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DOCTORAL THESIS

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Study of Crystalline Silicon Heterojunction Solar Cells with Amorphous Silicon Oxide Passivation Layers

（アモルファス酸化シリコンパッシベーション膜を用いたヘテロ接合型結晶シリコン太陽電池に関する研究）

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In this thesis, the application of a-$Si_{1-x}O_x$:H thin film as the passivation layer of heterojunction solar cells was studied. Emphasis is put on the realization of very low surface recombination velocities with thicknesses suitable for heterojunction solar cell application (<10 nm). To the best of our knowledge, the achieved surface recombination velocity of 1.6 cm/s with a 6-nm-thick layer is lowest ever reported for a-$Si_{1-x}O_x$:H films.

In Chapter 2, the basics of c-Si solar cells were presented. Effect of front and rear surface recombination velocities on solar cell performance was calculated using a simple *pn*-junction model. The solar cell performance is largely affected by rear surface recombination when wafer thickness is reduced. It was also demonstrated that high light confinement is required to avoid optical losses in thin solar cells. If rear surface recombination velocity lower than 1 cm/s and high light confinement are achieved simultaneously, V_{oc} higher than 760 mV and efficiencies higher than 25% can be achieved with substrates thinner than 100 µm.

In Chapter 3, 1D device simulation was performed to evaluate the effect of wafer thickness and interface defect densities on PV-parameters. The calculation model had a structure close to the actually fabricated solar cell. As predicted in the calculations of Chapter 2, the efficiency is almost determined by the rear surface recombination rate. If rear surface passivation losses are suppressed, the gain in V_{oc} compensates for the losses in J_{sc} when wafer thickness is reduced. The insertion of low refractive index films as rear reflectors between BSF and rear electrode was also considered. In_2O_3:H and *n*-μc-$Si_{1-x}O_x$:H films were effective in reducing the parasitic absorption at the rear electrode and increasing rear reflectance.

In Chapter 4, a-$Si_{1-x}O_x$:H thin films were fabricated for passivation of c-Si. The optical properties of a-$Si_{1-x}O_x$:H can be largely changed by controlling the CO_2 flow rate during deposition. The oxygen incorporation into the film structure was confirmed by FTIR measurements, from which oxygen content was estimated to be 3 to 12% within the experimental range. An optimum CO_2 flow rate is required to achieve a high passivation quality. Excessively low oxygen content leads to epitaxial growth, which in turn was detected by SE analysis. TDS measurements indicated that films with higher passivation quality have hydrogen desorption at higher temperatures. Compared to a-Si:H, the higher hydrogen thermal stability of a-$Si_{1-x}O_x$:H films is attributed to the oxygen back-bonding that increases H dissociation energy. Annealing treatment was effective in reducing surface recombination velocities. The lowest values achieved were 1.6 and 0.83 cm/s for a 6- and 25-nm-thick passivation layers, respectively.

Fabrication of n-μc-$Si_{1-x}O_x$:H thin films for application as rear reflectors is presented in Chapter 5. Refractive indexes between those of c-Si and ITO were obtained by controlling the CO_2 flow rate. Extinction coefficient is practically zero in the long wavelength range, indicating that free carrier absorption is negligible. A compromise between electrical and optical properties was observed, with high CO_2 flow rates leading to low crystallinity and low conductivity. Relatively low surface recombination velocity was achieved with an a-$Si_{1-x}O_x$:H/n-μc-$Si_{1-x}O_x$:H stack, indicating that n-μc-$Si_{1-x}O_x$:H deposition is not harmful to surface passivation.

Fabrication of heterojunction solar cells with a-$Si_{1-x}O_x$:H passivation layers are presented in Chapter 6. The annealing step performed after a-$Si_{1-x}O_x$:H deposition and prior to doped layers deposition was successful in reducing surface recombination and improving V_{oc}. Gains of 44 and 37 mV were obtained for textured and flat solar cells, respectively. The high surface passivation quality allowed the improvement of V_{oc} from 717 to 724 mV reducing the wafer thickness from 280 to 200 μm. The highest efficiency for a flat solar cell was 19.0% with the thinner solar cell. After front *i*-layer thickness optimization on textured wafers, *FF* was successfully improved, resulting in the best solar cell of this study, with an efficiency of 20.1% and V_{oc} of 708 mV. The a-$Si_{1-x}O_x$:H/c-Si interface of a textured solar cell with V_{oc} of 694 mV was evaluated by

TEM. A sharp interface at the facet, bottom, and top of pyramids indicated that a-$Si_{1-x}O_x$:H was successful in suppression of epitaxial growth on textured wafers despite the relatively high deposition temperature. Finally, an alternative *p*-μc-$Si_{1-x}O_x$:H rear-emitter structure, with *n*-nc-3C-SiC:H as front doped layer and In_2O_3:H as front TCO was fabricated. With this structure, promising *EQE* was obtained in the short and long wavelength ranges.

The low surface recombination velocity achieved indicate that high V_{oc} and high efficiency can be expected even when wafer thickness is reduced to less than 100 μm. Accordingly, a-$Si_{1-x}O_x$:H is a promising material for passivation of high efficiency thin heterojunction solar cells.