Resistance Considerations for Stacked Small Multi-junction Photovoltaic Cells

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***Abstract* — In this paper we propose a stacked multi-junction solar cell design that allows the intimate contact of the individual cells while maintaining low resistive losses. The cell design is presented using an InGaP and GaAs multi-junction cell as an illustrative example. However, the methodologies presented in this paper can be applied to other III-V cell types including InGaAs and InGaAsP cells. The main benefits of the design come from making small cells, on the order of 2×10^{-3} cm^2. Simulations showed that series resistances should be kept to less than 5 Ω for devices up to 400 µm in diameter to keep resistance power losses to less than 1%. Low resistance AuBe/Ni/Au ohmic contacts to n-type InGaP are also demonstrated with contact resistivity of 5x10-6 Ω-cm^2 when annealed at 420^o C.**

***Index Terms* — multi-junction solar cells, compound semiconductors, photovoltaic cells, III-V solar cells**

I. Introduction

Multi-junction solar cells have been widely explored in an effort to improve the cell efficiency. Monolithically-stacked junctions impose current-matching and lattice-matching constraints on the cell design. Alternatively, mechanically-stacked cells with independent contacts for all the junctions have also been proposed [1,2]. This frees the cells from the current matching constraint that limits the performance of the top junctions. However, it introduces the new challenge to reduce the optical losses between the cells. Since the compound semiconductors used for multi-junction cells have very close refractive indices, keeping the cells in very intimate contact is desirable to minimize reflections at cell interfaces. One proposed method of doing this is wafer bonding [3]. However, the need for metal gridlines within the cell aperture in larger cells to reduce resistive losses hinders the ability to make this intimate contact.

In this paper, we propose a stacked multi-junction solar cell design that allows the intimate contact of the individual cells while maintaining low resistive losses. The cell design is presented using an InGaP and GaAs multi-junction cell as an illustrative example. However, the methodologies presented in this paper can be applied to other III-V cell types including InGaAs and InGaAsP cells. The main benefits of the design come from making small cells, on the order of 2×10^{-3} cm^2. Other advantages of the small cell size include improved thermal management, improved robustness to partial shading and new module form factors as discussed in [4].

A representation of the cell stack as it is envisioned is shown in Figure 1. As shown all the cell contacts are accessible around the perimeter of the cell and there are no gridlines in the optical aperture. This allows the entire cell aperture to be planar and is compatible with being placed in intimate contact with a neighboring cell.

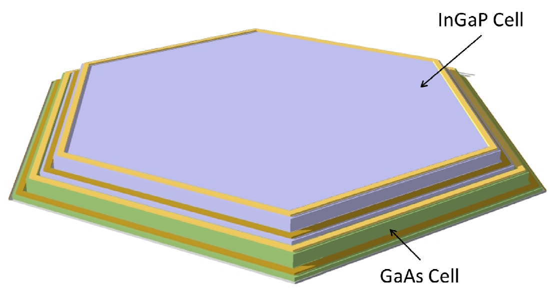

Figure 1: Drawing of an example of mechanically stacked solar cells.

II. Resistance effects on Cell Performance

Series resistance is a major contributor to power loss in a solar cell especially under concentration and it is important to minimize it to achieve the highest efficiency cell possible. This task is particularly challenging in independent multi-junction cells as there are two contacts per junction which can contribute to the series resistance compared with just two overall in a monolithic current-matched multi-junction cell. Therefore the first step in designing the overall cell is to investigate the effects of the extra series resistance as a function of light concentration on device efficiency and set a target for our operating conditions. Low concentration systems with small cells are of large interest to keep a low balance of systems cost since they can be designed with a larger acceptance angle and lower cost microlens arrays can be used [5]. Therefore, we have focused our design efforts on low concentration systems below 200 suns.

Figure 2 illustrates the main sources of series resistance of concern in a stacked independent multi-junction cell. This includes the contact resistance which is determined by the quality of the ohmic contacts and is discussed in Section IV. Additionally, spreading resistance is a much larger concern in the stacked cell as the current needs to be laterally collected at each contact rather than at just the top and bottom contacts. This spreading resistance adds series resistance that greatly affects the overall device efficiency and will be discussed in greater detail in Section III.

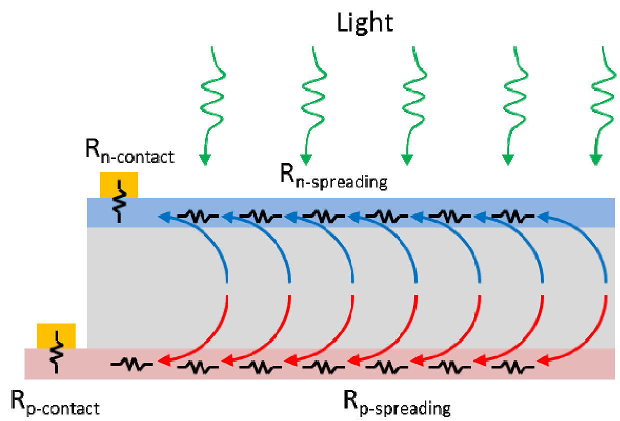

Figure 2: Diagram of the sources of excess resistance in a single junction for a stacked junction solar cell. The extra resistance includes contact and spreading resistance for both the p-contact and n-contact.

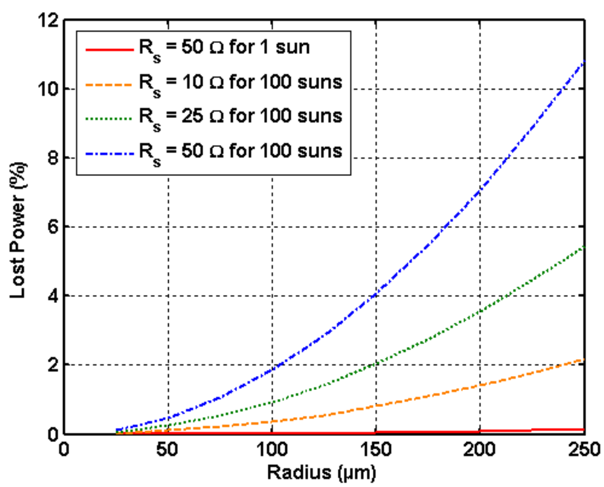

Figure 3: The relative power lost in the solar cell due to excess series resistance as a function of the size of a circular cell.

To analyze the effects of series resistance, a SPICE simulation was setup to monitor the output power as a function of current. In this simulation the output current from the cell is scaled as function of area and the resistance is represented as a single resistor in series with the current source. The maximum power point is then compared to the maximum power point with no excess resistance to arrive at the percent of power lost. The current density is scaled by the amount of concentration to look at the effects under concentration. It is important to realize that this model does not take into account how the device physics may change with additional light and current generation. However, it does give an accurate picture of how additional series resistance affects the power lost. The power lost to spreading resistance for an ideal top InGaP cell is shown in Figure 3. The simulation uses 14 mA/cm^2 current density for one sun and scales accordingly for higher concentrations. As can be seen higher concentrations push the cell size down and limit the resistance that can be tolerated. This pushes the desired overall resistance below 5 Ω and device diameters less than 400 µm in order to keep resistive losses to less than 0.7% of the total power generated.

III. Lateral Spreading Resistance

As mentioned in the previous section, one significant source of series resistance in the stacked device is lateral spreading resistance. This is more significant than the monolithic current-matched device because the current needs to be collected at each contact at the periphery. This spreading resistance is affected by the gridline geometry and the design of the contact layers. Looking first at the gridline geometry it is desirable to maintain only perimeter gridlines to give an open area for the optical aperture for maximum light collection as well as to provide a planar area for stacking the cells. Additionally, it is important to maintain the open aperture on both the front and back side of the cells unlike monolithic current-matched cells. From Wyeth [6], it is seen the absolute dimensions of the cell do not affect the overall spreading resistance for a perimeter contact geometry and uniform illumination. This independence is due to the uniform generation of carriers across the cell, however it is important to still realize that the larger the current generated in the cell will increase the lost power as shown in Figure 3. Therefore, we have constrained ourselves to perimeter contacts while adjusting for power losses through cell size and contact layer sheet resistances.

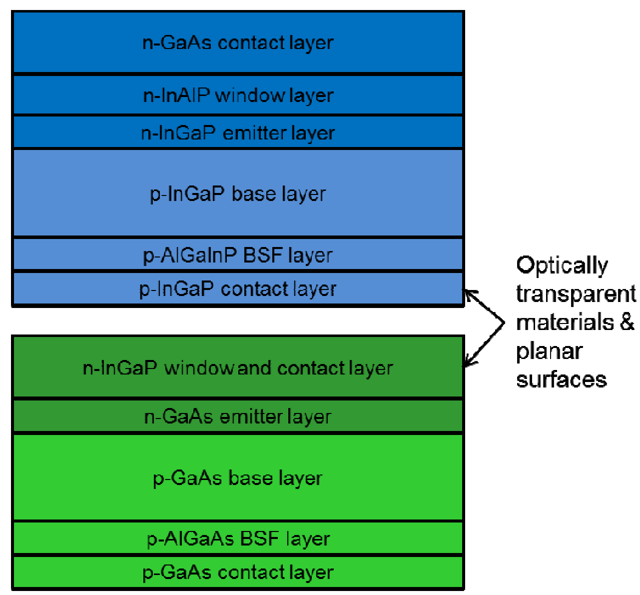

Figure 4: InGaP and GaAs cell designs for mechanical cell stacking.

The sheet resistances associated with the contact are largely influenced by the doping and thickness of the contact layer and window/BSF layer adjacent to it. As shown in Figure 4, we have combined the top contact and window layers and made the bottom contact layer transparent for all contacts that will be adjacent to another cell. For the InGaP cell the bottom contact is p-type InGaP. For the GaAs cell, the top contact and window layer are combined into a single n-type InGaP layer while the bottom contact is p-type GaAs. The main benefit of this design is maintaining a planar surface for stacking cells. This means the contact layers will be composed of a wider bandgap semiconductor than is typically used for contacts. This allows the layer thickness to be engineered for low spreading resistance without causing additional optical loss.

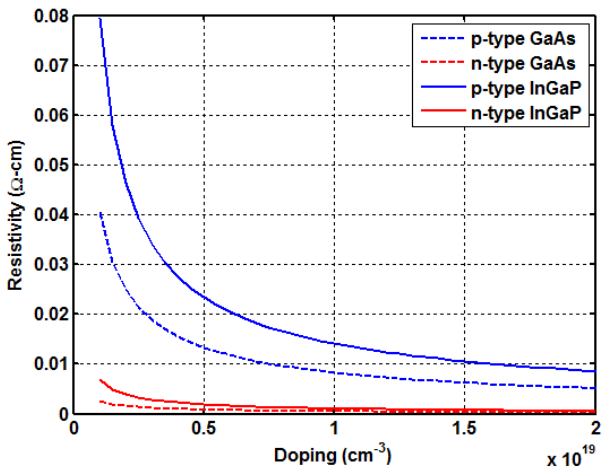

Figure 5: Resistivity as a function of doping for GaAs and InGaP lattice matched to GaAs. Calculation was based on the doping dependent carrier mobility for holes and electrons [6].

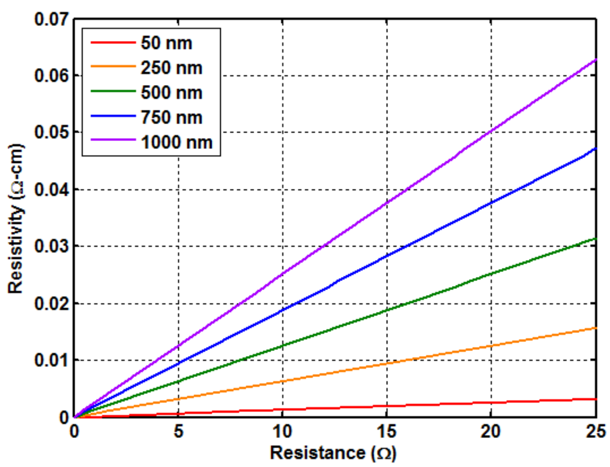

Figure 6: Effects of resistivity on the resistance of a circular cell with only parameter contacts and no internal gridlines for layer thicknesses between 50 nm and 1 μm.

It is important to take a critical look at what thickness and doping levels are required to achieve the targeted 5 Ω resistances for the example GaAs and InGaP cells. For simplicity we have constrained ourselves to circular device geometries with only perimeter contacts and calculated the resulting series resistance as a function of sheet resistance. From [6], the resistance for this full circle is:

$$R = \frac{1}{8\pi} \times \frac{\rho}{t}$$

where ρ is the layer resistivity and t is the thickness of the resistive layer. With our targeted resistance of 5 Ω this constrains the sheet resistance to less than 125 Ω/□ which requires a tradeoff between doping levels and layer thickness. The layer resistivities calculated from the doping dependent carrier mobility, [7], are shown in Figure 5. These resistivities can be used to calculate the needed layer thickness to achieve a given resistance as shown in Figure 6. It is important to remember that the resistance will be the result of the parallel spreading resistance of each layer so the final result has to take into account all the layers. However, we can already see that spreading resistance will not be a significant issue for the n-type transparent contact layer once it is thick enough to account for the contact metal diffusion. The p-contact is more difficult due the significantly lower hole mobility which translates into a higher resistivity and requires the contact layer to be thicker than 1 μm. This makes an n-on-p cell structure advantageous where the p-type layers include the thick base absorber layer and the thick transparent p-type contact can sit below the absorbing layers without causing additional loss while more light will penetrate the thinner topside n-type contact.

IV. Contact Resistance

The final important component of series resistance is contact resistance. It is desirable to minimize the contact area to reduce material costs and to maximize the optical aperture. As discussed above, both of the GaAs and InGaP cells designs incorporate atypical InGaP contact layers which are more difficult to make ohmic contacts to due to their larger bandgap. To support our design, a contact resistance study was conducted to identify contact metal stacks which would provide low contact resistance. This study was done using circular TLM structures and using the methodology described in [8]. Efforts to drive the gridline width to less than 5 μm while keeping the contact resistance contribution less than 100 mΩ for a 300 μm diameter cell led to the design constraint of requiring contacts with specific contact resistances less than 1×10^{-5} Ω-cm^2.

Contacts to InGaP, particularly p-type InGaP, are not well-known and a number of stacks and anneal conditions were explored. The AuBe/Ni/Au contacts used were shown to be very dependent on anneal conditions requiring an anneal at 420° C to achieve specific contact resistance below 5×10^{-6} Ω-cm^2. The contact resistance of 5×10^{-6} Ω-cm^2 leads to an ohmic contact resistance of 53×10^{-3} Ω for a 300 μm diameter circular cell and will account for ~1% of the overall series resistance budget. Contacts annealed at 380° C and below did not show ohmic behavior and had specific contact resistances above 1×10^{-5} Ω-cm^2. Cross sectional SEM images from these two anneal conditions are shown in Figures 7 and 8. The more significant metal/semiconductor interdiffusion seen in the 420° C image is responsible for the lower contact resistivity of this contact. It is important to design the thickness of the p-type InGaP contact layer to be thicker than this 0.25 µm of metal diffusion to prevent it from diffusing into the junction and possibly impacting the device performance.

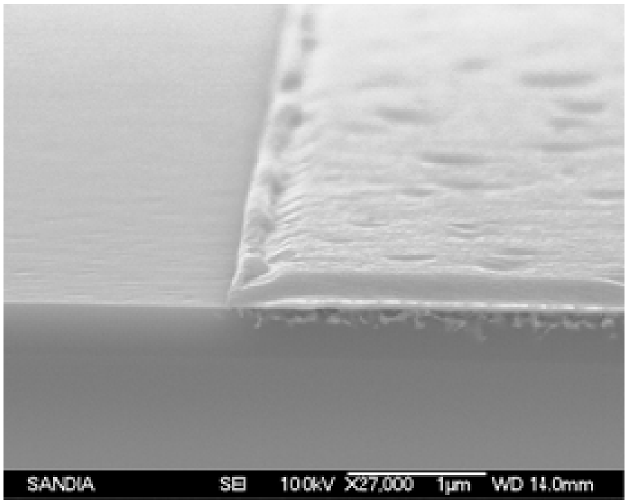

Figure 7: AuBe/Ni/Au contact annealed at 420° C

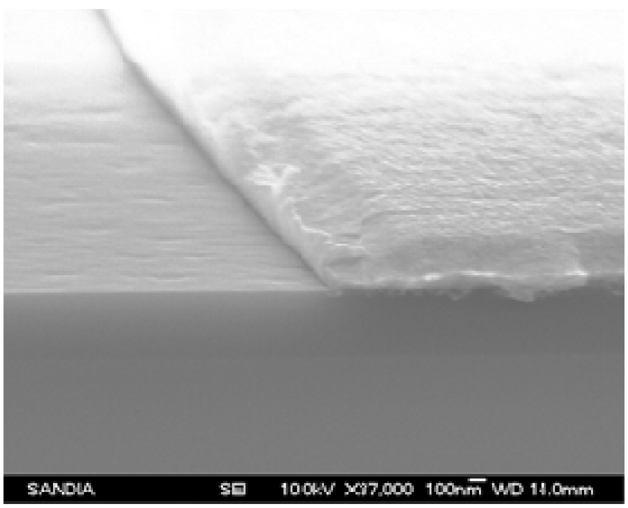

Figure 8: AuBe/Ni/Au contact annealed at 380° C

The other contact layers utilized more established metal stacks to achieve specific contact resistances less than 5×10^{-6} Ω-cm^2. The n-type InGaP contact layer and n-type GaAs are contacted using Au/Ge/Ni/Au. The p-type GaAs contact uses a Ti/Pt/Au contact.

V. Conclusions

In conclusion, there are a number of significant design modifications necessary to produce high-performance stacked independent junction cells. The contact layers must be designed for optical transparency. The cell size and concentration play a significant role in determining the final resistive power losses since gridlines in the optical aperture prevent the planar surfaces needed for bonding cells. Simulations showed that series resistances should be kept to less than 5 Ω for devices up to 400 µm in diameter to keep resistance power losses to less than 1%. Low resistance AuBe/Ni/Au ohmic contacts to n-type InGaP are also demonstrated with contact resistivity of 5x10-6 Ω-cm^2 when annealed at 420° C. Future work will focus on experimental verification of these designs and the demonstration of stacked cells utilizing these designs.

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