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Manufacturing and characterization of III-V on silicon multijunction solar cells

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Abstract

Tandem GaInP/GaAs//Si(inactive) solar cells were manufactured by direct wafer bonding under vacuum. At this early stage, an inactive silicon substrate was used (i.e. n+ Si substrate instead of an active n-p Si junction). Bonded devices presented an S-shaped *J-V* curve with a kink close to V_{oc} caused by a built-in potential barrier at the III-V//Si interface that reduces the fill factor and therefore the efficiency of the device by 7% compared to the stand-alone GaInP/GaAs tandem cells. Nevertheless, losses in J_{sc} and V_{oc} caused by the bonding process, account for less than 10%. AlGaAs single junction cells, designed to be bonded on a silicon cell for low concentrator photovoltaics (LCPV), were also manufactured reaching an efficiency of 15.9% under one sun AM1.5G spectrum for a 2 cm² cell.

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Keywords: solar cells ; photovoltaics ; multijunction ; III-V on silicon ; direct wafer bonding

1. Introduction

The refinement of mono-crystalline silicon technology has led to a record lab cell efficiency of 25.6% at one sun illumination [1], which is close to the maximum theoretical efficiency of about 29% set by the Shockley-Queisser limit [2] [3]. To overtake this limit, research using other materials and technologies is under progress, but usually

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with the drawback of higher costs, like III-V multijunction solar cells (MJSC) used in concentrator photovoltaics (CPV).

The key principle of CPV is the use of cost-efficient concentrating optics that reduces the area of expensive highly efficient MJSC, potentially allowing for a competitive levelized cost of electricity (LCOE) in some sunny areas with high values of direct normal irradiance. Double-axis tracking devices allows CPV systems to produce a larger amount of energy throughout the day, notably during late part of the day when electricity demand peaks. In addition, the use of multiple semiconducting materials in MJSC allows a more efficient conversion of photon energy from a broader range of the solar spectrum and therefore, cell efficiency is improved. This way, a record lab efficiency of 46.0% has been achieved for a four-junction cell at a concentration of 508 suns [4] thanks to the molecular bonding technology, developed by Soitec and CEA-LETI, that allows the use of III-V materials with improved bandgap configurations that could not be grown by direct epitaxy because of lattice parameter mismatch.

A possible intermediate solution to improve efficiency of silicon cells beyond 30%, but at a reasonable cost compared to high CPV, is tandem III-V on silicon cells. Detailed balance modeling shows a Shockley-Queisser limit conversion efficiency of up to 45.0% for a III-V/Si tandem solar cell with a top-cell band gap of about 1.7 eV under the AM1.5G spectrum [5]. The cost reduction can be achieved by the use of cheap and widely available silicon substrates and less expensive single-axis tracking devices for low concentration optical systems (10 to 20 suns). Furthermore, the possibility of reusing the III-V substrate [6] could lead to a low cost high efficiency photovoltaic technology [7].

The direct wafer bonding approach presented here can circumvent the problems originated from epitaxial growth of III-V on Si, like degradation of crystal quality, caused by a 4% lattice parameter mismatch and interface heterovalency, or cracks caused by the different thermal expansion coefficients [8]. However, this approach also presents a technological challenge because the III-V//Si interface that has to be electrically conductive and transparent at the same time, often contains defects or even cavities originated during the bonding process, which causes a non ohmic contact and may absorb light reducing this way the efficiency of the device.

In this work, we first describe the manufacturing process and structure of the two different devices that were characterized: an AlGaAs single junction cell designed to be bonded on a silicon cell and a dual junction GaInP/GaAs cell bonded to an inactive silicon substrate by direct wafer bonding under vacuum. Afterwards, we analyse the results and finally we explain the conclusions.

2. Single junction AlGaAs cells designed to be bonded on silicon

The growth process of III-V epitaxial wafers consisting of single junction AlGaAs cells with a band gap of 1.7 eV was done by the IIIVLab. These cells are designed to be part of an AlGaAs//Si tandem device and therefore its bandgap has been chosen to be compatible with the silicon spectral range of absorption, i.e. both cells

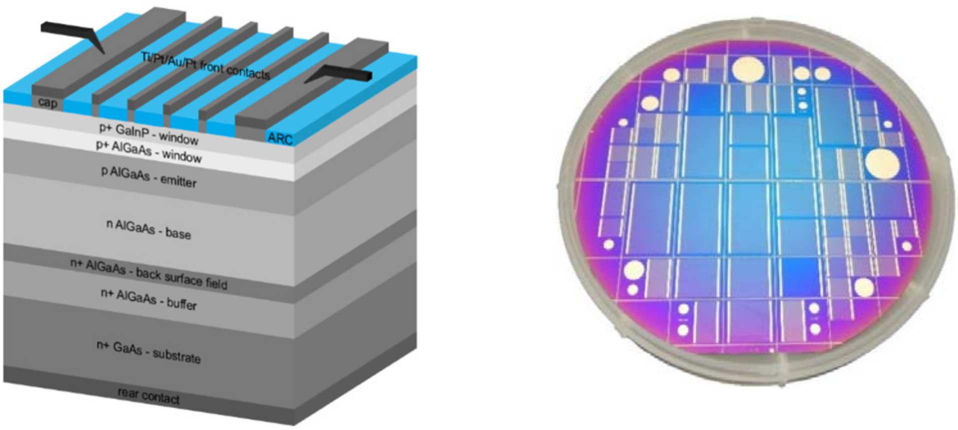

Fig. 1. (a) Not to scale scheme of a single junction AlGaAs cell showing its constituent layers and characteristics; (b) GaAs wafer of 100 mm in diameter after manufacturing of AlGaAs single junction cells of different sizes (20x10mm^2, 10x10mm^2, 10x5mm^2, 5x5mm^2).