Status of Multijunction Solar Cells and Future Development

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Abstract

Over 30% efficiency InGaP/InGaAs/Ge triple junction solar cells which consist of III-V single crystal layers grown on Ge substrate have already been put to practical use in power generator for space satellites. The same type triple junction concentrator cell has demonstrated over 40% efficiency and high concentration photovoltaic system by using the triple junction cells is being developed energetically. R&D approach targeting 50% efficiency is proceeding by using the invert lattice mismatch, quantum well/dot and InGaAsN material. Cost reduction technology should be developed for future applications.

PROGRESS IN III-V SOLAR CELLS

Figure 1 shows progress in world record conversion efficiency of compound solar cells. In the 1980s, GaAs single-junction and AlGaAs/aAs dual-junction cells were developed. InGaP material was proposed instead of AlGaAs which had quality problem due to oxygen. In the 1990s, InGaP/(In)GaAs/Ge triple-junction cells were developed by combining with GaAs/Ge hetero-epitaxial technique. Since 2000, the triple-junction cells have been practically used for space and developed for terrestrial concentrator. Efficiency of the cell reached to 32% (1sun) and 40% (1000sun).

Recently, InGaP(~1.7eV)/InGaAs(~1.2eV)/Ge lattice mismatch cell which has lower band-gap for both top and middle cells has been developed to obtain current matching among three cells and the maximum efficiency has reached to 40.7% (240sun) at Spectrolab and 41.1% (454sun) at Fraunfoher-ISE. The invert epitaxial structure of InGaP/GaAs/InGaAs(1eV) cell aiming the same current matching has been developed by using 1eV InGaAs lattice mismatch bottom cell and the world record efficiency of 33.8% (1sun) and 40.8% (326sun) has been achieved

CELL STRUCTURE AND KEY TECHNIQUES

Figure 2 shows schematic of the main stream triple junction structure. Key techniques for improving efficiency are (1)current matching between top and middle cells, (2)wide band-gap tunnel junction, (3) lattice matching by adding 1% Indium, (4)InGaP hetero epitaxial layer on Ge, (5)disordered InGaP top cell.

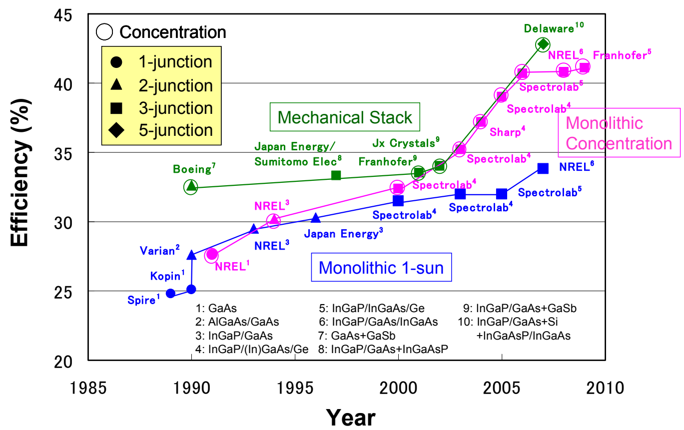


Figure 1: Progress in world record conversion efficiency of compound solar cells

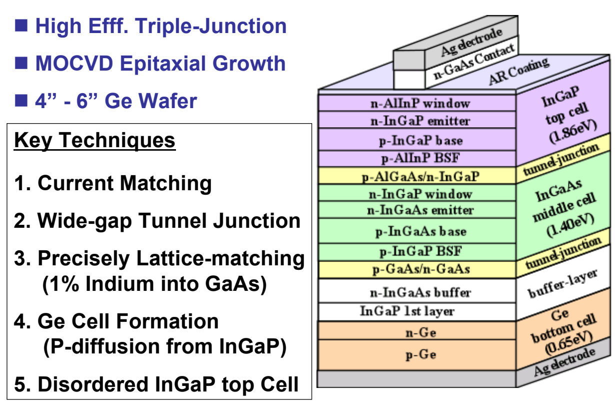


Figure 2: Schematic of the main stream triple junction structure and key techniques for improving efficiency

CELL MANUFACTURING

High efficiency InGaP/InGaAs/Ge triple junction cells have been produced at SHARP and provided for Japan's domestic satellites. Distribution of efficiency for the cells which were produced for the JAXA program is shown in Figure 3, as an example. Average AM0 efficiency of the cells is 28.6%. Concentrator cells are also produced for concentrator system being developed in-house. Average efficiencies are 29% and 37% at 1-sun and 180-sun, respectively, as shown in Figure 4. Very high efficiency of the triple-junction cells has been confirmed in manufacturing level.

Design of the cell is different between space and concentrator applications. For the concentrator cell, cell size and grid pitch are reduced with considering higher current density. Lower sheet resistance of about 300Ωcm/sq is necessary for epitaxial structure, although sheet resistance is reduced to 1/5 by increasing irradiation intensity over 200-sun. High tunneling peak current density of over 100A/cm^2 is also required for the concentrator cell.

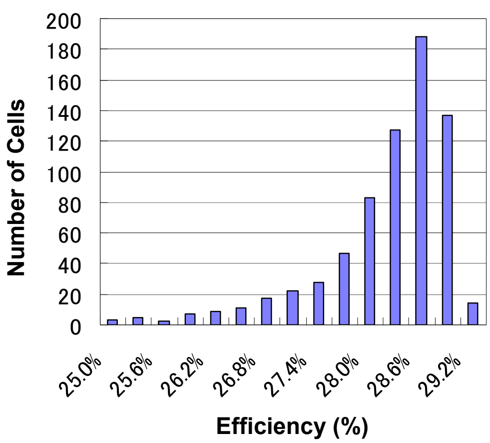


Figure 3: Distribution of efficiency in production of space solar cells, as an example for JAXA program.

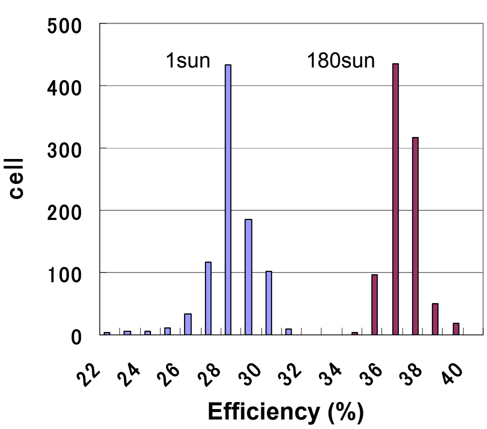


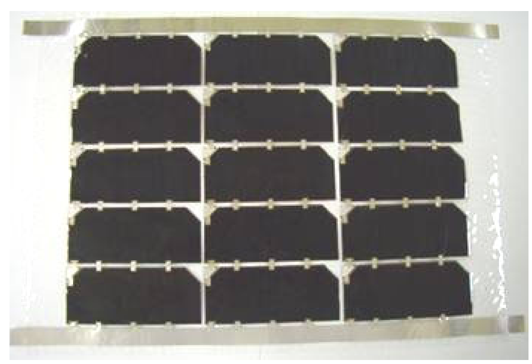
Figure 4: Distribution of efficiency in production of concentrator solar cells for CPV system in-house..

R&D ACTIVITIES

(1) Space Application

Flexibly bending and lightweight solar panel with high efficiency which enables to be compactable in a launcher and expandable in outer space is desired. Prototype flexible thin film solar sheet has been developed by using thin film InGaP/GaAs dual-junction solar cells which have been realized by very thin single crystal epitaxial layers without substrate. The solar sheet consisted of the thin film cells, newly developed flexible bypass diodes, silicone adhesive and transparency films. Figure 5 shows (a) a photograph of the sheet and (b) a schematic cross section view. Fifteen thin film cells are connected in five series and three parallel in the sheet. Flexible bypass diodes are welded to the corner of each cell with inter-connectors. They are laminated by 75 micron transparent films with silicone adhesive at both sides. The weight of prototype solar sheet is about 19.7g. The efficiency of the sheet is 22% (Voc=11.83V, Isc=1.12A, FF=0.854) as shown in Figure 4, so output power per weight is about 0.57W/g. The efficiency is lower than expected value (25%). It should be improved by optimizing cell structure and fabrication process of solar cell. In addition, the filling factor of cells in the sheet area is not so good because of large gaps between cells. Laminate-film and inter-connectors are still heavy. So output power per weight of 1W/g is thought to be possible by improving the filling factor of cells area and reducing the weight of the sheet.

(a)



(b)

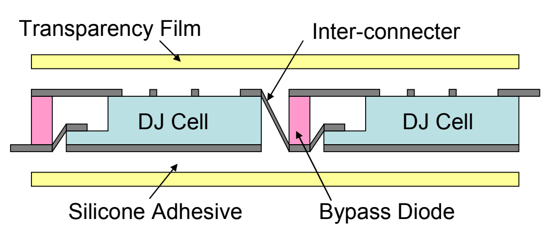


Figure 5: (a) Photograph of space solar sheet and (b) schematic cross section view.

(2) Concentrator Application

Energy loss in the concentrator cell under high intensity illumination is basically expressed by I^2R. So, reduction in absolute current by reducing cell size is though to be effective to improve cell efficiency under assumption of constant R. However, series resistance of the cell is increased by reducing cell size. The most dominant factor is calculated to be sheet resistance. Figure 6 shows an increase in efficiency by reducing cell size as a function of concentration ratio for the cells with different sheet resistance. The sheet resistance of the concentrator cell is found to be reduced from ~300 to ~60 Ωcm/sq by increasing illumination intensity over 200-sun. This fact is thought to be due to excess of number of carrier generated by photons over carrier concentration of the epitaxial layer.

Increase in efficiency by reducing cell size was demonstrated in Figure 7. Concentration ratio which gives the maximum efficiency is increased by reducing cell size. High efficiency of over 40% is achieved under 1100-sun with a 4.5mm2 size cell.

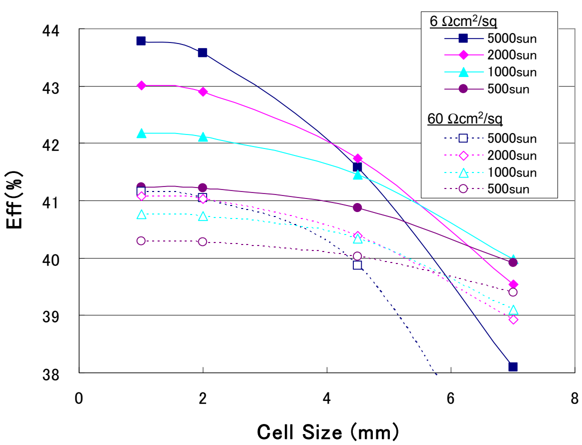


Figure 6: Increase in efficiency by reducing cell size, as a dependence of sheet resistance. (Calculation)

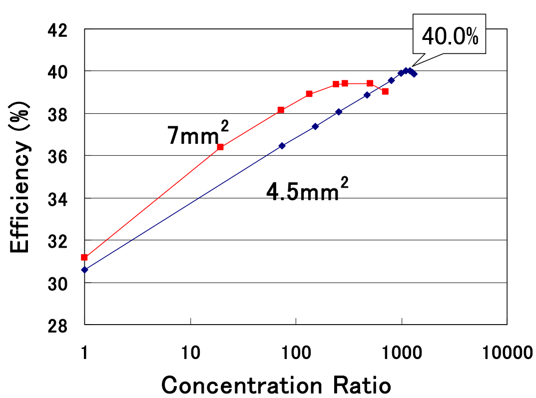


Figure 7: Efficiency as a function of concentration ratio for the cells with different size.

(3) High Efficiency Approaches

Combination of band-gaps for the current triple-junction structure is not optimal. One way to optimize band-gaps of the triple junction cell is to reduce band-gaps of top and middle cells. So, band-gap combination of 1.7eV, 1.2eV and 0.65eV is the optimal structure including Ge bottom cell. The other way is to increase band-gap of the bottom cell. Combination of 1.9eV, 1.4eV and 1.0eV is the optimal. Four junction cell with band-gaps of 2.0eV, 1.4eV, 1.0eV and 0.65eV is ideal structure by using Ge cell. A lattice-matched InGaAsN cell is thought to be the best for 1.0eV cell in the ideal four junction structure, if the crystal quality of InGaAsN material is good.

Figure 8 shows high efficiency approach in NEDO innovative solar cell development project. In this theme, development on invert lattice mismatch cell, 3 or 4 junction cell by utilizing quantum well/dot, and 4 junction cell using InGaAsN material, are proceeding under the collaboration with Univ. of Tokyo and Toyota Technological Institute. In 2008-2009 FY, 45% efficiency is targeted by focusing the structure of invert triple-junction cell with 1.9eV, 1.4eV and 1.0eV band-gaps. Figure 9 shows the cell fabrication process to realize high efficiency InGaP/GaAs/InGaAs(1eV) triple-junction cell. In the invert structure, lattice-match top and middle cells are grown and then lattice-mismatch bottom cell is grown at last. An advantage of this structure is that bad crystal quality of a lattice-mismatch bottom cell does not influence lattice-match two cells. If the epitaxial cell layer can be separated from the substrate, by etching, reuse of the substrate might be possible.

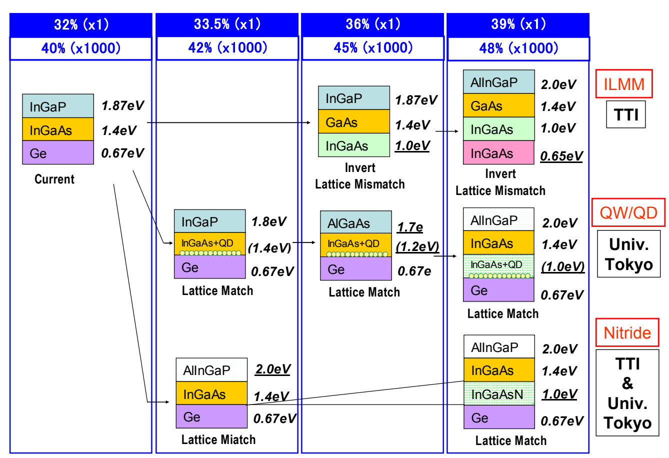


Figure 8: High efficiency approach in NEDO innovative solar cell development project

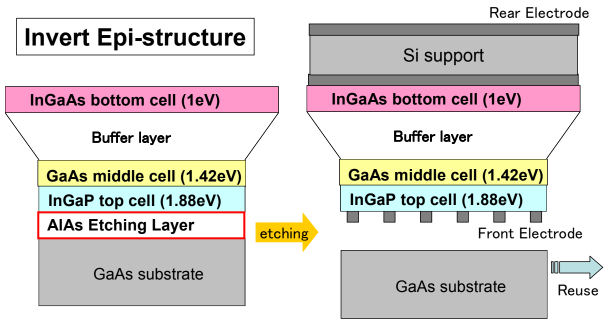


Figure 9: Cell fabrication process to realize high efficiency InGaP/GaAs/InGaAs(1eV) triple-junction cell.

CONCLUSIONS

InGaP/(In)GaAs/Ge triple junction cells are practically used for space application and expected to be applied for terrestrial concentrator system. Further improvement on efficiency will be expected by the development on multijunction structure by utilizing the invert lattice mismatch, quantum well/dot and InGaAsN material.

ACKNOWLEDGEMENTS

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