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DESIGN AND ANALYSIS OF HIGH EFFICIENCY MULTI-JUNCTION SOLAR CELLS WITH TUNNEL JUNCTIONS

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ABSTRACT

Multi-junction solar cells (MJSC) are the future of renewable energy production. MJSC have rapidly gone laboratory cells, to large-area, high-efficiency manufacturing cells. The introduction of wide-bandgap tunnel junctions between the sub-cells in MJSC has made these devices a super-efficient energy producing device. In this paper we have discussed the important aspects of MJSC design and manufacturing. Device examples are presented. Recent advances and future challenges in multi-junction solar cells are summarized.

Keywords: Metal Organic Vapor Phase Epitaxy, Multi-Junction Solar Cells, Tunnel Junction

I. INTRODUCTION

Energy is very important to our day-to-day life. Future development of humans very much depends on the availability of energy sources that are dependable, safe, and environmental friendly. There is an increased demand for renewable energy sources due to concern over global climatic change and over dependence on non-renewable fossil fuel reserves. The Photovoltaic (PV) solar energy is an important contribution to a future sustainable non-polluting energy supply for mankind. In 2013, the world photovoltaic power capacity reached 136 GW with Germany leading in solar electricity production. Concentrator photovoltaic technology helps to keep the cost of solar power to be lower than 1$/W [1].

Multi-junction solar cells (MJSC) are cell modules with multiple p–n junctions made to absorb different wavelengths of light, corresponding to their bandgaps, to create electric current. The maximum theoretical efficiency of a single-junction cell is about 34%. Theoretically, infinite number of junctions would give an efficiency of 86.8% under concentrated sunlight [2]. Crystalline silicon solar cells have achieved efficiencies about 25%,while multi-junction cells have reached efficiencies over 45% [3]. The design and material choice are critical in multi-junction cells. Here in this paper we have discussed about the design and fundamental issues of multi-junction solar cells and a brief overview about the current status of multi-junction solar cell.

II. MULTI-JUNCTION SOLAR CELL STRUCTURE

III-IV semiconductors are used in multi-junction solar cells such as gallium arsenide (GaAs), gallium antimonide (GaSb) indium phosphide (InP) and ternary compounds like gallium indium phosphide (GaInP). These semiconductor materials have the properties like direct energy band gap, high optical absorption coefficient, and good mobility and minority carrier lifetimes [2]. The important parameters considered for designing MJSC are Band gaps, lattice constant matching, and current matching.

The sub-cells in a MJSC are stacked in such a way that the top layer of the cell will have the largest band gap and the bottom layer will have the smallest band gap. The top layer cells absorb the high energy photons and the lower layer cells absorb the lower energy photons that are not absorbed in the top layers. For example, in a triple junction solar cell, the band gap of the middle cell less than that of the first cell but larger than the third cell. For these stacked devices current must flow from an n-type semiconductor layer into a p-type and the sub-cells should satisfy the current matching condition in order to achieve the maximum efficiency.

When one solar cell is stacked over another directly in series, the n side of the bottom cell makes contact with the p side of the upper cell. This will create a reverse p-n junction to the solar cells in series which will block the current flowing through it. There are two ways to circumvent this issue. First way is to make metal contacts to both the cells (in the case of dual-junction cells) and extract current from the cells separately. But this method is more complicated and gives less efficient MJSC due to less light receiving at the bottom cell by shadow made by the contacts. Further, there will be voltage drop at the metal contacts. The second method to connect the sub-cells is to connect the sub-cells by tunnel junctions. Andtunnel junctions are the best option for joining the stacked sub-cells since they do not create shadows and no voltage drop at the tunnel junction. A schematic of such dual-junction cell, GaInP on GaAs, with tunnel junction in between the sub-cells [4] and the equivalent electrical circuit diagram are shown in Fig.1.

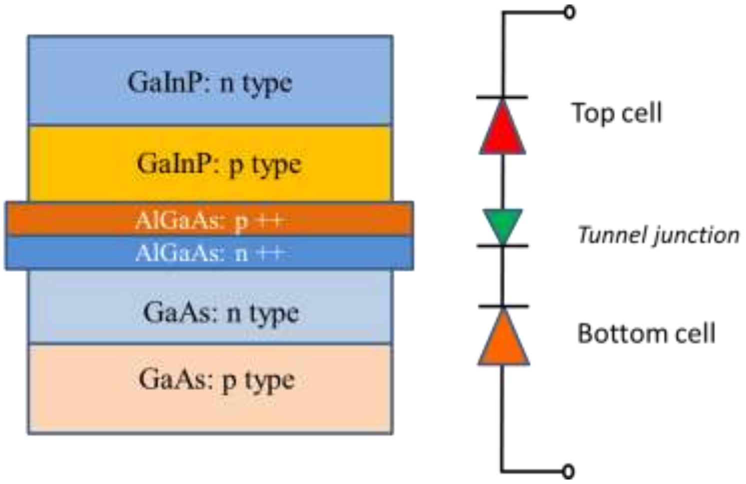

Fig.1: schematic of GaInP on GaAs dual-junction cell with AlGaAs tunnel junction and the equivalent electrical circuit diagram.

A tunnel junction connecting the two sub-cells of a multi-junction solar cells are highly doped p- and n-type semiconductor layers. The doping concentrations are typically $>10^{19}$ cm^{-3}. Due to the very high doping the depletion region is very thin and the barrier width is narrow. The length of the depletion region*l*,is reduced by the high doping as the equation:

$$l_{dep} = \sqrt{\frac{2\epsilon(\varphi_0 - V)}{q}\frac{N_A + N_D}{N_A N_D}}$$

where, N_D and N_A are the number of ionized donors and acceptors respectively. And φ_0 is built-in potential and V is applied voltage.

This allows the electrons to tunnel through the junction regardless of the barrier height. The high doping also minimize the optical loss by creating an effective potential barrier for minority carriers. Due to tunneling there is almost no voltage drop while connecting two cells in series.Band diagram of the tunnel junction is schematically shown in the Fig. 2. [5]. For each sub-cells, an n-type Window layer,to reduce surface combination, and a p-type back-surface field layer,to decrease the scattering of carriers towards the tunnel junction, are present on the top and bottom respectively. In order to avoid defect creation in the layers, the window layer and the back-surface field layer must not have large lattice mismatch with the cell's material. The bandgap of the window layer must be greater than the back-surface field layer.

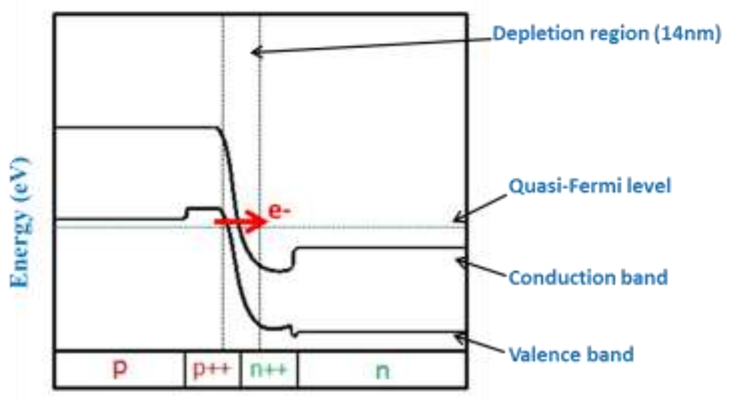

Fig. 2: Band diagram of a tunnel junction showing tunnel injection of electrons.

In the tunneling region, the energy difference between the bands on both sides of the heavily p-n junction must be low enough that the electrons which tunnels through the junction occupy states available on the other side of the barrier. For tunneling mechanism, the resistance in the barrier becomes extremely low since the electrons does not need energy to tunnel as they tunnel to the same energy state available at the other side of the barrier. Thus the voltage drop at tunnel junction is almost zero.

III. THERORETICAL ANALYSIS OF J-V CHARACTERISTICOF MJSC

Current matching of the sub-cells is an important requirement for multi-junction solar cells to achieve high efficiency. The optimal J-V (current density-voltage) parameters are not necessarily equal for each sub-cell since the total current through the module is the lowest among the sub-cells. In order to calculate J_{SC} spectral response measurement is done on MJSC sub-cells and quantum efficiency is found out. The short-circuit current.J_{SC} = min (J_{SC1}, J_{SC2}, J_{SC3}) where $J_{SCi}(\lambda)$ is the short-circuit current density at a given wavelength λ for the sub-cell i. To get J_{SC1}, J_{SC2}, J_{SC3}, quantum efficiency QE(λ) is used. Where QE(λ) is defined as the ratio of the amount of electron-hole pairs created to the incident photons at wavelength λ [6]. The quantum efficiency for sub-cell iis defined as:

$$QE_i(\lambda) = \frac{J_{sc_i}(\lambda)}{q\varphi_i(\lambda)}$$

where$\varphi_i(\lambda)$ is the photon flux incident on corresponding subcell i and $J_{sc}(\lambda)$ is the photogenerated short-circuit current density at the wavelength λ. Therefore, J_{sc} of a solar cell can be given as:

$$J_{sc_i} = \int_0^{\lambda_2} q\,\varphi_i(\lambda) QE_i(\lambda) d\lambda$$

By measuring the quantum efficiency of the solar cell, one can calculate the J_{sc} of the solar cell at given conditions from the above equation.The maximum theoretical efficiency or the limiting efficiency of ideal infinite multi-junction solar cells is evaluated to be around 68% [7].

IV. HIGH EFFICIENCY TRIPLE-JUNCTION SOLAR CELL DEVICE STRUCTURE

Most of the multi-junction solar cell devices made are triple junction solar cells. Epitaxially grown III-V materials are ideal candidates for these devices because of its tunable band gaps and easy manufacturing capabilities. The manufacturing is mostly done with metalorganic vapor phase epitaxy and molecular beam epitaxy [8]. Most devices are based on GaAs and related compounds, often germanium as the bottom cell and substrate with GaAs as the middle sub-cell and GaInP as the top sub-cell. An example of a multi-junction solar cell with GaInP/InGaAs/Ge sub-cells andAlGaAs tunnel junction device structure is shown in figure 3.AlGaAs tunnel junctions are well-suited for multi-junction solar cells where temperatures and current densities are dramatically higher than normal single junction solar cells [9].

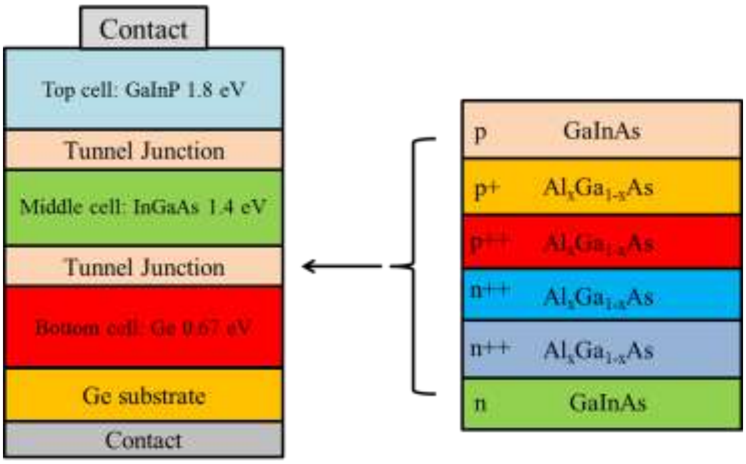

Fig. 3: Schematic of a triple junction solar cell with GaInP/InGaAs/Ge sub-cells and a single tunnel junction is shown in expanded view.

V. CONCLUSION

Multi-junction solar cells are used in space applications due to its better radiation-resistance and high efficiency [9]. For commercial use of multi-junction solar cell, the cost has to come down. Due to expensive manufacturing process the multi-junction solar cells have higher price-to-performance ratio than other sources of energy.MJSC is preferred in space applications due to its light weightiness and high efficiency. $Ga_{0.5}In_{0.5}P$/GaAs/Ge cells are used in some space applications.3-junction and 4-junction solar cells have already realized high-efficiency of over 40%. 1st generation crystalline Si solar cells and 2nd generation thin-film solar cells being the leaders in renewable energy, the 3rd generation super-efficient concentrator III–V compound multi-junction solar cells are going to dominate the renewable energy production in the near future. The challenges in multi-junction solar cell research are to develop low-cost and high output power concentrator multi-junction solar cell modules.

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