain size, roughness, and hardness of metal gridlines during thermal cycling as it pertains to top cell cracking behavior. As is fairly typical in multijunction PV systems [20], gridline metals composed primarily of silver are used, and are deposited at a tunable rate,

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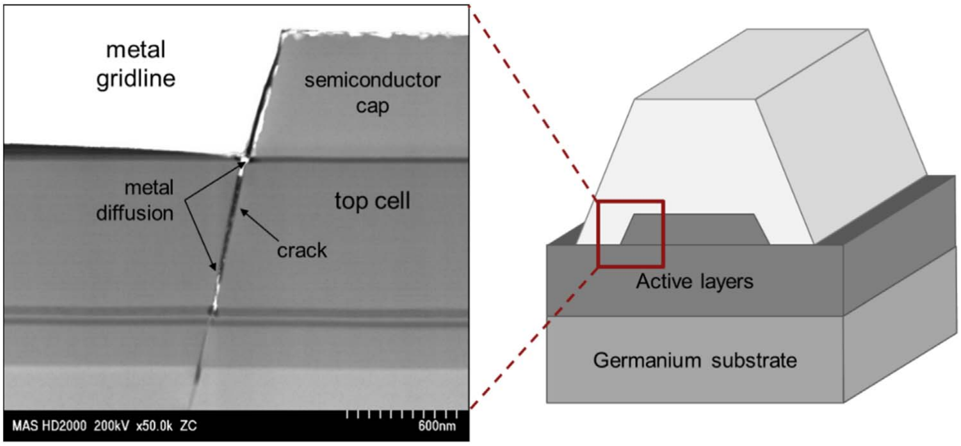

Fig. 1. A cross-sectional area of a gridline structure atop a multijunction cell imaged via SEM. This cell has been thermally cycled, causing the top cell to develop a crack originating from the corner of the semiconductor cap, which serves as a catastrophic failure mechanism as metal subsequently diffuses into the cell and shorts it.

allowing for comparison of fast and slow depositions. Thermal cycling conditions were varied including the use of exaggerated temperature extremes in order to accelerate degradation and simulate full lifetimes over the course of 2000 thermal cycles. While this study focuses specifically on one type of gridline structure/photovoltaic system, and it is likely that the development of cracks is specifically enabled by the relatively low fracture toughness of the top cell material (InGaP) [22], the methodologies employed herein can be broadly applied to any photovoltaic with similar geometries and design constraints. Ultimately this suite of characterization techniques reveals the underlying behavior leading to gridline-induced top cell cracking failures in multijunction photovoltaics, paving the way for future engineering to prevent such failures and extend operating lifetimes of these devices.

2. Experimental procedures

2.1. Metal coating and gridline depositions

Metal layers were deposited atop epitaxially grown multijunction photovoltaic cells on 180 µm germanium substrates (Spectrolab). A schematic of these test structures is shown in Fig. 2. Deposition rates of either 20 Å/s or 50 Å/s were used. Four-inch wafers with blanket coatings and four-inch wafers with patterned gridline structures were created. The wafers with gridline structures each included 11 sets of 250 µm, 100 µm, 25 µm, 15 µm, and 10 µm wide lines, spaced 1 mm apart and approximately 75 mm long. As is typical for these gridline structures, the edges had a slight pitch, on the order of a few micrometers of horizontal run. In all cases, nominal metal thickness was 6 µm. Following deposition, sets of three wafers underwent three different cycling conditions: a control group, a −180 °C to +125 °C cycle, and a −40 °C to +125 °C cycle, for specified durations, at a rate of 20 cycles per day, up to 2000 cycles. Cycling was performed with zero dwell time, resulting in approximate temperature ramp rates of 8 °C per minute. The maximum and minimum temperatures are somewhat in excess of what would be expected in field exposures, and we therefore expect 2000 cycles to approximately represent an accelerated full lifetime exposure. The draft IEC standard for CPV cell qualification has a requirement of 2000 thermal cycles, while others have suggested a minimum of 500 thermal cycles for full lifetime qualification [23]. Simulation of a full lifetime over a smaller temperature range would require up to 70,000 thermal cycles [6].

2.2. Wafer curvature stress measurement

A well-established technique for the measurement of thin film stresses, wafer curvature is used to quantify the residual stress in the blanket coated films following deposition, and subsequently used to quantify the change in residual stress following thermal cycling [24–27]. Wafers are placed into a temperature- and humidity-controlled wafer curvature instrument (FLX-2320, Toho Technology, Chicago, IL) film-side down, and the curvature is measured by using a laser to scan a line across the surface while quantifying the angle of deflection of the reflected light, as shown in Fig. 3. Two measurements of curvature are made for each specimen, orthogonal to one another, and averaged. The film stress is then quantified using Stoney's equation:

$$\sigma_f = \left(\frac{E_s}{1-v_s}\right)\frac{h_s^2}{6h_{met}}\Delta\kappa\,[\mathrm{MPa}] \tag{1}$$

where E_s, v_s, and h_s are the young's modulus, Poisson's ratio, and thickness of the substrate, respectively, and h_{met} is the metal thickness. In order to quantify the residual stress produced strictly by the metal deposition process, wafers with epitaxial layers (no metal) were used as the baseline curvature measurement (κ_o) for all subsequent measurements, measured for each individual wafer.

2.3. Optical grain size characterization

Grain size is measured directly via optical characterization for both

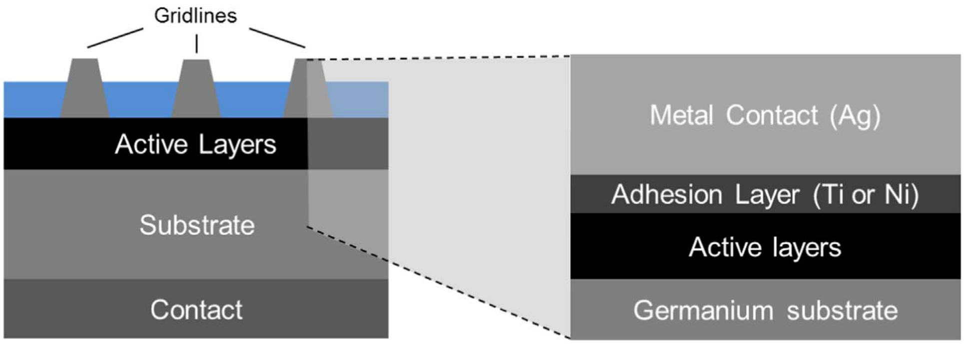

Fig. 2. Schematic representation of multijunction solar cell (left), with a schematic of the test structures created for the purposes of this study (right). In the case of wafer curvature specimens, wafers with blanket depositions of each of the layers depicted were prepared.