RADIATION HARD, DOUBLE GRADED, DRIFT DOMINATED InP SOLAR CELLS

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ABSTRACT

Double graded and drift dominated InP solar cells have been designed, fabricated and characterized. By grading the doping concentration in both the emitter and the base of the InP solar cell, we create an electrical field through the active layer, and thus efficiently collect carriers by drift which results in higher than 80% overall internal quantum efficiency. By adding an InP P^{++} delta doped layer, we eliminate the depletion region between the substrate and the epitaxial layers, thereby reducing the series resistance and improving cell quality. The power remaining factor after 10^{15} electrons/cm^2 1MeV electron irradiation is 93.7%. The results indicate that our design promises to result in a gravimetrically efficient and radiation hard space solar cell.

1. INTRODUCTION

It has been recognized that the radiation hardness, cell efficiency and power to weight ratio are key factors to space solar cells. High radiation resistance is especially crucial for satellites or spacecraft in the extreme radiation environment of the van Allen Belts, at an altitude of about 3000km, which is an advantageous orbit for global coverage in terms of number of satellites needed and communication delay [1]. InP has attracted attention as a space solar cell material due to its proved superior radiation resistance compared to other semiconductor materials [2][3], as well as its optimal bandgap, which is 1.35eV, for high efficiency cells [4]. Our specially designed double graded and drift dominated InP based solar cell, with its novel but very simple design in which the major mechanism for collection of photo-generated carries is by drift due to the internal electrical field instead of diffusion associated with the normal PN junction cells, promises to be extremely radiation hard as well as very efficient and lightweight.

2. DEVICE DESIGN AND STRUCTURE

2.1 Drift Dominated Device

The essence of our design is to collect the generated carriers by drift by creating an internal electrical field throughout the active (quasi-neutral) layer. The idea of using drift instead of diffusion as a major carrier collection mechanism associated with normal PN junction cells is based on two factors. First, drift cells are more efficient. Carriers generated in the drift region will be collected due to the internal electrical field, while for the diffusion cells, only carriers generated in the junction or within the minority carrier diffusion length of the junction can be collected. Second, drift cells are expected to have higher radiation resistance. The minority carrier diffusion length will be largely degraded after the radiation due to the generation of recombination centers; the PN junction solar cells whose collection efficiencies rely on minority carrier diffusion length are degraded as a result. Drift cells, on the other hand, will be less affected since the carrier collecting mechanism is independent on the minority carrier diffusion length.

2.2 Previous Cell Structure

We implement this drift dominated design by varying the doping concentration in the active layers. In our previous design [1] shown in Fig. 1, we have achieved drift fields of 1,000-10,000 volts/cm in the 200-300 nm n-type quasi-neutral region between the p-n junction and the cell surface by varying the Si doping concentration from mid 10^{16}/cm^3 at the p-n junction to nearly 10^{20}/cm^3 at the surface.

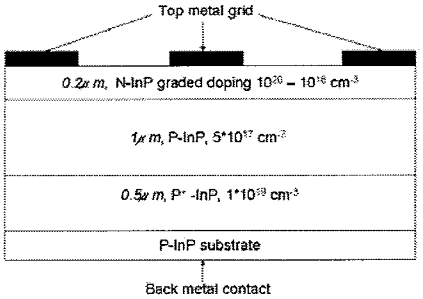

Fig. 1 Structure of our previous drift dominated InP solar cells

Furthermore, we successfully decreased the surface dead layer width, which is usually about 10-100nm and is caused by caused the reverse band bending due to surface Fermi level pinning, which drives photo generated carriers away from the p-n junction. This can greatly reduce the collection efficiency for high energy photons (blue-UV) of most cells, since the absorption coefficient for this photon energy range is usually above 10^5 cm^{-1} for most materials. With the very high doping concentration at the surface of our InP based cells (~10^{20}cm^{-3}), this dead layer is modeled to be less than 3 nm in our device. As a result, we attained excellent spectral response for high energy photons.

However, our pervious cells showed a large series resistance. This large resistance comes about because we have a depletion region between the p-InP substrate and the first p^+-InP epitaxial layer due to Fermi level pinning, which was observed when the photocurrent saturated above a certain input radiation power and further demonstrated in the electrochemical C-V (ECV) carrier concentration profile shown in Fig. 2.

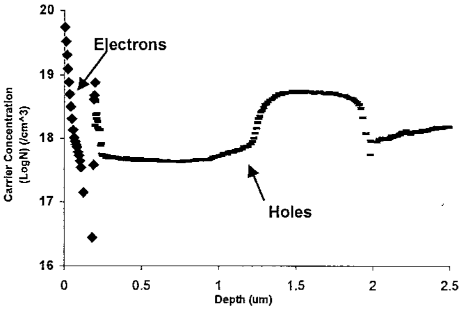

Fig. 2 ECV carrier concentration profile for pervious InP drift dominated solar cells

2.3 New Structure

In order to reduce the cell series resistance and to further improve our cell design, we added an InP P^{++} delta doped ($1x10^{20}cm^{-3}$) layer to decrease the resistance between the substrate and the epitaxial layer. We also graded the InP p^+-layer from $10^{17}cm^{-3}$ to $10^{19}cm^{-3}$ to create another drift field to improve the collection efficiency at longer wavelengths. The new design, which we called D3 InP solar cells, is shown in Fig. 3. Therefore, we have an internal electrical field between the surface and a depth of 1.2μm. Photo-generated carriers in this region will all be collected efficiently by drift. The 0.5μm p-InP layer, homogeneously doped at $10^{17}cm^{-3}$, between the graded doped n-InP region ($10^{20}cm^{-3}$-$10^{16}cm^{-3}$) and graded doped p-InP region ($10^{17}cm^{-3}$-$10^{19}cm^{-3}$) is used as a barrier to prevent Be diffusing into the PN junction.

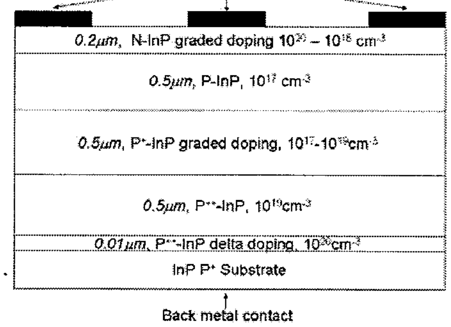

Fig. 3 Structure of the improved design of drift dominated InP solar cells

3. EXPERIMENTS

The new and improved structure was grown by Molecular Beam Epitaxy (MBE). A composite layer of 20nm Ti and 180nm Au forms the front contact, and 200nm a Au-Zn alloy annealed at 450°C in nitrogen has been used as back contact. No heat treatment is necessary for the front contact because the n-InP front surface is pinned near the conduction band and the doping level at the front surface is high ($10^{20}cm^{-3}$). This results in a low resistance, tunneling, ohmic contact. All metal contacts have been deposited by e-beam vacuum evaporation. The front contact finger patterns were fabricated by a lift-off photoresist process. After metallization, the cells were mesa etched for isolation. After the fabrication, we have profiled the carrier concentration using the Electrical Chemical C-V (ECV) carrier concentration profiler, characterized the current density as a function of voltage under AMO illumination and measured the quantum efficiency as a function of wavelength both before and after 10^{15} electrons/cm^2 1MeV electron irradiation.

4. RESULTS

4.1 ECV Carrier Concentration Profile

The ECV profiler can be used to measure the sample carrier concentration as a function of depth. The ECV system consists of an electrochemical capacitance-voltage (C-V) measurement system, which allows the measurement of the carrier concentration from C-V measurement as a function of depth in the sample. In this system, we use a conductive electrolyte solution to make electrical contact for C-V measurement. And we employ variation of the voltages on the electrolyte cell, which leads to dissolution of the semiconductor, thereby the semiconductor can be repetitively etched and measured, leading to an accurate measurement of carrier concentration versus depth in the sample. The ECV doping concentration profile on our doubly graded, drift dominated (D3) InP cell is shown in Fig 4. It demonstrates the very thin depletion region (dead layer) at the surface and the linearly graded doping in both n-InP and p-InP region which lead to the internal electrical field. It also shows that the depletion region between the substrate and first epitaxial layer due to Fermi level pinning previously shown in Fig 2 is greatly diminished due to the 10nm $10^{20}cm^{-3}$ delta doped InP P^{++} layer.

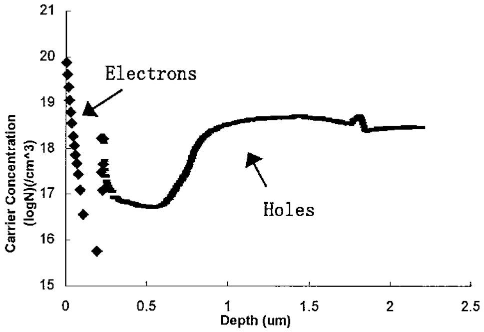

Fig. 4 ECV carrier concentration profile for double graded, drifted dominated InP solar cells

4.2 Current density vs. Voltage Characterization

The current density vs. voltage characteristic under AMO illumination has been measured at the Naval

Research Laboratory (NRL), and is shown in Fig. 5. Note that this sample had no anti-reflection coating, so the short circuit current density of 23mA/cm^2 can be expected to increase to about 35.4mA/cm^2 with an anti-reflection coating, which is very close to the upper limit short circuit current density for AM0 illumination of 42.6mA/cm^2. The upper limit J_{sc} we indicate here is calculated by making the ideal assumption of 100% absorption of all photons with energies greater than the bandgap, 100% collection of all generated carriers, and ideal junction characteristics. In addition, the overall performance, including the open circuit voltage which is 0.78V, fill factor 76%, the efficiency is much better than our previous cells for which we measured an open circuit voltage of 0.56 and fill factor of 65%.

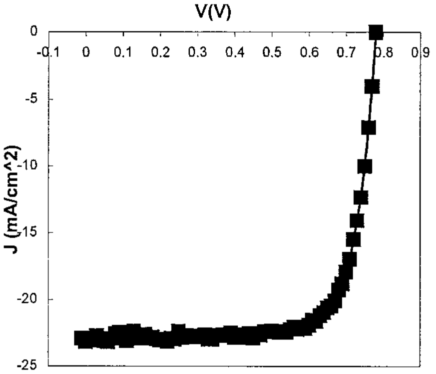

Fig. 5 Current density vs. voltage for double graded, drift dominated InP solar cells under AM0 illumination before irradiation.

4.3 Spectral Response

We measured the quantum efficiency as a function of wavelength by using 1000W Quartz Tungsten Halogen Lamp focusing into the monochrometer, and using 1mm diameter core fiber to transmit the monochromatic light from the monochrometer onto our device. We used an optical detector to measure the incident photon power and an HP4156B Semiconductor Parameter Analyzer to measure the photon generated current under zero volt bias. The results are shown in Fig. 6. The internal quantum efficiency is derived from the measured external efficiency and the theoretical value of InP reflectivity as a function of wavelength. The results show high and flat quantum efficiency from UV to near infrared. It is worth noting that the cell shows > 80% internal quantum efficiency at 350nm, which is as we expected, since our surface band bending layer is very thin (<5nm) due to the very high surface doping concentration (10^{20}cm^{-3}).

4.3 Radiation Resistance

To test the radiation hardness of our drift dominated InP solar cells, we measured the current density vs. voltage characteristic and spectral response after irradiation with 10^{15} cm^{-2} 1MeV electrons.

4.3.1 Current density vs. Voltage Characterization after Irradiation

Fig. 7 shows the current density vs. voltage characteristics for our double graded drift dominated InP solar cells before and after radiation with 10^{15} cm^{-2} 1MeV electrons. It shows that the cell performance is not affected except for a slight decrease in fill factor, which drops from 76% before the radiation to 72% after the radiation. Both the open circuit voltage and the short circuit current remain the same. The power remaining factor after irradiation is 93.7%. The small decrease in output power indicates that our InP D3 cell is very resistant to energy irradiation, especially when compared to the best reported value of 87.5% for an InGaP/GaAs/Ge triple-junction solar cell after 10^{15} electron/cm^{-2} 1MeV electron irradiation [5]. Note that for our previous cell, whose structure is shown in Fig. 1, the open circuit voltage remaining factor is 78% after 7×10^{11}cm^{-2} 1MeV proton radiation [1]. Therefore, the radiation hardness has been greatly improved for our new InP drift-dominated cells.

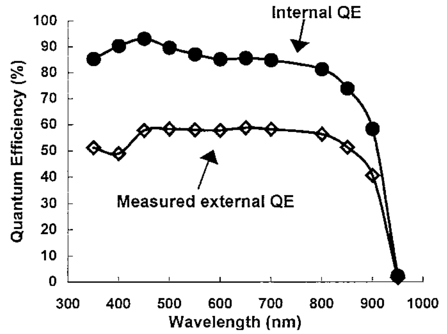

Fig. 6 Quantum efficiency vs. wavelength for double graded, drift dominated InP solar cells

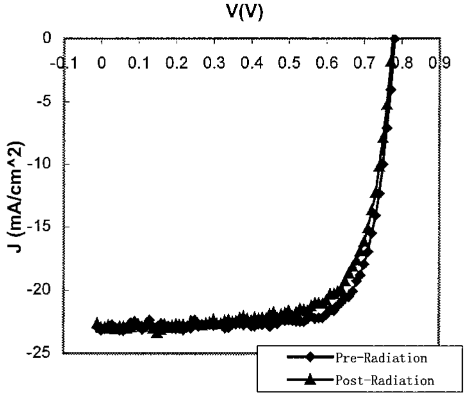

Fig. 7 Current density vs. voltage for double graded and drift dominated InP solar cells before and after 10^{15}cm^{-2} 1MeV electron fluence

4.3.2 Spectral Response after Radiation

Fig. 8 shows the measured external quantum efficiency and calculated internal quantum efficiency of the InP solar cell before and after irradiation with 10^{15} cm^{-2} 1MeV electrons. The irradiation had essentially no affect on the cell response. This is the case because carrier collection in our cells is by drift along the electrical field rather than diffusion associated with standard p-n junction solar cells, so our cells are insensitive to radiation-induced degradation of the minority carrier diffusion length. This is the mechanism for the extreme radiation resistance of the short circuit current in our InP cells.

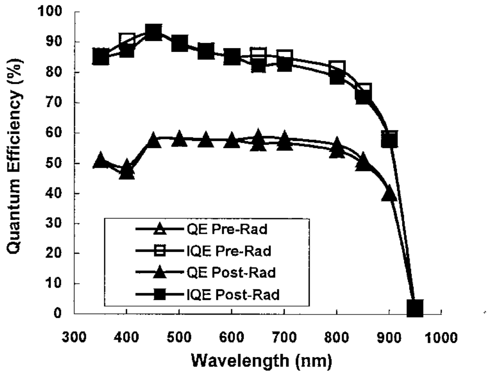

Fig. 8 Quantum Efficiency vs. Wavelength for Double Graded, Drift Dominated InP Solar Cells before and after irradiation

5. CONCLUSION

Our results show the improved double graded and drift dominated D3 InP solar cells to display very good radiation resistance. By double grading the doping concentration in both the n-InP and p-InP region, we create an electrical field all through the active layer, and thus efficiently collect carriers by drift, which results in higher than 80% overall internal quantum efficiency for the AM0 solar spectrum. By adding an InP P^{++} delta doped layer, we eliminated the depletion region between the substrate and epitaxial layers, thereby greatly reducing the series resistance and improving the cell quality. The current density vs. voltage characteristics measured before and after 1 MeV electron irradiation up to a fluence of $10^{15}cm^{-2}$, demonstrated the superior radiation resistance of our cells as we expected, since we use InP as an radiation hard material, and more importantly, our carrier collection mechanism, drift, is mostly independent of the minority carrier diffusion length., and. therefore, much less vulnerable to the radiation damage. Furthermore, the open circuit voltage of our cells which was 0.78 V before irradiation, showed essentially no degradation after irradiation. All these results indicate that our design promises to result in gravimetrically efficient and radiation hard space solar cells.

6. ACKNOWLEDGEMENT

The authors would like to thank NRL for the radiation characterization work.

7. REFERENCES

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