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Characteristics of InGaP/GaAs double junction thin film solar cells on a flexible metallic substrate

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A B S T R A C T

We have investigated the characteristics of InGaP/GaAs double junction thin film solar cells (TFSCs) on a flexible metallic substrate prepared by electroplating copper (Cu). Both photoluminescence peaks of InGaP and GaAs sub-cells maintained the original positions after transferring the epilayers onto Cu carrier, but a peak shift occurred when the epilayers were bent under intense strain. A slight efficiency improvement up to 29.09% was obtained, compared with 28.25% of conventional structure with GaAs grown substrate under air mass 1.5 (AM1.5) illumination. The TFSCs have a total thickness of about 30 μm, showing an excellent flexibility. Performance measurements of TFSCs were conducted under different strain by bent into the corresponding central angles. It was found that the efficiency was keeping more than 90% when the strain was less than 0.1%, although a rapid decrease down to below 45% occurred till the strain was increased to 0.2%. The favorable performance maintaining after up to 100 bending recycles proved the superior mechanical stability of the TFSCs. Our presented transferring substrate technology based on electroplating in this paper enables the TFSCs with an outstanding performance uniformity, a high yield and a large power weight ratio, which will exhibit an enormous potential to fabricate flexible, low-weight, thin film optoelectronic devices.

1. Introduction

III–V compound semiconductor solar cells exhibit the highest conversion efficiencies compared with those of other types (Green, 2016; Farhadi and Naseri, 2016). GaAs based thin film solar cells (TFSCs) as the representatives possess extensive applications in such widespread fields as aeronautics and astronautics, concentration photovoltaics, wearable electronic devices and intelligent internet of things, due to the merits of high conversion efficiency, ultra-thin style, light weight, excellent mechanical flexibility and improved thermal dissipation ability (Wu et al., 2014; Kim et al., 2017). Alta Devices. Inc. has fabricated the GaAs based TFSCs on metal foil or flexible backing, and reported on his GaAs single junction and InGaP/GaAs double junction TFSCs with an efficiency up to 28.8% and 30.8% respectively under air mass 1.5 (AM1.5, 100 mW/cm^2) illumination (Kayes et al., 2011, 2014). The metamorphic InGaP/(In)GaAs/InGaAs triple junction solar cells inversely bonded on Si or glass handle achieve a higher efficiency over 33% under the same illumination (Geisz et al., 2007, 2008). Despite all these achievements, the theoretical simulations show the efficiencies of multiple junction solar cells still have much space to be improved (Farhadi and Naseri, 2016a,b). It seems that the solar cells are increasingly updating efficiency records by further optimizing structure design, materials growth process and device preparation technology (Geisz et al., 2008; Farhadi and Naseri, 2016a,b).

The current TFSCs are usually fabricated by substrate thinning (Luo and Dornfeld, 2001; King et al., 2003) and/or substrate transferred technology (Zhu et al., 1997; Schone et al., 2006; Ferguson et al., 1991; Lee et al., 1997; Sorianello et al., 2013; Cheng et al., 2013). Substrate thinning is accomplished through the combination of chemical etching and mechanical polishing technologies (King et al., 2003). It is not only quite challenging to control the thickness and uniformity exactly, but also the thinned substrate turns too fragile for subsequent processing (Luo and Dornfeld, 2001). Bonding is generally adopted to transfer device epilayers onto a secondary carrier such as glass, metal film, Si wafer, ceramic foil or organic plastic handle (Schone et al., 2006; Ferguson et al., 1991; Sorianello et al., 2013). The substitutional carrier contributes to achieve the thinner and lighter property, preferable electrical conductivity, thermal dissipation ability or mechanical

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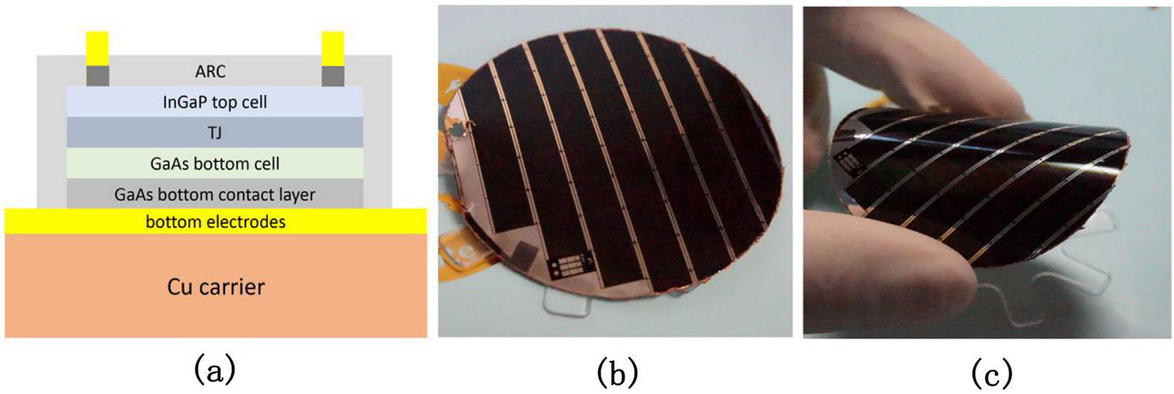

Fig. 1. (a) Schematic diagram of the fabricated InGaP/GaAs double junction TFSC device. (b) Photograph of a 2-in. TFSC wafer on a plane in natural state and (c) Photograph of a 2-in. TFSC wafer in bending state.

flexibility, resulting in a broader applications (Wu et al., 2014; Kayes et al., 2014; Ferguson et al., 1991). Furthermore, the epitaxial lift-off process could allow GaAs substrate reused for considerable cost savings (Cheng et al., 2013; Bauhuis et al., 2010; Lee et al., 2012). However, bonding is conducted through a "hard-to-hard" contact mode, which is normally limited to the relatively high pressure and high temperature operation in ultra-clean conditions (Zhu et al., 1997; Schone et al., 2006; Sorianello et al., 2013). Voids or crevices are of frequent occurrence at the bonding interfaces (Zhu et al., 1997; Moon et al., 2016). These disadvantages will lead to a yield reduction as a result of the wafer bowing, surface roughness or residual particles, especially for large-area solar cells (Moon et al., 2016; Lee et al., 2015). It is urgent to put forward a new method to prepare TFSCs provided with these merits at the same time.

Electroplating, as a conventional technology to deposit electrochemically metal or alloy films in solutions, can realize the transferring substrate process instead of bonding (Wang et al., 2005; Andricacos et al., 1998; Schlesinger and Paunovic, 2014). It has numerous advantages such as fast deposition rate, adjustable film thickness, conducting at normal temperature and pressure, selective deposition assisted by pre-prepared patterns (Wu et al., 2014; Schlesinger and Paunovic, 2014). This method has been used in the thin film light emitting diodes (LEDs) and solar cells fabrication successfully (Wu et al., 2014; Kim et al., 2017). The thin film LEDs showed significant performance enhancements because some technical improvements for example, bending caused by the stress have a relatively small influence on the tiny-area LEDs (Wang et al., 2005; Doan et al., 2006). Electroplating can also exhibit potentials to fabricate TFSCs if the process is further optimized. In this work, we fabricate a type of InGaP/GaAs double junction TFSCs on a flexible metallic substrate by electroplating copper (Cu). All merits mentioned above can be satisfied simultaneously, and the TFSCs show a high efficiency of 29.09% under AM1.5. With a total thickness of approximate 30 μm, our TFSCs are of excellent flexibility. We have researched the performances of TFSCs under different strain by cylindrically bending and after various bending recycles. It is proved that this substrate transferred method provides a favorable performance uniformity and yield as expected.

2. Experiments

The multilayers of InGaP/GaAs double junction solar cells were grown epitaxially on 2-in. diameter n-type (1 0 0) GaAs substrates misoriented 15° toward [1 1 1] by using a Veeco E450 metal-organic chemical vapor deposition (MOCVD) system. High-purity H_2 were employed as the carrier gas. Trimethylgallium (TMGa), Trimethylaluminum (TMAl) and Trimethylindium (TMIn) were used as element III precursors for Ga, Al and In, and Arsine (AsH_3) and Phosphine (PH_3) were used as element V sources for As and P, respectively. The substrate temperature and the reactor pressure were kept at 650 °C and 42 Torr respectively during the process of arsenide and phosphide based materials growth, while a lower temperature of 560 °C was adopted for the tunnel junction growth. The epilayers started with a 160 nm GaAs buffer layer followed by a 1 μm InGaP etching stop layer (ESL). Then the DJSCs were grown uprightly as follows: a 2 μm p-type GaAs contact layer with a hole concentration of 2E18 cm^{-3}, GaAs bottom cell, n^+-GaAs/p^+-GaAs reverse tunneling junction, InGaP top cell and a 500 nm n-type GaAs contact layer with an electron concentration of 5E18 cm^{-3}. The GaAs bottom cell consisted of a 45 nm-thick 5E18 cm^{-3} p-type $Al_{0.3}Ga_{0.7}As$ back surface field (BSF) layer, a 3.5 μm-thick 3E17 cm^{-3}p-type GaAs base layer, a 100 nm-thick 1E18 cm^{-3} n-type GaAs emitter layer and a 100 nm-thick 2E18 cm^{-3} n-type InGaP window layer sequentially. The InGaP top cell consisted of a 60 nm-thick 4E18 cm^{-3} p-type $Al_{0.7}Ga_{0.3}As$ BSF layer, a 700 nm-thick 2E17 cm^{-3} p-type InGaP base layer, a 100 nm-thick 1E18 cm^{-3} n-type InGaP emitter layer and a 30 nm-thick, 2E18 cm^{-3} n-type InAlP window layer in succession.

After epilayers growth, the top-grid Ni/Au/Ge/Ni/Au n-type electrodes were firstly deposited by electron beam evaporation and lifted off through standard photolithographic processing, followed by a rapid thermal annealing process at 400 °C in N_2 ambient to improve ohmic contact property. The effective mesas of 5 mm × 5 mm were defined by isolation trenches through selective chemical etching layer by layer. The bilayer anti-reflective coating (ARC) of SiO_2/TiO_2 was deposited subsequently after the exposed n-type GaAs contact layer was selectively removed. The front surface process which is compatible with conventional process has been finished so far. Then we adhered the wafer onto an intermediate carrier inversely. The bottom Ti/Au p-type electrodes were prepared after removing GaAs substrate and InGaP ESL successively by wet etching. With the current spreading of bottom electrodes, the Cu carrier was finally prepared by electroplating in acidic copper sulfate solutions. The TFSC wafer was completed after separating it from the intermediate carrier. The 2-dimentional schematic diagram of the fabricated InGaP/GaAs double junction TFSC is shown in Fig. 1(a).

3. Results and discussion

As electroplating is a way of electrochemical deposition at normal temperature and pressure, ideal contact interfaces can be achieved in large areas (Wu et al., 2014; Schlesinger and Paunovic, 2014). Voids or crevices, mainly resulting from the different thermal expansion coefficients of epilayers, solders and carrier material, are averted efficiently, although they are easily introduced in bonding process (Moon et al., 2016; Lee et al., 2015). The tight contact interfaces will not add extra