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Study of Transparent Cu_2O Solar Cells for High-efficiency, Low-cost Tandem Photovoltaics

Naoyuki Nakagawa, Soichiro Shibasaki, Mutsuki Yamazaki, Yuya Honishi, Yoshiko S. Hiraoka, and Kazushige Yamamoto

Toshiba Corp. Research & Development Center
1, Komukai-Toshiba-cho, Saiwai-ku
Kawasaki 212-8582, Japan
Phone: +81-44-549-2131 E-mail: kazushige.yamamoto@toshiba.co.jp

Abstract

Novel transparent Cu_2O thin-film solar cells and prototype four-probe Cu_2O/Si tandem cells were developed for high-efficiency, low-cost tandem cells. Cu_2O thin-film solar cells were fabricated using reactive sputtering of Cu in an oxygen atmosphere. High transparency and power generation of these Cu_2O cells were confirmed. For the tandem cell, transmittance of the Cu_2O top cell was sufficiently high that the Si bottom cell generated almost 80% of its maximum power output. Cu_2O top cell efficiency reached 6.2%. The result is a tandem efficiency of 23.8%, exceeding the 22% of the Si bottom cell.

1. Introduction

Solar cells of III–V compound semiconductors such as InGaP/GaAs/InGaAs are known as high-efficiency tandem photovoltaics, with power conversion efficiency in excess of 37% in one case [1]. However, these compound semiconductor solar cells are too expensive for consumer applications, so there is demand for new low-cost, high-efficiency solar cells.

Cu_2O (bandgap energy 2.1 eV) solar cells have several advantages for use as the top cell in tandem photovoltaics. Cu and O atoms are earth-abundant, so the material cost of Cu_2O solar cells would be low. Also, Cu_2O solar cells offer high efficiency, with theoretical and experimental maximum power conversion efficiencies respectively exceeding 16% [2] and 8.2% [3]. Furthermore, when Cu_2O solar cells are used as a top cell, Si solar cells are a potential bottom-cell candidate, because the overlap of spectral sensitivity between Cu_2O and Si is small.

Although Cu_2O is a top-cell candidate in tandem cell structures, conventional Cu_2O solar cells are opaque [4]. In this study, we focused on two properties of Cu_2O solar cells: realizing high transparency to allow a Si bottom cell to generate electricity, and power generation in a Cu_2O top cell.

2. Experimental

Cu_2O thin films (2-μm thickness) were deposited on a substrate by a conventional reactive sputtering method. There are three phases in the Cu–O phase diagram: Cu, Cu_2O, and CuO. Cu_2O is a metastable phase, so a large oxygen supply forms the CuO phase, while a low oxygen supply forms the Cu phase. These two impurity phases reduce both transmittance and hole mobility of Cu_2O thin films. With the aim of fabricating high-quality Cu_2O thin films, we studied Cu_2O deposition morphology on a glass substrate and on a transparent conducting oxide (TCO) substrate.

To measure the properties of the solar cells, an n-layer, front TCO layer, metal grid, and anti-reflective coating (ARC) were deposited on top of the Cu_2O thin film.

Figure 1 shows the measurement configuration of the four-probe Cu_2O/Si tandem cells and a cross-sectional image of the Cu_2O cell. Tandem efficiency is estimated by adding the efficiencies of the top and bottom cells.

3. Results and discussion

An XRD pattern of the Cu_2O thin film on a glass substrate showed that a (111)-oriented Cu_2O thin film was obtained. There are no Cu or CuO phase peaks, demonstrating the high quality of our Cu_2O thin film.

Figure 2 shows the transmission spectra of a Cu_2O thin film deposited on a TCO substrate over wavelengths at which the Si bottom cell can generate electricity (600–1200 nm) versus relative oxygen gas mass flow.

The optical absorption edge of Cu_2O is near 600 nm, meaning that transmittance should be high for wavelengths longer than 600 nm so long as the thin film is a single phase of Cu_2O. The transmission spectra strongly depend on oxygen mass flow, indicating that impurities strongly affect Cu_2O transmission. When oxygen gas mass flow is relatively low compared with the optimum point, thin-film transmittance decreases due to the emergence of a Cu impurity phase. Moreover, when oxygen gas mass flow is relatively high compared with the optimum point, the transmittance value decreases due to the smaller bandgap of the CuO impurity phase. Combining a high-quality p-Cu_2O thin film with optimized oxygen mass flow and an under-development n-layer, we fabricated a Cu_2O top cell and verified its high transparency. We also investigated power generation of a prototype tandem structure.

The transparency of a Cu_2O solar cell with an ARC is higher than that of a bare Cu_2O thin film, showing 79% of average transmittance at 600–1200 nm. Both the top and bottom cells were found to successfully generate power.

Transmittance of the Cu_2O top cell was sufficiently high for the Si bottom cell to generate almost 80% of its maximum power output. Furthermore, Cu_2O top-cell efficiency reached 6.2%. The result is a tandem efficiency of 23.8%, exceeding the 22% efficiency of the Si bottom cell.

Table I shows the measured photovoltaic characteristics of the prototype tandem cell, along with ideal characteristics as obtained by device simulation. Realizing these ideal characteristics is a mid-term goal for this research.

Comparison of the measured Cu_2O top-cell efficiency with the simulation results shows that the low open-circuit voltage (V_{oc}) limits the efficiency. This is due to an energy mismatch between the p-Cu_2O layer and the under-development n-layer. It is important to control the p–n band alignment to improve the V_{oc} of the Cu_2O top cell by controlling the material composition of the n-layer to achieve a tandem efficiency in excess of 30%.

3. Conclusions

We successfully fabricated transparent Cu_2O solar cells and prototype Cu_2O/Si tandem solar cells and confirmed high transparency of the Cu_2O top cell and power generation of the tandem solar cell. By improving the top-cell efficiency, a Cu_2O/Si tandem solar cell with efficiency exceeding 30%, which greatly exceeds the efficiency of single Si solar cells, might be achievable. Obtaining a tandem efficiency exceeding 30% at reasonable cost may lead to photovoltaic applications for new energy businesses, such as energy aggregation, distributed power systems, and household power generation systems with batteries, as well of long-dreamed-of applications such as solar-powered cars and trains.

References

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TABLE I
Efficiencies and Properties of Cu_2O/Si Tandem Cells

		observed	Mid-term goal
Tamdem (%)		23.8	30
Cu_2O top cell (%)		6.2	10
Si bottom cell (%)		17.6	* 20
Si cell (%)		22	* 25
Top cell	Transmittance (%)	** 79	** 80
	Voc (V)	0.94	1.4
	Jsc (mA/cm^2)	9.7	10

*Adopting a 25%-efficient Si bottom cell
**Average between 600 and 1200 nm

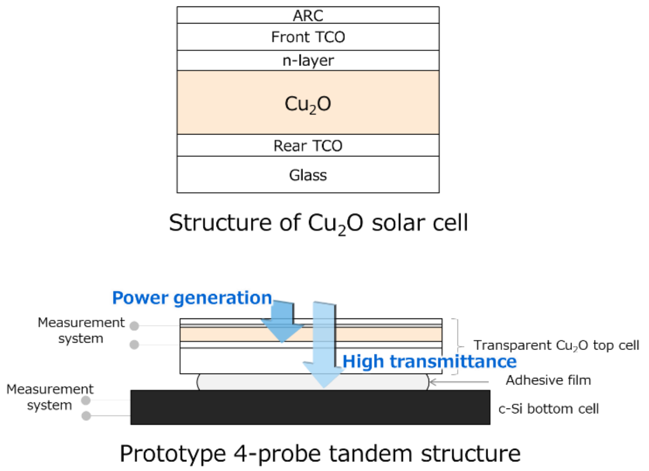

Fig. 1. Measurement configuration for Cu_2O/Si tandem photovoltaics and cross-sectional view of the Cu_2O top cell.

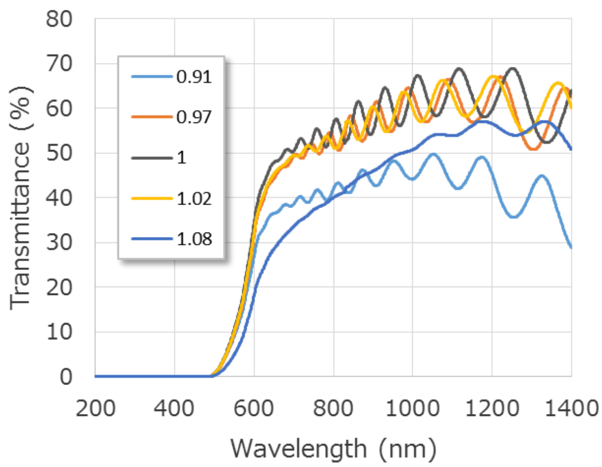

Fig. 2. Transmission spectra of Cu_2O thin films on TCO substrates.