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Real-Time Spectroscopic Ellipsometry as an In-Situ Diagnostic for Hot-Wire CVD Growth of Amorphous and Epitaxial Si

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D. Levi, C. Teplin, E. Iwaniczko, T. Wang, Q. Wang, Y. Yan, and H. Branz

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D. Levi, C. Teplin, E. Iwaniczko, T. Wang, Q. Wang, Y. Yan, and H. Branz
National Renewable Energy Laboratory
1617 Cole Blvd., Golden, CO 80401 USA
Dean_Levi@NREL.gov

ABSTRACT

Real-time spectroscopic ellipsometry (RTSE) has proven to be an exceptionally valuable tool in the optimization of hot wire CVD (HWCVD) growth of both silicon heterojunction (SHJ) solar cells and thin epitaxial layers of crystal silicon (epi-Si). For SHJ solar cells, RTSE provides real-time thickness information and rapid feedback on the degree of crystallinity of the thin intrinsic layers used to passivate the crystal silicon (c-Si) wafers. For epi-Si growth, RTSE provides real-time feedback on the crystallinity and breakdown of the epitaxial growth process. Transmission electron microscopy (TEM) has been used to verify the RTSE analysis of thickness and crystallinity. In contrast to TEM, RTSE provides feedback in real time or same-day, while TEM normally requires weeks. This rapid feedback has been a key factor in the rapid progress of both the SHJ and epi-Si projects.

1. Objectives

The first objective of this work is to facilitate rapid progress in development of SHJ solar cell technology and epi-Si technology through the use of advanced in-situ characterization using RTSE. The second objective of this work is to further develop advanced in-situ characterization techniques that can be transferred to the photovoltaics industry.

2. Technical Approach

Spectroscopic ellipsometry determines thin film properties by measuring the change in polarization of light reflected from the film. Ellipsometry can determine thickness, surface roughness, crystallinity, temperature, void fraction, and optical and electronic properties through the dielectric function. Recent advances in hardware, software, and analysis techniques have enabled ellipsometry to be applied to growing films in real time.

The research reported in this paper uses in-situ RTSE both for real time feedback, and post-deposition characterization. Silicon heterojunction solar cells are fabricated by growing extremely thin layers of intrinsic and doped amorphous silicon (a-Si), on the order of 5 to 10 nm thick, onto c-Si wafers. Because growth rates can change with changing deposition conditions, it is critical to have a real time measurement of the layer thickness. This allows researchers to explore the parameter space of different temperatures, pressures, and hydrogen dilution while maintaining layer thickness as a known parameter. Besides accurate thickness control, SHJ solar cells also require an abrupt transition from c-Si wafer to the a-Si intrinsic layer for effective passivation of the c-Si surface. Post-deposition analysis of the RTSE data enables us to determine the degree of crystallinity of the intrinsic layer as a function of deposition time which is equivalent to film thickness. The only other measurement capable of determining a-Si film thickness and crystallinity is TEM, which requires weeks of time after the growth run to provide feedback. This lag time creates an information bottleneck as researchers can perform as many as three deposition runs per day. The rapid feedback provided by RTSE provides film growers with information to adjust parameters run by run to optimize device efficiency.

Research into epi-Si growth has similar characterization challenges as the SHJ research, although the goals of the growth process are in one sense opposite. The goal for the epi-Si project is to grow c-Si directly on the silicon substrate for the maximum thickness possible. If the epi-Si growth process is successful, the optical properties of the epitaxial layer are identical to the underlying c-Si substrate, and it is very difficult to distinguish the two with an optical technique such as ellipsometry. This initially appeared to be to a barrier to using RTSE as an in-situ diagnostic for epi-Si growth. During the course of the project we determined a way to use this apparent barrier to our advantage. By directly viewing the effective dielectric function determined by RTSE in real time during epi-Si growth, we can tell when the epitaxy process breaks down because the shape and amplitude of the dielectric function begin to change as soon as the material being deposited is no longer optically identical to c-Si. Thus we are able to qualitatively determine the degree of crystallinity in real time and stop the growth process once epitaxy has broken down. Using more complex analysis methods after the deposition we can determine the epi-Si thickness and the degree of crystallinity versus thickness from the RTSE data.

3. Results and Accomplishments

The major successes of this research are reflected in the progress in both the SHJ and epi-Si projects. T.H. Wang et al. describe the progress of the SHJ project in their paper in this proceeding. The team has achieved record energy conversion efficiencies of 16.9% for a p-type planar float zone silicon substrate, and 14.8% for a p-type Czochralski silicon substrate. The epi-Si project has surpassed the previous record thickness of 0.2 μm for HWCVD growth of epi-Si and achieved a maximum thickness of 0.5 μm at a growth rate of 2.0 angstroms per second. Both projects benefited from contributions from teams of a

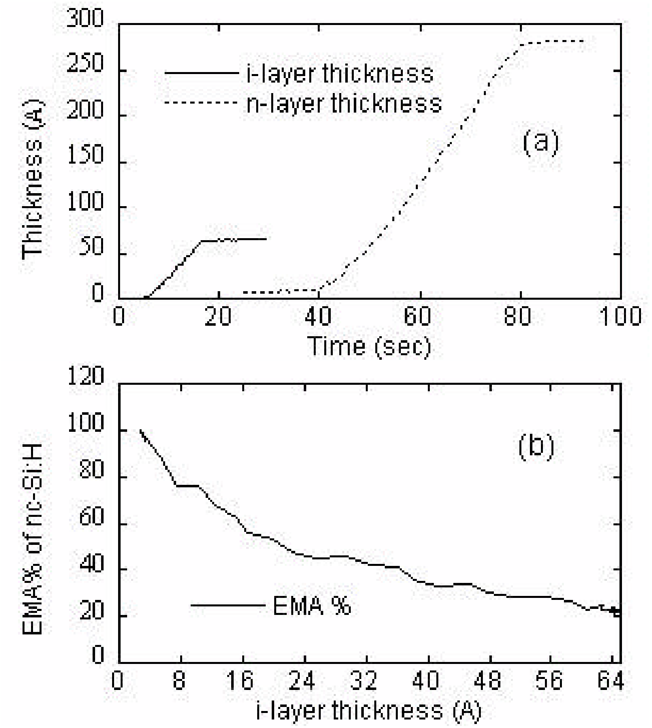

Fig. 1. (a) Thickness vs. time for i- and n-layer growth, and (b) percentage of nc-Si in i-layer vs. thickness, both from analysis of RTSE data.

half-dozen or more researchers. Our contributions using RTSE were part of these team efforts.

Figure 1(a) illustrates the thickness versus time information for the i- and n-layers that is used in real time during SHJ growth. Figure 1 (b) shows the percentage of nanocrystalline silicon vs. i-layer film thickness as determined from post-growth analysis of the RTSE data. Both the thickness and crystallinity information determined from the RTSE data has been verified using TEM. Figure 2 shows a high-resolution cross sectional TEM image for the sample from Figure 1. The diagonal black line marks the interface between the c-Si substrate and the i-layer. The dark areas are c-Si while the lighter gray areas are a-Si. The scale marker perpendicular to the interface shows 6 nm. There is excellent qualitative agreement between the degree of crystallinity from RTSE analysis and the TEM image. Overall film thickness determined from the TEM measurement ranges from 35.2 to 37.7 nm. This is in good agreement with the value of 34.5 nm from RTSE.

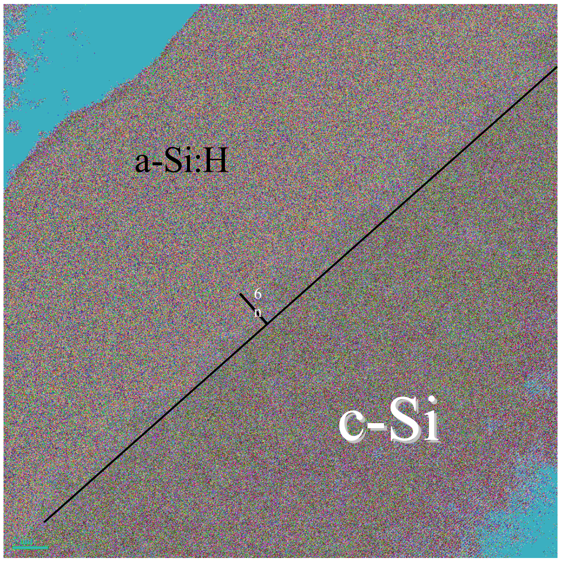

Fig. 2. High resolution cross sectional TEM image of SHJ sample analyzed in Figure 1. Diagonal line marks interface between c-Si substrate and i-layer.

Figure 3 illustrates TEM and RTSE analysis of an epi-Si film that grew to a thickness of approximately 300 nm before breakdown of epitaxial growth. The graph at the bottom of the figure shows the percent of a-Si present in the film as a function of growth time as derived from two different post-deposition analyses. The time axis is scaled to correspond to the thickness of the film in the TEM image. There is a very good correspondence between the point in time that RTSE shows the film is no longer pure c-Si, and the location in the TEM image where the film appears to begin to break down into a-Si growth. Numerous similar comparisons between TEM and RTSE analysis have verified that RTSE provides a sensitive measure of the breakdown of epitaxial growth in real time.

.4. ACKNOWLEDGEMENTS

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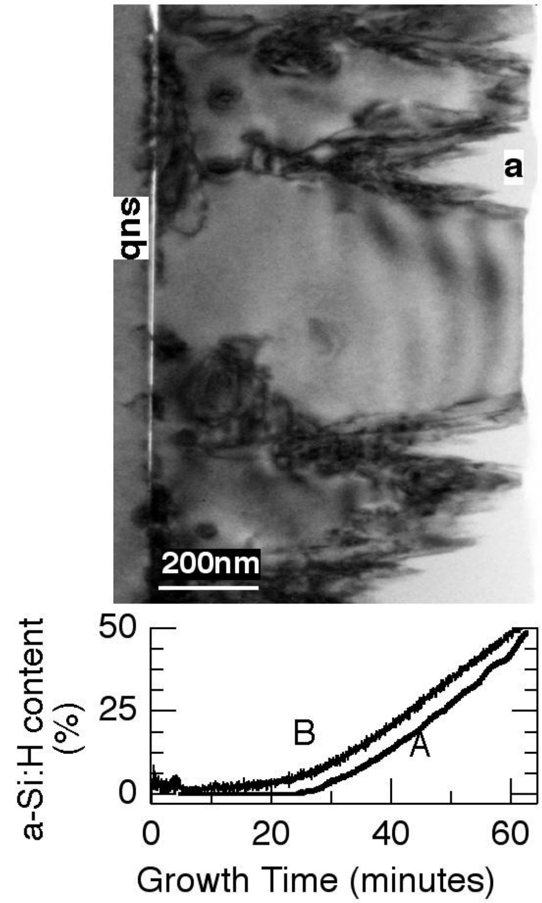

Fig. 3. TEM and RTSE analysis of epi-Si film showing good correspondence in degree of crystallinity.

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15. SUBJECT TERMS

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