Experimental Approach to Silicon Heterojunction Tandem Solar Cells

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A solar cell, or a photovoltaic (PV) cell, is an electrical device that converts light energy directly into electricity by the photovoltaic effect. There are different types of solar cells. Tandem solar cells could have a very good conversion efficiency in comparison with other types of solar cells. Tandem solar cells are considered the industry’s next step in photovoltaics due to their excellent conversion efficiency. A very good example is the perovskite absorber material that has been developed for efficient tandem solar cells.

Keywords: Cu2O/c-Si tandem heterojunction SC ; perovskite ; silicon heterojunction tandem solar cells (SHTSCs)

1. Introduction

A solar cell, or a photovoltaic (PV) cell, is an electrical device that converts light energy directly into electricity by the photovoltaic effect. The operation of a photovoltaic (PV) cell requires three essential features: (a) the absorption of light, generating electron–hole pairs; (b) the separation of charge carriers of opposite types; and (c) the separate extraction of those carriers to an external circuit.

There are different types of solar cells: (1) amorphous silicon (A-Si) solar cells; (2) biohybrid solar cells (which are based on a combination of organic and inorganic matter); (3) silicon buried-contact solar cells; (4) cadmium telluride solar cells; (5) concentrated PV (CPV) cells; (6) copper indium gallium selenide (CIGS) solar cells; (7) dye-sensitized solar cells (DSSCs); (8) gallium arsenide solar cells (GaAs SCs); (9) hybrid polymer solar cells (HPSCs); (10) luminescent solar concentrator cells (LSCCs); (11) monocrystalline silicon solar cells (Mono-Si SCs); (12) polycrystalline silicon solar cells (Poly-Si SCs); (13) multijunction solar cells (MJSCs); (14) quantum dot solar cells (QDSCs); (15) tandem solar cells (TSCs).

Tandem solar cells could have a very good conversion efficiency in comparison with other types of solar cells. Tandem solar cells use two different materials that absorb solar radiation; this means that a tandem solar cell can absorb more of the solar spectrum—and so produce more electricity—than if one material is used (such as silicon solar cells).

Tandem solar cells are considered the industry’s next step in photovoltaics due to their excellent conversion efficiency. A very good example is the perovskite absorber material that has been developed for efficient tandem solar cells. The European Solar Test Installation has verified a 32.5% efficiency for perovskite/silicon tandem solar cells.

Solutions related to tandem solar cells based on silicon are studied, using three advanced architectures with different material structures, namely, metal oxide, thin film, and perovskite [1][2].

1.1. Metal Oxide Tandem Heterojunction Solar Cells

Currently, more than 90% of the photovoltaic (PV) market is dominated by crystalline Si solar cells [3]. Silicon-based tandem heterojunction solar cells having a metal-oxide subcell represent an attractive approach in the development of the next generation of SCs.

Cutting the cost of PV-producing technology would be possible if low-cost metal oxides were used in fabrication of Si-based tandem solar cells to be developed further.

Cuprous oxide (Cu_2O), as a p-type semiconductor with high optical absorption and a direct bandgap of about 2.1 eV, is suggested to be a good match for PV applications. A p-n heterojunction could be designed and fabricated using an n-type semiconductor such as ZnO. As both TiO_2 and ZnO are low-cost oxides, the premises to develop a low-cost heterojunction solar cell are met. Since only 8% conversion efficiency has been achieved experimentally to date [4][5], further investigation of Cu_2O-based solar cells could create the premises to fully achieve the potential of PV technology, as it is known that the maximum theoretical efficiency of such SCs is 19% [6][7].

Three different versions of flexible ZnO/Cu_2O solar cells have been developed, respectively: (1) thin film; (2) nanowire; and (3) nanotube [8]. ZnO nanowires and nanotubes are implied to have higher efficiency than thin films, at about 0.12%. ZnO thin films have relatively low efficiency of 0.02%.

The key limitations of the power conversion efficiency (PCE) of a metal oxide SHTSC are given by three factors: material and charge collector quality, material absorption coefficient, and interface quality. Thus, special efforts must be made to understand SHTSC behaviour and the most important parameters for achieving optimum performance.

1.2. III–V Tandem Solar Cells

A III–V tandem SC with 6 junctions is characterized by an efficiency of 47.1% under concentrated solar irradiance [9]. Tandem SCs using Si as a bottom cell, with a high efficiency, are classified conceptually as III–V/Si. For the cases of 2-junction GaAs/Si SC, and 3-junction GaInP/GaAs/Si SC the maximum efficiency values obtained are 32.8% and 35.9%, respectively.

New investigations have shown an increased efficiency for 2-junction and 3-junction SCs designed by direct growth technology. At the same time, smart stacking technology confers a significant efficiency advantage. It has been noted that the cost of a Si-based III–V tandem SC is lower than that of a III–V tandem SC. The usual degradation conditions are defined by heat, moisture, oxygen, and UV radiation, leading to long-term stability. Thus, Si-based III–V tandem SCs are very stable and reliable.

Plasmonic Solar Cells

An improved approach of increased efficiency for SHTSCs based on metal oxides can be applied for III–V tandem SCs by incorporating plasmonic nanocomponents [10]. Due to their ability to scatter light back into the PV structure and their low absorption, plasmonic nanoparticles are studied as a method for increasing solar cells' efficiency [10][11][12].

The plasmons excited by optical radiation induce an electric current from hot electrons in materials made from gold particles and light-sensitive molecules of porphin. The wavelength to which the plasmon responds is a function of the size and distance between particles. The material is made by ferroelectric nanolithography. Compared to conventional photoexcitation, the material produces three to ten times the current [13][14]. The same idea applies to the discussion of perovskite tandem SCs [15].

Metallization is performed on doped regions at either low or high temperatures. Low-temperature metal contacts can be made in Ni/Si, ITO/a-Si, or ITO/Si configurations. High-temperature metallization is based on screen printing and simultaneous annealing of Al (positive) and Ag (negative) paste contacts in a conveyor-belt furnace as it transits across multiple temperature zones.

1.3. Perovskite Tandem Solar Cells

The highest verified efficiency obtained for perovskite tandem SCs to date is 29.15% [11]. Rapid improvements have been made for tandem perovskite/Si-based SCs, with the advantage of much lower cost. For perovskite/Si solar cells, the laboratory performance record achieved is 32.5%. Most of the existing high-efficiency perovskite tandem SCs are technologically acceptable for low-cost SCs; specifically, the estimated cost of perovskite SCs is one-third of the cost of Si SCs. In contrast, the long-term stability of perovskite/Si-based SCs is low because moisture causes deterioration of its performance. Therefore, special efforts are needed to prevent this degradation. Perovskite SCs have shorter lifetimes, ranging from a few days to months and up to a year at most. It is imperative to study, develop and test a long-life perovskite tandem SC. For perovskite SCs, the requirements are increases in efficiency and long-term stability, along with reductions in manufacturing costs. However, there have been promising approaches for simultaneously achieving higher efficiency and stability. As perspective, there is much more open potential for the coming years.

2. The Fundamental Idea of SHTSCs

The tandem solar cell is composed of (i) a top subcell formed from an Al-ZnO/Cu_2O heterojunction and (ii) a bottom subcell based on c-Si. The visible-light transparency and the electrical conductivity of the ZnO layer are improved as a result of Al doping. That is why an Al-doped ZnO layer would represent a promising transparent conducting electrode for nano-optoelectronic solar devices [16].

The proposed approach aims at increasing of the power efficiency beyond the conventional limit of the Si solar cell. Through the top subcell, the low-energy photons are transmitted, while through the bottom subcell, the high-energy photons are absorbed. Thus, a 4-terminal configuration for the tandem solar device was determined because the current density of the top subcell is half that of the bottom subcell.

A layer of cuprous oxide (Cu_2O) can act as a photoabsorber [6][7][8][9][17]. Cu_2O is preferred due to the following main merits: (1) it is present in great quantities on earth; (2) it has reduced toxicity, and (3) it has low costs of synthesis. The main characteristics that qualify it for photovoltaic applications are the following: (1) Cu_2O is a p-type semiconductor; (2) its bandgap is E_{go} = 2.1 eV; (3) it has a high absorption coefficient of 10^5 cm^{-1}; (4) its absorption edge is sharp; (5) it has a high carrier mobility (100 cm^2 V^{-1} s^{-1}); (6) the electron affinity is low (3.2 eV); (7) it has band offsets with an n-type heterojunction partner; (8) the heat of formation is low (−171 kJ/mol); and (9) the interface is prone to oxidation and formation of an interface defect layer (IDL). Theoretically, the conversion efficiency of the copper oxide layer is 19%, but experimentally, a maximum conversion efficiency of only 8% has been obtained.

3. SHTSC Experimental Approach: Deposition, Characterization, and Physical Parameters of Cu_2O Films

3.1. Cu_2O Films Deposition by a Sputtering System

A magnetron sputtering method was used to deposit Cu_2O films on a quartz substrate [18][19][20][21][22]. The Cu target was placed in O_2/Ar, and the substrate temperature was kept at 400 °C. Cu_2O films with a thickness of around 500 nm were deposited at a rate of ~25 nm/min, then further annealed at 900 °C and p~0.1 Torr for 3 min.

An Al-doped ZnO layer was deposited by co-sputtering of a 99.99% ZnO target and a 99.999% Al target in an Ar atmosphere using a 400 °C substrate temperature.

This innovative solution would contribute to the achievement of an improved solar cell by using low-cost materials and non-toxic metal oxides, which remove the disadvantages of conventional solar cells.

3.2. Morphological Characterization of Cu_2O Films

A scanning electron microscope (SEM) equipped with an electron emission gun was used to investigate the morphology of the Cu_2O film samples [22][23] with a resolution of 1.2 nm.

The average grain size increased after the annealing, as noticed from the SEM images of 500 nm thick Cu_2O coatings as grown (**Figure 1**) and annealed at 900 °C (**Figure 2**).

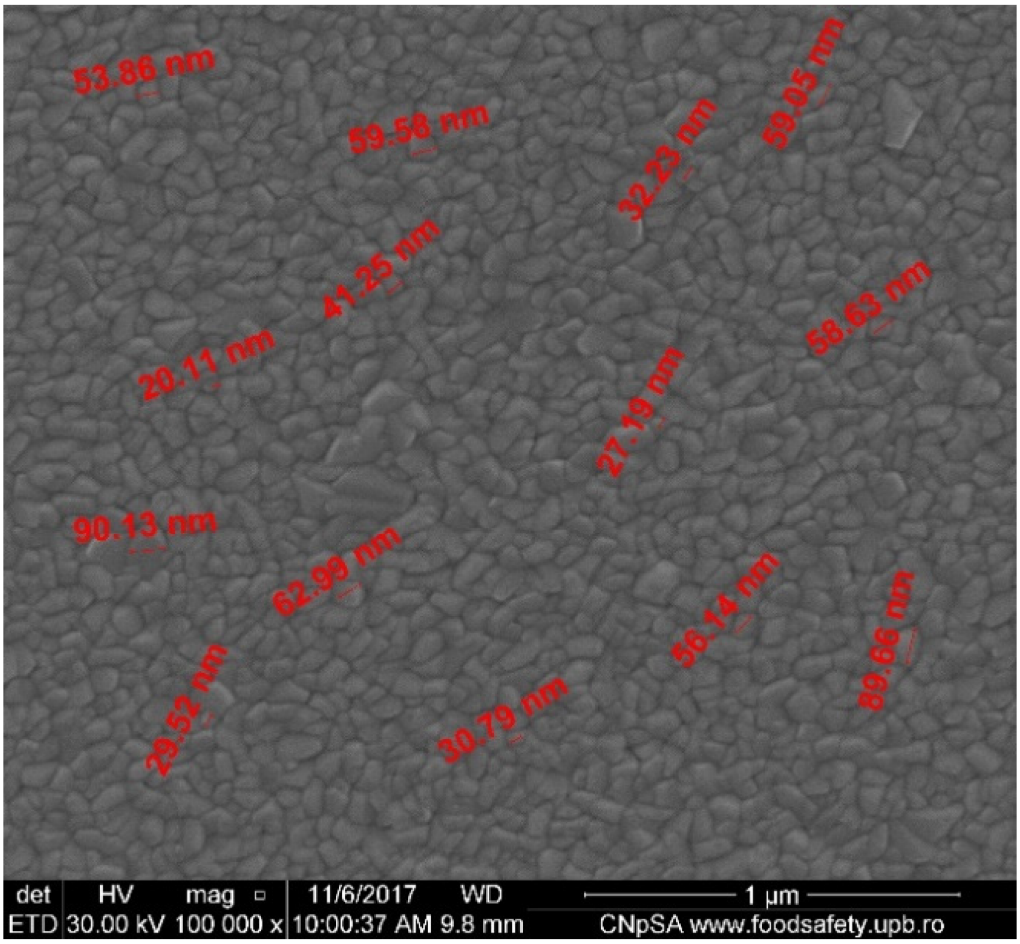

Figure 1. SEM image of as-grown Cu_2O film, 500 nm thickness.

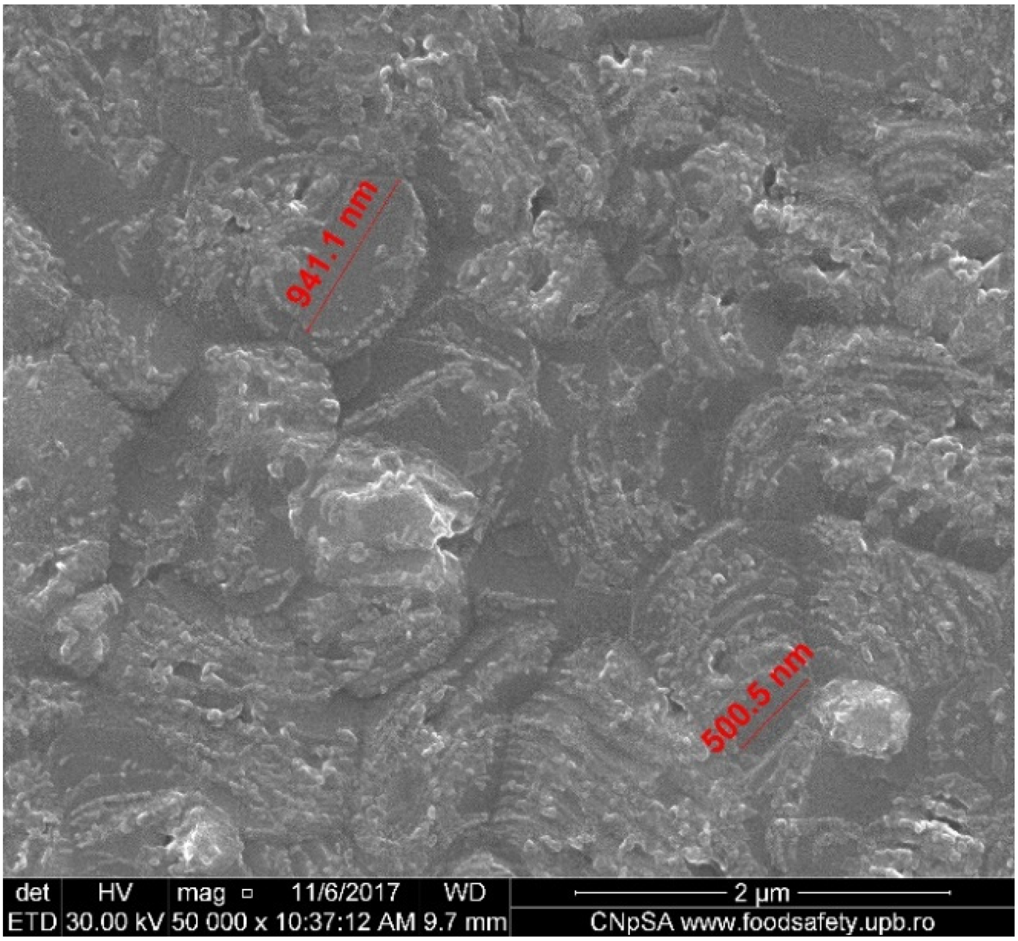

Figure 2. SEM image of Cu_2O film annealed at 900 °C, 500 nm thickness.

At the same time the samples were analysed using an atomic force microscope (AFM), with a Si-doped probe. It was noted that the surface roughness R_{RMS} for the as-grown Cu_2O coatings deposited on quartz increases after annealing at 900 °C for 3 min in vacuum, and the largest R_{RMS} reaches about 21 nm the largest R_{RMS} [23].

3.3. Optical Characterization of Cu_2O Films

The X-ray fluorescence measurements were carried out using an XRF material analyser [24]. An ellipsometer in the wavelength range of 190 to 2100 nm allowed the determination of the film thickness and complex refractive index [25][26]. Delta psi was the model used to fit the measured ellipsometry parameters.

It was noticed that the optical transmittance properties of the Cu_2O films were improved in the Vis and near-IR wavelength range after annealing, which is likely to be due to the larger grain size and a corresponding reduction in grain-boundary scattering, possibly together with less strained film [22][27].

It was suggested that the effect of broadening of the optical band gap after annealing might be due to partial elimination of defects and possibly to less contaminated Cu_2O films. In this way, the optical band gap increases from E_g = 2.06 eV for as-grown Cu_2O film to E_g = 2.19 eV after annealing at 900 °C.

The energy-dispersive X-ray spectroscopy (EDX) spectrum for Cu_2O film of 500 nm thickness (**Figure 3**) revealed the composition of the film, namely, the net Cu/O gravimetric ratio of the sample. It is suggested that the gravimetric ratio of the Cu_2O film deposited by magnetron sputtering is Cu/O = 4:1, which means that there are mostly Cu_2O compounds of high purity.

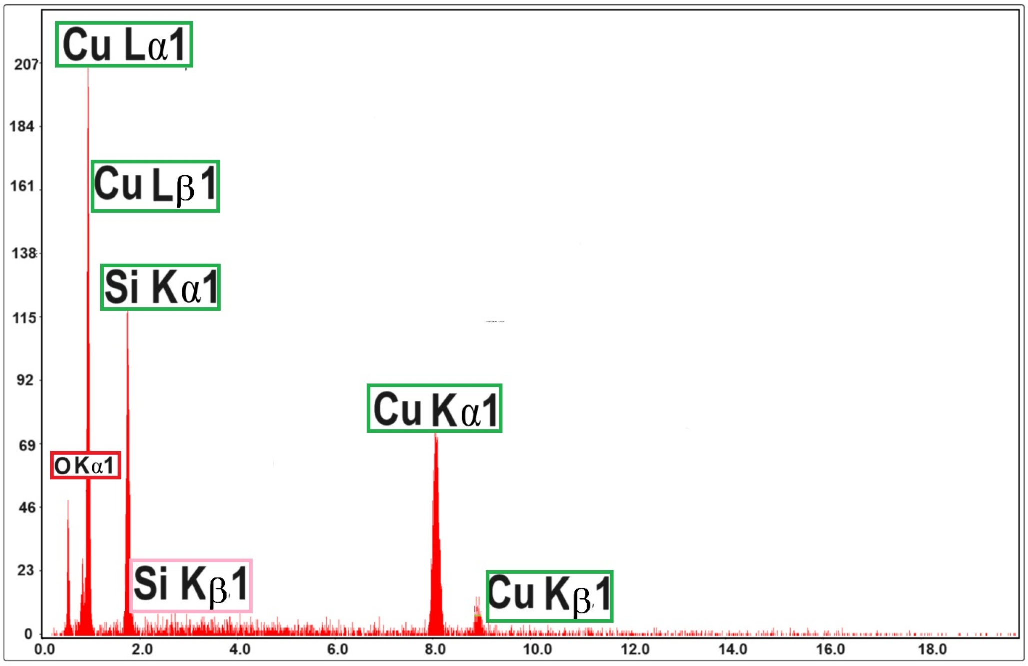

Figure 3. EDX spectrum for Cu_2O film of 500 nm thickness, deposited by magnetron sputtering on quartz substrate.

3.4. Physical Parameters of Cu_2O Films

The measurements of the Hall effect at room temperature were carried out using the van der Pauw configuration. The room-temperature Hall effect measurements allowed the evaluation of hole mobility, film resistivity, and hole concentration for the 500 nm thick as-grown and annealed Cu_2O films on quartz. The majority carrier (hole) mobility of the Cu_2O coatings increased from 10 to 50 $cm^2\ V^{-1}\ s^{-1}$ after annealing, and the resistivity decreased from 560 to 200 Ω·cm [28][29]. These values are comparable to those reported previously for sputter-deposited polycrystalline Cu_2O films on quartz [21][30], which suggests that the annealed Cu_2O thin films are well suited for photovoltaic applications. The increase in the carrier mobility after annealing could be attributed to the increase in grain size and reduced grain-boundary scattering.

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