Abstract

Solar energy have a huge the potential to cut the world's reliance on fossil fuels. Multi-junction photovoltaic (PV) cell has the potential to reach 50% of energy conversion efficiency. However, the efficiency of typical lattice-matched triple-junction (InGaP/Ga(In)As/Ge) PV cell can only reach 41% under concentrated suns. This is due to the excess current wasted by the Ge sub-cell. With an addition of a 1-eV sub-cell between Ga(In)As and Ge sub-cell, it has been predicted to achieve an efficiency of 50% under concentrated suns. In this work, high efficiency PV cells were grown on a silicon substrate to increase the conversion efficiency and reduce the PV production cost.

We have demonstrated a 1-eV GaNAsSb PV cell on Si-Ge/Si substrate using molecular beam epitaxy (MBE). The cell exhibited the lowest ever reported $E_g/q\text{-}V_{OC}$ value of 0.50 eV. This indicated that the 1-eV GaNAsSb layer has high crystalline quality with long carrier lifetime. Growth conditions of GaNAsSb layer was optimised by varying As/Ga ratio, growth temperature and annealing temperature and annealing duration. As/Ga ratio was found to affect the concentration of arsenic anti-site defects and nitrogen related defects. On the other hand, growth temperature was found to affect nitrogen phase separation or segregation. Annealing at 700°C for 5 mins is capable of improving the performance of the PV cell by removing non-radiative defects. However, annealing at temperature exceeding optimal temperature of 700°C for more than 5 mins severely deteriorates the PV cell performance.

Previous modelling works assumed an ideal QE for all the sub-cells. However, experimental quantum efficiency of 1-eV GaNAsSb was well below ideal condition. Modelling work was carried out to optimise the bandgap energies of top two sub-cells using published experimental quantum efficiency (QE) of InGaP, GaAs, 1-eV GaNAsSb and Ge. The bandgap energies of bottom two sub-cells was fixed at 1.03 eV and 0.66 eV, which represented GaNAsSb and Ge sub-cell, respectively. The model showed that optimised bandgap energy of first and second sub-cells were 2.00 eV and 1.56 eV, respectively. These bandgap energies are higher compared to bandgap energies of top two sub-cells in typical triple-junction cells, which are 1.86 eV (InGaP) and 1.42 eV (Ga(In)As), respectively.

Increase in bandgap energy in top two sub-cells allows more light to be transmitted to the third sub-cell. With the optimised bandgap of 2.00/1.56/1.03/0.66 eV in a quadruple junction cell, energy conversion efficiency at one sun condition can be up to 38.8%. Energy conversion efficiency can be boosted to 49% under 500 suns condition. Under this configuration, a short circuit current density of 11.8 mA/cm^2, open circuit voltage of 3.65 V and a fill factor of 90% can be achieved in a photovoltaic cell.

1.56 eV PV cells were also grown and fabricated using AlGaAs on Si-Ge/Si substrate. Material quality of AlGaAs layer was optimised by varying V/III ratio, growth temperature and base thickness to obtain maximum performance in PV cell. This growth process is important in showing the potential of the 1.56 eV AlGaAs PV cell on Si-Ge/Si substrate and future integration with 1-eV GaNAsSb PV cell as well as the 2.0 eV sub-cell (AlGaInP) and Ge sub-cell. The four materials are closely lattice matched with GaAs and can be grown directly on the Si-Ge/Si substrate.