Epitaxial Lift-Off of Large-Area GaAs Thin-Film Multi-Junction Solar Cells

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Abstract

MicroLink Devices is currently transitioning into production a wafer-scale, epitaxial lift-off process technology for GaAs- and InP-based materials. This process enables the separation of thin, epitaxially-grown layers from the substrate on which they were deposited, and multiple reuses of the original substrate. Key advantages include cost reduction, weight reduction, improved thermal conductivity and high flexibility.

INTRODUCTION

Epitaxial lift-off (ELO) is a processing technique that enables thin epitaxial layers grown on GaAs or InP substrates to be "peeled off" from the host substrate. Although explored by many groups since the 1970s [1-3], ELO is finally transitioning to a viable manufacturing technology. The ELO process offers several important advantages for both performance enhancement and cost reduction of III-V electronic and optoelectronic devices. The epitaxial films can be transferred to new support substrates that are thin, flexible, lightweight, and with higher thermal conductivity than the original growth substrate. The GaAs or InP substrate can be reused many times. At MicroLink Devices we have developed an industry-first ELO process capable of lifting off large areas of semiconductor material from substrates up to 6 inches in diameter without any degradation of material quality or performance characteristics [4-6]. An example of a 4-inch GaAs foil with large-area solar cells is shown in Figure 1. We are actively pursuing the commercialization of this technology for fabricating thin, flexible large-area multi-junction solar cells with very high efficiency. Potential applications include electric-powered, unmanned aerial vehicles (UAVs), space satellites, and terrestrial solar concentrator systems.

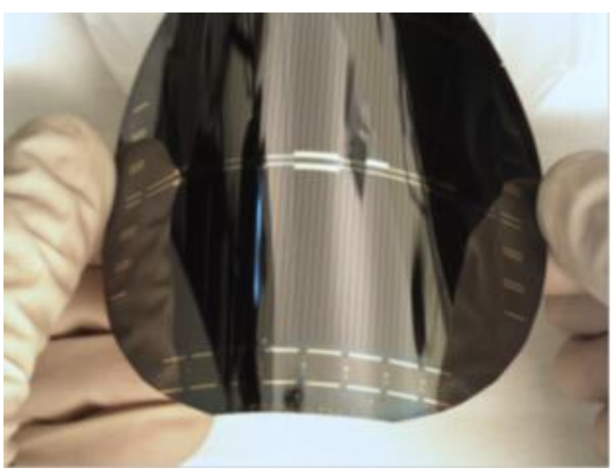


Figure 1: 4-inch GaAs ELO foil attached to a thin and flexible metal backing. The wafer contains two large-area (20-cm^2) solar cells.

EXPERIMENTAL

All epitaxial structures were grown by metallorganic chemical vapor deposition (MOCVD) at 100 mbar using arsine (AsH_3), phosphine (PH_3), trimethylindium (TMI), trimethylgallium (TMG) as precursors and using a V/III ratio >50. Inverted metamorphic multijunction (IMM) InGaP/GaAs/InGaAs structures were grown on GaAs substrates.

Figure 2 and 3 show schematics that outline the basic ELO process. The first layer deposited on the substrate is a thin, AlAs release layer (~5 nm). The solar cell epitaxial layers are then deposited, followed by application of a thick (1-2 mil) flexible metal carrier layer. The wafer is then immersed in a concentrated HF-acid chemistry, which selectively dissolves the release layer (the etch selectivity relative to the GaAs epitaxial structure is greater than 1E5). The thin, composite structure consisting of the metal carrier

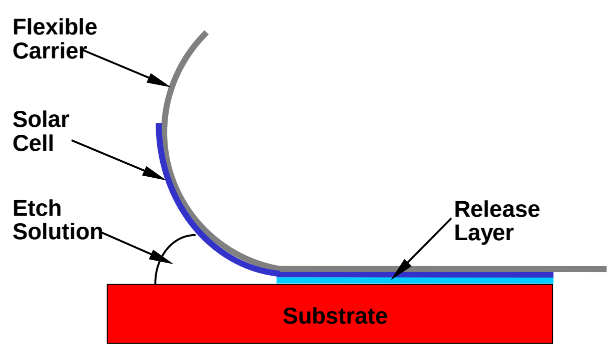


Figure 2: Schematic of epitaxial lift-off process.

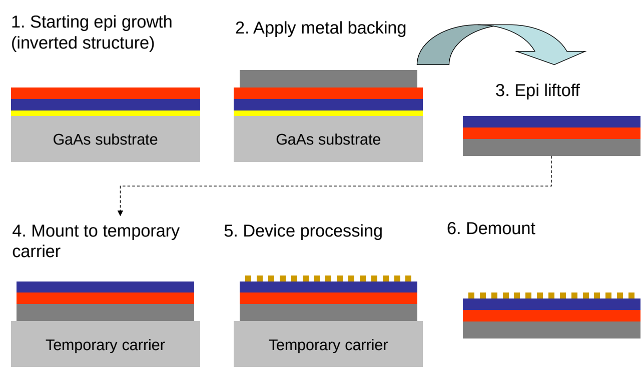


Figure 3: Schematic of solar cell fabrication process using epitaxial lift-off structures.

layer and solar cell epitaxial layers is thereby completely separated from the GaAs substrate. The ELO process requires approximately 12 hours to complete, but is amenable to batch processing, enabling scaling up of the process to lift off hundreds of substrates within a 24-hour period.

As shown in steps 4-6 in Figure 3, the released ELO foils are next mounted to a temporary, rigid carrier in order to carry out solar cell device processing (evaporation and lift off Ti-Au grid metallization, wet etch isolation, evaporation of TiO_2-Al_2O_3 antireflection coating, device singulation). The completed solar cells are then removed from the temporary carrier.

DISCUSSION

The ELO material that has been lifted off is of high quality and comparable to that of epitaxial material on the original substrate. In collabration with the National Renewable Energy Laboratory (NREL) we have carried out TEM analysis of the ELO structure, as shown in Figure 4. The cross-section shows the interface of the ELO layer and the metal handle substrate. No delamination, cracking, threading dislocations, or voids were observed in the TEM study. We have successfully fabricated large-area triple-junction IMM devices on ELO material. Figure 5 shows I-V characteristics measured at NASA Glenn under AM0 spectrum for small (1-cm^2) and large (20-cm^2) devices. Similar performance is observed for small- and large-area devices, with a typical efficiency of 29%. The ability to fabricate large-area devices with high efficiency requires material that is highly uniform and free of cracks or defects.

We have fabricated flexible solar sheets consisting of arrays of interconnected large-area ELO solar cells, as shown in Figure 6. The cells are interconnected using welded Ag-based foil ribbons and laminated between transparent sheets of polymer-based materials. The composite structure has high flexiblity and can be conformally attached to a curved structure, such as the wing of a solar-powered plane. The combination of high efficiency and low weight enables a very high specific power: more than 400 W/kg has been achieved.

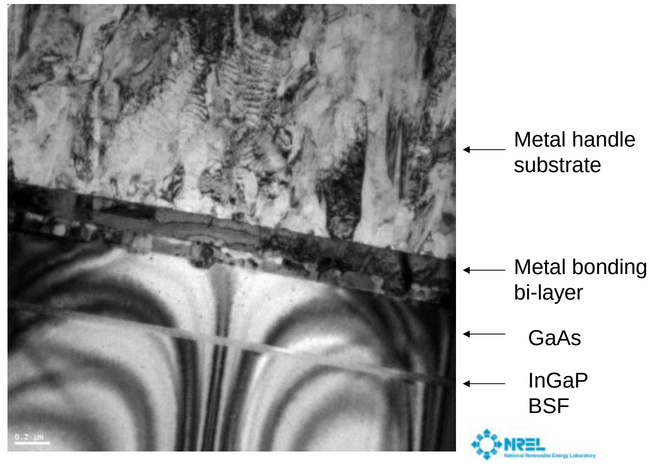
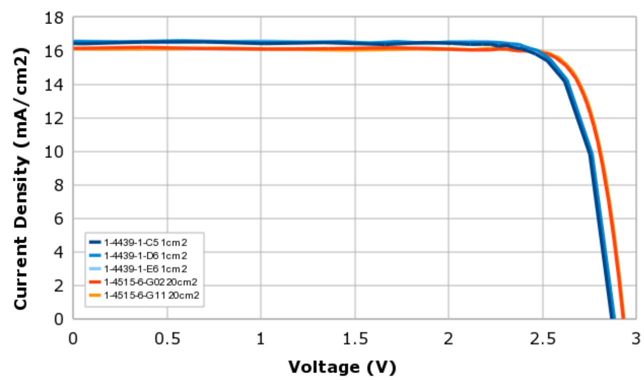


Figure 4: TEM cross-section of a single-junction GaAs solar cell.



Cell	Area cm²	Isc mA	Voc V	Imax mA	Vmax V	Pmax mW	FF %	Eff %
1-4515-6-G02	20.1	322.88	2.93	311.63	2.57	800.69	84.6	29.1
1-4515-6-G11	20.1	322.09	2.93	311.45	2.59	805.88	85.3	29.3
1-4439-1-C5	1.0	16.56	2.87	15.93	2.46	39.23	82.5	28.7
1-4439-1-D6	1.0	16.68	2.88	16.14	2.47	39.93	83.0	29.2
1-4439-1-E6	1.0	16.70	2.88	16.06	2.47	39.69	82.5	29.0

Figure 5: I-V characteristics of a triple-junction IMM ELO solar cells measured at NASA Glenn under AM0 spectrum. Similar performance is observed between small (1-cm^2) and large (20-cm^2) cells.

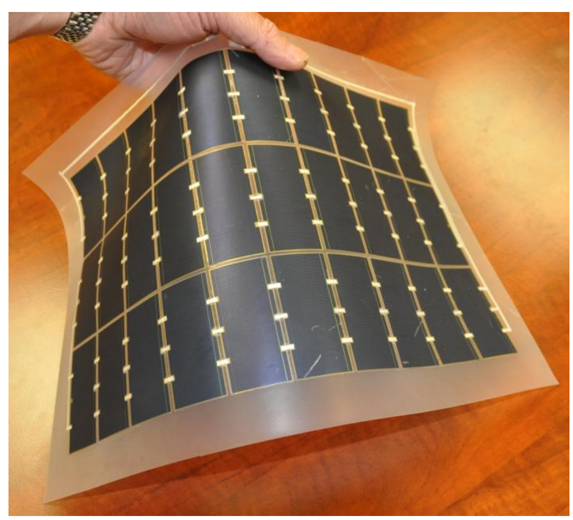


Figure 6: Flexible solar sheet consisting of an array of 30 interconnected, large-area GaAs ELO solar cells.

At MicroLink Devices we have demonstrated the ability to scale the ELO process up to 6-inch GaAs substrates, as shown in Figure 7. The ability to process 6-inch GaAs ELO wafers is critical for enabling cost reductions in MOCVD growth and device processing, as well as building solar cells with larger active areas (ie, > 60 cm^2). Solar panel assembly costs can also be reduced by transitioning to larger cell sizes. We have also demonstrated the ability to lift off large-area ELO foils from 4-inch InP substrates, as shown in Figure 8.

After the ELO process has been performed, the original substrate can be restored to epi-ready quality using a short repolishing step. The ability to reuse the substrate can enable significant cost reduction, particularly when the value of the substrate represents a significant fraction of the value of the final devices. In the case of InP, the potential cost savings can be substantial, as InP substrates are nearly an order of magnitude more expensive than GaAs. InP ELO is therefore an enabling technology for new applications that may not be currently feasible because of the high cost of InP substrates.

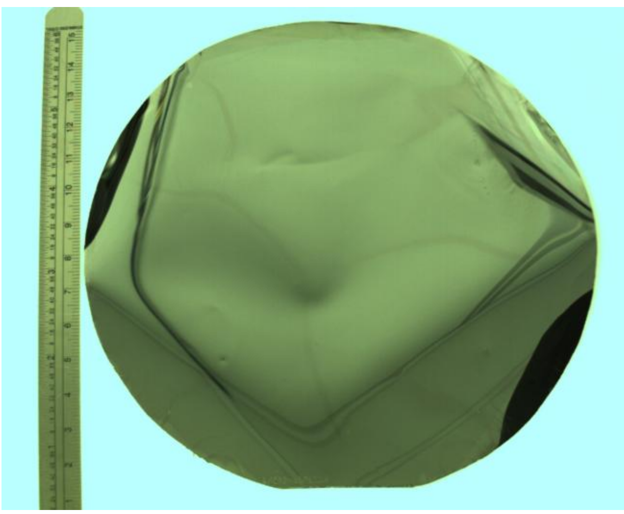


Figure 7: Six-inch-diameter GaAs ELO foil.

We have demonstrated the ability to reuse 4-inch GaAs and InP substrates multiple times. Figure 9 shows a histogram of triple-junction IMM cell efficiencies (1-cm^2 active area) measured from a collection of 25 substrates that have been processed through four epitaxial growths and three repolishing cycles. The first epixaxial growth on the original GaAs substrate is labeled “prime”. The average cell efficiency on the three repolished device populations is comparable to that of cells grown on the original, prime GaAs wafers, demonstrating high quality material. The number of possible reuses is limited primarily by the amount of material removed during repolishing. During this campaign the amount of polishing each cycle was approximately 40 µm, however we have shown that as little of 10 µm of polishing can be utilized. Therefore as many as 10 or more substrate reuses should be readily achieveable.

Figure 8: Four-inch-diameter ELO foil lifted off from an InP substrate.

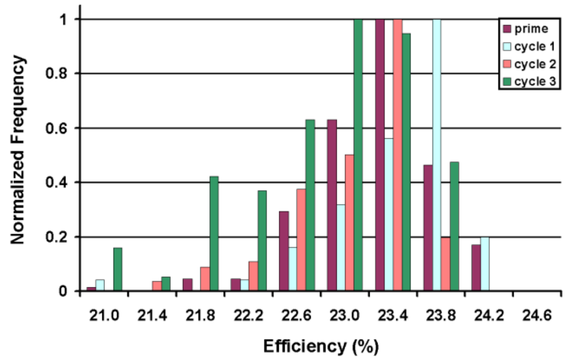


Figure 9: Histogram of solar cell efficiencies showing device performance through three successive substrate reuse cycles.

CONCLUSIONS

MicroLink Devices has developed a wafer-scale epitaxial lift-off process technology for structures grown on GaAs and InP substrates. The process is scalable for high production throughput as well as large-diameter (6-inch) substrates. The lifted-off semiconductor material is of high quality and has low defect density, enabling the fabrication of large-area (20-cm^2) multi-junction solar cell devices. We have demonstrated triple-junction IMM solar cells with verified AM0 efficiencies greater than 29%. We have also successfully integrated large-area ELO cells into lightweight and flexible solar arrays. Finally, we have demonstrated the ability to carry out multiple reuses of the original substrates. Epitaxial lift-off is an enabling process technology for cost reduction and improved device performance not only of multi-junction solar cells, but also potentially for a wide range of III-V electronic and optoelectronic device applications such as lasers, LEDs, photodetectors, and HBTs.

ACKNOWLEDGEMENTS

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ACRONYMS

ELO: Epitaxial Lift-Off
IMM: Inverted Multi-junction Metamorphic
HBT: Heterojunction Bipolar Transistor
LED: Light emitting diode
MOCVD: Metal Organic Chemical Vapor Deposition
TMI: Trimethylindium
TMG: Trimethylgallium
UAV: Unmanned Aerial Vehicle