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INVERTED THIN FILM InGaP/GaAs TANDEM SOLAR CELLS FOR CPV APPLICATIONS USING EPITAXIAL LIFT OFF

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ABSTRACT

The epitaxial lift-off technique has been applied to dual-junction III-V solar cells grown in inverted order (subcell with highest band gap is grown first). It is shown that growing in inverse order is not trivial since both the tunnel junction and the InGaP subcell perform differently.

INTRODUCTION

The efficiencies obtained with III-V multi-junction (MJ) solar cells are steadily raised and in recent studies efficiencies well above 40% were demonstrated. If CPV systems are to become competitive with power generation from fossil fuel sources, it will be necessary to increase the efficiency of the MJ III-V cells and reduce the costs of the CPV system. The III-V MJ cell is one of the most significant cost contributors to the overall CPV system. The cost of these cells could potentially be reduced through the realization of an inorganic, thin film MJ cell by removal and re-use of the expensive substrate whilst simultaneously maintaining the high conversion efficiency, especially under concentrated sunlight.

Cost reduction by wafer reuse can be obtained using the Epitaxial Lift-Off (ELO) method [1] to separate the epitaxial III-V layer structure from the wafer on which it was deposited. Lifted off thin-film cells can be processed on a metal support, which allows a better heat transfer to a heat sink than for cells on a substrate. In a CPV system these cells can therefore operate at a lower temperature. A third advantage of a thin-film cell is that it can be grown in normal or reverse order which opens new possibilities for cell structures. The ELO process is naturally compatible with the growth and fabrication of an inverted metamorphic multijunction (IMM) cell which has shown itself capable of producing world leading efficiencies under concentration [2]. In the IMM cell the high band gap subcells with the active layers consisting of InGaP and GaAs, are grown lattice matched on the GaAs substrate starting with the highest band gap material. The InGaAs third subcell with a band gap of 1.0 eV is grown on a virtual substrate with a higher lattice constant. Therefore a transparent graded buffer layer is used between the GaAs and InGaAs subcell in which the lattice constant is gradually increased. Light enters the MJ cell from the InGaP subcell side, which implies that the GaAs substrate has to be removed after growth. Generally this was done using selective chemical etching, which means the substrate is lost. In contrast to this method, ELO allows for reuse of the expensive substrates thereby saving costs and material.
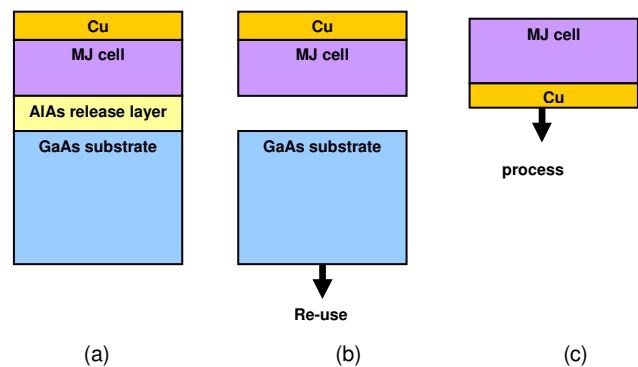
Figure 1 The MELO process: (a) MJ cell with release layer and electroplated Cu layer, (b) lift-off step: removal of the release layer, (c) structure is inverted and processed into solar cell.
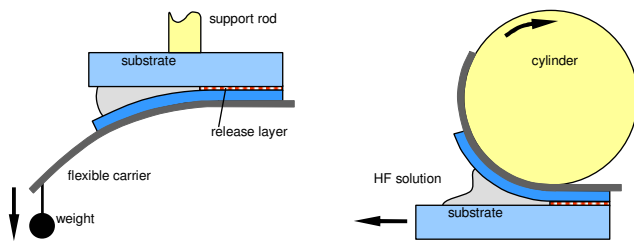
The group at the Radboud University Nijmegen has a long research history on ELO. The experience build up in the last 15 years is applied to combine the IMM concept with ELO. In this paper we will describe our variant of the ELO process i.e. Metal-backed Epitaxial Lift Off (MELO). The MELO process is shown schematically in fig.1. MELO was first tested on dual junction cells grown in the normal order, then followed by inverted growth of dual junction cells. We will show in this work that the step from normal order to inverted is non-trivial, because the quality of critical tunnel junction layers and probably also of the InGaP subcell changes.

Work on the metamorphic junction material is in progress but will not be reported in this paper.

EPITAXIAL LIFT OFF

Epitaxial lift-off is based on selectively etching an AlAs release layer between the substrate and the cell structure

in an HF solution. We have tested a number of different set-ups for ELO (fig.2) [3] and investigated the mechanism of the etch process in detail [4,5].

Figure 2 Two ELO set-ups developed at Radboud University Nijmegen: in the left set-up a weight is used to allow the etchant to enter, in the right set-up a rotating cylinder is used.

Optimization of the ELO process for etchant concentration, etchant temperature and release layer thickness has resulted in high etch rates and wafer sized thin-films (fig.3). It was also demonstrated that ELO can be applied to III-V structures grown on GaAs as well as Ge wafers [6].
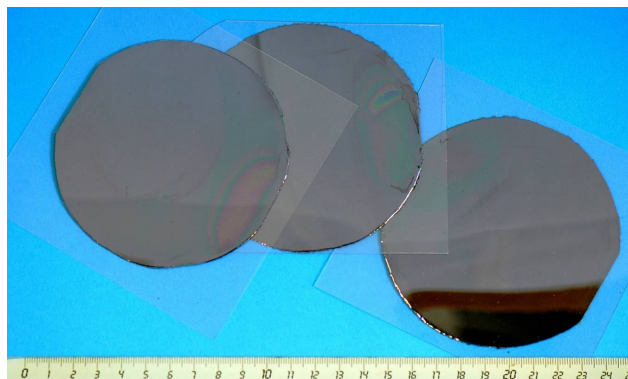
Figure 3 Thin film structures on plastic supports lifted off from 4 inch Ge wafers.

ELO does not affect the quality of the solar cell. We have demonstrated this for a single junction GaAs thin-film cell which showed a record efficiency of 26.1% under AM1.5G conditions [7]. This is the same efficiency as obtained with our regular GaAs cell on substrate.
After ELO, the device structure with metal backing layer can be processed into a solar cell using standard fabrication techniques. The wafer can be re-used after some treatment of the top surface. Since a basic wet chemical smoothing etch procedure appeared insufficient to remove all surface contamination, wafer re-preparation is done by a surface cleaning followed by a chemo-

mechanical polishing procedure. Multiple wafer re-use without degradation in solar cell quality was shown using this procedure [4].
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TANDEM CELLS GROWN IN NORMAL ORDER

Dual junction cells and tunnel junction test structures were grown by MOCVD in the normal order (GaAs subcell followed by InGaP subcell) on 2-inch (100) oriented GaAs wafers in an Aixtron200 system. Two substrate misorientations were tested: 2° off to (110) and 6° off to (111)A.
Our standard misorientation for GaAs substrates is the 2° off, which has resulted in excellent GaAs and InGaP solar cells. The 6° off misorientation was chosen because this is the standard value for growth of III-V MJ cells on Ge, which would make it relatively easy to transfer the growth process to Ge substrates.
The tunnel junction between the subcells is heavily doped in both n-GaAs (Si) and p-AlGaAs (C) layer. Diffusion of dopant atoms at high temperatures can influence the doping profile which decreases the peak current. Therefore, the tunnel junction test structures utilized in this study contain an InGaP top layer with a thickness similar to the tandem topcell to account for the thermal load the tunnel junction undergoes during growth of a tandem cell. In table 1 the maximum current densities for tunnel junctions grown on different substrate orientations are shown.

Substrate misorientation	Growth pressure [mbar]	Growth order	Peak current density [A/cm^2]	Conc. factor
2 degrees	50	NOR	40	2900
		INV	50	3600
6 degrees	50	NOR	65	4300
		INV	22	1500

Table 1 Results of IV-measurements on tunnel junction test structures grown on different substrates. The structures are either grown in normal (NOR) or inverse order (INV).

Next a series of thin-film dual junction concentrator cells was produced grown in the normal order. Cells are ~5mm x 4mm in size and have a top contact and grid finger pattern suitable for use under concentration.   The concentrator cells shown on the MELO thin-film from a 2 inch wafer were singulated and die attached using a Ag-loaded epoxy to a Al-pcb submount designed for use in Circadian's CPV system (Fig.5). Top contacts were made to the PV cell by either ribbon bonding using Al-ribbon or by wire bonding with Au-wires.
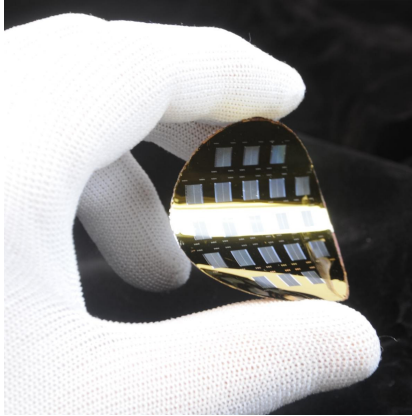
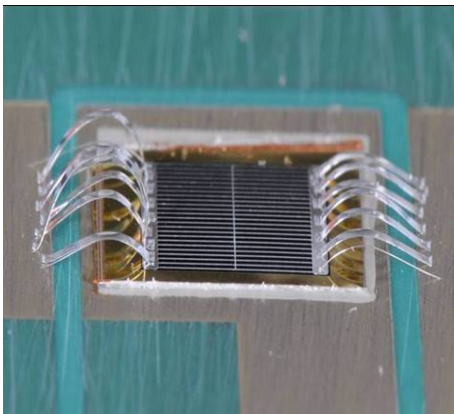**Figure 4 MELO thin-film from 2 inch wafer.**

Figure 5 MELO thin-film cell attached to a pcb.

In Table 2 1-sun IV-data are collected for the dual-junction MELO cells (without ARC) grown in normal order on the two types of substrates. The efficiency of the 6° off oriented tandem cell is 2% (absolute) lower than for 2° off. The Quantum Efficiency (QE) data (Fig.6) show a lower response for 6° off substrates mainly in the InGaP subcell, caused by a lower material quality of the InGaP base layer.

Substrate misorien- tation	Growth order	V_{oc} [V]	J_{sc} [mA/cm^{-2}]	FF [%]	EFF [%]
2 degr.	NOR	2.443	9.2	84	19.0
6 degr.	NOR	2.325	8.5	86	17.0
	INV	2.331	5.2	86	10.4

Table 2 Results of 1-sun IV-measurements on dual junction MELO cells grown on 2 and 6 degrees off substrates in normal (NOR) or inverse order (INV). No ARC was applied.
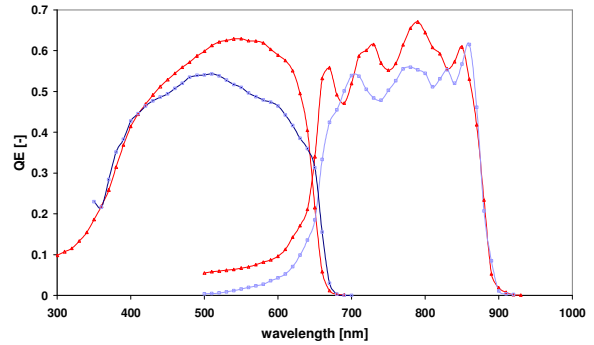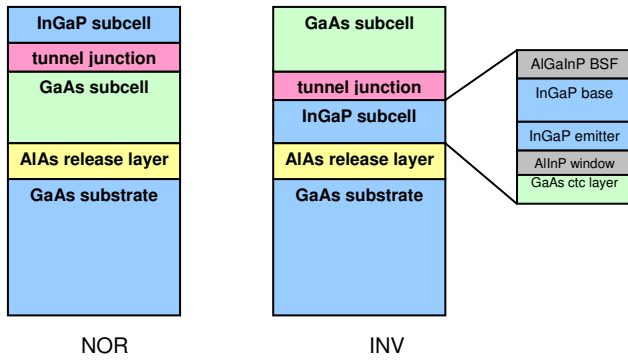

Figure 6 Quantum efficiency measurement of dual junction MELO cells grown in normal order on 2° off (red) and 6° off (blue) substrates. No ARC was applied.
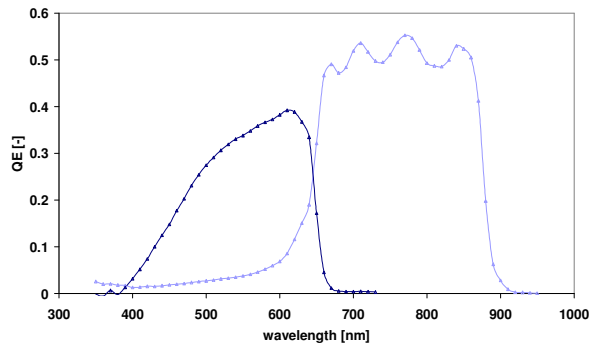
TANDEM CELLS GROWN IN INVERSE ORDER

As can be seen in Fig.7, in an inverse tandem cell the tunnel junction is grown on top of the InGaP cell. As a consequence, the thermal load on the tunnel junction is increased due to the longer growth time needed for the thicker GaAs cell. In addition, growth of the tunnel junction in inverse order involves growing the p-AlGaAs layers on the AlGaInP back surface field layer (BSF) of the InGaP cell. The p-AlGaAs layer of the tunnel junction is autodoped with carbon under extreme growth conditions (temperature well below 600 C and V/III ratio around 1). Going down in temperature after BSF growth under PH_3 leads to reduced surface quality as the decomposition rate of PH_3 below 600 C is extremely low. The resulting AlGaAs layer is of poor quality and the tunnel junction shows no tunneling. This problem was solved by tuning the growth conditions at the BSF-tunnel junction interface. The results of the inverted tunnel junction are shown in table 1 for the two substrate orientations. For a 2° off substrate the inverted tunnel junction can handle an even higher current than the tunnel junction grown in normal order, whereas for 6° off the maximum current is only one third of the normal order value.

Figure 7 Tandem cell structure grown in normal (NOR) and inverse (INV) order.

In Table 2 the IV-data of the MELO tandem cells grown in NOR and INV order on 6° off substrates are given. The INV cell shows a much lower short circuit current density, which is caused by the low QE of the InGaP subcell (Fig.8).

Figure 8 Quantum Efficiency measurement of a dual junction MELO cell grown in inverse order. No ARC was applied.

The shape of the InGaP QE curve indicates a problem in the n-doped part of the cell. As shown in Fig.7 this part consists of a GaAs contact layer, AlInP window and InGaP emitter. A SIMS measurement reveals the Si doping profile in these layers. A strong Si diffusion into the InGaP emitter is visible in the profile shown in Fig.9. To investigate if the heavily doped GaAs contact layer (5×10^{18} cm^{-3}) is the Si source, the measurement was repeated for a cell with a lower doped contact layer (1.5×10^{18} cm^{-3}). The SIMS profile for Si shows no difference in the InGaP emitter layer part of the cell, therefore the n-GaAs contact layer can be excluded as Si source. N-type doping of AlInP with Si is an inefficient process. To obtain a sufficiently high n-type carrier concentration a relatively high gas phase concentration of Si_2H_6 is needed during growth. The Si concentration present in the window layer is therefore much higher than in the surrounding layers. Also, the Si profile is symmetric around the window layer. These observations could indicate that the window is the

Si source. Further work is needed to clarify if this is the reason for the poor InGaP subcell response.
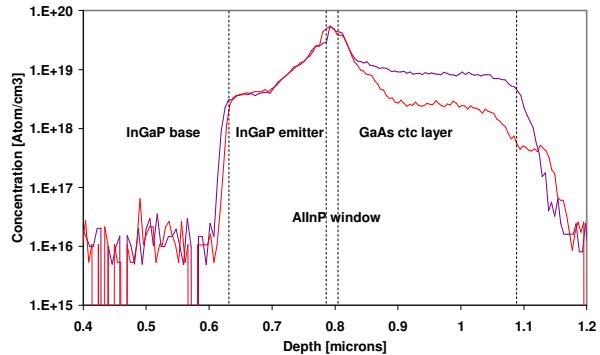
Figure 9 SIMS measurement of Si doping profile of MELO cell grown in inverse order. Two doping levels of GaAs contact layer were investigated.

SUMMARY

Progress in combining the ELO technique with thin-film dual junction cells grown in inverse order has been reported.

As a first step thin-film tandem cells grown in the normal order were produced from GaAs substrates with two types of misorientation. A 2° off misorientation was superior to 6° off in cell efficiency.

An inverted TJ has been developed capable of providing an ohmic interconnect between sub-cells with a maximum current sufficient for concentration factor >2000x. A first attempt at an inverted GaAs/InGaP DJ cell has been successfully made with good diode characteristics but lower than desirable efficiency. The efficiency is currently limited by the performance of the top InGaP cell. Work to improve this is in progress.

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