Influence of Na in Cu$_2$SnS$_3$(CTS) films with different Na contents on their photovoltaic performances was investigated. Moreover, the recombination losses at buffer/absorber interface, in space charge region (SCR), and quasi-neutral region (QNR) were analyzed in the CTS solar cells with different Na contents. The CTS films with different Na contents were fabricated by the sulfurization of NaF/Cu/SnS$_2$ stacked precursors in Fig. 1(a). In Fig. 1(a), the Cu (190 nm)/SnS$_2$ (530 nm) stacked precursors were first prepared on Mo-coated soda-lime glass (SLG) substrates for the Cu/Sn atomic ratio of 1.55 by radio frequency magnetron sputtering. Then, NaF precursors with different thicknesses of 0, 25, and 60 nm were grown on the samples by electron-beam evaporation in Fig. 1(a), where the NaF layer is used as the main Na source for Na introduction into the CTS films. It is found that the Na content in the resulting CTS films is increased with NaF thickness.

After preparing the CTS films with different Na contents, the CTS solar cells were fabricated with a structure of Al/Ni/ZnO:Al (AZO)/ZnO/CdS/CTS/Mo/SLG as depicted in Fig. 1(b). As a result, the conversion efficiency ($\eta$) of the CTS solar cells with increasing NaF thickness from 0 to 60 nm was significantly enhanced from 2.3 to 4.6%. Moreover, the $\eta$ of the CTS solar cell with the NaF thickness of 60 nm is further increased up to 4.8% by adding anti-reflective coating MgF$_2$ layer in the solar cell structure. It is disclosed that the Na in CTS films plays an essential role in enhancing the $\eta$.

To understand the effect of Na introduction on the improvement of the cell performances, the individual recombination rates at buffer/absorber interface ($R_i$), in SCR ($R_d$), and QNR ($R_b$) in the CTS solar cells with different NaF thicknesses of 0, 25, and 60 nm were estimated by the method reported in Ref. [1], which were extracted from temperature-illumination-dependence open-circuit voltage [1]. In addition, according to the method [1], the voltage-independent recombination coefficients at buffer/absorber interface ($R_{i0}$), in SCR ($R_{d0}$), and QNR ($R_{b0}$) were calculated. Ultimately, Fig. 2 demonstrates $R_{i0}$, $R_{d0}$, and $R_{b0}$ of the CTS solar cells as function of NaF thicknesses of 0, 25, and 60 nm for preparing their CTS absorbers. It is revealed that the $R_{i0}$, $R_{d0}$, and $R_{b0}$ in the CTS solar cell with NaF thickness of 60 nm are lower than those of the solar cells with Na thicknesses of 0 and 25 nm. The results confirm that recombination losses in each region in the CTS solar cell are decreased by the Na introduction in the CTS film, thus leading to the increases in the $\eta$ up to 4.8% in the CTS solar cell with NaF thickness of 60 nm. The detail will be discussed.

Reference