Development of an Ultra-Light Curvilinear Prismatic Window Which Mitigates Reflections and Glare for PV Modules and Other Surfaces

[1]Mark O'Neill, [2]Chris Youtsey, and [2]Robert McCarthy

[1]Mark O'Neill, LLC, Fort Worth, TX, 76244, USA

[2]MicroLink Devices, Inc., Niles, IL 60714, USA

***Abstract*—As presented at the last PVSC, a novel transparent window for PV modules and other surfaces has been developed to both eliminate glare and minimize front-surface reflections. The new window technology can be implemented with a thin, ultra-light, manufacturable curvilinear prismatic film which can be applied to both space and ground PV modules to increase power output, using appropriate materials and coatings. The new window can also be applied to non-PV-related surfaces to eliminate glare. This paper describes the key recent development of the new window under NASA funding.**

Keywords—PV module window, anti-reflection, anti-glare, performance enhancement

I. INTRODUCTION

Conventional PV module windows typically comprise planar glass or polymer layers providing protection for the underlying PV cells from the environment. In space, the environment can include charged particles, solar ultraviolet radiation, atomic oxygen, etc. On the ground, the environment can include rain, snow, sleet, and hail, etc. Front-surface reflection losses from such conventional windows reduce the current and power output of the PV cells, especially for high solar ray incidence angles. The flat surfaces of conventional windows can also lead to glare due to the specular component of the reflected sunlight. Glare problems have led to cancellations of some terrestrial PV systems near airports, highways, and occupied buildings. Glare problems from constellations of spacecraft in low earth orbit (LEO) have also caused problems for ground-based telescopes. A new curvilinear prismatic window has recently been developed which overcomes the glare problem and minimizes the front-surface reflection power losses for PV modules both in space and on the ground [1 and 2].

The optical and thermal benefits of texturing window layers for PV modules have been recognized by many previous researchers [3 and 4]. Various textures have been analyzed and tested for transmittance improvements due to reduced front-surface reflections. Various textures have also been analyzed and tested for enhanced front-surface waste heat rejection due to the greater front-surface area of textured windows compared to flat windows. But these previous textured surface geometries have not incorporated curved surfaces which eliminate glare.

II. DESCRIPTION OF THE CURVILINEAR PRISMATIC WINDOW

The curvilinear prismatic window is a variation of the linear prismatic window achieved by changing the prismatic path from a straight line to a curved line. Fig. 1 shows the basic configuration with greatly exaggerated prism size. The curvilinear prisms follow a curvilinear path with orientation such that a liquid can run from top to bottom without encountering a barrier. For terrestrial applications, this liquid could be rain or cleaning water. For space applications, this liquid could be a cleaning fluid such as isopropyl alcohol used before launch. Other textured surface geometries such as inverted pyramids can trap liquids and dirt in regions where barriers to flow exist.

Fig. 1 also shows the triangular cross-sectional geometry of each prism. The sun's direction relative to the prismatic pattern is defined by the azimuth (az) and elevation (el) angles shown in Fig. 1. Compared to a linear prismatic pattern, the new curvilinear prismatic pattern offers major performance improvements for very small values of both az and el angles.

The curvilinear prismatic window can be mass-produced by embossing a polymer film or by casting a different polymer against an embossed polymer film. For terrestrial applications, the preferred material for the embossed polymer film is acrylic plastic. For space applications, the preferred material is space-grade silicone, which is easily cast and cured against embossed acrylic film. Thus, the same embossed film can be used directly for terrestrial applications or as a disposable molding tool for

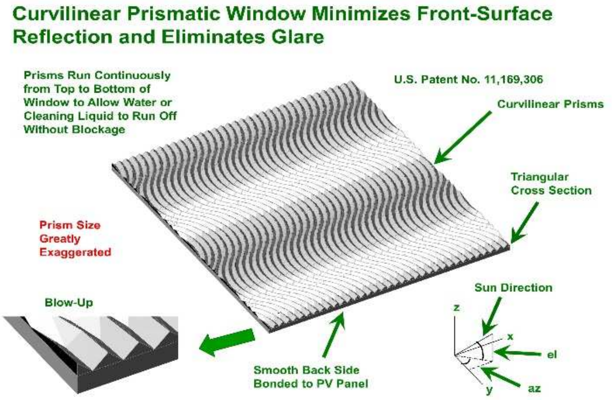


Figure 1

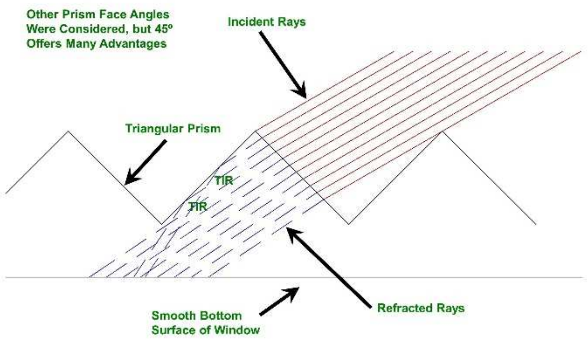
silicone prismatic windows for space applications. The preferred attachment method for a space PV module is still under evaluation. The preferred attachment method for a terrestrial PV module is to laminate an acrylic pressure sensitive adhesive (PSA) to the embossed acrylic curvilinear prismatic film to enable easy bonding to the PV module on top of the existing flat glass window. For terrestrial applications, the curvilinear prismatic film could be attached in the factory or in the field for already deployed arrays.

III. How the New Curvilinear Prismatic Film Works

The curvilinear prismatic film works in two ways:

- The triangular prisms minimize front-surface reflections for both large and small sun elevation angles for all sun azimuth angles.
- The curvilinear prismatic path eliminates glare by spreading the reflected light in all directions due to the curvature.

Fig. 2 shows how the prismatic film works for high lateral incidence angles. The prisms shown have 45° faces which work very well to minimize reflection losses for solar rays arriving at large lateral incidence angles. This minimization occurs because the tilted faces of each prism intercept the incoming rays at a more normal incidence angle than a flat window. The rays which enter each prism make their way to the PV cell below the window either directly or after total internal reflection (TIR) from the opposing prism face.

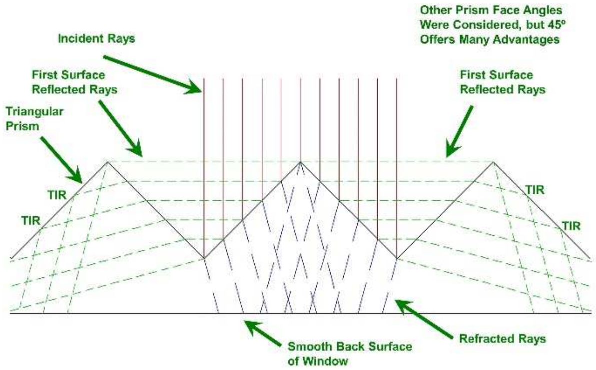


High Lateral Incidence Angle Light Is Efficiently Captured by 45° Prisms

Figure 2

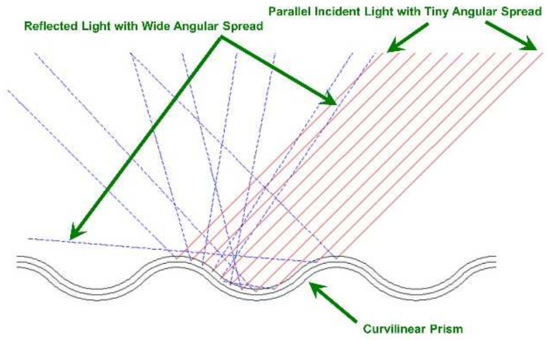
Fig. 3 shows how the prismatic film works for small lateral incidence angles. The prisms shown have 45° faces which work very well to minimize reflection losses for solar rays arriving at near normal incidence angles. This minimization occurs because the rays which are reflected by the outer surface of the tilted faces of each prism intercept the neighboring prisms which recover most of the reflected light and deliver it to the PV cell.

The curvilinear path of the prisms eliminates glare by spreading the reflected light into a wide range of departing angles, as shown in Fig. 4. Since there are no flat surfaces on the exposed face of the curvilinear prismatic window, there can be no glare from rays reflected by the exposed face of the window. Furthermore, rays which are reflected from the PV cells below the window are refracted by the curved surfaces of the new prismatic window and spread into a wide range of departing angles, eliminating glare from these reflections too.



Small Lateral Incidence Angle Light Is Efficiently Captured by 45° Prisms Including First Surface Reflections

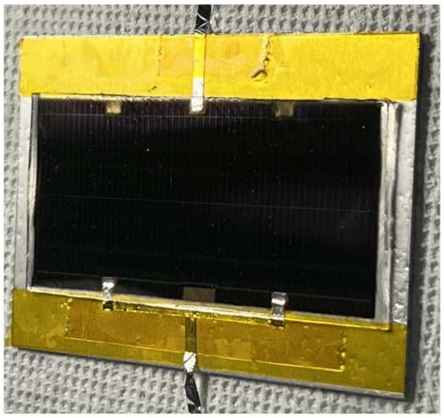
Figure 3



Glare Elimination Is Accomplished by Curved Surfaces Which Spread Light

Figure 4

A typical prototype multi-junction cell (about 3.1 cm wide x 6.5 cm long) with a curvilinear prismatic window is shown in Fig. 5. The appearance from a distance is similar to black velvet. The prismatic window for this prototype is relatively thick, but our team has developed processes for making very thin windows of any desired thickness.



Prototype Cell with New Curvilinear Prismatic Window

Figure 5

IV. PERFORMANCE

The new curvilinear prismatic window provides excellent performance over the full range of possible sun azimuth and elevation angles of incidence. Fig. 6 shows results of parametric optical analysis of the preferred geometry of the new window made of silicone (1.4 refractive index). Note that the net transmittance into the window is much higher than for a flat ceria-doped glass (CMG) window over the full range of sun azimuth and elevation angles. Prototype testing has confirmed the accuracy of the optical analysis, as shown in Fig. 7.

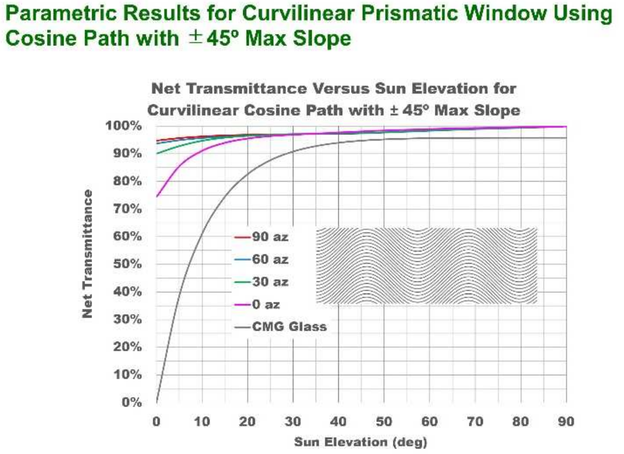

Parametric Results for Curvilinear Prismatic Window Using Cosine Path with ±45° Max Slope

Figure 6

The standard window on the comparison cell without the prismatic window in Fig. 7 used FEP as the window material instead of CMG glass. FEP has a much lower refractive index than glass, resulting in a smaller reflection loss and therefore a smaller gain from the prismatic window. This difference was treated in the predicted results in Fig. 7. Since the two cells used to compare the prismatic window to the flat window were not current matched when bare, the results in Fig. 7 are normalized to the perpendicular incidence angle to provide a relative comparison instead of an absolute comparison, which would be larger.as shown in Fig. 6.

Fig. 8 shows the typical gain in current and power from application of the curvilinear prismatic window to a multi-junction cell under normally incident space solar irradiance (AM0) in a simulator. The gains are close to expectations.

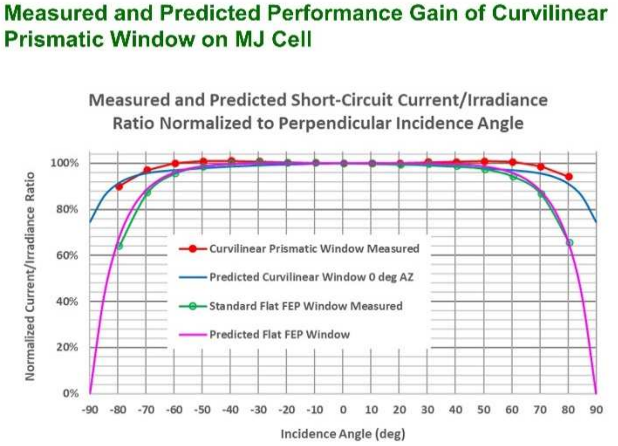
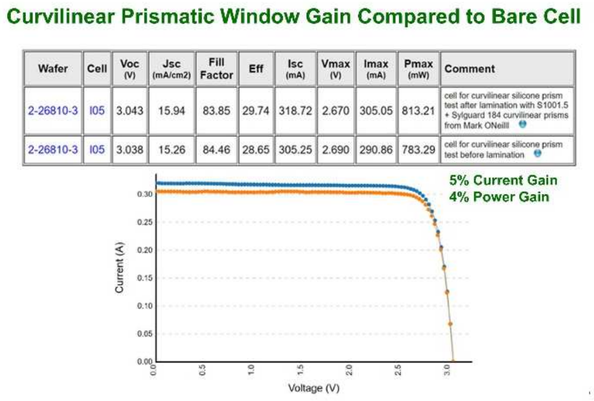

Measured and Predicted Performance Gain of Curvilinear Prismatic Window on MJ Cell

Figure 7

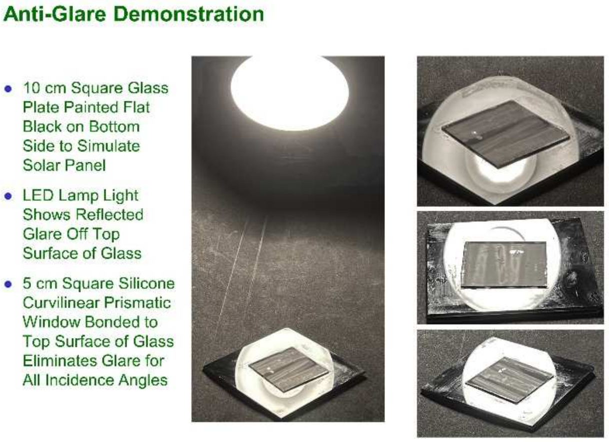

Curvilinear Prismatic Window Gain Compared to Bare Cell

Wafer	Cell	Voc (V)	Jsc (mA/cm2)	Fill Factor	Eff	Isc (mA)	Vmax (V)	Imax (mA)	Pmax (mW)	Comment
2-26810-3	I05	3.043	15.94	83.85	29.74	318.72	2.670	305.05	813.21	cell for curvilinear silicone prism test after lamination with S1001.5 + Sylguard 184 curvilinear prisms from Mark ONeilll
2-26810-3	I05	3.038	15.26	84.46	28.65	305.25	2.690	290.86	783.29	cell for curvilinear silicone prism test before lamination

5% Current Gain
4% Power Gain

Figure 8

We have also successfully demonstrated glare elimination on multiple prototypes, with typical results shown in Fig. 9. This demonstration model used a 10 cm x 10 cm piece of glass with its back surface painted black to simulate a solar cell. A lamp illuminated the sample at an angle of incidence of about 60 degrees and the first surface reflection of the lamp light showed typical glare. But a smaller curvilinear prismatic window about 5 cm x 5 cm in size was bonded to the top surface of the glass and curtailed the reflected light from the lamp thereby eliminating the glare from the top surface as shown. Glare elimination is an important consideration for both space solar arrays and ground solar arrays.


Anti-Glare Demonstration

- 10 cm Square Glass Plate Painted Flat Black on Bottom Side to Simulate Solar Panel
- LED Lamp Light Shows Reflected Glare Off Top Surface of Glass
- 5 cm Square Silicone Curvilinear Prismatic Window Bonded to Top Surface of Glass Eliminates Glare for All Incidence Angles

Figure 9

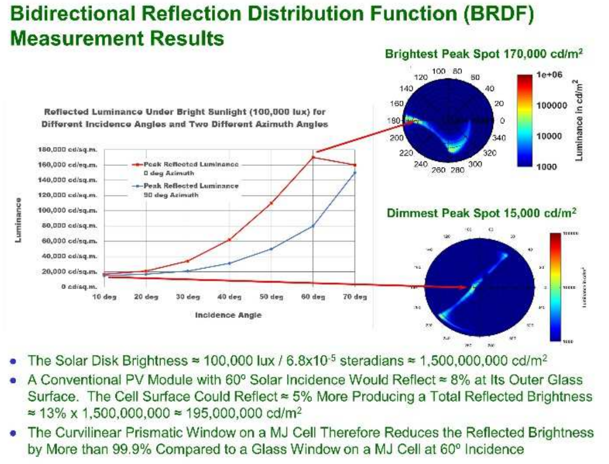
To quantify the glare properties of a MicroLink multi-junction (MJ) cell equipped with the new curvilinear prismatic window, the SPF Institute for Solar Technology in Switzerland tested a sample for Bidirectional Reflection Distribution Function (BRDF) under a variety of incidence angles and two azimuth angles. The test conditions simulated a clear day on the Earth's surface with bright sunshine at 100,000 lux. The reflected light distribution in the hemisphere above the test sample was measured for each set of incidence and azimuth angles to provide the reflected luminance distribution from all possible viewing directions. Fig. 10 shows the sample and describes the test.

Bidirectional Reflection Distribution Function (BRDF) Measurements for MJ Cell with Curvilinear Prismatic Window

- To Quantify the Glare Properties of a MicroLink Multijunction (MJ) Cell with the New Curvilinear Prismatic Window, BRDF Measurements Were Made by SPF Institute for Solar Technology in Switzerland
  - The Test Sample Used a MicroLink Cell (about 3 cm x 6 cm) Shown Before (Top Photo) and After Window Application (Bottom Photo)
  - Test Conditions Simulated a Clear Day on Earth with Bright Sunshine at 100,000 lux
  - Incidence Angles Were Varied from 10 to 70 degrees and Tests Were Made at 0 and 90 degrees Azimuth Angles (Along the Cell and Across the Cell
- The Main Source of Reflections Is the Cell Itself, Including Its AR-Coated Surface and Gridlines

Figure 11

The results of the BRDF testing are summarized in Fig. 11. The two curves correspond to the two azimuth angles (0° and 90°) while the data points correspond to the various incidence angles (0° to 70°). Two example plots of the distribution of the reflected luminance for the brightest and dimmest data points show the small regions of relatively bright reflections and the much larger region of relatively dark reflections over the rest of the hemisphere above the sample. The brightest peak value corresponds to a very small spot shown by the red dot on the upper hemisphere in Fig. 11. The dimmest peak value likewise corresponds to a very small spot shown by the red dot on the lower hemisphere. To put the brightest peak value in perspective, Fig. 11 provides a comparison with a glass window over a multi-junction cell. The new prismatic window reduces the peak reflected brightness by more than 99.9% compared to the glass window.



Bidirectional Reflection Distribution Function (BRDF) Measurement Results

- The Solar Disk Brightness ≈ 100,000 lux / 6.8x10^{-5} steradians ≈ 1,500,000,000 cd/m^2
- A Conventional PV Module with 60° Solar Incidence Would Reflect ≈ 8% at Its Outer Glass Surface. The Cell Surface Could Reflect ≈ 5% More Producing a Total Reflected Brightness ≈ 13% x 1,500,000,000 ≈ 195,000,000 cd/m^2
- The Curvilinear Prismatic Window on a MJ Cell Therefore Reduces the Reflected Brightness by More than 99.9% Compared to a Glass Window on a MJ Cell at 60° Incidence

Figure 10

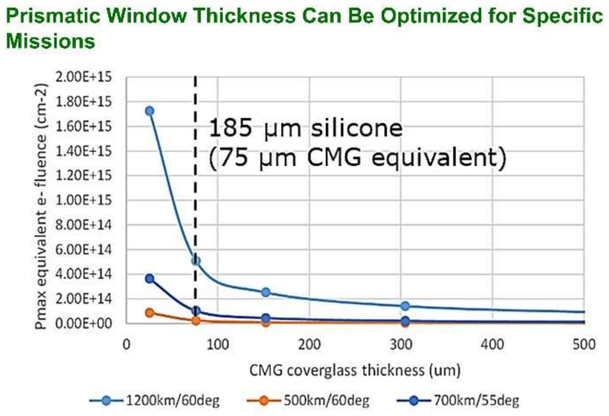
V. Tooling and Process Development

We are making progress on mass production of the new curvilinear prismatic window. We originally thought that diamond turning would be the best approach to make master tooling for the new curvilinear prismatic window, but we found another approach with many advantages, grayscale lithography (GSL), as implemented by Wavefront Technology (WFT). We then worked with WFT on the final design of the tooling to enable not only early prototypes like the one used in the testing shown in Fig. 7 above, but also later roll-to-roll production of acrylic prismatic film. The results were excellent. The first roll of acrylic lensfilm material is shown in Fig. 12. The blue tint is from a disposable film used to protect the prisms on the rolled-up acrylic "lensfilm" produced by the roll-to-roll process. The actual lensfilm is perfectly clear.

Figure 12

VI. Advantages for Space Applications

The new curvilinear prismatic window offers significant advantages for space applications. One major advantage is the selectable thickness of the window for specific missions. Our team sees LEO missions as the first target for multi-cell modules using the new window. Different LEO missions (with differing altitude, orbital inclination, and lifetime) require different amounts of shielding to provide adequate protection against charged particle radiation, as shown in Fig. 13. Conventional windows use ceria-doped microsheet glass windows of specific thicknesses such as 75, 100, and 150 micrometers. The new silicone window can be cast to whatever thickness is desirable. Due to its lower specific gravity, the new window requires a larger thickness (about 2.47X) for the same equivalent radiation shielding. For some missions, the required thickness can be lower than the thinnest microsheet glass available, and the new window offers significant mass reductions.



Prismatic Window Thickness Can Be Optimized for Specific Missions

Figure 13

The new window also offers high robustness in the space environment as shown by the results of space environmental effects (SEE) testing. Atomic oxygen testing, 1 MeV election testing, 30 keV proton testing, and ultraviolet radiation testing results have all been very positive in demonstrating durability in the LEO environment. The new window uses a previously space-proven ultraviolet rejection (UVR) coating to block high-energy, low-wavelength vacuum ultraviolet (VUV) space solar radiation which is known to darken the space-qualified silicone material. The UVR coating is also useful in mitigating the effects of low-energy charged particle radiation.

Another major advantage of the new window technology is its ability to encapsulate the entire multi-cell module, including interconnects and gaps between cells, thereby maximizing protection of the complete cell circuit from arcing or other interactions with the space environment. Conventional modules use individual cell-level cover glass windows which cannot provide this module-level protection. Fig. 14 shows a prototype module with a single prismatic window over the entire module. The module is also flexible and offers substantial mass savings and specific power gains over conventional multi-junction cell modules.

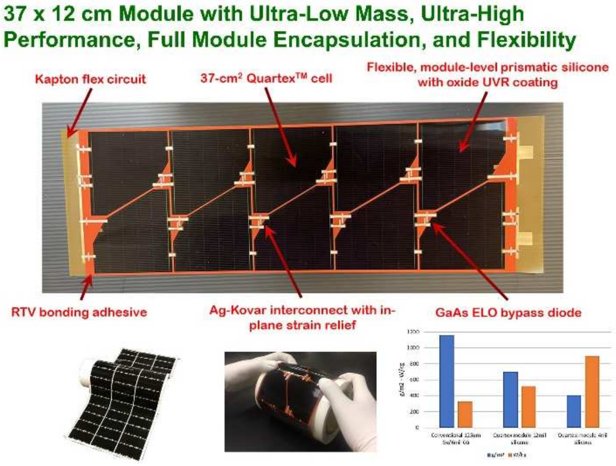


Figure 14

The new module also offers a small reduction in cell operating temperature on orbit due to its exposed structured surface, which slightly increases the effective emittance of this surface [1].

VII. ADVANTAGES FOR TERRESTRIAL APPLICATIONS

While our work to date has focused on space applications, we have identified a number of spin-off applications in the booming terrestrial solar energy area. A number of projects have drawn opposition due to glare, especially large solar farms near highways, airports, of occupied buildings. The new window in acrylic lensfilm form could be applied to terrestrial photovoltaic modules at modest additional cost in the factory to minimize glare for such applications. It would also provide performance gains due to reduced front-surface reflections and slightly reduced cell operating temperature. A conservative analysis predicts 5-10% additional power output for a solar farm equipped with the new curvilinear prismatic windows.

Another interesting potential terrestrial application is in the emerging technology area of solar-equipped electric vehicles. Several firms (e.g., Lightyear in Europe and Aptera in the U.S.) are introducing such vehicles. Since the solar cells are embedded on the roof and upward-facing surfaces of these vehicles, the angle of incidence of sunlight is generally very large, and the power output gains of the new window would be substantial. The minimization of glare is also an important consideration as such vehicles proliferate.

VIII. SUMMARY

The new curvilinear prismatic window offers power output advantages over conventional PV module windows for both space and ground applications for all sun incidence angles. It also eliminates glare, which is a significant and growing problem both on orbit [5] and on the ground [6].

The new window also provides small advantages in heat rejection, lowering cell operating temperature a few degrees compared to flat windows both in space and on the ground. Mass-production processes are being developed for both space and ground applications.

Space environmental effects testing is showing the new window to be durable in the space environment when made of space-qualified silicone with an ultraviolet rejection coating.

The new window can be optimized in thickness to meet the radiation shielding requirements of specific missions, thereby offering substantial mass savings and gains in specific power. Module-level specific power may exceed 1,000 W/kg.

The new window is flexible and provides module-level encapsulation and protection of the complete cell circuit.

Terrestrial spin-off applications include solar farms near highways, airports, and occupied buildings. Solar electric vehicles are another potential ground application.

IX. ACKNOWLEDGEMENT

Development of the new curvilinear prismatic window is being supported by NASA under a Phase II SBIR contract with MicroLink Devices.

X. REFERENCES

[1] M. O'Neill, "Curvilinear prismatic film which eliminates glare and reduces front-surface reflections for solar panels and other surfaces," U.S. Patent No. 11,169,306, November 9, 2021.

[2] M. O'Neill and C. Youtsey, "Curvilinear prismatic window which eliminates glare and reduces front-surface reflections for PV modules and other surfaces," 49th IEEE Photovoltaic Specialists Conference, Philadelphia, June 9, 2022.

[3] M. Duell, M. Ebert, M. Muller, B. Li, M. Koch, T. Christian, R.F. Perdichizzi, B. Marion, S. Kurtz, D.M.J. Doble, "Impact of structured glass on light transmission, temperature and power of PV modules," 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain.

[4] Z. Zhou, Y. Jiang, N. Ekins-Daukes, M. Keevers and M. A. Green, "Optical and thermal emission benefits of differently textured glass for

photovoltaic modules," in IEEE Journal of Photovoltaics, vol. 11, no. 1, pp. 131-137, Jan. 2021.

[5] K. Whitt, “Satellites versus stars: which will dominate the sky?,” https://earthsky.org/space/satellites-versus-stars-night-sky-kessler-syndrome/, September 28, 2021.

[6] K. Ulenhuth, “Glare study prompts utility Evergy to cancel solar array at Kansas City airport,” https://energynews.us/2020/12/10/glare-study-prompts-utility-evergy-to-cancel-solar-array-at-kansas-city-airport/, December 10, 2020.