Moving forward from 44% to 50% conversion for III-V solar cells

Simulations propose structures that could reach even higher performance for multi-junction devices. Mike Cooke reports.

In the past year, researchers have reported record-breaking multi-junction solar cells with conversion efficiencies of up to 44%, and scientists are now looking at overcoming the next performance barrier of 50%.

Multi-junction solar cells work by stacking subcells sensitive to radiation of different wavelengths, with the regions responsive to shorter wavelengths at the top and those responsive to longer wavelengths at the bottom. This means that wider-bandgap materials are used for the top layers, since they absorb short wavelengths, allowing the longer-wavelength radiation to penetrate deeper into the device where it can be converted to electrical energy.

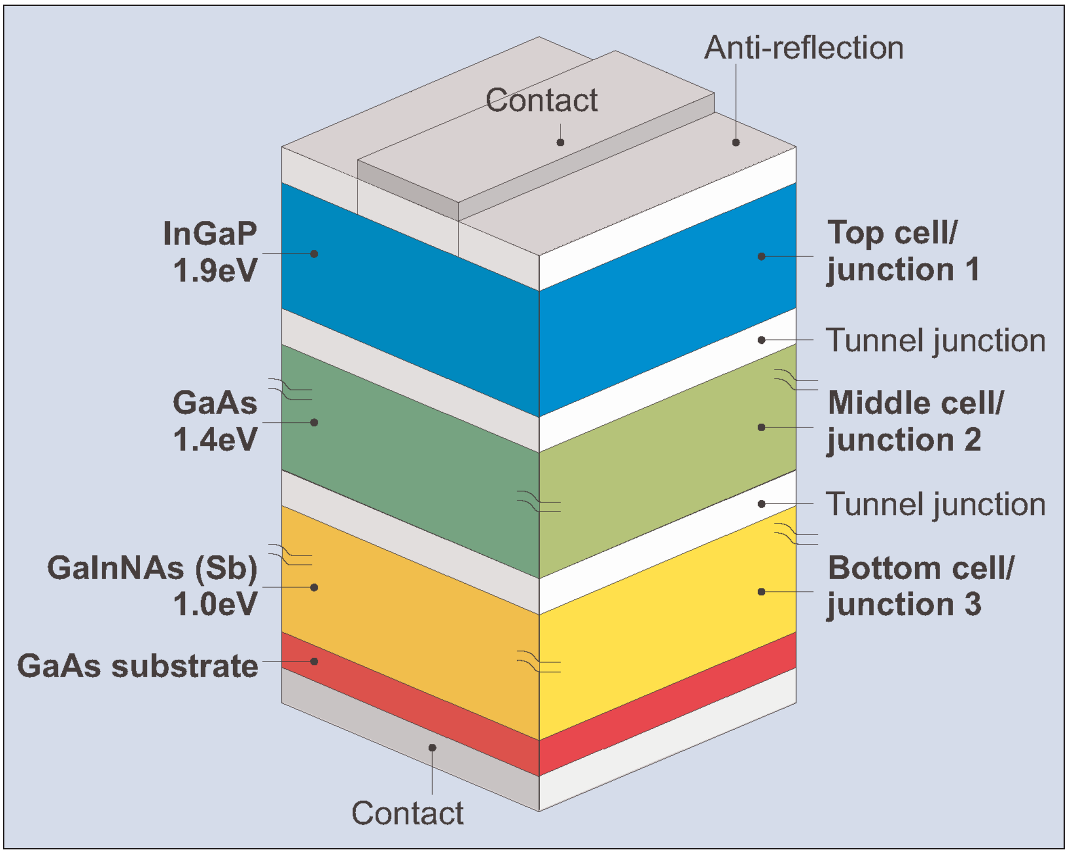

Figure 1. Schematic of Solar Junction / NREL SJ3 multi-junction cell.

In a theoretical device with an infinite number of varying-bandgap layers, a maximum power conversion efficiency of nearly 87% has been calculated. To approach this sort of performance in reality will require development of materials with high crystalline quality with low numbers of defects. The highest-performing multi-junction cells presently use III-V compound semiconductors with direct bandgaps. Although lower-cost solar cells are generally made from silicon, that material has an indirect bandgap, which means that a larger amount of energy is lost in the initial conversion process, before any other losses come into play.

Here, we survey some of the achievements and prospects for high-performance solar cells based on multi-junction technology.

Concentrating on efficiency

The highest-performing devices generally achieve their peak performance under multiple-sun illumination, a technique known as concentrated photovoltaics (CPV) where optical systems are used to focus light on a small device. This is attractive since it reduces the amount of expensive III-V semiconductor material needed for PV systems.

In October 2012, Solar Junction reported 3-junction solar cells with 44% conversion efficiency under 947-

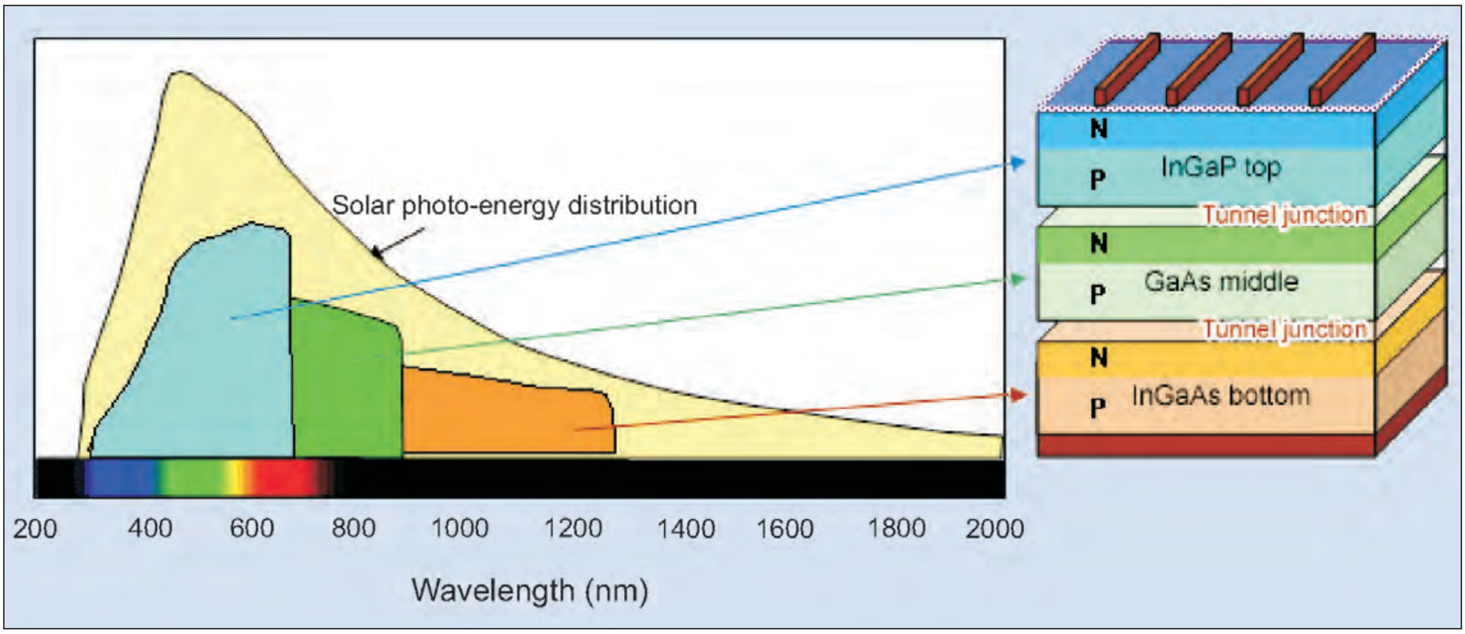

Figure 2. Wavelength distribution of solar photo-energy and wavelength sensitivity of Sharp's triple-junction solar cell.

sun illumination, beating its previous April 2011 record of 43.5% under 418 suns. The records were verified by US National Renewable Energy Laboratory (NREL). The company's founders developed their technology at Stanford University. Also, the firm partners with NREL in its research.

Solar Junction uses molecular beam epitaxy (MBE) to grow its epitaxial material with a proprietary Adjustable Spectrum Lattice Matched (A-SLAM) multi-junction solar cell architecture that provides bandgap tunability over the target range 0.8–1.42eV. The new devices extend the bandgap range to 1.9eV using indium gallium phosphide (InGaP) as the top layer (Figure 1).

The 'dilute-nitride' bottom cell of antimony-doped gallium indium nitride arsenide (GaInNAs(Sb)) is described as the 'heart' of the solar cell design. The bottom layer is important since the quality of upper layers depends on that of those below them.

Solar Junction/NREL has also worked on ultra-concentration tunnel junctions between the subcells. The team looks to four-junction devices as the route to 50% conversion efficiency and beyond.

Sharp in Japan has claimed a record for 1-sun 3-junction solar cells that achieved 37.7% conversion efficiency in December 2012. The firm has also matched Solar Junction's 43.5% with 360-sun illumination. The records were verified at Japan's National Institute of Advanced Industrial Science and Technology (AIST). In the Sharp device, the top cell consisted of InGaP, the middle cell is GaAs and the bottom cell is InGaAs (Figure 2). Again, the electrical connections between cells were through tunnel junctions. The Japanese company is aiming at CPV, as well as space satellite and vehicle applications.

Preparing the way for 50%

One US team looking to 50% multi-junction solar cells is based at California Institute of Technology, US National Institute of Standards and Technology, University of Maryland, and Boeing-Spectrolab Inc [Marina S. Leite et al, Appl. Phys. Lett., vol102, p033901, 2013]

Based on simulations, the researchers propose a structure that could deliver efficiencies greater than 50% with concentrated illumination of 100 suns. The best device would require a lattice-matched structure with a lattice constant of 5.807Å (Figure 3). The layer structure would need a top layer of indium aluminium arsenide (1.93eV bandgap, $In_{0.37}Al_{0.63}As$), a middle layer of indium gallium arsenide phosphide (1.39eV, $In_{0.38}Ga_{0.62}As_{0.57}P_{0.43}$), and a bottom layer of indium gallium arsenide (0.94eV, $In_{0.38}Ga_{0.62}As$).

The researchers believe that templates with a 5.807Å lattice constant could be produced using strain engineering of single-crystalline layers combined with epitaxial lift-off. The lift-off of the template layer from the bulk substrate would allow it to be reused, reducing cost.

The researchers tested their ideas by producing solar subcells from lattice-matched layers of $In_{0.52}Al_{0.48}As/In_{0.52}Ga_{0.47}As_{0.42}P_{0.58}/In_{0.53}Ga_{0.47}As$ (1.47eV/1.06eV/0.74eV) on 50mm p-type indium phosphide (InP) substrates using metal-organic vapor phase epitaxy (MOVPE). The subcells were designed to match currents at 12.0mA/cm^2 density, maximizing power output. Current matching between subcells is a key requirement for achieving maximum performance. Since electric charge is conserved through a solar cell device, it is impossible for subcells to deliver different currents.

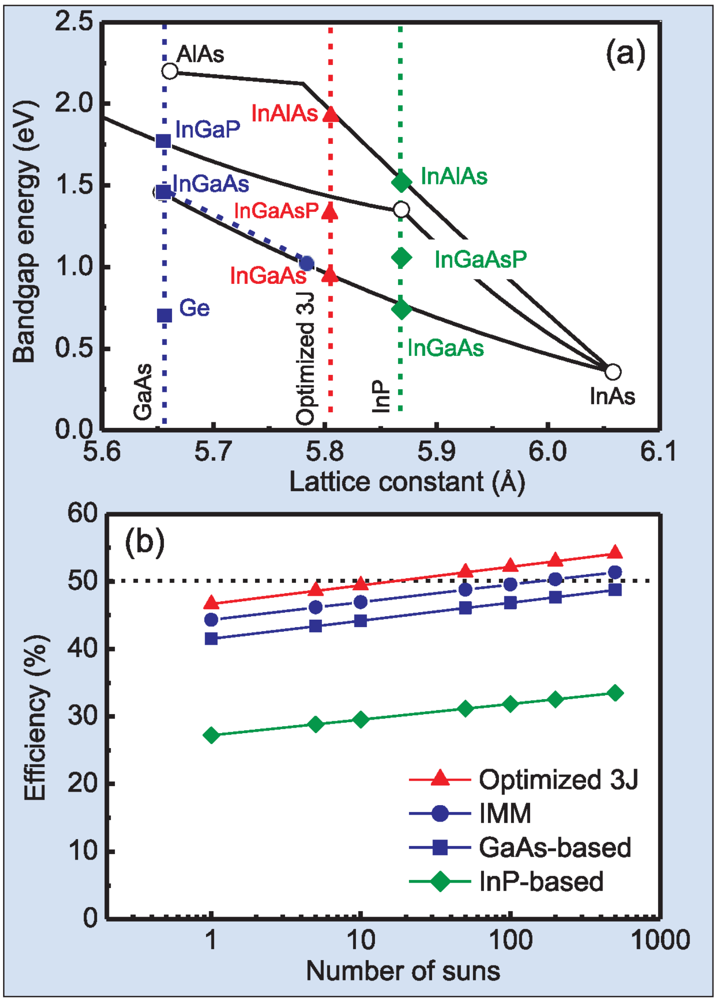

Figure 3. (a) Energy bandgap diagram as a function of lattice spacing for selected III-V compound semiconductor materials. (b) Efficiency as a function of number of suns (light intensity) obtained by detailed-balance calculation for four different triple-junction designs shown in (a), including a recent inverted metamorphic multi-junction (IMM) proposal. The optimized 3-junction design of CalTech, NIST, University of Maryland, and Boeing-Spectrolab (red triangles) can ideally achieve more than 50% in efficiency under 30-suns illumination.

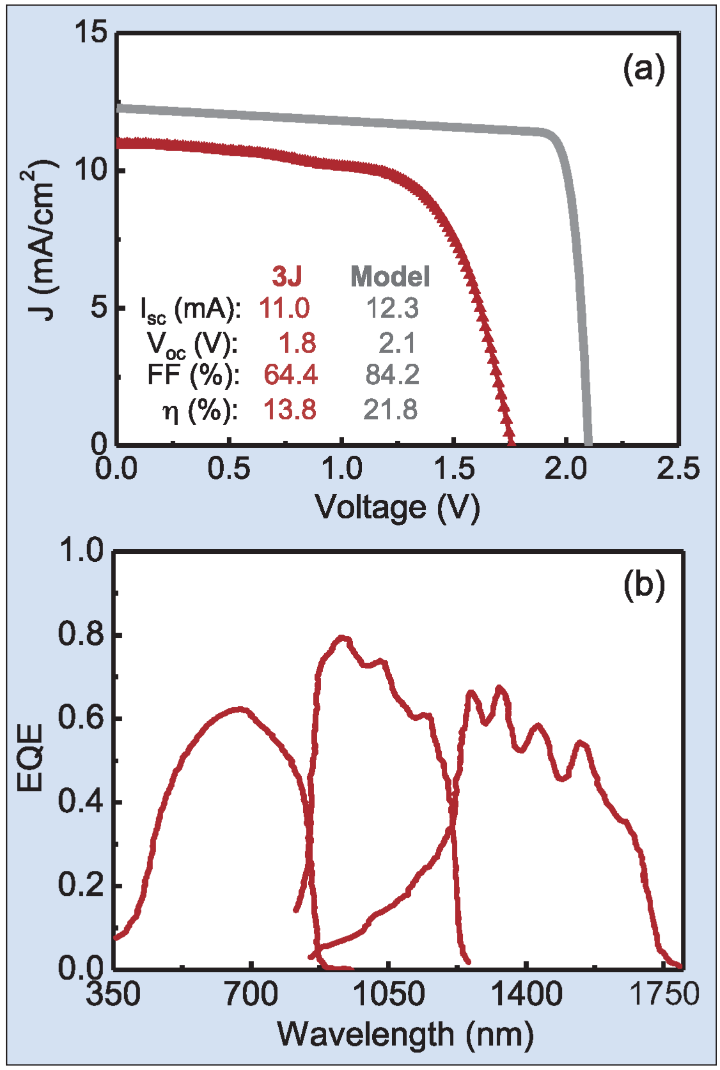

Figure 4. (a) Light current-voltage curve measured under 1-sun AM1.5 direct illumination for InP-based 3-junction test device of California Institute of Technology, US National Institute of Standards and Technology, University of Maryland, and Boeing-Spectrolab Inc (red triangles), compared with 1-dimensional device modeling (grey solid line). (b) External quantum efficiency for InP-based 3J solar cell.

The subcells were connected in a six-terminal series configuration. A 3-junction device was mimicked by using optical splitting with 850nm and 1200nm long-pass filters to subject the middle and bottom subcells to the spectrum that would remain after passing through upper layers.

The open-circuit voltage of the assembly was 1.8V. This compares with a value from the model of 2.1V. The closed-circuit current was also lower than the design at 10.3mA/cm^2, due to "resistance and possible leakage current within the electrical contacts between the subcells". The maximum external quantum efficiency (EQE) of all the cells was around 80%.

A true 3-junction (3J) cell was produced (Figure 4). However, the device was sub-optimal in omitting window and back-surface field layers. Also, the thicknesses of the middle (InGaAsP) and bottom (InGaAs) layers were 1μm rather than the optimal values.

The researchers comment: "The monolithically grown 3J device shows similar performance compared to the independently connected subcells. This demonstrates the extremely low resistance of the fabricated tunnel junctions, validating our device modeling assumption for the lattice-matched optimized 3-junction solar cells presented earlier."

Window and back-surface field layers would reduce surface recombination velocity and light absorption losses. Anti-reflective coatings and increased middle and bottom subcell thicknesses would further boost performance. Such improvements could lead to 20%

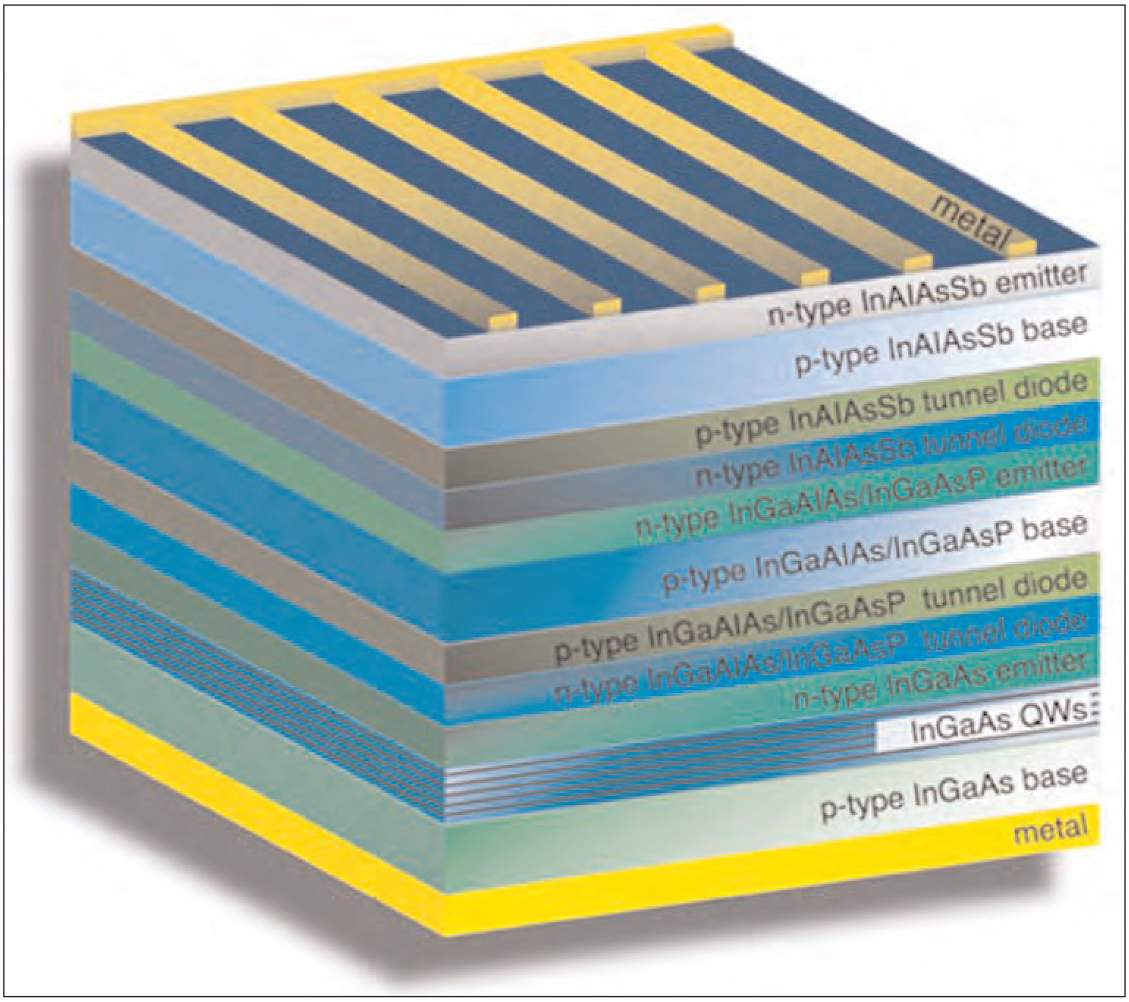

Figure 5. Schematic diagram of multi-junction (MJ) solar cell formed from materials lattice-matched to InP with bandgaps designed for maximum efficiency, according to a design of NRL, Imperial College, and MicroLink Devices Inc (Image: US Naval Research Laboratory)

efficiency under 1-sun illumination.

The researchers comment: "Although the efficiency of this InP-based 3J solar cell is far from the theoretical prediction, the results are promising and demonstrate the capability of growing high-quality Al-rich epitaxial layers, very low-resistance tunnel junctions, and an integrated all-lattice-matched multi-junction solar cell."

Another group that believes 50% efficiency with a 3-junction solar cell is within reach is based variously at US Naval Research Laboratory, Imperial College London and MicroLink Devices Inc [Robert J. Walters, et al, IEEE Photovoltaic Specialists Conference (PVSC), p122, 2011]. The researchers have proposed a design using antimony (Sb) along with the usual III-V compound semiconductor suspects (Figure 5).

The structure is again lattice matched to InP. The bandgaps of the layers have been theoretically optimized for maximum efficiency with the solar radiation spectrum. The bandgaps cover the range 0.7–1.8eV. Normal ternary alloy materials lattice-matched to InP are usually limited to less than ~1.4eV. The researchers therefore propose the use of InAlAsSb quaternary alloy to give a 1.8eV bandgap, while still being lattice matched to InP.

The NRL team already has extensive experience with Sb-based compounds from work on detectors and lasers that was used in modeling the band structure of InAlAsSb. Along with showing the potential for a direct bandgap of 1.8eV, further simulations created a design with power conversion efficiency of more than 50% under concentrated solar illumination.

Moving from theory to practice, NRL is joining with MicroLink and Rochester Institute of Technology in a US Department of Energy (DoE) Advanced Research Projects Agency-Energy (ARPA-E) project that, over three years, will develop materials and device technologies to realize the design.

Textured ZnO windows

While the epitaxial material for solar cells is the basis for solar cells, it is also important to improve the absorption of light by devices through reducing optical losses such as reflection from the top layer. National Formosa University, Taiwan, has developed a liquid-phase deposition (LPD) process of textured zinc oxide on III-V semiconductor to provide improved absorption for multi-junction solar cells [Po-Hsun Lei et al, J. Phys. D: Appl. Phys., vol46, p125105, 2013].

The textured layer reduces reflection of the incident light over a broad band of wavelengths (300–1000nm). Traditional anti-reflective coatings tend to be wavelength selective. The researchers were seeking a low-cost process to produce randomly textured surfaces as a means to improve solar cell light-absorption performance.

The GaInP/InGaAs/Ge solar cell material formation process consisted of metal-organic chemical vapor deposition (MOCVD) on germanium for the active material and a liquid-phase deposition in a Teflon vessel

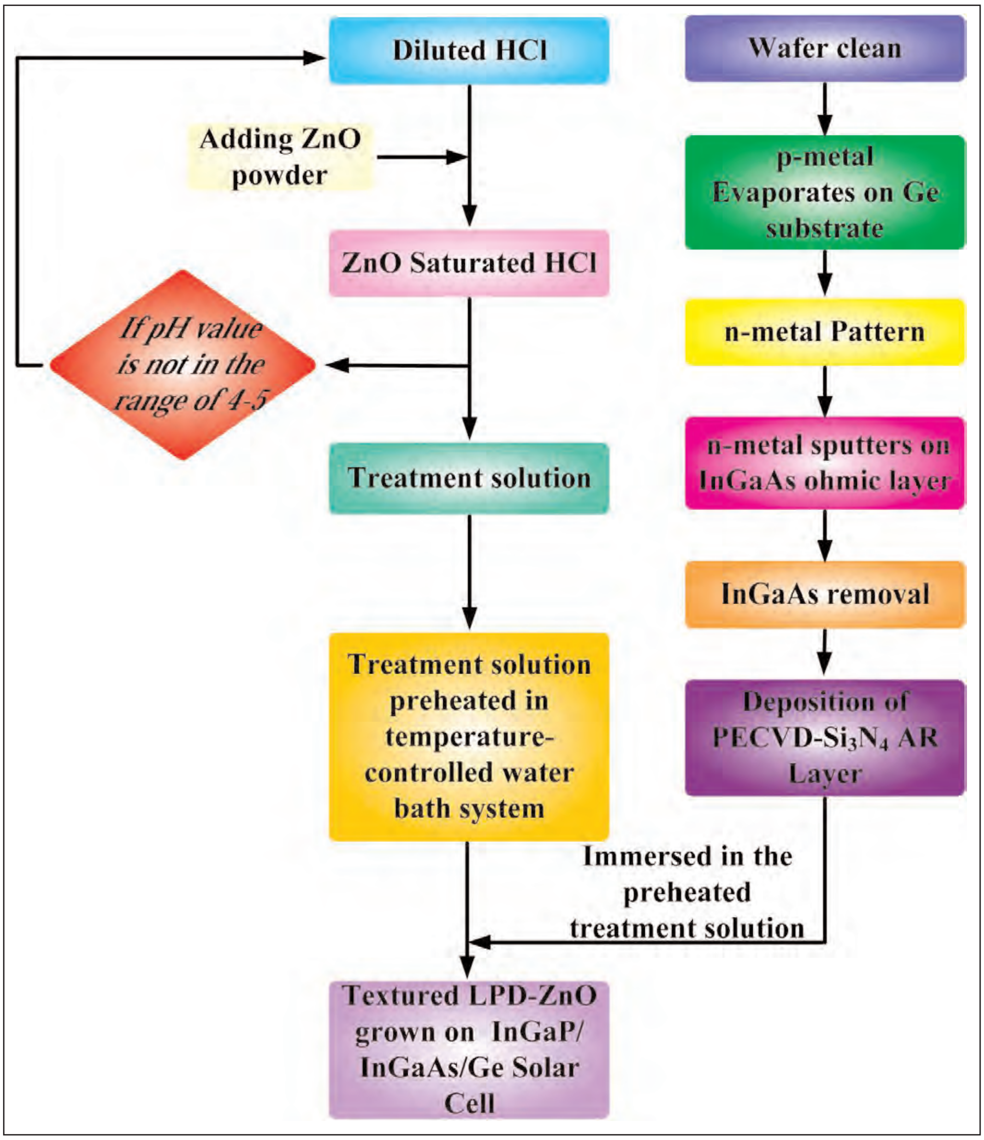

Figure 6. Flow chart for National Formosa University, LPD-ZnO process (left side) and fabrication of GaInP/(In)GaAs/Ge solar cells (right side).

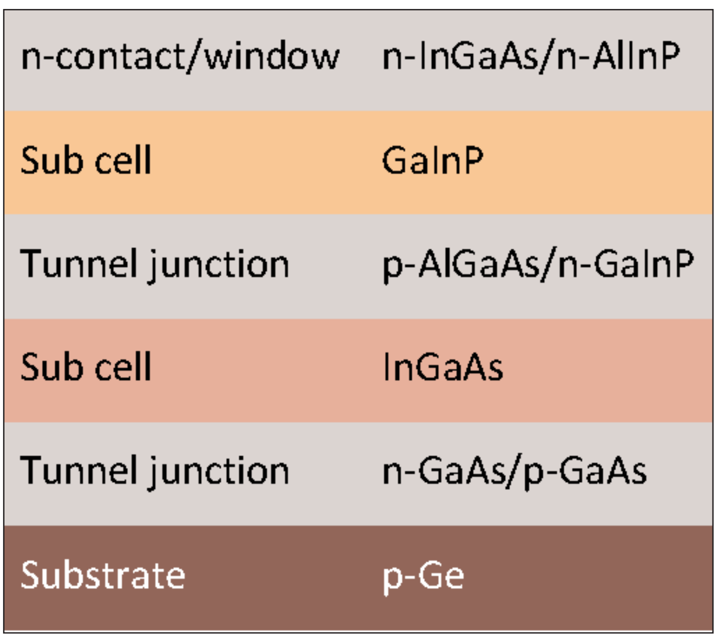

Figure 7. National Formosa University's MOCVD heterostructure.

in a controlled-temperature water bath for the textured zinc oxide layer (Figures 6 and 7).

The epitaxial material was cut up into 5mm x 5mm square chips. The ohmic p-contact was made to the back of the Ge substrate with a gold/zinc/silver/gold alloy. The ohmic n-electrode structure consisted of germanium-gold/nickel/gold on the n-InGaAs top layer. A ridge n-contact was made by partially exposing regions of n-type aluminium indium phosphide (n-AlInP) window layer underneath by etching into the n-InGaAs.

A silicon nitride (Si_3N_4) anti-reflective coating was applied to the n-AlInP using plasma-enhanced chemical vapor deposition (PECVD). The n-InGaAs is used for the electrical contact, but absorbs wavelengths that should be converted by the GaInP layer.

The ZnO was deposited on the silicon nitride. The researchers carried out a number of experiments to optimize the process parameters (pH, temperature) for control of layer thickness and root-mean-square (RMS) roughness. The textured ZnO layer consisted of nests of hexagonal flakes (Figure 8).

The aim of the ZnO layer was to reduce the reflection of light away from the solar cell. The optimum growth conditions for this were found to be 25°C with 6 mole/liter (M) hydrochloric acid solution. Also, the researchers performed simulations suggesting that the maximum enhancement for solar cells designed for a broad wavelength range would come from 95nm RMS roughness.

A bare solar cell without ZnO had a short-circuit current density of 12.5mA/cm^2 and energy conversion of 24%. This is similar to the performance achieved by others, according to the researchers. With ZnO deposited from 6M solution at 25°C, these were increased to 14.22mA/cm^2 and 29.8%, respectively.

Over a series of runs (Table 1), ZnO deposited from 6M solution at 25°C showed small variations in the character of the ZnO layer and in the performance of the solar cells. The RMS roughness of the ZnO layer varied in the range 90–100nm, while the pH value of the growth solution was kept in the range 4–5.

The researchers comment: "The uniformity of the RMS roughness is extremely significant because this is the primary factor determining the absorbed light intensity or scattering between air and the textured LPD-ZnO."

The variation in performance values were 3.31% for short-circuit current, 0.87% for open-circuit voltage, 3.75% for conversion efficiency, and 2.51% for fill factor.

The solar cells were also tested at operating temperatures up to 100°C. The variation in open-circuit voltage was 5.8mV/°C for cells without textured ZnO and 5.9mV/°C with textured ZnO. The respective rates for short-circuit current density were 7.9μA/°C-cm^2 and 8.0μA/°C-cm^2.

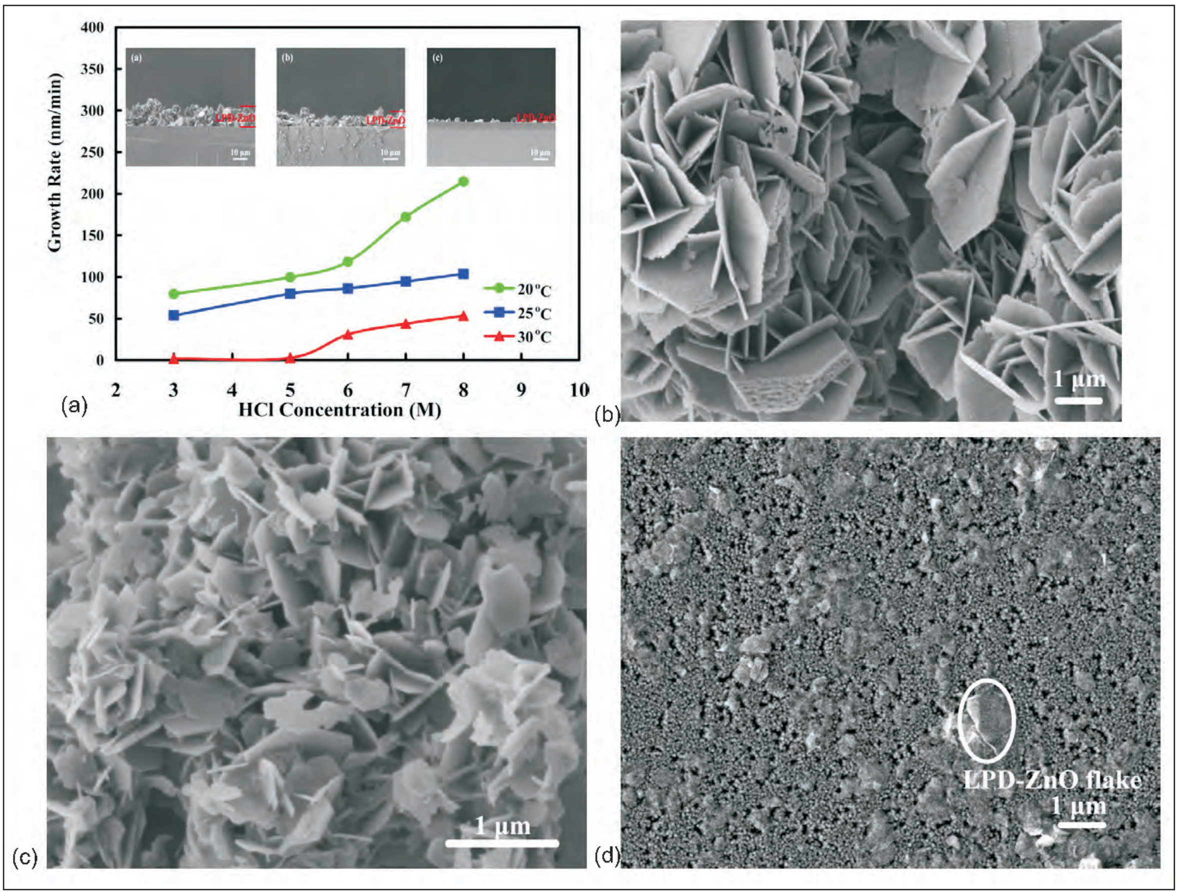

Figure 8. (a) Deposition rate of LPD-ZnO grown on Si_3N_4 as a function of HCl concentration at various deposition temperatures, and FESEM images for LPD-ZnO grown at (b) 20°C, (c) 25°C and (d) 30°C. Insets of (a) show the cross-section FESEM images for LPD-ZnO grown at (a) 20°C, (b) 25°C and (c) 30°C at 6M HCl.

The performance of solar cells tends to show degraded energy conversion at high temperature, and an increase in thermal resistance from added layers can be a concern for thermal management. The negligible changes in performance at raised temperature suggest that the ZnO layer does not significantly trap heat.

The researchers comment: "Introduction of the textured LPD-ZnO window layer for GaInP/(In)GaAs/Ge solar cells shows similar temperature characteristics as compared with those without the textured LPD-ZnO window layer. This may be attributed to the porosity of LPD-ZnO, which offers a path for reducing the thermal energy." ■

Table 1. Performance of GaInP/(In)GaAs/Ge solar cells with textured LPD-ZnO window layer grown at 25°C in 6M HCl solution.

Run no.	Short-circuit current density (mA/cm^2)	Open-circuit voltage (V)	Conversion efficiency (%)	Fill factor
1	14.25	2.43	29.71	0.85
2	14.35	2.43	29.65	0.84
3	15.09	2.41	29.64	0.81
4	14.92	2.34	28.43	0.81
5	14.57	2.42	29.78	0.84
6	15.00	2.42	29.79	0.82
7	14.85	2.41	29.81	0.83
8	14.81	2.41	28.92	0.811
9	14.73	2.39	29.50	0.83
10	14.73	2.39	29.63	0.84
11	14.81	2.39	29.81	0.84
12	14.72	2.38	29.80	0.85