M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07a as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18 Project Abstract
For the Period Ending June 30, 2022

PROJECT TITLE: Develop Solar Window Concentrators for Electricity
PROJECT MANAGER: Uwe Kortshagen
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07a as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

APPROPRIATION AMOUNT: $350,000
AMOUNT SPENT: $350,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results
This project demonstrated the potential of semi-transparent “solar windows” based on silicon nanocrystals to produce carbon-free, renewable electricity. Greenhouses were identified as an attractive application. As greenhouses are becoming more widespread in Minnesota, this project will contribute to reducing their environmental footprint in terms of energy and water usage.

Overall Project Outcome and Results
This project focused on exploring inexpensive “solar windows” that are transparent and produce clean electricity. Solar windows are based on solar concentrators using highly luminescent nanometer-sized silicon crystals, a technology developed at the University of Minnesota. The silicon crystals, embedded in or coated onto the windowpane, absorb harmful-to-humans ultraviolet and blue light and turn it into red light, which is guided by internal reflection to the edge of the window pane, where it is concentrated onto a small-area solar cell.

Over the course of this project, the project team learned that these solar windows are of particular interest to greenhouses. While being partially transparent, they can produce electricity while not impeding or even enhancing plant growth. The project team initially focused on exploring experimental prototypes of the technology. Based on characterization of these prototypes, models were developed that allow us to predict the performance of larger scale devices. These models were extended into a comprehensive simulation tool that can describe the renewable electricity produced by a solar greenhouse, the light available for plant growth, as well as the overall energy balance of a greenhouse.

For Minnesotans, results of this research may have significant future benefits. Greenhouses allow us to produce certain crops locally that are hard to grow in open-field farming in Minnesota. Locally grown produce is fresher and reduces the emissions associated with shipping of produce across the county. Greenhouses also only use a fraction of the water and fertilizer that is required in open-field farming. While generally energy-intensive, this research project has pointed the way to reduce the energy consumption of greenhouses through solar windows.

Project Results Use and Dissemination
Results of this research have been published in the scientific literature and presented at conferences. Three scientific papers were published related to:

- The influence of scattering on the performance of silicon luminescent solar concentrators
- The demonstration of silicon thin film luminescent solar concentrators
- The application of silicon luminescent solar concentrators to agrivoltais

Among the conference presentations presented by graduate students working on this project, one was chosen for the “best presentation” award.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2018 ENRTF Final Work Plan

Today's Date: November 17, 2022

Final report

Date of Work Plan Approval: 06/05/2018

Project Completion Date: June 30, 2022

PROJECT TITLE: Develop Solar Window Concentrators for Electricity

Project Manager: Uwe Kortshagen

Organization: University of Minnesota

College/Department/Division: College of Science and Engineering / Mechanical Engineering

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Location: statewide

Total Project Budget: $350,000

Amount Spent: $350,000

Balance: $0

Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07a as extended by M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18

Appropriation Language: $350,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota to develop, evaluate, and optimize thin film silicon-based luminescent solar window concentrators in order to produce inexpensive, clean energy and reduce air pollution. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2021, by which time the project must be completed and final products delivered.

M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2022]

I. PROJECT STATEMENT:

The objective of this project is to produce inexpensive "solar windows". Solar windows are based on solar concentrators using highly luminescent nanometer-sized silicon crystals, a technology developed at the University of Minnesota. The silicon crystals, embedded in or coated onto the window pane, absorb harmful-to-humans ultraviolet and blue light and turn it into red light, which is guided by internal reflection to the edge of the window pane, where it is concentrated onto a small area solar cell. See Figure 1 in section IX.B for an illustration. The concentrator sheet can be made largely transparent such that it can serve as a window. As light is collected by the large area of the window but only a small and thus cheap solar cell is required, the cost of solar electricity is reduced. Moreover, these luminescent solar concentrators collect light from any direction and virtually invisibly integrate with buildings, thus eliminating aesthetic objections and the *cost of land* for solar installations. This cheap renewable energy technology may widely expand the adoption of clean solar electricity, reduce air pollution, and ameliorate climate change.

The progress of luminescent concentrators has long been hampered by the lack of suitable luminescent species. Recently, University of Minnesota investigators demonstrated that luminescent silicon crystals have virtually ideal properties for this application. First silicon-based window concentrators have shown promising efficiencies. The project will focus on solving the remaining bottleneck science and engineering problems on the way to producing large-area solar windows.

II. OVERALL PROJECT STATUS UPDATES:

First Update January 31, 2019

During this first project period, significant progress has been made in fabricating light-concentrating thin films on glass using a draw blade coating technique. We find this industrially-friendly technique is suitable for producing uniform films over a wide range of thicknesses on essentially any sized glass substrate. While some optimization is required for each different polymer system, we have developed a technique to coat a common acrylic polymer doped with silicon nanocrystals on glass. Devices covering a wide range of film thicknesses and silicon nanocrystal concentrations have been fabricated. Freestanding, flexible polymer films have also been made. Initial results from examining these samples have allowed us to start narrowing down the design space for continued optimization of efficient, light harvesting devices for window applications.

Second Update June 30, 2019

During the second project period, prototype light-concentrating acrylic films with varied thicknesses and silicon nanocrystal concentrations have been fabricated on glass by doctor blading polymer / monomer mixtures. Our study of these films has found that the agglomeration of the silicon nanocrystals can cause significantly more light-scattering losses than surface roughness or polymer inhomogeneities from these high-quality prototype films. Even more interestingly, we find that the silicon nanocrystal concentration limit before the onset of significant light scattering in doctor bladed films is an order of magnitude higher than in similarly produced bulk polymerized slabs that have previously been studied. We hypothesize that the fast solidification rate is the main enabling mechanism and have an article describing these findings under submission for peer review. These results may be applicable to other material systems, with potential for wide impact.

Third Update January 31, 2020

During the third project period, we have developed a technique to fabricate silicon nanocrystal doped polymer films on large-area glass substrates, which allows us to make progress toward next goals on large-area solar window concentrator. While previously, adhesion of the coated thin films to the substrate was a problem, we found that by increasing the width of glass substrates, the adhesion of thick films to glass surface can be improved. By measuring the quantum yield of silicon nanocrystals in thin films, we have demonstrated that the silicon nanocrystals in doctor-bladed films have the same trend of the quantum yield changing with exposure to air as silicon nanocrystals in solution.

Fourth Update June 30, 2020
Some of the experimental activities of this project have been delayed due to the COVID pandemic. Laboratories at the University of Minnesota were shut down at the end of March 2020, and reopening at reduced capacity occurred in June of 2020. Laboratory operation continues to be at reduced capacity, because the number of researchers allowed in any laboratory and in central characterization facilities has been limited. However, our team had collected enough experimental data to switch to exploring properties of the silicon nanocrystal solar windows based on theoretical models. The main progress during this report period relied on the development of an analytical model to describe solar window performance.

Fifth Update January 31, 2021

The team has made good progress on performance characterization of the solar windows through numerical modeling. Experimental activities continue to be hampered by COVID related reduced capacity of laboratories and central user facilities, which limit the number of researchers that can be in the lab or user facility at one time. Nonetheless, the team has made progress on understanding the optical color transmission characteristics of solar windows and has identified new potential application areas, in particular, in the field of agrivoltaics, which focuses on combining agricultural crop production with electricity generation.

Project extended to June 30, 2022 by LCCMR 7/1/21 as a result of M.L. 2021, First Special Session, Chp. 6, Art. 6, Sec. 2, Subd. 18, legislative extension criteria being met.

Sixth Update June 30, 2021:

This report period, the team has made good progress both with experimental work and modeling work. Work has focused on understanding how different quantum dots used affect the properties of the absorbed and transmitted light. It was found that by using two different quantum dot materials, the color of the transmitted light can be tuned in a way that it may be beneficial for plant growth. Simulation work also uncovered how changes in transmitted light will affect the power conversion efficiency of the solar windows that are being studied.

Seventh Update January 31, 2022:
Work during this report period focused on exploring the efficiency of solar windows in greenhouse applications. A model was developed to assess the electricity produced by greenhouse solar windows and the energy consumption of the greenhouse for heating and cooling. The model indicates that net-zero-energy greenhouse operation based on solar windows can be achieved in high-insolation places like Arizona. However, the model indicates that even in Minnesota, the energy demand of greenhouses can be reduced. On the experimental side, the team has made significant progress in improving the environmental stability of silicon quantum dots for solar window applications.

Final Update June 30, 2022
Work during this final project period finalized the modeling work conducted under this project. We performed a comparative study of solar windows based on environmentally benign silicon quantum dots and on quantum dots of competitive materials that have good optical performance, but also pose environmental concerns, such as cadmium selenide. The results of our modeling work indicate that solar windows based on silicon quantum dots perform as well as devices that pose environmental challenges. We also performed experimental work to improve the long-term stability of silicon quantum dots by coating them with silica coatings. This work turned out to be very promising and will enable future progress on silicon quantum dot-based solar windows.

Amendment Request, June 30, 2022

We are requesting funds to be shifted from capital equipment and laboratory services to personnel:

- The personnel budget would be increased by $13,005 to $322,041
- The capital equipment budget would be reduced by $8,000 to $0
- The budget for "Other" (laboratory services) would be reduced by $5,008 to $8,814
- The budget for equipment/tools/supplies would be increased by $3 to $19,145

The requested budget shifts reflect that we learned, during the project execution and due to COVID related laboratory shut downs, that the modeling of the solar window performance was an accurate way to explore the performance of large scale devices. Hence, different from our original proposal, we did not pursue the experimental fabrication of large-scale devices. Accordingly, we did not purchase the capital equipment to coat large-scale devices and had less charges for materials characterization services. Instead, we had increased personnel cost for the modeling activities.

Amendment approved by LCCMR 11/7/22

Overall Project Outcomes and Results

This project focused on exploring inexpensive "solar windows" that are transparent and produce clean electricity. Solar windows are based on solar concentrators using highly luminescent nanometer-sized silicon crystals, a technology developed at the University of Minnesota. The silicon crystals, embedded in or coated onto the window pane, absorb harmful-to-humans ultraviolet and blue light and turn it into red light, which is guided by internal reflection to the edge of the window pane, where it is concentrated onto a small area solar cell.

Over the course of this project, the project team learned that these solar windows are of particular interest to greenhouses. While being partially transparent, they can produce electricity while not impeding or even enhancing plant growth. The project team initially focused on exploring experimental prototypes of the technology. Based on characterization of these prototype, models were developed that allow to predict the performance of larger scale devices. These models were extended into a comprehensive model that can describe the solar electricity produced by a solar greenhouse, the light available for plant growth, as well as the overall energy balance of a greenhouse.

For Minnesotans, results of this research may have significant future benefits. Greenhouses allow to locally produce certain crops that are hard to grow in open-field farming in Minnesota. Locally grown produce is fresher and reduces the emissions associated with shipping of produce across the county. Greenhouses also only use a fraction of the water and fertilizer that is required in open field farming. While generally energy-intensive, this research project has pointed the way to reduce the energy consumption of greenhouses through solar windows.

III. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Demonstrate Efficient Silicon-Based Window Luminescent Concentrators
Description: Largely transparent window solar concentrators will be produced by coating thin films of luminescent silicon crystals dispersed in common plastics onto inexpensive sheets of glass. Luminescent silicon crystals are ideal for this application, as they strongly absorb invisible ultraviolet light with limited loss of visible light. They are also compatible with common, sturdy plastics like poly(methyl methacrylate), also known as Plexiglas®. By carefully selecting the silicon crystal concentration in the plastic coating, the optical properties of the luminescent concentrators can be tuned to produce transparent to semi-transparent devices, ideal for window applications.

ENRTF BUDGET: $119,241

Outcome	Completion Date
1. Produce silicon-based test concentrator windows of least 100 cm^2 in area	Jan 31, 2019
2. Characterize device efficiency as function of concentration & film roughness	June 30, 2019
3. Evaluate visible transparency for suitability for window applications	June 30, 2019

First Update January 31, 2019

Major progress has occurred during this first project period. Importantly, we have developed a technique to draw coat poly(methyl methacrylate), also known as acrylic, onto glass substrates in order to produce optically clear films on glass. This polymer can be coated from a viscous, organic solvent-based mixture or from the "prepolymer" stage, wherein polymerization is partially proceeded and then quenched, allowing the remaining monomer phase to act like a solvent. We have produced these acrylic films ranging from a few micron thick to ~0.1 mm thick. We found that thick films can be delaminated from the glass substrate to produce a flexible, freestanding film that might be retroactively adhered to different surfaces and substrates while thinner films tend to remain solidly adhered on the initial glass surface.

The development of this film coating technique has allowed us to easily add our silicon nanocrystals prior to polymerization to yield luminescent solar concentrating films and make progress toward goal 2. We have fabricated films with concentrations of silicon nanocrystals ranging from ~0.3 to 3 weight percent. The concentration of silicon nanocrystals appears vitally important in determining the optical properties of the device, especially as we achieved high levels of smoothness in our fabricated films. We have narrowed our design space significantly, finding that our thinnest films with the lowest silicon nanocrystal concentrations are too ineffective at light absorption to easily characterize. Conversely, thick films with high concentrations of silicon nanocrystals can exhibit significant levels of light scattering that reduce the light concentrating performance. We conclude that thick films with middling silicon nanocrystal concentrations or thin films with high silicon nanocrystal concentrations must be examined further in order to optimize the system. The interplay of film thickness and the silicon nanocrystal's tendency to form light-scattering aggregates at high concentrations are important design factors that require better understanding.

While we have made good progress on this topic, actual expenses have not yet been incurred because the students performing the work are supported by different fellowship. Materials and supply charges to date have been covered by a supplementary funds. This will change in the second half of the first year, as new students have joined the project who do not have fellowship support.

Second Update June 30, 2019

During the second project period, we leveraged the knowledge developed in the first project period to create several prototype silicon nanocrystal doped polymer films on glass using the "prepolymer" approach described above. We produced films about 2.5, 8.3, 25, and 83 micron in thickness at silicon nanocrystal loadings of 0, 1, and 3.3 wt%. In characterizing these films, we found that the main barrier for efficient light concentration remains light-scattering losses due to the formation of large, >100 nm agglomerates of silicon nanocrystals. Using scanning electron microscopy, we imaged these agglomerates directly to confirm their existence. We found these light-scattering agglomerates form in films with silicon nanocrystal loadings of ~3.3 wt% and in bulk polymerized slabs formed from leftover "prepolymer" solutions with silicon nanocrystal loadings of ~0.5 wt%. Very interestingly, however, films with silicon nanocrystal loadings of 1 wt% showed no large agglomerates and exhibited no extra light scattering as compared to an undoped polymer film on glass. Since the main difference between the prototypes doctor bladed as films compared to the bulk polymerized sample is just the speed at which the nanocomposite solidifies, we conclude that the solidification rate is an important parameter in determining the properties of silicon nanocrystal / polymer composites. We hypothesize that even higher silicon nanocrystal concentrations in polymers may be achieved if fast solidification processes are leveraged. This approach may also be applicable to other nanocrystal / polymer systems.

Using transmission spectroscopy, we found that the films we produced with 1 wt% silicon nanocrystals scatter little light yet have absorption properties that change as a function of film thickness. The thickest films examined here (83 micron) loaded with 1 wt% silicon nanocrystals absorbed more than 80% of ultraviolet light while transmitting more than 87% of visible light clearly, with haze less than 1%. Daylight scenes viewed through this film appear indistinguishable from an unfiltered view. The high ultraviolet absorption paired with the high visible transmission is ideal for solar harvesting window applications. We could achieve similar levels of visible transmission in thinner films loaded with 3.3 wt% silicon nanocrystals but found the waveguiding was 5 times less effective due to light scattering in such films. We find it is easier to produce a visibly transparent silicon nanocrystal / polymer film than one that effectively concentrates light for solar harvesting. These important findings are under submission for peer review.

Third Update January 31, 2020
During the third project period, we have developed a technique to fabricate silicon nanocrystal doped polymer films on larger glass substrates. To verify the feasibility of this film coating technique, we produced an undoped polymer film about 83 micron in thickness on 10 × 10 cm glass substrates. We believe that we are easily able to coat silicon nanocrystal doped polymer films on large-area glass substrates up to 25 cm in length with this technique. The development of this film coating technique has allowed us to make progress toward next goals on large-area solar window concentrator.

Furthermore, we produced films about 83 micron in thickness at silicon nanocrystal loadings of 0, 0.5, 1, 1.5 wt% on 5 × 5 cm glass substrates. Compared to the second project period, in which we produced films on 2.5 × 7.5 cm glass substrates, the width of glass substrates was increased. We found that by increasing the width of glass substrates, the adhesion of thick films to glass surface was improved. Using transmission spectroscopy, we found that the films with about 83 micron thickness with 1.5 wt% silicon nanocrystals still exhibit almost no significant light scattering as compared to an undoped polymer film on glass.

Finally, we measured the quantum yield of silicon nanocrystals in thin films. Exposed to air, the quantum yield of oxidized silicon nanocrystals in thin films drops from about 45% and stabilizes at about 35%. Thus the silicon nanocrystals in doctor bladed films have the same quantum yield trend when exposed to air as silicon nanocrystals in solution.

Fourth Update June 30, 2020 **N/A**
Activity 1 completed

Fifth Update January 31, 2021 **N/A**
Activity 1 completed

Sixth Update June 30, 2021:
Activity 1 completed

Seventh Update January 31, 2022:
Activity 1 completed

Final Update June 30, 2022
Activity 1 was completed as originally proposed. While some 10x10 cm^2 LSCs were produced, the majority of the work was performed with smaller LSCs, due to the enhanced ease of fabrication. We learned that LSCs can be doped with as much as 1.5 wt% of silicon nanocrystals before significant scattering starts to occur. This is important information for the design of silicon LSCs, as it provides guidelines for the concentration and thickness

of LSC films and the amount of solar light absorption than can be achieved. We further determined that the quantum yield of silicon quantum dots decreases over time from 45% to 35%, which shows that further work on the environmental stability of these materials is needed.

ACTIVITY 2: Explore Maximum Silicon-Based Concentrator Efficiency
Description: While transparent concentrators have great potential for window applications, the efficiency may be improved by absorbing and concentrating more solar light with semi-transparent to opaque devices. Such designs may find applications as colored architectural façades, siding panels, or stand-alone solar concentrators. The interplay between silicon crystal properties, concentration, and concentrator size will be examined in order to determine the upper efficiency limit of these devices. Additionally, the concentrator efficiency may change for curved devices, which will be studied.

ENRTF BUDGET: $113,976

Outcome	**Completion Date**
1. Explore optimum efficiency on devices of at least 100 cm^2	*Jan 31, 2020*
2. Evaluate transparency / color for applications as windows or opaque building panels	*Jun 30, 2020*

First Update January 31, 2019 **Activity start after completion of Activity 1, expected June 30, 2019**

Second Update June 30, 2019 **Activity start after completion of Activity 1, expected June 30, 2019**

Third Update January 31, 2020
Towards the goal of exploring the optimum efficiency of devices of at least 100 cm^2, the team has developed two different kinds of models that enable the design of solar concentrators. One model is based on a Monte Carlo ray tracing technique and allows for the accurate physical description of elementary processes such as scattering of light and absorption. While highly accurate, this model is computationally very expensive. For this reason, we have also developed a simplified analytical model and verified its accuracy by comparisons with the Monte Carlo model. Based on these models, we are now in the position to predict the efficiency of solar concentrators depending on different design parameters. Currently, work is in progress to model how these design parameters will impact the color of the transmitted light and how this will impact their utility for window applications. These model predictions will be evaluated with comparisons to experimental measurements.

Fourth Update June 30, 2020
During this report period, the team developed an analytical model, which enables the rapid determination of solar window performance parameters by being able to explore a wide range of device parameters. The model was originally proposed by a research group at KTH-Royal Institute of Technology in Stockholm, Sweden, for bulk polymer devices. Our team adapted this model for thin film devices that are studied as part of this grant. After the completion of the model development, our model was tested against a first-principles Monte Carlo simulation code developed by the Ferry research group, and the analytical model was found to be in good agreement with the computationally much more expensive Monte Carlo code. The main advance is that our team is now able to perform predictive parametric studies in a very short time. Similar studies using a Monte Carlo code may take weeks or even months to complete.

Based on the results of the analytical model, the team has been able to identify optimal device parameters from 100 cm^2 devices. The studies suggest that device performance is optimized by increasing the concentration of the silicon nanocrystals as much as possible without inducing agglomeration of the silicon crystals during polymer film deposition. Experimentally, we determined that agglomeration sets in at silicon nanocrystal concentrations in the polymer matrix exceeding 1.5% by volume. Future work will focus on how silicon nanocrystal concentrations at this level shape the spectrum of the transmitted radiation.

Fifth Update January 31, 2021
Our efforts during this report period have focused on exploring the color characteristics of the transmitted light and identifying optimal applications for the solar window technology. We found that achieving good device efficiencies requires applying a significant concentration of silicon quantum dots to the devices. This leads to a yellow tint of the solar windows that some may find objectionable for applications in living or work spaces. However, we determined that the transmitted color spectrum maybe very well suited to plant growth, for instance, in green houses. Solar windows absorb the blue and green components of sunlight to create photovoltaic electricity, but let yellow and red light pass for crops to grow. Plants utilize blue and red light for photosynthesis, while green light is unused and reflected. Energetic blue light, which can lead to cell damage and inhibits cell elongation, is absorbed by solar windows. Red light, which is required for germination and plant growth, passes through solar windows. Especially the broad-leaf crops perform well under the red light. Our ongoing efforts focus on validating the results of our models through experiments.

Our team also found that silicon nanocrystals are relatively weak absorbers of sun light. Hence, we have focused on combining silicon nanocrystals with other nanocrystal materials that are stronger light absorbers. In preliminary studies, we have found that quantum dots of cadmium selenide can enhance the absorption of silicon quantum dots and hence “sensitize” them. Modeling results predict that a combination of silicon with cadmium selenide quantum dots leads to improved device efficiency. Experimental studies are in progress to validate these model predictions.

Sixth Update June 30, 2021:
Activity 2 completed

Seventh Update January 31, 2022:
Activity 2 completed

Final Update June 30, 2022
During this activity, we learned the silicon quantum dots are relatively weak emitters of light. The efficiency of silicon LSCs can be enhanced by combining them with other quantum dot materials such as cadmium selenide. We also identified applications in greenhouses as a promising area for silicon LSCs. While LSCs strong absorb blue light, they do not absorb strongly in the red range of the spectrum, which is essential for many plant growth applications.

ACTIVITY 3: Characterize Efficiency of a Large Concentrator Window
Description: Published research on luminescent concentrators is largely limited to devices on the scale of 100 cm^2 or less, primarily due to optical losses encountered by the luminescent materials studied thus far. The team will develop large area devices to prove the silicon-based concentrator technology on a realistic scale and encourage commercialization. They will demonstrate a concentrator as large as standard size windows to enable study of the device in its real-world environment, provide an educational tool for visitors to the University, and break records on luminescent concentrator size. Prolonged assessment of the device performance will establish expected lifetime estimates.

ENRTF BUDGET: $116,783

Outcome	Completion Date
1. Develop large-area thin film coating technology	Jan 31, 2021
2. Scale luminescent concentrator devices up to at least 2,000 cm^2	Jun 30, 2021
3. Evaluate performance & stability over time	Jun 30, 2021

First Update January 31, 2019 **Activity start after completion of Activity 2, expected June 30, 2020**

Second Update June 30, 2019 **Activity start after completion of Activity 2, expected June 30, 2020**

Third Update January 31, 2020 **Activity start after completion of Activity 2, expected June 30, 2020**

Fourth Update June 30, 2020
The start of this activity has been delayed due to COVID related lab closures and reduced operations in the laboratories since March 2020.

Fifth Update January 31, 2021
The start of this activity has been delayed due to COVID related lab closures and reduced operations in the laboratories since March 2020.

Sixth Update June 30, 2021:
During this report period, we developed an analytical model to predict the performance of large area solar windows. The model takes into account the absorption of solar radiation via the quantum dots used in the solar windows, the reemission with a certain quantum efficiency, the transport of the remitted radiation with a certain waveguide efficiency, and the conversion of the waveguided radiation to electricity with edge mounted solar cells. The accuracy of the model was tested by comparison to first-principles Monte Carlo ray-tracing calculations and good agreement was found. The model is also consistent with experimental results for smaller solar window devices.

Using this model, we predicted the performance of large area solar window modules. We also developed a cost-model that estimates the manufacturing cost and computes the "levelized cost of energy", which is given by the electricity that a device produces over its projected lifetime divided by the cost of manufacture, installation, and operation. Results of this model suggest that while the power conversion efficiency of the devices decreases as device size increases, due to stronger losses for larger devices, the levelized cost of energy decreases. Our results indicate that solar windows based on silicon nanocrystals may achieve a levelized cost of energy that is comparable with other solar photovoltaic technologies.

As part of our experimental work, we found that silicon quantum dots suffer from environmental degradation due to oxygen and water vapor. Very promising work is in progress to cover silicon quantum dots with an environmentally stable silicon oxide layer. This work will be continued in the next project period.

Seventh Update January 31, 2022:
The work exploring the performance of large area solar window modules via numerical models continued during this period. Our efforts shifted from exploring a concept with edge mounted solar cells to a concept with surface mounted solar cells. Such configurations may be very well acceptable for greenhouse and agrivoltaic applications and have the advantage of enhanced efficiency. Since the surface mounted solar cells can absorb the light both from the solar window (luminescent concentrator) section and directly from the sun, the overall efficiency is improved.

Currently work is in progress to optimize the efficiency and the spectrum of the transmitted light for these devices. We are investigating the amount of light that is transmitted in the blue and red absorption bands of chlorophyl and predict how it affects the overall device performance and plant growth. We also model that performance of large-scale devices in actual greenhouses. Our results indicated that solar windows incorporated into greenhouses can lead to net-zero-energy greenhouses in locations such as Arizona. However, even in locations like Minnesota, the solar windows can cover a significant fraction of the electricity consumption of greenhouses and can help with the thermal management by reducing cooling loads in the summer and heating loads in the winter.

Experimental work continues to focus on producing environmentally stable silicon quantum dots. Our results appear very promising because the method of hot water oxidation that we are pursuing to produce environmentally stable silicon oxide layers around the silicon quantum dots is very fast and energy efficient and only utilizes water as a chemical reactant. Our preliminary results indicate that hot water oxidation produces silicon quantum dots that are now more stable and efficient than produced with our previous approaches.

Final Update June 30, 2022

In this period, we extended the modeling work to compare the efficiency of silicon quantum dot-based solar windows to those of devices based on other quantum dots, many of which pose environmental concerns, such as cadmium selenide. While silicon quantum dot feature a weaker absorption than other materials in the blue range of the spectrum, they actually have improved absorption in the green spectral range. Hence, we learned that solar windows based on silicon quantum dots can have an overall performance very similar to other quantum dot materials when the silicon quantum dot concentration is adjusted accordingly.

The final result of our efforts to develop a model for silicon quantum dot solar windows is a comprehensive model for the function of these devices in greenhouse settings. This model is capable of describing the solar electricity produced, the light admitted into the greenhouse for plant growth, and the thermal conditions of the greenhouse. As such, this model has become a capable tool for modeling silicon quantum dot solar windows in greenhouse settings.

Our work on environmentally stable silicon quantum dots has also been very promising. The hot water oxidation method used to produce silica coated silicon quantum dots is significantly faster and environmentally benign compared to other methods to coat the silicon quantum dots. Different from other approaches that utilize chemical solvents and surfactants, this method utilizes only water that is boiled at high temperatures and pressures. The so coated silicon quantum dots have an optical performance similar or better than that of quantum dots produced by other methods and largely retain their good optical properties when exposed to the environment. The coating method explored in this project is very promising for future work on silicon quantum dots.

IV. DISSEMINATION:

Description:

Professors Kortshagen, Francis, and Ferry are active members of their scientific communities. As such, they routinely disseminate results of their research through the publication of peer-reviewed research papers in scientific journals, conference papers and presentations, and seminar presentations at other universities and companies.

The characterization techniques previously discussed will provide a wealth of data in many custom formats for each application. In general, computer data will be stored both in custom format as well as in a universal form that does not require specific software for access. Methods and conditions used for synthesizing and characterizing the samples will be recorded by the student researchers in the form of handwritten or electronic laboratory notebook entries. Access to the data will be provided, upon request to the project director, within a reasonable period of time after collection. Data and laboratory notebooks will be maintained and stored for at least 3 years beyond the project end date, or 3 years following publication, whichever date is later.

The proposed project does not involve intellectual property rights at the moment. However, if an invention or proprietary discovery arises from the project and involves the stored data, the data will be made accessible to interested parties only after the intellectual property has been legally protected and conditions of the property rights are satisfied. The data collected and managed for this project is also subject to the data management and intellectual property policies established by the University of Minnesota.

First Update January 31, 2019

N/A

Second Update June 30, 2019

A first paper based in this project was published during this report period:

Hill, S. K., Connell, R., Peterson, C., Hollinger, J., Hillmyer, M. A., Kortshagen, U., & Ferry, V. E. (2018). Silicon Quantum Dot–Poly (methyl methacrylate) Nanocomposites with Reduced Light Scattering for Luminescent Solar Concentrators. *ACS Photonics*, *6*(1), 170-180.

A second paper has been submitted.

Third Update January 31, 2020

A second paper based in this project was published during this report period:

Hill, S. K. E., Connell, R., Held, J. T., Peterson, C., Francis, L. F., Hillmyer, M. A., ... & Kortshagen, U. R. (2020). Poly (methyl methacrylate) Films with High Concentrations of Silicon Quantum Dots for Visibly Transparent Luminescent Solar Concentrators. *ACS Applied Materials & Interfaces*, 12(4), 4572-4578.

Fourth Update June 30, 2020
Nothing new to report.

Fifth Update January 31, 2021
John Keil, Yaling Liu, Uwe Kortshagen, Vivian E. Ferry, "Evaluating Tandem Luminescent Solar Concentrator Performance Based on Luminophore Selection," Paper presented at the 48th IEEE Photovoltaic Specialists Conference

Sixth Update June 30, 2021:
The following paper has been submitted to ACS Applied Energy Materials and is currently under review:
John Keil, Yaling Liu, Uwe Kortshagen, Vivian E. Ferry, "Bilayer Luminescent Solar Concentrators with Enhanced Absorption and Efficiency for Agrivoltaic Applications"

Seventh Update January 31, 2022:
John Keil, Yaling Liu, Uwe Kortshagen, Vivian E. Ferry, "Bilayer Luminescent Solar Concentrators with Enhanced Absorption and Efficiency for Agrivoltaic Applications" ACS Applied Energy Materials (2021), **4** (12), 14102-14110

Final Update June 30, 2022

Yaling Liu and Uwe R. Kortshagen. Feasibility Analysis **of** Integrating Silicon Luminescent Solar Concentrators into Greenhouses. EN01.04.05, 2022 MRS Spring Meeting, Honolulu, HI, May 8-May 13, 2022 (**this** paper was awarded a best presentation award).

Project Results Use and Dissemination
Results of this research have been published in the scientific literature and presented at conferences. Three scientific papers were published related to:

- The influence of scattering on the performance of silicon luminescent solar concentrators
- The demonstration of silicon thin film luminescent solar concentrators

- The application of silicon luminescent solar concentrators to agrivoltais

Among the conference presentations presented by graduate students working on this project, one was chosen for the best presentation award.

V. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview: See attached budget spreadsheet

Explanation of Capital Expenditures Greater Than $5,000:
No capital equipment purchases under this project.

Explanation of Use of Classified Staff: N/A

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours: 1,760	Divide by 2,080 = TOTAL FTE: 0.85

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation:

Enter Total Estimated Personnel Hours:	Divide by 2,080 = TOTAL FTE:

B. Other Funds:

SOURCE OF AND USE OF OTHER FUNDS	Amount Proposed	Amount Spent	Status and Timeframe
Other Non-State $ To Be Applied To Project During Project Period:			
	$	$	
Other State $ To Be Applied To Project During Project Period:			
	$	$	
Past and Current ENRTF Appropriation:			
	$	$	
Other Funding History:			
past federal funding (National Science Foundation, Department of Energy, Army Office of Research) to Professors Kortshagen for developing luminescent silicon technology and Prof. Francis for developing coating technologies. (estimate)	~$ 9M	~$ 9M	This is an estimate of past funding.

VI. PROJECT PARTNERS:

A. Partners receiving ENRTF funding

Name	Title	Affiliation	Role

B. Partners NOT receiving ENRTF funding

Name	Title	Affiliation	Role

VII. LONG-TERM- IMPLEMENTATION AND FUNDING:

The project team has a strong track record in technology transfer from academic labs to industry. The nanocrystal plasma synthesis process developed in Kortshagen's lab has been patented and was exclusively licensed to Innovalight, Inc. (acquired by DuPont) and Dow Corning. Professor Lorraine Francis, is an expert in the area of coating microstructures and processing and has strong industrial cooperations through the Coating Process Fundamentals Program of the Industrial Partnership for Research in Interfacial & Materials Engineering (IPRIME). The project team is interested in continuing this proactive interaction with industry in order to translate any outcomes of the proposed research quickly into industry and interact with local Minnesota window manufacturers.

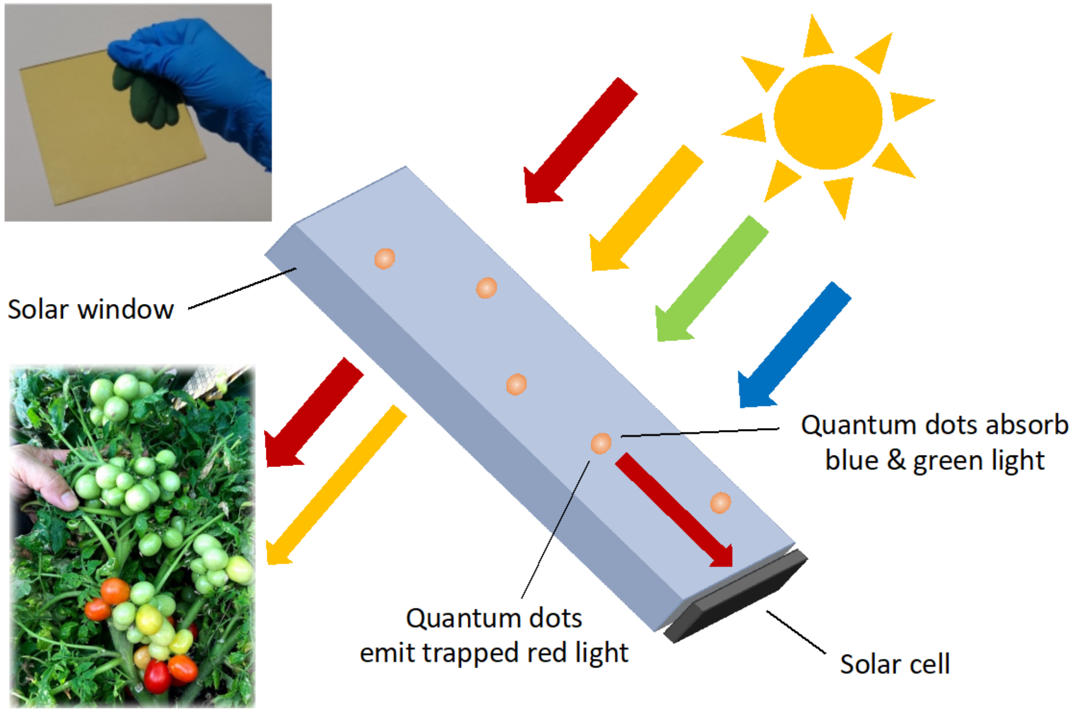
VIII. REPORTING REQUIREMENTS:

- **The project is for 4 years, will begin on July/1/2018, and end on June/30/2022.**
- **Periodic project status update reports will be submitted Jan./31 and June/30 of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2022.**

IX. SEE ADDITIONAL WORK PLAN COMPONENTS:

A. Budget Spreadsheet
B. Visual Component or Map

Solar Windows: How they work



C. Parcel List Spreadsheet
D. Acquisition, Easements, and Restoration Requirements
E. Research Addendum

Attachment A:
Environment and Natural Resources Trust Fund
M.L. 2018 FINAL Budget Spreadsheet

Project Title: Develop Solar Window Concentrators for Electricity
Legal Citation: M.L. 2018, Chp. 214, Art. 4, Sec. 02, Subd. 07a
Project Manager: Uwe Kortshagen
Organization: University of Minnesota
College/Department/Division: College of Science and Engineering / Mechanical Engineering
M.L. 2018 ENRTF Appropriation:
Project Length and Completion Date: 4 years, June 30, 2022
Date of Report: June 30, 2022

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Budget [11/7/22]	Amount Spent	Balance
BUDGET ITEM			
Personnel (Wages and Benefits)	$322,041	$322,041	$0
Uwe Kortshagen, PI: $13,673 (75% salary, 25% benefits); 4% FTE each year for 3 years, 3% increase years 2-3		$16,014	
Lorraine Francis, Co-PI: $8,204 (75% salary, 25% benefits); 3% FTE each year for 3 years, 3% increase years 2-3		$6,292	
Vivian Ferry, Co-PI: $4,764 (75% salary, 25% benefits); 3% FTE each year for 3 years, 3% increase years 2-3		$25,506	
2 RAs at 37.5%: $73,821 (60% salary, 40% benefits); 37.5% FTE each year for 3 years, 3% increase years 2-3		$274,229	
Equipment/Tools/Supplies	$19,145	$19,145	$0
Based on historical data, cost for purchasing supplies for coating operation ($1,056/yr) for yrs 1-2 and $1,358/yr for year 3		$9,518	
Based on historical data, cost for purchasing precursor gases ($756/yr), sample substrates ($756/yr), and chemicals ($1356/yr) for nanoparticle synthesis, and chemicals for nanoparticle functionalization ($2356/yr)		$9,627	
Capital Expenditures Over $5,000	$0	$0	$0
Custom coating die and wider base plate for this batch coater to be able to coat large area samples			
Other	$8,814	$8,814	$0
User fees for usage of facilities at the campus CharFac center for nanoparticle structural/property characterization (X-ray diffraction, secondary electron microscopy, Raman spectroscopy, electron microscopy, and electron energy loss spectroscopy)		$8,814	
COLUMN TOTAL	$350,000	$350,000	$0