# Low Mass Printable Devices for Energy Capture, Storage, and Use

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## Abstract

**The energy-efficient, environmentally friendly technology that will be presented is the result of a Space Act Agreement between NthDegree Technologies Worldwide, Inc., and the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC). The work combines semiconductor and printing technologies to advance lightweight electronic and photonic devices having excellent potential for commercial and exploration applications. Device development involves three projects that relate to energy generation and consumption: (1) a low-mass efficient (low power, low heat emission) micro light-emitting diode (LED) area lighting device; (2) a low-mass omni-directional efficient photovoltaic (PV) device with significantly improved energy capture; and (3) a new approach to building super-capacitors. These three technologies, energy capture, storage, and usage (e.g., lighting), represent a systematic approach for building efficient local micro-grids that are commercially feasible; furthermore, these same technologies, appropriately replacing lighting with lightweight power generation, will be useful for enabling inner planetary missions using smaller launch vehicles and to facilitate surface operations during lunar and planetary surface missions. The PV device model is a two sphere, light trapped sheet approximately 2-mm thick. The model suggests a significant improvement over current thin film systems. For lighting applications, all three technology components are printable in-line by printing sequential layers on a standard screen or flexographic direct impact press using the three-dimensional printing technique (3DFM) patented by NthDegree. One primary contribution to this work in the near term by the MSFC is to test the robustness of prototype devices in the harsh environments that prevail in space and on the lunar surface. It is anticipated that this composite device, of which the lighting component has passed off-gassing testing, will function appropriately in such environments consistent with NASA's exploration missions. Advanced technologies such as this show promise for both space flight and terrestrial applications.**

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## I. Introduction

NthDegree, a small innovative company that has taken on acceptable risks toward addressing national technology needs while servicing special NASA research and development interests, has joined with NASA to repurpose their unique class of inorganic semiconducting inks and associated energy capture, storage, and lighting technologies for space exploration. These inks allow printing of semiconductor devices such as area lighting systems, thin PV cells, and super-capacitor storage systems.

NASA is interested in fielding technologies that offer lightweight, efficient power generation useful for enabling deep space and inner planetary missions using smaller launch vehicles and for facilitating surface operations during lunar and planetary surface missions (Fig. 1). To this end, NASA has partnered with NthDegree to design and model a radically new type of PV device that is a significant improvement over current thin film PV systems. The device uses silicon dioxide ($SiO_2$) and mono-crystalline silicon spheres as concentrator and conversion elements respectively. No heavy metals or other toxic materials are used. The device is printable via either screen or flexographic presses, with the entire device being made “in line”. The optical model indicates at least a 50% improvement over current thin film systems and, by use of an engineered substrate such as a light trap, increased conversion efficiency into the thick silicon range is anticipated. The combination of inexpensive materials and production techniques should provide very cost effective, lightweight solar cells. Also, NASA and NthDegree are developing a new and significantly different super capacitor technology. This approach uses high purity, selectively conductive single-walled carbon nanotubes and ionic liquids, which are printable via either a flexographic or screen process. This technology has a strong potential to offer greater energy densities with a long, useful life.

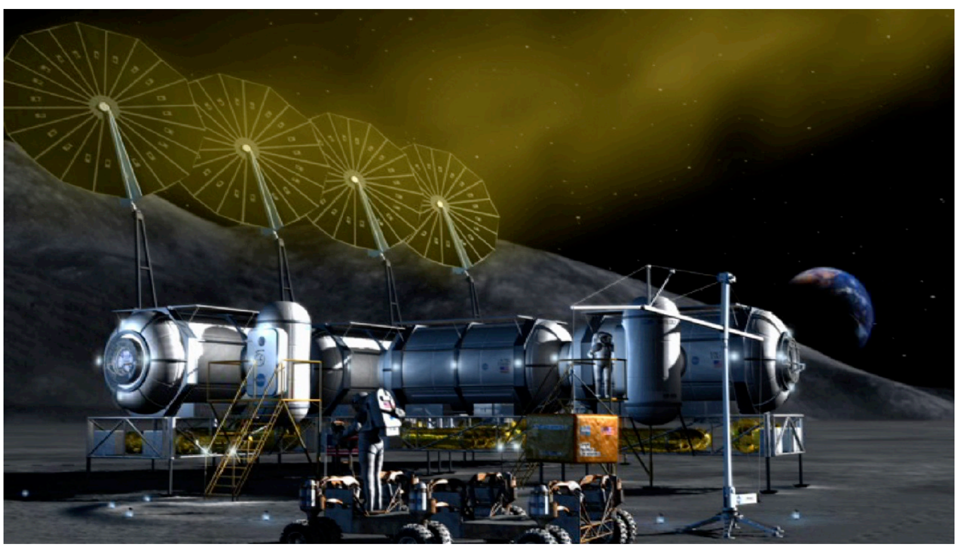

**Figure 1. NASA lunar exploration concept.**

For NASA, it is important to identify potential missions and the operational environments that these devices might support. To better define the environmental test facilities that could support device development for such applications, it is imperative to characterize a test program that addresses all the potential applications for these devices. To this end, the space environment is divided into four general categories: (1) low Earth orbit (LEO), (2) geosynchronous Earth orbit (GEO), (3) deep space, and the (4) lunar surface. The environmental constituents for each of these typical environments are dissimilar and, therefore, require different tests to qualify the devices for use in harsh space applications and ensure safe operations for crewmembers. This approach will automatically qualify device stability for Earth-based commercial applications.

The three critical technologies — capture, storage, and lighting (or power generation for other critical space applications) — represent a systematic approach that is both commercially feasible for building very local micro-grids as unsubsidized alternatives / additions to the traditional grid, and represent a level of redundancy that does not exist today for the energy consuming public. This paper describes: (1) optimization of the ink systems for the various device components, (2) testing of the printed prototype devices, (3) examples of potential NASA applications, and (4) appropriate environmental testing methods.

## II. Photovoltaic

Texas Instruments has reported several spherical PV designs in the literature [1, 2]. Spherical PVs have not been successfully commercialized as it is difficult to cost effectively manufacture the early designs. However, spheres have intrinsic advantages in terms of the light absorption efficiency when compared to thin films. A dense array of Si spheres has about π/2 times the surface area that can be realized with a section of wafer that has the same geometric cross section. This is illustrated in Fig. 2 by using equivalent cylinders to compare the total solar power adsorbed by a 2-micrometer-thick film as compared to a 10-micrometer sphere — in this case these are equivalent masses. The total power adsorbed by the sphere is 1.588 times that adsorbed by the film. The theory and calculations applied to the modeling effort are exact, and were developed by Fuller et al. [3] for the study of multi-sphere particles in photonics and atmospheric radiative transfer.

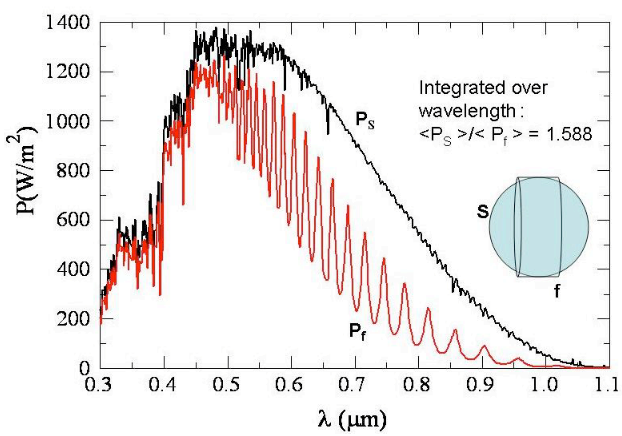


**Figure 2: Absorption cross-section of spheres versus films. Note that solid curves are modeled data.**

From the model, NthDegree is building a printed two-sphere PV device. The proposed forward optics design is a two-sphere system that uses a top layer of $SiO_2$ spheres (5) and a bottom layer of polycrystalline Si (1) sphere. The advantage of this approach is the concentration of polychromatic light. The device will be built in sequential layers on a standard screen or flexographic direct impact press in a series of layers. One significant benefit that the two sphere optical system provides is a dramatic reduction in reflectance. Silicon reflects about 35% of light at a normal incident angle to a silicon wafer. This number becomes greater (e.g., the percent reflection is greater) as the light angle becomes more acute. The $SiO_2$ upper spheres will only reflect about 5% of normal incident light and maintain most of this efficiency across the tangent of the sphere, even at fairly acute angles. This concentrated light is injected into the underlying Si sphere, with the only loss at this coupling resulting from scattering. The total scattering loss will be on the order of about 10%. However, as this is a forward optical system built as a massive array, much of the scattered light will strike other silicon spheres or strike the back reflector. Current modeling indicates that up-scattered loss will be on the order of 20% of the scatter — e.g., about 2% of the total injected light.

Yoon [4] demonstrates that using a lenticular lens array (of low concentration ratio) increases current density and maximum power output by about 2.5 times. Current modeling of the two-sphere system indicates that the NthDegree design should result in a 50% conversion efficiency improvement with respect to existing thin film Si PV systems. Furthermore, both the positive/negative junction and the focal length can be adjusted so that an electron deficient area is located near the junction, thus providing a convenient sink for removing electrons before recombination. We anticipate achieving a significant improvement upon existing thin film Si systems, with a net conversion rate in the 15% range.

Silicon sphere fabrication, a relatively nonexistent process for mono-crystalline silicon in the optimum size class, is a key element to the improved efficiency of this PV system. Members of the project team have researched the literature for methods to manufacture such spheres. Some promising methods have been identified, including container-less processing, an area in which NASA has developed significant expertise in MSFC's 360-foot-tall Dynamic Test Stand. The Dynamic Test Stand was constructed approximately 50 years ago for the early development of the Redstone rocket and the Saturn V rocket, as well as for the Space Shuttle.

During many years spent studying low-gravity phenomena and processes, the Drop Tube Facility, which is located in the Dynamic Test Stand, was one of NASA's primary means of providing minimal free-fall times of about 4.6 seconds for scientific observations. The Drop Tube Facility offers an extremely quiescent container-less processing environment, ideal for studies involving nucleation, solidification, and under-cooling phenomena. It is under such a condition of cooling during free-fall, that a molten body, such as silicon above its melting point (~1410 °C), is likely to assume a spherical or near-spherical shape. It is our goal to fabricate reasonable quantities of 10 – 20 μm silicon spheres having adequate degrees of sphericity and monodispersity in a similarly designed facility.

A paper by Liu, et al, [5] provides an approach for consideration. In this paper, polycrystalline silicon sphere distributions with mean sphere diameter ~1.0mm were formed by dropping molten silicon through a nozzle in a drop tube using a seeding technique for sphere formation. The researchers aimed to decrease the degree of under-cooling during solidification so as to increase the degree of crystallinity in the resultant silicon spheres. This reduction in under-cooling is enhanced by the presence of the seed powders that served as nuclei for stimulating solidification. Since minimal under-cooling is an objective, a refurbished Drop Tube Facility would not have the 360-foot height requirement for deep under-cooling in alloys, but could be sufficient at approximately 20-foot heights. Crystallinity is a factor for increasing the average carrier lifetime from $\leq 0.1\mu s$ to $\geq 1.0\mu s$. In the Liu paper, a rather polydisperse silicon powder (~1–75μm) seeded the molten silicon, whereas our efforts will seek to seed with a higher degree of crystalline monodispersity. A potentially attractive model is to utilize highly monodisperse and plentiful silica ($SiO_2$) cores, of almost any size class in a fluidized bed, as substrates for ~1μm thick silicon coatings. Modeling predicts that such an approach could enhance carrier multiplication, which also offers conversion efficiency improvement, although possibly at the expense of carrier lifetime.

## III. Super-capacitor

Electrochemical super-capacitor technology promises to play a critical role in local energy storage systems. Other available energy storage technologies such as batteries and conventional dielectric capacitors have drawbacks. Batteries are characterized by high energy, low power, and short cycle life, while dielectric capacitors are low energy, high power, and have a long cycle life. In contrast, super-capacitors are characterized by mid-range energy storage capability, high power and long cycle life. Three general types of super-capacitors can be identified: (1) carbon based active materials with high surface area; (2) redox super-capacitors that use surface or near-surface reactions for charge storage, and; (3) hybrid capacitors that combine capacitive and battery electrodes [6]. Fig. 3 illustrates a fairly common "sandwich" design seen for these devices. Note that the charge holding electrode structure can be complex — e.g., two or more layers placed upon some metallic conductor. Carbon based high surface area super-capacitors store electricity by physical charge separation. Super-capacitor charge is stored through reversible ion adsorption on high surface area electrodes.

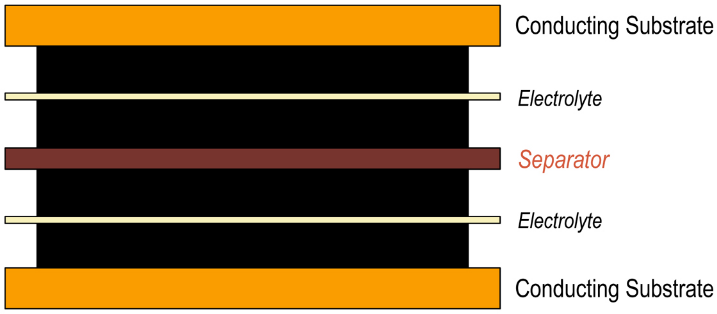


**Figure 3. Generic super-capacitor schematic.**

The purpose of this project is to build a much simplified device based upon high surface area single walled carbon nanotube (SWCNT) electrodes using an ionic liquid (IL) electrolyte media placed in layers where some of those electrolyte layers are doped with multi walled carbon nanotubes (MWCNT). Ionic liquids are molten salts at room temperature that have immeasurably low vapor pressure, are nonflammable, have high ionic conductivity, and have a wide range of thermal and electrochemical stabilities. A great deal of available data demonstrate that high conductivity CNT material can be deposited such that an acceptable super-capacitor can be built with reasonably high specific capacitance [7, 8, and 9]. However, these devices have not yet been optimized so, considerable improvement should be possible.

Fig. 4 illustrates the proposed layer construction of the new device. The N1 layer is a SWCNT mesh deposited so as to act as both the buss and, in part, the electrode. Layer N2 consists of SWCNTs dispersed in the IL electrolyte and organized via a magnetic field (**B** field) [10]. Layer N3 is an IL gel containing MWCNTs. The purpose of such layering is to massively increase the charge surface area with nearly optimum pore-size storage.

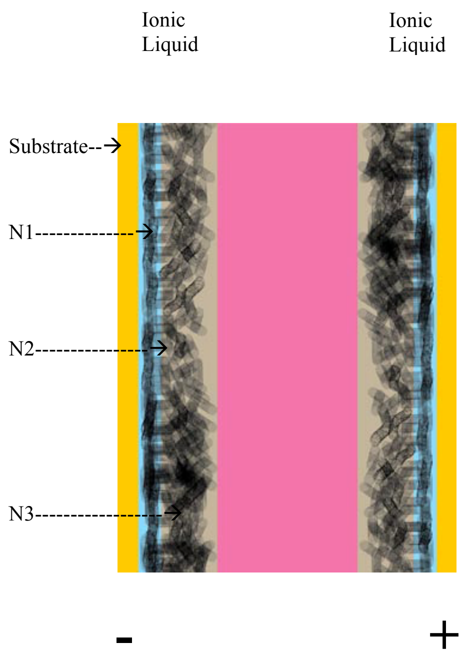


**Figure 4. Multi-layered CNT super-capacitor.**

NthDegree's super-capacitor is designed to maximize function over a wide temperature range (–40 °C to 62 °C) without compromising performance. This goal is achievable by use of these materials, which have wide temperature windows of materials thermal stability. In addition, following the cure step, all layers are solids or stabilized gels. This allows a continuous roll-to-roll manufacturing process. NthDegree is proposing a new design with a capacitance per gram on the order of 110 F/g using a current density of 1mA/mg of material. With optimization, the performance may be substantially better. This design allows super-capacitor modules to be manufactured rapidly and inexpensively using printing technology. These super-capacitor modules may be combined to form storage units of various sizes, ranging from those useful for single appliances, such as lighting, to much larger energy storage units.

The choice of electrolyte is an important aspect to the design and performance of super-capacitors. The electrolyte impacts the charge storage density, the charge and discharge rates, and the thermal and electrical stability of the device. Aqueous solutions have long been used as electrolytes, but they suffer from such drawbacks as high water vapor pressure, hence can evaporate, and the very limited electrochemical window of water (on the order of 2V), which can lead to dielectric breakdown problems. Phosphoric acid has been somewhat effective as an electrolyte, but is unfortunately corrosive. ILs, because of their low volatility do not evaporate readily, and can be made non-corrosive. In addition, many ILs have excellent thermal and chemical stabilities, and can possess wide electrochemical windows (as high as 5 – 6V). Because of their design flexibility, ILs can be engineered at the molecular level to have a range of desired properties; e.g., in the case of CNT super-capacitors, the size of the ions can be tailored in order to control the wetting of the pores of the CNTs. ILs such as 1-ethyl-3-methylimidazolium bis(trifluoromethanesulfonimide) and 2-fluoropyridinium trifluoromethanesulfonate (to name a few) have shown promise as ILs for batteries, fuel cells, and super-capacitors.

One drawback with ionic liquids is that they tend to have lower ion conductivities than aqueous solutions. This is primarily due to the greater viscosity of ILs, which can range from one to several orders of magnitude greater than water. One possible way to overcome this limitation is to use protic ILs. This class of ILs has the potential of achieving higher conductivities than what would be expected based on viscosity because proton transfer mechanisms can take place; such "superionic" behavior is observed in concentrated solutions of phosphoric acid. Finding protic ILs that can exhibit superionic conductivity (also known as "dry" proton conductivity) is an active area of research.

It is at this point we consider a variety of interfaces that utilize the captured and stored energy for commercial or space applications. For example, we can consider development of commercially feasible, efficient local microgrids and lightweight power generation, the latter being quite useful for enabling inner planetary missions using smaller launch vehicles, and to facilitate surface operations for lunar and planetary exploration missions.

## IV. Lighting

For lighting applications, the three technology components are printable in-line by printing sequential layers on a standard screen or flexographic direct impact press using the three-dimensional printing technique (3DFM). The major advantage of printing lights is that it offers the potential of a three- to six-fold increase in efficiency when compared to lighting products and displays manufactured using traditional large die LEDs. A further advantage is that the technique will provide these benefits at a cost significantly below either present or known future LED array systems and lower than proposed organic LED systems. Furthermore, such printed systems are built from non-toxic materials. The NthDegree lighting solution could reduce 220 million metric tons of carbon dioxide emissions per year. Further, we estimate the cost to be competitive with current compact fluorescent light (CFL) costs and the useful lifetime of the device will be five to ten times greater than CFL devices currently on the market.

The authors believe that a key step toward practical area diode lighting devices is solving the light extraction efficiency problem. Shuji Nakamura's group opined that: "When it comes to the extraction efficiency, because of large differences in the refractive indices of air and the GaN materials system, a considerable fraction (90–95%) of the generated photons within the LED are trapped by total internal reflection." [11]. Whereas the internal quantum efficiency can now be placed at something like 75% or better, the key to LED efficiency lies in dramatically increasing extraction [11, 12, 13].

From the literature [11, 12, 13] it is clear that the index of refraction of GaN is a primary factor in low extraction efficiency. There is some evidence that altering die shape may help to improve this [12]. Further, it seems clear from the microLED literature [14, 15, 16] that the longer the light path within a GaN die, the greater the potential of photon recapture. Fig. 5, drawn from Choi [14], illustrates the impact of reducing LED die size in terms of light extraction and, therefore, apparent LED efficiency. Thus, for efficiently functioning LEDs, small is good.

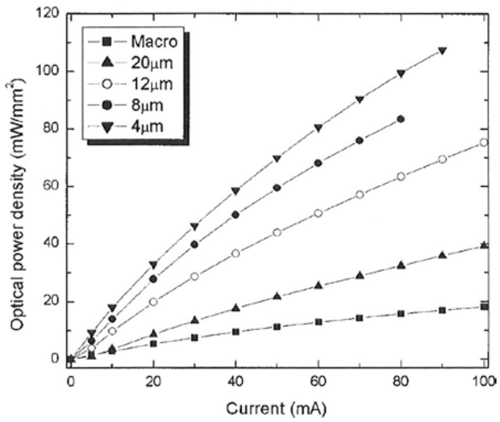


**Figure 5. Die size versus optical power density**
**(from Choi et al., Journal of Applied Physics, Vol. 93, p. 5978, 2003).**

Other organizations, such as the Tyndall National Institute in Ireland, have also found increased output from micro-LEDs where they claim up to eight times the efficiency of traditional large die devices with minimal heating and power.

Two other properties — device lifetime and output droop — are of significant interest. Approaching the lighting problem from the perspective of small devices spread over a large area provides another degree of freedom. Device lifetime appears to be related to junction heat [12] and junction heat is directly related to current. Therefore, the greater the forward current (after a certain point for a given device), the faster the LED degrades over time. Results from the use of large numbers of small LEDs to produce light, is less temperature rise for each die. Droop is the phenomenon of decreased LED efficiency when the forward current density exceeds a certain value. Droop has no settled mechanism as far as the authors know, but is a very real limitation to conventional LED lighting. Conventionally wired discrete LEDs within a large die array commonly generate a great deal of heat resulting in the need for heat sink packaging which is a significant engineering, manufacturing, and cost item. Pong and colleagues noted [17] that smaller micro-LEDs, when given an appropriate heat path, demonstrate an abnormal" blue shift (see Fig. 6 of [17]) indicating significantly less heat within each die for these smaller devices. Pong further notes that the photon energies of these micro-LEDs are stable within the larger operating current range.

NthDegree has also developed data that indicate that existing techniques of wiring LEDs into the packaging are inefficient both from a production and an electrical point of view. The approach of using small discrete devices requires an assembly technique other than wire bonding the die when packaging the device. Printing solves this problem and also suggests that wire bonding may not be the optimum connection technique even for large die devices. Fig.6 illustrates a 9X18 large die matrix (230 micron commercially available die) wired via printing both top and bottom leads. This device produces 4,200 cds at 4.2 Watts with a 5V square wave pulsed input. The surface temperature of the device was about 72 °C (measured periodically over a period of hours) without a heat sink.

The NthDegree approach for building very large printed arrays is based on obtaining low resistance contact to each LED. Any individual die within the array will not be driven to the point that droop is an issue. Also, the widely distributed die array on the composite substrate sinks the heat that is generated by each die over the large substrate surface to which the die are intimately attached.

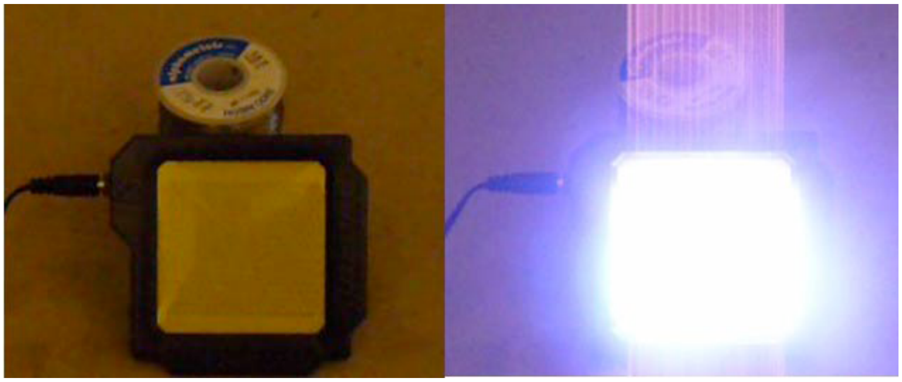

**Figure 6. A 9X18 large die array off and on.**

The technology developed by NthDegree seeks to exploit the “small is good” approach by the combination of improved ohmic contact and reduced forward current to improve LED luminary performance. Increased productivity and reduced cost are also a result of printing leads in an LED array.

The reason that this approach will work for area lighting is that, in the end, lighting is about generating photons and putting those photons where the user wants them. With the printed die approach, we have two very significant advantages that need to be emphasized: (1) the ability to add photon output over an area by simply increasing the concentration of die in the ink, and (2) the ability to get to whatever color temperature the user desires by simply color mixing die and easily achieving optical convergence, because those radiating die are only twice the size of a human blood cell. The required die per $cm^2$ for various products is not yet finalized, but this number can vary significantly without greatly altering the cost of the product. Consider that any one die, in small research quantities, costs about $0.0004, while die in moderate scale quantities cost about $0.00005 each. So, even if you assume that there is no light output benefit to the micro-LED approach, the device will still be unique in the sense that it will have, at least, the efficiency of a large die point source (likely much better due to the better thermodynamics of the small devices) and will do something that the intense point source devices cannot do — act as an area light source.

In order to build a semiconducting ink, NthDegree has developed tiny, discrete semiconductors having shapes that optimize performance. We call these inks micro discrete semiconductor inks (MDSI). Fig. 7 shows the resulting I/V curve of a printed micron size silicon diode. Note that the curve in Fig. 7 is quite similar to that seen in large die silicon diodes.

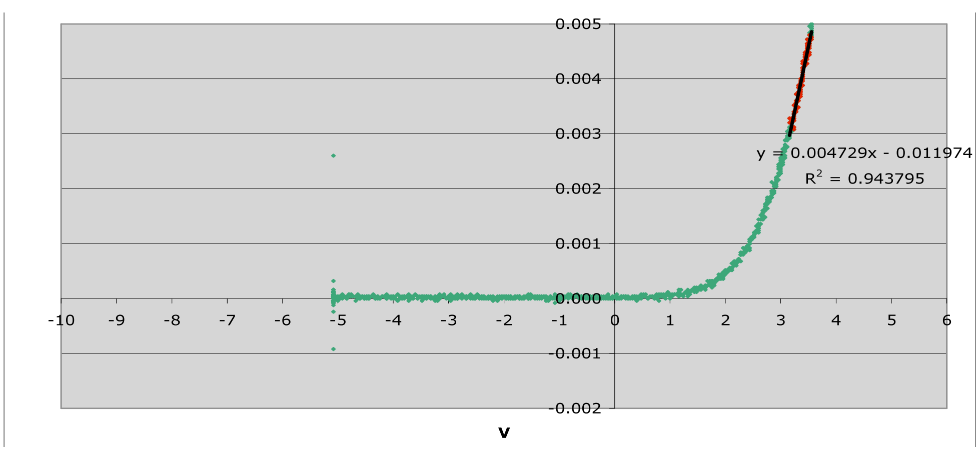


**Figure 7. I/V curve of a 20 micrometer Si RDI sandwich.**

One die design is a fabrication such that the dies are asymmetric and have a metal bar. This design is used in what is termed the spin diode ink (SDI), which is capable of die alignment in a **B** field. The metal bar will align itself in a preferred orientation (e.g., the lowest energy state) due to mass and air resistance (again, a more favorable energy state). The spinning of the diode (thus the name "spin diode ink") occurs very rapidly on the printing press given that certain physical process preconditions are met. The LEDs are not printed on a flat surface, but in parallel grooves of high precision (variance < 0.5 µ), which can be cast via a roll-to-roll technique that includes metallization of the groove valleys, but not the peaks. The SDI is then scrape-printed into the grooves, leaving the peaks free of the SDI and the valleys partially filled with the ink. Once the grooves are filled, the spin and cure process takes place. The microgroove placement of small discrete devices in combination with the spin effect achieved with the proper die design is called three dimensional field manufacturing (3DFM). NthDegree believes that 3DFM is an entirely new and a profoundly transformative technique for electronics manufacturing, among other things. We note that the emitting spectrum of the device is in the near UV range to optimize downshifting to white light.
With regard to white light generation, inorganic diode technologies that lead to solid-state lighting suffer a fundamental self contradiction when available phosphor downshifting technologies are employed. Efficacy is at odds with color temperature. So, while the desire is to obtain a color rendering index (CRI) approaching 90, this CRI yields poorer efficacy than is desired. This will be difficult to overcome with large die array approaches. However, by using an MDSI approach, LED die that are on the order of twice the size of a red blood cell can be color mixed much as pigments are mixed in inks. Different emission levels at different frequencies are compensated for by adding or subtracting die of the given frequency. This approach is effective using only InGaN die with the addition of a yellow red phosphor to smooth the color intensity into the higher wavelength spectrum. The resultant power distribution is, effectively, a straight line therefore yielding a linear polychromatic solution within the visible range; i.e., a sunlight simulant. To obtain any given desired color temperature the ink mixture is simply altered to the characteristics desired. It is feasible to do this because micro LEDs will optically merge at very short distances giving the viewer an area output that is the average of the various die and YAG-red output.

### V. Power Generation and Environmental Testing for Some Critical Space Applications

NASA MSFC's Advanced Concepts Office has suggested two possible aerospace applications of these printed technologies applications: the Solar Powered Unmanned Aerial Vehicle (SPUAV) and Solar Electric Propulsion (SEP) cargo vehicles (fig. 8). For both of these in-space solar cell applications, the materials must be compatible with hard vacuum and other harsh environmental conditions. Therefore, it is critical to reliably test materials stability with such conditions in mind prior to space use. The following sections will summarize these two applications, while describing the NASA MSFC facilities designed to test materials stability in the appropriate environments.

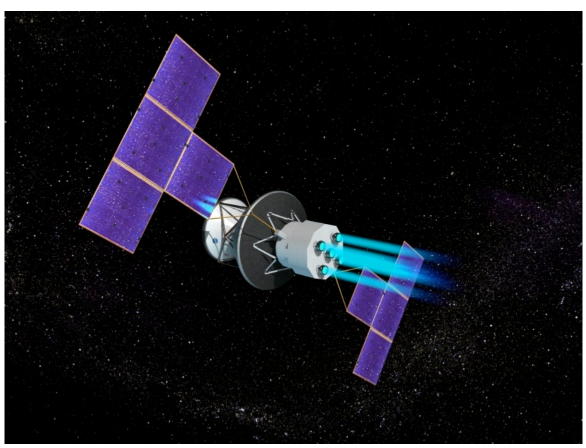

**Figure 8. Solar Electric Propulsion concept.**

Because it is extremely expensive to build and launch communications satellites into Earth orbit, other means of providing transmission relay and aerial photographic capability are under consideration. One of the most promising of these is the SPUAV. The SPUAV is basically an unpiloted aircraft powered by electricity generated from solar light. The aircraft flies at altitudes well above commercial flight levels (60,000 – 70,000 feet) in a flight pattern that takes it over the most beneficial ground areas for transmission relay or photography. This is especially advantageous for cellular telephony in that it provides relay capability close to the ground and with little transmission delay. Because it flies at such a high altitude and above cloud cover, it gets excellent solar irradiation during the daytime. It uses the sunlight to power the aircraft and to store energy for nighttime flight operations. The energy storage subsystem must be able to save enough energy to allow the aircraft to fly and to operate independently until morning, although the craft may glide to the minimum safe altitude during the night. Unlike a satellite, which must function without repair for its entire lifetime, the SPUAV may be returned to the ground for upgrades and repairs and redeployed.

The SPUAV may be an excellent application for the energy capture and storage technologies described in this paper. Because of the possibility for surface conformance, the PV array may be printed on a flexible plastic sheet and then glued as a veneer to the wing and fuselage surfaces. Because it is thin and flexible, the array sheets will interfere little with the aerodynamics of the craft. Thin film arrays have often been considered for SPUAV applications and their low conversion efficiencies are considered to be close to the minimum required to power the aircraft, therefore marginal. The higher conversion efficiencies expected by these printable arrays, will enable more power and hence more design freedom. Further, the printable arrays are lightweight, affording more payload for the same sized aircraft.

For SPUAV feasibility the energy storage subsystem requires an energy storage density of 250-500 Whrs / kg. The energy stored by a capacitor is given by $E = ½ CV^2$ where C is the capacitance in Farads and V is the difference in potential (in Volts) across the capacitor. E is the energy in joules. Assuming for the moment that NthDegree's printable super capacitor technology gets $1/10^{th}$ of the storage density that it expects (11 F / g) and assuming that the final potential difference across the capacitor is 20V, the energy storage capacity will be 2.2 Mj / kg or 611 Whrs / kg. Unlike some applications where the decreasing available voltage of a discharging capacitor causes problems, the electric motor is ideally suited to being powered by a large capacitor. Pulse-width modulation to the motor windings allows for controlling the motor torque easily and with a variable pitch propeller to control the torque of the load, it should be a simple matter to keep the propulsion system operating at near optimum.

For the delivery of large cargo mass in the solar system and inside Mars orbit, another application, SEP offers a reusable, low-cost delivery option. SEP is a low thrust, high specific impulse ($I_{SP}$) propulsion system in which electric power generated from the Sun is used to accelerate a charged propellant (usually Xenon) in an electric engine. The thrust levels are very small (fraction of 1N), but the amount of propellant required is also very small. Unfortunately, typical power levels for large craft can be quite high (500 – 600kW). These SEP vehicles could be used to transfer cargo to the Moon, Mars, or near-Earth asteroids in advance of human flights, potentially carrying multiple large payloads over long periods of time. The principal benefit of the printable photovoltaic array to the SEP application is its very high power density (W/kg). This is a result of its low mass and reasonable conversion efficiency. Assuming that printed PV/super-capacitor technologies can eventually get power densities of 1 kW/kg (and that is a reasonable density even for thin film), 600kW would require only 600kg of array. Assuming that supporting structure and deployment could be had for twice that mass, we have a solar generation system < 2000 kg. To be useful for space applications, PV arrays must have high power to mass density. Each kg launched into space is costly; i.e., each kg of power system is a lost kg of payload; therefore, PV arrays for space use must have as high a ratio of power capacity to mass (W/kg) as possible

Some of the environmental challenges that SEP applications will encounter in space include rapid thermal cycling — SEP applications require some time in LEO as they accelerate. During this time, the solar arrays will undergo changes in temperature from –80 °C to 80 °C on every orbit (90 – 120 min); long UV radiation exposure — SEP vehicles are usually long-life vehicles, so the PV arrays must have a long useful life. UV radiation typically causes performance degradation in PV arrays (usually about 3% per year). To be useful, the arrays must maintain performance for as long as possible. Degradation on the order of 3% per year is considered a worst case. Trapped particle radiation — the Earth's magnetosphere traps protons and electrons. In LEO, there is little of this radiation. As the cargo vehicle expands its orbit into the magnetosphere, however, this radiation might become a problem. MSFC's Materials and Processes Laboratory Environmental Effects Branch is equipped to test a range of space environments likely to be encountered over a range of potential missions.

The materials considered to be at greatest risk for damage in these conditions have been identified at the MSFC Environmental Test Facility. Thermal vacuum stability testing will be performed on these PV device materials. The MSFC Photo-deposition System chamber has been selected for these tests. The system is a bell jar that is evacuated by a turbomolecular pump, providing a hard vacuum environment, < $10^{-5}$ Torr. Results from these tests will help guide the development of the PV device for space applications. Candidate PV systems with acceptable performance in the thermal vacuum tests will undergo additional space environmental testing, including exposure to ultraviolet radiation. These screening studies will be performed to permit rapid identification of outgassing problems and prevent contamination of test chambers and sensitive instrumentation of other space environmental test equipment.

The SPUAV and SEP represent potential vehicle types to encounter a moderate range of space environment conditions and a basis for establishing a harsh environment test matrix. In order to characterize a test program that addresses potential environmental encounters for these and other launch vehicles requiring these types of devices, the space environment is divided into four general categories: LEO, GEO, deep space, and the lunar surface. The environmental constituents for each of these typical environments are different and require different tests to qualify the devices for use. For example, in LEO, atomic oxygen (AO) is a significant concern, while AO is not a concern in other environments.

Environmental conditions that the low mass solar cells will experience at different locations in space are specified in Table 1. At the lunar surface, the radiation environment is that of deep space. In deep space, the solar radiation (UV, VUV) and the solar wind are that at the Earth's orbit adjusted for the $1/r^2$ effect, where r is the distance from the Sun to the body (lunar surface or spacecraft). Table 1 also gives the maximum dose for the radiation environment [18, 19, 20] and average conditions for the other environments [18, 21]. The environmental conditions can be refined once a specific mission profile is defined.

| Environment | LEO | GEO | Deep Space | Lunar |
|---|---|---|---|---|
| Radiation dose electrons/protons (rads/yr in Si for 0.025mm Al) | $10^3$ / $10^5$ | $10^8$ / $10^5$ | $10^5$ | $10^5$ |
| Solar Wind (std) (nA/m$^2$ of electrons or protons) | 650 | ~650 | $1/r^2$ variation | ~650 |
| Solar VUV/UV radiation at 1AU (w/m$^2$) | 0.1082/108.2 | 0.1082/108.2 | $1/r^2$ variation | $1/r^2$ variation |
| AO at 600km & Solar Max(atoms/m$^2$-yr) | $10^{25}$ | Not Applicable | Not Applicable | Not Applicable |
| Thermal Environment Extremes | $T_{min}$ < -95C<br>$T_{max}$ > +110C | $T_{min}$ < -175C<br>$T_{max}$ > +80C | Location Dependent | –150 °C to 150 °C |

**Table 1. Environmental conditions for LEO, GEO, Deep Space, and the lunar surface.**

These exposure conditions are for articles exposed directly to space. For PVs (solar cells), the effects (e.g., charging) of an ambient plasma on the devices will need to be considered. In deep space and on the lunar surface when the Moon is not in the Earth's magnetotail, the solar wind is the plasma environment. At LEO, GEO, and on the lunar surface when the Moon is in Earth's magnetotail, the plasma environment of the Earth will need to be considered. The thermal environment on the Moon will depend on location. A general temperature range on the lunar surface is –150 °C to 150 °C, and it is recommended that tests be planned around this range until a mission profile is better defined. A deep space thermal environment will be determined by the mission profile also; i.e., how far out the spacecraft travels. The temperature limits for LEO and GEO are taken from the American Institute of Aeronautics and Astronautics' standard [5], which also specifies a number of thermal cycles for each location.

Because of the uncertainty in environmental conditions, which are dependent on the specific mission location and duration, a stepped approach to space environmental effects testing is recommended. Samples can be exposed to gradually increasing radiation doses within a potential range for the general target location in space. Then, when a specific application is defined, the actual expected radiation dose can be compared to the tested values to determine an expected performance lifetime in the actual environment. It is recommended that the values in Table 1 be the starting point for this stepped approach. Worst-case values can be added to the test plan as appropriate.

An important question in space environmental effects testing is how to measure the degradation on the test article due to the environment. Usually, there is no hard pass or fail criteria. A common measure is typically performance lifetime within the environment. For light bulb applications, this could be a simple determination of luminosity after exposure to environmental conditions. For PV devices, a common measure is cell performance. PV cells are also evaluated for plasma charging effects, particularly when targeted for higher orbits. Electrostatic discharge testing can be performed at both room and cryogenic (–70 °C) temperatures. Multiple facilities in the MSFC Environmental Effects Branch are useful for simulating different aspects of the space environment. These include the Pelletron Combined Environmental Effects Facility, the Solar Wind Test Facility, UV and VUV chambers, the Atomic Oxygen Beam Facility, the Plasma Interactions Laboratory, and the Lunar Environment Test System.

## V. Conclusion

The inks under development in this work allow printing of, among other things, inorganic micro LED area lighting systems, thin PV cells, and super-capacitor storage systems. Direct impression printing presses similar to those found in commercial printing plants are used in these manufacturing processes. The combination of inexpensive materials and production techniques will result in low-cost, highly efficient solar cells that are also extremely lightweight.

The low mass requirement for space travel (e.g., trans-lunar insertion) will benefits from mass reduction in the launch vehicle and payloads, which will include batteries, wiring, solar panels, and other system components. The mass of the PV device will be similar to that of thin film devices, an appreciable mass reduction from traditional, heavy Si PV devices with the added improvement in power conversion efficiency. This trend would be of significant value to NASA's exploration missions.

The successful conclusion to this work will result in the commercial development of low cost, flexible solar panels, hardened to environmentally induced damage, that are extremely lightweight with, potentially, the flexibility for installation as window shades, roof shingles, or other unobtrusive dwelling add-ons. This would be a notable improvement over the bulky structures currently in use on houses and other buildings. Furthermore, the projected advantage in energy conversion efficiency is a highly significant advancement as we seek regenerative energy sources to reduce overall energy consumption.

In addition, the lighting solution made possible by this development could reduce 220 million metric tons of atmospheric $CO_2$/year. We can estimate the cost to be competitive with current CFL costs and the useful lifetime of the device to be five to ten times greater than CFL devices currently on the market. An added advantage is that, unlike CFLs, the micro-LEDs are nontoxic, for environmentally friendly waste disposal. Future tests aboard the International Space Station will demonstrate their usefulness for NASA's missions, while simultaneously opening new possibilities for using these revolutionary lighting devices in homes and offices on Earth.

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