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Improving the performance of pure sulfide $Cu(InGa)S_2$ solar cells via injection annealing system

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ABSTRACT

In this study, we present an effective method of improving the performance of pure sulfide $Cu(InGa)S_2$ (CIGS) solar cells via injection annealing system. The injection annealing system can perform annealing at desired temperatures, and therefore, the CIGS thin film passed over the temperature range in which secondary phases occurs. Via the injection annealing system, secondary phase InS_x was effectively removed from the surface of the CIGS thin films at the temperatures over 550°C. This resulted in the formation of good-quality P–N junction CIGS devices, thereby improving significantly the performance of the CIGS solar cell. In addition, the open-circuit-voltage (V_{OC}) and fill factor (FF) of the CIGS devices increased gradually with increasing annealing temperature in the range of 550–640°C. It is speculated that the bulk defects were decreased as the annealing temperature increased. Finally, via injection annealing system, a pure sulfide CIGS solar cell with an efficiency of 12.16% was achieved.

1. Introduction

In recent years, the single junction solar cells achieved high conversion efficiencies of over ~25%, and they have been reaching the theoretical limit [1]; no further improvement in efficiency is expected. To overcome this limited conversion efficiency, there is a need for tandem solar cell, which absorb a wide part of the solar spectrum. As a result, various tandem architectures have been researched recently such as the perovskite/$Cu(InGa)Se_2$ tandem cell, the perovskite/c-Si tandem cell, the perovskite/perovskite tandem cell, etc. Among them, perovskite/c-Si tandem cell achieved high efficiency of 29.15% [1]. To achieve well-established tandem architecture, the important roles of the top cell should be considered. The top cell has an absorber with a wide bandgap of ~1.7–1.8 eV, which reduces thermalization losses of high energy photons and, thereby, increases the open-circuit-voltage (V_{OC}) [2,3]. Among them, perovskite solar cells have an acceptable band gap of 1.5–1.6 eV, and they have achieved high efficiency of 25% [4,5]. However, the insufficient lifetime of the perovskite solar cells is still a problem [5]. Therefore, it is necessary to develop alternative top-cell absorbers that exhibit long-term reliability. Chalcopyrite semiconductors have been researched for applications in thin-film solar cells. Among the chalcopyrites, pure sulfide $Cu(InGa)S_2$ (CIGS) has tunable wide bandgaps ranging from 1.5 to 2.4 eV [6]. At the earlier stage, pure sulfide CIGS achieved 11.2% by using Na-containing Cu-In-Ga precursors followed by sulfurization in H_2S environment [7]. And then, CdS/CIGS based solar cell achieved 12.9% by sulfurization at high temperature 650°C via optimized rapid thermal process [8]. After that, large boosting of V_{OC} was observed by converting from Cu-excess to Cu-deficient metal precursor to prepare the CIGS thin film, and it led to large improvement efficiency of 15.5% [8,9]. And recently, CIGS solar cells achieved a conversion efficiency of 16.9% [10]. Therefore, pure sulfide CIGS is thought to be a promising top-cell material for tandem devices.

To improve the performance of CIGS solar cells, it is vital to suppress of the secondary phases on the CIGS thin films. It is reported that sharp-shaped InS_x and island-shaped Cu_xIn_y are easily formed on the surface of CIGS thin films during annealing processes [11]. The presence of these secondary phases on the CIGS thin film increases recombination at the

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