DEVELOPMENT OF A HIGH EFFICIENCY UVR/IRR COVERGLASS FOR TRIPLE JUNCTION SOLAR CELLS.

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Introduction.

Cover glasses have been a necessary and integral part of space solar arrays since their inception. The main function of the cover glass is to protect the underlying solar cell from the harsh radiation environment of space. They are formed either from fused silica or specially formulated ceria doped glass types that are resistant to radiation damage, for example Pilkington's CMX, CMG, CMO.

Solar cells have steadily increased in performance over the past years, from Silicon cells through textured Silicon cells to GaAs cells and the multijunction cells of today. The optimum coverglass solution for each of these cells has been different. The glass itself has also evolved. In some cases it has had its expansion coefficient matched to the cell substrate material, and in addition, added value has been derived from the application of thin film optical coatings to the coverglass. In the majority of cases this has taken the form of a single layer of MgF_2 which acts as an antireflection coating. There are also conductive coatings to address electrostatic discharge issues (ESD) and Ultra Violet Reflective (UVR) and Infrared Reflective (IRR) coatings designed for thermal enhancement. Each type of coating can be applied singly or in combination. This paper describes a new type of UVR/IRR (or blue red reflector BRR) specifically designed for triple junction solar cells.

For space applications, where radiation is the principal mechanism for removing heat from the satellite, it is the emittance and solar absorptance that primarily determine the temperature of the array. It is therefore essential that any coatings designed to have an effect on the temperature by reducing the solar absorption have a minimal effect on the overall emittance.

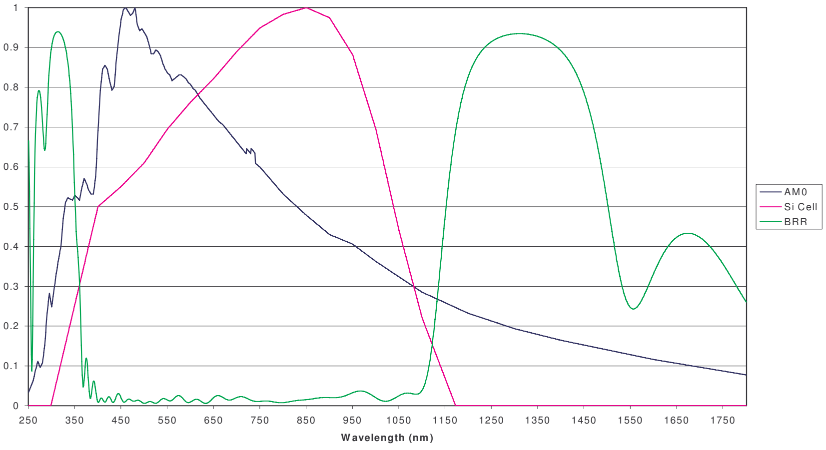

Figure 1

A typical Silicon cell UVR/IRR coverglass' spectral reflectance curve is shown in green in figure 1. The normalised spectral response of a typical Silicon cell is also shown along with the normalised AM0 spectrum. The aim of the coating is to reflect the solar spectrum that falls outside the region of cell's spectral response whilst maintaining high transmittance within it. In this case the spectral response is approximately 350nm to 1150nm. The unwanted energy only serves to heat the cell, and in turn, this heating effect reduces the cell's efficiency. The typical change in efficiency is around 0.5% per Kelvin for Silicon cells and around 0.25% per Kelvin for GaAs cells. So by reducing the amount of unused radiation incident on the cell by using a UVR/IRR coating it is possible to increase the output of the cell when compared to a cell without a UVR/IRR coverglass. The crucial points for a BRR coating are then: that it reduce the unwanted radiation incident on the cell, whilst maximising the transmittance to the cell in the region of the cell's spectral response and that it does not significantly change the emittance.

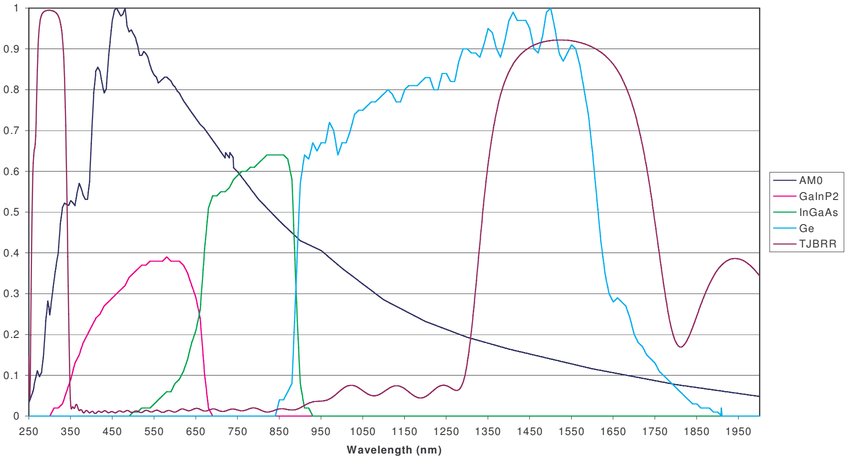

Figure 2

The advent of the triple junction cell has extended the range of the spectral response from 1100nm at the red end of the spectral response to 1800nm (see Figure 2) The efficacy of the normal BRR coatings is impacted in three ways by this extension of the cell's spectral response. Firstly the amount of radiation falling outside the cell's spectral response is reduced as can easily be seen from comparison with the solar spectrum and this would reduce the effectiveness of any BRR coating. Secondly the coating complexity and thickness would increase due to the necessity to reduce the effects of harmonics in the spectral response area. Thirdly the temperature coefficient of efficiency for multi-junction cells is smaller than for the other cell types.

Currently the spectral response of triple junction cells is based on the monolithic integration of three junctions, each with adjacent spectral response regions. Due to the monolithic integration of these junctions the cell is essentially current limited by the top junction's performance. The bottom Ge junction is essentially in current excess. This means that a portion of the solar energy that falls on this junction is not being usefully utilised in the production of power. This energy is essentially heating the cell, thereby raising the temperature of the cell and hence reducing the cell's overall efficiency.

The novel concept behind the new type of BRR proposed here is to place the IRR reflection peak in the spectral response of the bottom junction and, in addition, to maximise its effectiveness by current balancing the bottom junction to that of the rest of the cell.

Theory

In order to provide the theoretical basis for the new coating, an iterative model has been used. At the heart of this model is evaluation of the I_{sc} of the bottom Ge junction of triple junction cells and the junction's response when used in conjunction with an IRR coating. Several IRR designs were generated and the effect of their cut-off wavelength and bandwidth on the bottom junction I_{sc} was evaluated. The best candidate designs were optimised to provide the best match possible to the current in the other junctions while still leaving some current excess to accommodate end of life (EOL) effects in the cell. The I_{sc} modelling was achieved using the following equation.

$$J_{ph} = q\int_{\lambda_1}^{\lambda_2} AM\,0(\lambda)SR(\lambda)d\lambda \qquad \text{Equation 1}$$

Where q is the electronic charge and $AM\,0(\lambda)$ and $SR(\lambda)$ are the sun curve and the spectral response of the relevant junction respectively. J_{ph} is the total photocurrent density. The reflectance profile of the IRR was adjusted until the appropriate current was obtained from the junction. Once this had been achieved the cell efficiency was modelled using an effective energy balance model as in equation 2. Reference [1], [2], [3].

For a solar cell in steady state equilibrium the operating temperature is determined by the incident solar radiation, heat lost through radiation and the cell output. Heat absorbed is radiated from the front and back of the array until equilibrium temperature is achieved. The temperature of the cell can then be calculated from the following simplified equation.

$$T = \left[\frac{(\alpha_s - N)S}{(\varepsilon_f + \varepsilon_b)\sigma}\right]^{\frac{1}{4}} \qquad \text{Equation 2}$$

Where:

S = Solar constant
T = Cell operating temperature
ε_f = Front surface emissivity
ε_b = Rear surface emissivity
N = Cell efficiency
σ = Stefan-Boltzmann Constant
α_s = Cell solar absorption

Since the cell response or quantum efficiency as well as the emittance are functions of temperature an iterative approach has been used to solve for T. We have assumed as a basis an AR coated coverglass giving a temperature of 310K and estimated the equilibrium as if the efficiency were not temperature dependent. The increased efficiency generated from a temperature reduction provided by the IRR or BRR can then be estimated using a cell temperature coefficient of efficiency, in this case 0.06 abs %/K.

Results of modelling

The use of the above model has resulted in the generation of several spectral profiles for the IRR filter. The UVR design has a secondary effect on the bottom junction and is designed to be IRR compatible.

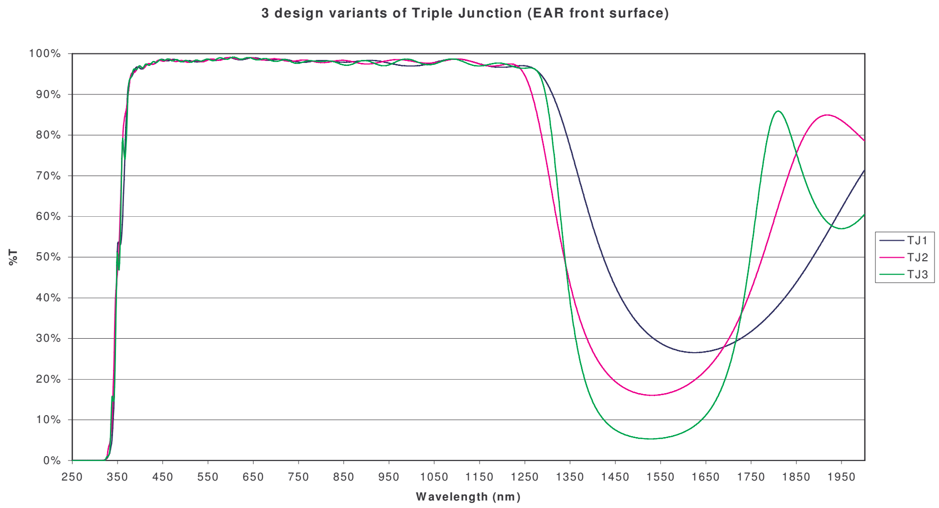

Figure 3

The UV cut-off wavelength of the UVR filter is determined primarily by the absorption edge of the glass, which is in turn determined by the glass type and thickness. Three IRR spectral traces are shown in figure 4. From these the design shown in figure 5 was chosen. Figure 5 shows the same basic IRR coating design tuned to different cut-off wavelengths.

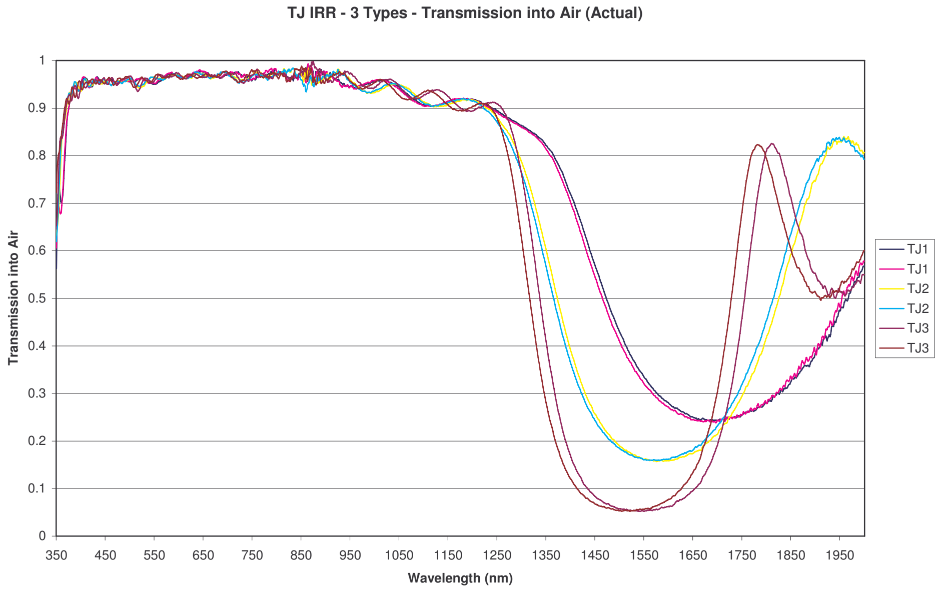

Figure 4

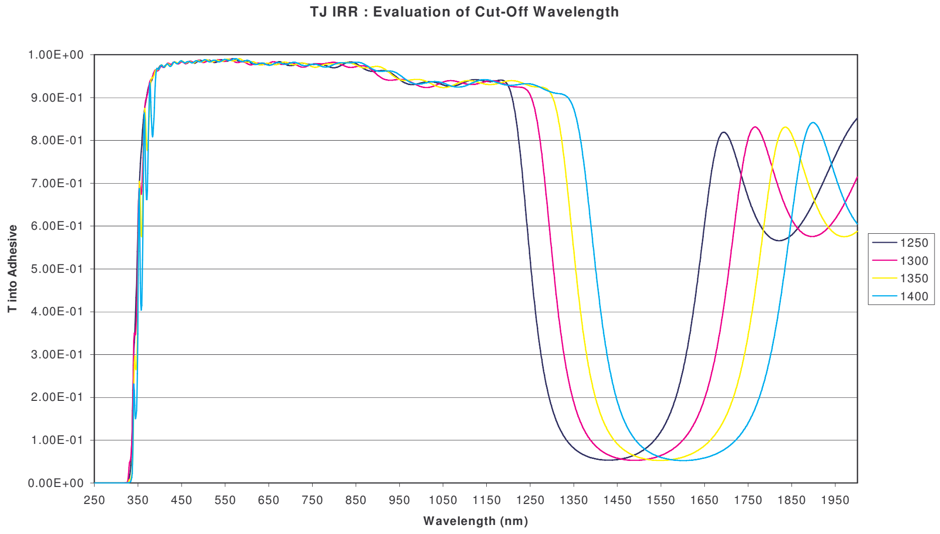

Figure 5

As can be seen from Figure 5 cut-off edge (approx 350nm) effects start to appear as the wavelength of the IRR is increased. This can be minimised but the filter design becomes more complex and as in figure 6 increasing the cut-on wavelength beyond 1400nm is of little benefit since it effectively reduces the thermal benefit.

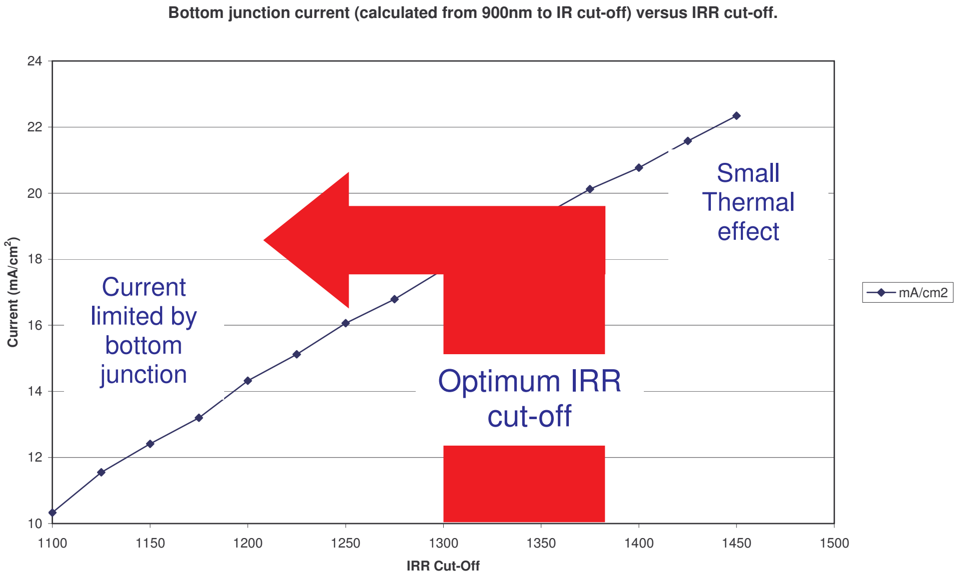

Figure 6

As can be seen from Figure 6 increasing the cut-off wavelength of the IRR increases the current generated in the bottom junction. The wavelength range 1300 to 1370nm would appear to be the optimum region for the wavelength cut-off for the IRR assuming the junction is to remain in slight current excess at the EOL and that the other junctions produce around 17-20mA/cm^2.

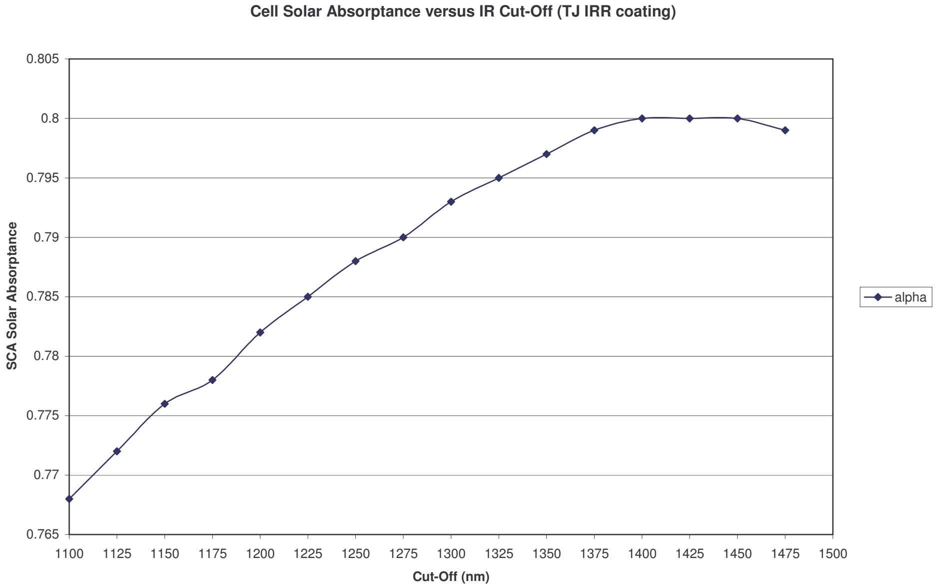

Figure 7

Figure 7 shows the solar absorption of the cell plotted against the cut-off of the IRR. The cell's solar absorption increases as the cut-off wavelength of the IRR increases.

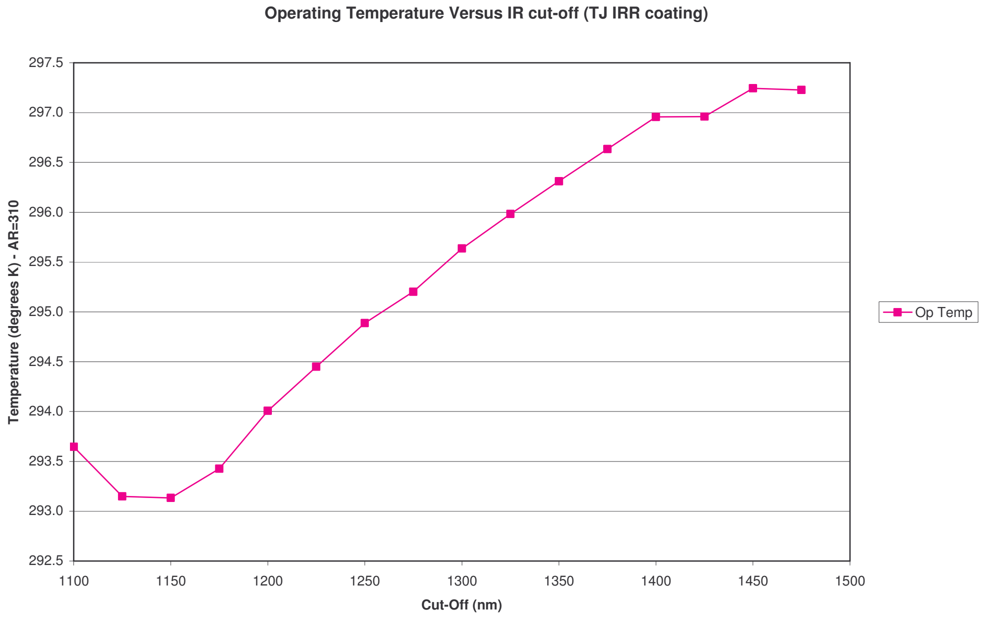

Figure 8

As can be seen from figure 8 the operating temperature of the cell will increase as the IRR cut-off wavelength increases. This is in line with the increases in solar absorptance seen in figure 3.

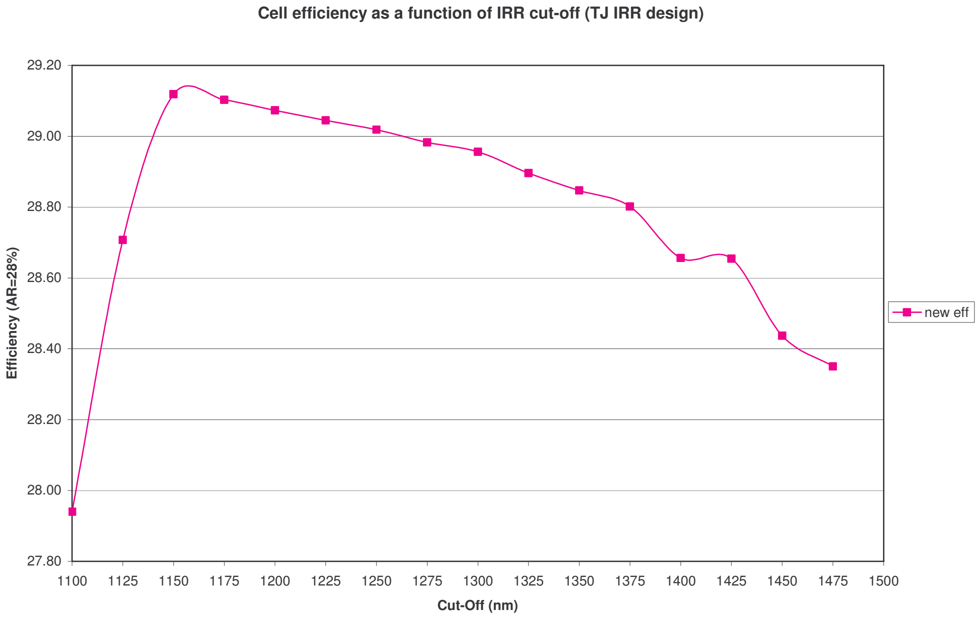

Figure 9

Figure 9 shows the reduction in efficiency as the IRR cut-off increases to longer wavelength.

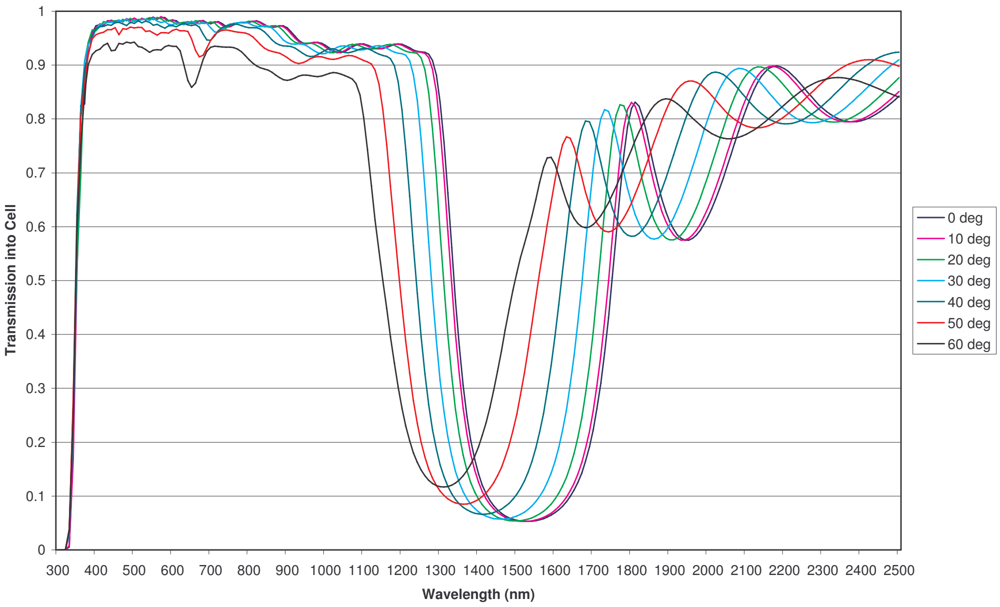

Figure 10

The transmission spectrum for the IRR as a function of angle of incidence is shown in Figure 10. It can be seen that the cut-off wavelength shifts to shorter wavelength with increasing angle of incidence and that its bandwidth reduces. The transmission in the region 400 to 1000nm is reduced at high angles of incidence, which will have some effect on the top and middle junctions. There are other effects on the cell at high angles of incidence that are beyond the scope of the simple model used in this paper.

Table 1 below summarises the potential gains to be expected from various combinations of the UVR and IRR coatings. The gains are given relative to single layer AR, and uncoated (UC) figures are also included. The coatings themselves have been designed and prototype manufactured using space qualified materials and where possible existing space qualified coatings have been used. Front coating in this case means the space facing coating of the coverglass, with the Rear coating being on the cell side of the coverglass.

Front Coating	Rear Coating	Solar Abs	Emissivity (5 to 50μm)	ΔT (Kelvin)	Δ Absolute Efficiency %	% Gain
UC	UC	0.874	0.89	-5.3	-0.6	-2.2
AR	UC	0.895	0.89	0	0	0
UVR	IRR	0.797	0.88	-17.6	1.1	3.8
AR	IRR	0.828	0.89	-13.1	0.7	2.4
UVR	UC	0.856	0.88	-8.8	0.6	2.3
UC	IRR	0.807	0.89	-14.9	-0.1	-0.5

Table 1

Conclusions

A new type of UVR/IRR coated coverglass for triple junction solar cells has been designed and evaluated. Simple modelling of the thermal benefits of this coating shows that a temperature reduction of 17K could be expected. A temperature reduction of 17 K would result in an increase in efficiency of 1% absolute that is from 28% to 29%. Additionally, AR/IRR and UVR alone can provide significant temperature reductions and their associated absolute efficiency gains of > 0.5%. Further optimisation of the coatings and matching them to specific cell types could realise further gains.

References

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