# The Glass Industry Approach to Global Megatrends: A Fusion of Macro-, Micro-, and Nano- Technologies for Next Generation Products

**James J. Finley**
**PPG Glass Technology Center, PPG Industries, Inc.**
**400 Guys Run Rd, Cheswick, PA, 15024**
**finley@ppg.com**

## ABSTRACT

Technology that will be essential in addressing the needs of commercial glazing over the next five years and beyond will be determined by current trends in the areas of energy, the environment, and aesthetics. These trends have become so universal that they have taken on the distinction of a “megatrend.” The Glass Industry has been able to continuously evolve over its long history to keep up with these trends, due in part to the creative approach of R&D in dealing with technologies spanning several orders of magnitude: from macro to micro to nano in size, i.e., from large area substrates manufactured on the float line to thin film coatings with nanometer thick layers. The unique “fusion” of these technologies has resulted in a significant contribution to energy savings and conservation, both for the industry itself and the market, globally. These technologies will continue to develop and provide the next generation of products that will (1) further reduce energy cost for both producers and consumers, (2) produce environmental benefits through the reduction in fossil fuel consumption and production of greenhouse gasses, and (3) provide aesthetic building glazing while maintaining energy cost and environmental functions. To meet the challenges of tomorrow’s commercial glazing market, products employing specialty glass and coatings solutions will continue to lead the way. These will include, to a greater or lesser extent, spectrally selective and electrochromic glazing, and photovoltaic systems. Leveraging existing technology, along with partnerships with government and academic institutions will be necessary to alleviate cost and risk for future development. But it is clear that the glass industry’s future path will be different than any time in its history, and the opportunity for growth will be great and driven primarily by energy, environmental, and aesthetic megatrends.

## INTRODUCTION

Technology that will be essential in addressing the needs of commercial glazing over the next five years and beyond will be determined by current trends in the areas of energy, the environment, and aesthetics. These trends have become so universal that they have taken on the distinction of “megatrend.” Corporations study these trends and use them to guide marketing and R&D efforts to innovate products for tomorrow’s marketplace.

The Glass Industry has been able to continuously evolve over its long history to keep up with these trends due in part to the creative approach of R&D in dealing with technologies spanning several orders of magnitude, i.e., from macro to micro to nano in size. Macro, ranging from meters to millimeters, incorporates large area ($m^2$ by mm thick) substrates of specialty glass compositions for solar reduction or high light transmittance. Micro ($10^{-6}$) is evident in thicker coatings for transparent conductive oxides and reflective coatings, and patterns for antennas or detectors. Nano ($10^{-9}$) is the order of the wavelength of visible light and is evident in the thin layers in low emissivity and antireflective coatings which use the property of interference of light waves to achieve their performance characteristics.

This unique “fusion” of technology has resulted in a significant contribution to energy savings and conservation, both for the industry itself and globally. Old guard technologies like melting and forming have developed more energy efficient processes, and new technologies employing nanotechnology have enhanced the function and value of glass. These technologies will continue to develop and provide the next generation of products that will (1) further reduce energy cost for both producers and consumers, (2) bring about environmental benefits through the reduction in fossil fuel consumption and production of greenhouse gasses, and (3) provide aesthetic building glazing while maintaining energy cost and environmental functions.

This paper presents an overview of how the glass industry has evolved to keep up with current trends, and how it is using megatrends to guide current technical efforts to meet the challenges for the tomorrow’s commercial glazing market. The focus will be on products that employ coatings and specialty glass to provide solutions. These will include spectrally selective and electrochromic glazing, and photovoltaic systems. Finally, the question of leveraging existing technology, and partnerships with government and academic institutions to alleviate cost and risk in future development will be discussed.

## GLASS INDUSTRY TECHNOLOGIES

The description of the glass industry as a monolith to glass technology is somewhat of a misnomer. The glass industry has invested R&D resources in diverse technical areas of specialty glass and thin film coating technology to produce products that have revolutionized commercial building design. Glass has gone from a basic construction element to an aesthetic design element with enhanced energy conservation and savings functions. Advances in new materials and nanotechnology are leading to products with quality and performance that could only be imagined a dozen years ago. Improvements in technology transfer and advances in process control and deposition equipment for large area coating processes both on and off the glass float line have led to manufacturing efficiencies that help contain the cost for these products. The chemical vapor deposition (CVD) process has been developed to produce transparent conductive oxide (TCO) coatings at high throughput on the float line, taking advantage of the high glass temperatures to react chemical precursors to form films. Low emissivity glazing used for the residential and commercial market, transparent conductive coatings for the photovoltaic (PV) and appliance industry are produced by this process. The magnetron sputtering vacuum deposition (MSVD) process is a high throughput, off-line process for depositing multilayers of highly uniform thin films on large substrates (up to 2 meters wide). These films are in the nanometer thickness range and have product applications in the areas of spectral selectivity, antireflectance, and transparent conductive oxides. In addition, the sputtering process is environmentally friendly, with no toxic effluents and little or no waste materials which make it an attractive “green” industrial process.

## SPECTRALLY SELECTIVE COATINGS

Spectrally selective coatings transmit some portion of the solar spectrum while blocking others. To increase energy efficiency and make maximum use of natural daylighting, the goal of spectrally selective coatings for commercial glazing is to block the solar infrared while maintaining high visible light transmission. Figure 1 shows a spectrally selective coating on a glass substrate (red line), “ideally” designed to allow maximum visible and zero solar infrared transmittance. The spectral irradiance curve, which is the energy distribution from the sun at the earth’s surface, is superimposed over the ideal spectrally selective coating to illustrate the amount of energy in each of the spectral regions. A spectrally selective coating is defined in terms of the Light to Solar Gain ratio (LSG) as the ratio of visible transmission (VLT) to solar-heat gain coefficient (SHGC).

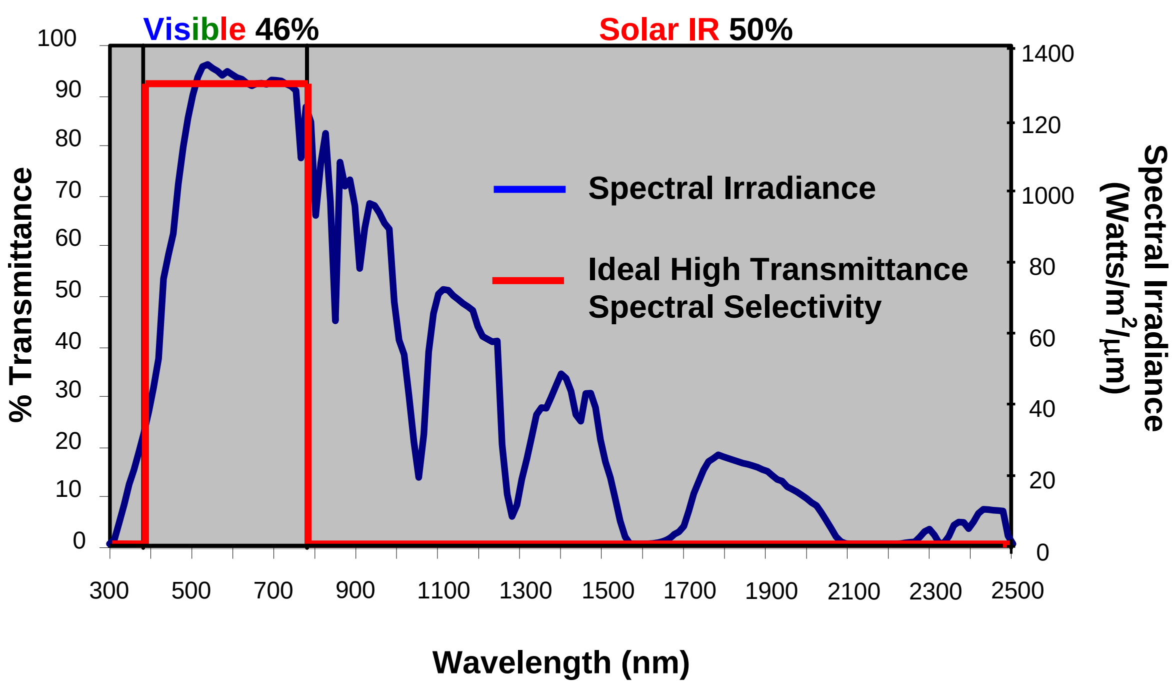


**Figure 1**. Solar energy distribution at sea level for air mass = 2

The U.S. Department of Energy (DOE) considers any glass that achieves an LSG of 1.25 or more to be spectrally selective. The DOE, following a study by the Lawrence Berkeley National Laboratories (LBNL), recommended that all commercial buildings in the U.S. be glazed with spectrally selective glass. [See **TERMS DEFINED** at the end of the paper for a summary of the performance glazing terms.]

There has been a steady progression in the performance of coatings for commercial glazing, starting with low transmitting, highly reflective products introduced in the early 1960's [Hill and Nadel 1999] with LSG values less than 1.0. In the early 1980's, the first generation of high transmittance-low emissivity, or High-*T* /Low-*E*, coatings were introduced with LSG values of 1.40. These coatings were produced utilizing the MSVD process, newly introduced for the large volume commercial manufacturing. This is the only industrial process with the capability to deposit "multilayers" of uniform thin films of metals and inorganic materials such as metal oxides and nitrides on large area glass substrates. The first generation High-T/Low-E coatings consists of a single silver layer surrounded by metal oxide layers (metal oxide – silver – metal oxide) where each layer measures only tens of nanometers in thickness. The primary use of this generation of High-*T* /Low-*E* coatings is for passive solar Low-E glazing to provide low U-values and high light transmittance. It was not until the development of the "double layer silver" coating, shown in Figure 2 and first commercialized for the automotive industry in the late 1980's (Finley 2001), that enhanced spectral selectivity was realized with LSG values approaching 1.8 or greater. The drive to reduce energy consumption in buildings and meet environmental standards only increased the demand for higher performing spectrally selective glazing, and today the double layer silver coating is the dominant spectrally selective glazing product. The optimum coating for spectrally selectivity, considering performance, aesthetics, and cost effective processing is the "triple layer silver" coating (metal oxide – silver – metal oxide – silver – metal oxide – silver – metal oxide layers) with the highest LSG value approaching 2.4. There is, however, only a slight decrease in U-value. The triple layer silver coating is now appearing in the marketplace and has been shown to offer quick and substantial short term (capital equipment savings) and long term (annual energy savings) returns (PPG Industries 2007). Beyond energy and equipment cost-savings, the triple layer silver coating can also dramatically reduce the level of $CO_2$ emissions associated with the heating and cooling of commercial buildings. As a result of these benefits, the triple layer silver product is expected to have the greatest market growth in the area of commercial glazing.

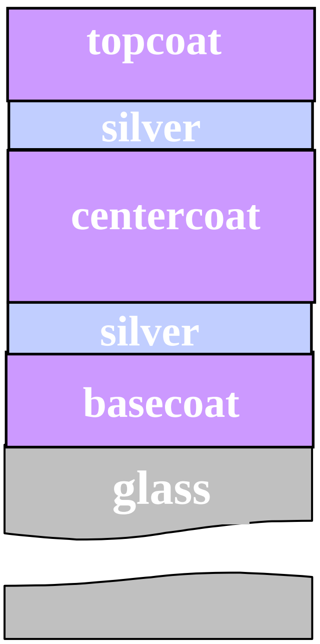


**Figure 2**. Schematic diagram of a double layer stack coatings with silver.

**Table 1: Performance – Low Emissivity Coatings**

| Number of Silver Layers [metal oxide – silver – metal oxide] | VLT | SHGC | LSG | U-Value |
|---|---|---|---|---|
| Uncoated | 79 | 0.70 | 1.13 | 0.48 |
| 1 Layer | 73 | 0.52 | 1.40 | 0.31 |
| 2 Layers | 70 | 0.38 | 1.84 | 0.29 |
| 3 Layers | 64 | 0.27 | 2.37 | 0.28 |

Table 1 summarizes the performance of Low-E coatings in terms of the percent visible light transmittance (VLT), solar heat gain coefficient (SHGC), and ratio of the visible light transmittance to solar heat gain coefficient or LSG, and U-Value. The low emissivity coatings are denoted by the number of silver layers surrounded by metal oxide layers on the glass substrate. The data are for an insulating glazing unit with two-¼ inch clear glass lites separated by a ½ inch air space. U-value (BTU/hr. • ft2 • °F) is for winter night-time.

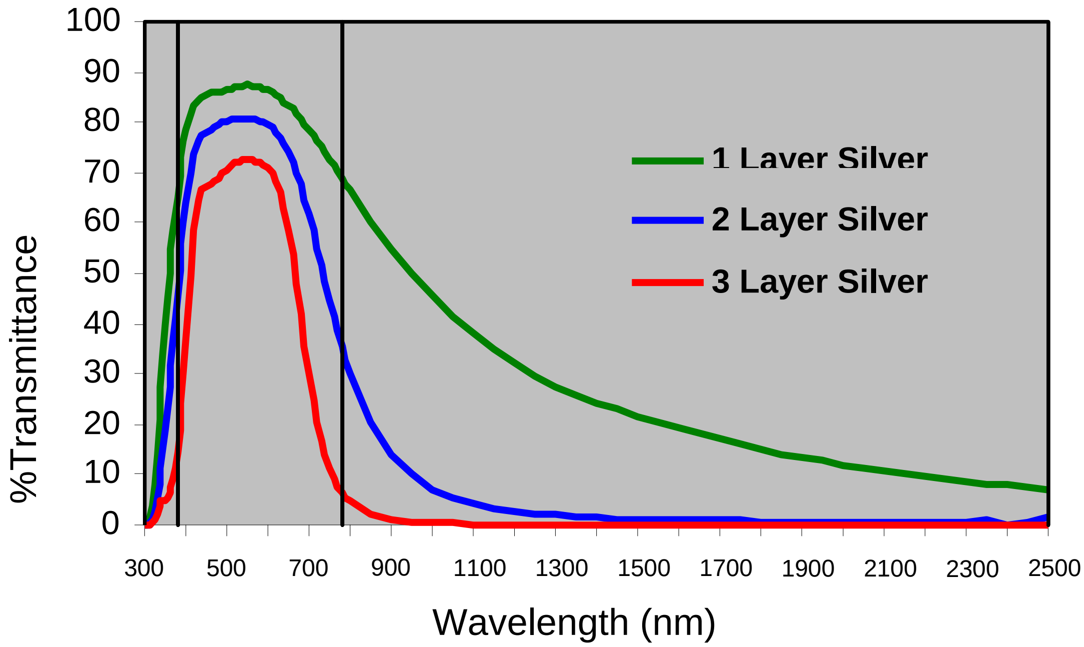


**Figure 3**. Percent transmittance for behavior of 1, 2 and 3 layer silver coatings as a function of wavelength in the visible and solar infrared region of the spectrum

Spectrally selective coatings act to filter out the solar infrared, with more layers producing a sharper cutoff in the solar infrared and less attenuation in the visible region. This behavior gives these coatings their high LSG values. This is illustrated in Figure 3 which shows the percent transmittance for 1 (single), 2 (double) and 3 (triple) layer silver coatings as a function of wavelength in the visible and solar infrared region of the spectrum. The curves approach the "ideal" design shown in Figure 1.

Figure 4 shows the SHGC values as a function of VLT and LSG. The chart illustrates the performance of MSVD Low-E coatings on clear and tinted glass. Clear and a range of tinted glasses, along with a Low-E CVD coating on clear are included for comparison. (Note: the MSVD Low-E coatings are on the tinted glass with the lowest value of VLT and SHGC shown on the chart). The forbidden region indicates the limit of LSG values for VLT greater than zero.

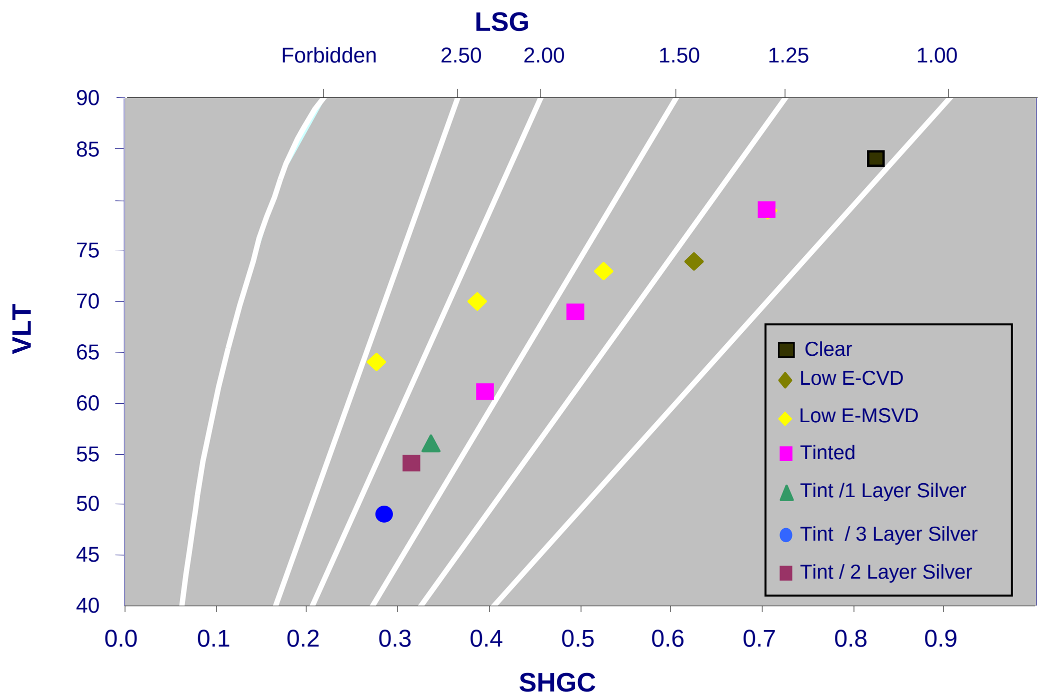


**Figure 4**. VLT and LSG as a function of SHGC shows behavior for 1,2 and 3 layer silver coatings on clear and tinted glass. Clear and tinted glass, along with CVD deposited coated glass are shown for comparison. Data are for an insulating glazing unit with two- ¼ inch clear glass lites separated by a ½ inch air space.

Over the next 5 years and beyond, the area of spectrally selective glazing for commercial buildings will receive increasing attention from R&D. New products will be based on designs to modulate the solar spectrum to produce a desired aesthetic, e.g., combining coatings with specialty glasses, and tuning the performance of the product for specific commercial building application, e.g., geographic location or orientation in a building. Since these variations are nearly limitless, the application of Building Information Modeling (BIM) will be critical in understanding glazing combinations in commercial building installations.  The glass industry's capability to design and produce spectrally selective glazing, combined with BIM will decrease the time and cost to design and build green, energy efficient buildings.

Although new products require additional investment in capital equipment and R&D, along with the expense of product rollout, the already existing equipment and knowledge base from previous generations of spectrally selective coatings contribute to reducing the expense and shortening the time to market. The glass industry has made significant investment in this area and will continue to leverage its investment in the future to develop new products that meet the needs of a changing market.

Table 2 gives a short summary of the current and future status of spectrally selective glazing in the areas of Commercial Applications, Glass Industry and Manufacturing Process.

| | **Current Status** | **Future Status** |
|---|---|---|
| **Commercial Applications** | High LSG based products (triple layer silver) yield immediate energy and environmental payback. Expect high growth. | BIM will be utilized to optimize glass & coating combinations to design energy efficient green buildings. In-building monitoring and feedback of performance will provide database for BIM. |
| **Glass Industry** | Significant R&D and capital investment made in this area. | Assets continue to be leveraged to reduce cost and time to market |
| **Manufacturing Process** | MSVD process is cost effective, environmentally friendly process capable of running family of low-E coatings. | Flexibility of MSVD process allows effective integration of non low-E products (PV) into manufacturing process. Emphasis will be on process control and modeling. |

## ELECTROCHROMIC GLAZING

Electrochromic glazing can be considered a major technical accomplishment, however, it has not met with broad commercial success. Generally, products do not reach the level of large scale success in the marketplace because they do not achieve a certain price point, have limited functionality, or lack broad aesthetic appeal. Today’s electrochromic glazing falls, to a greater or lesser extent, into all these categories. It does not met the price point, ranging from a factor of 5 to10 times over existing glazing systems due to costly components, complex manufacturing processing and installation. There is also additional hardware to power and control the system and the question of lifetime and warranty for the entire system. The aesthetics have limited appeal, due to, e.g., the coloring electrode imparting a deep blue color in the darkened state. Functionality is exceptional but restricted, since both visible and solar infrared regions of the spectrum change in transmittance simultaneously, and high LSG cannot be realized with this system alone. However, for low transmittance, low shading conditions this system has exceptional performance and has applications where it is desirable to reduce direct sunlight during the day, such as sunroofs. It is also effective in combination with spectrally selective coatings, but this further increases the overall cost of the glazing.

Figure 5 shows the transmittance as a function of wavelength in the clear and darkened state for an electrochromic device using thin film $WO_3$ as coloring electrode (Greenberg 2001). The chart illustrates the simultaneous change in transmittance in the visible and solar infrared portions of the spectrum from the lightened to darkened state.

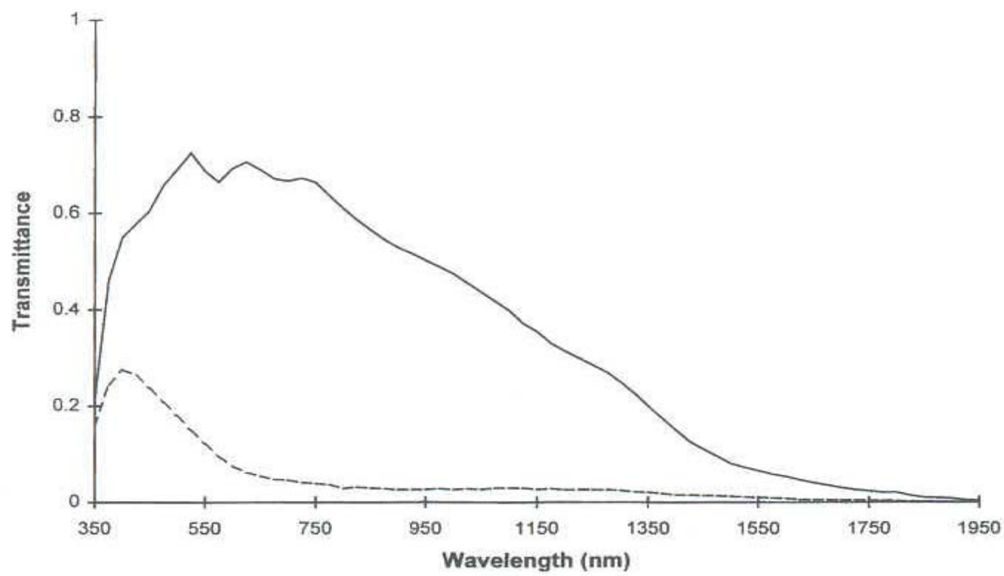


**Figure 5**. Solar energy distribution at sea level, air mass = 2 (taken from Greenberg 2001).

The most successful large area EC systems commercialized for windows include inorganic coloring electrodes, the most common being thin film tungsten trioxide ($WO_3$) with excellent optical properties. Suspended particle display (SPD) technology, which effectively scatters light in the off-state and is clear in the energized-state has been on the market for several decades, but has seen limited commercialization. Some EC systems have been successfully commercialized for non-window applications, such as dye based systems for dimmable aircraft cabin windows and automotive mirrors. This system is very simple in construction, requiring only an electrochromic dye between transparent conductive electrodes, but technical hurdles remain for large scale applications. Organic EC's, which claim to have the potential to become the lowest priced system with low cost materials and processing, have been explored in recent years. However, as with all organic systems, there are issues not only with stability upon exposure to sunlight, but with cycling between light and dark states during exposure at elevated temperature. New materials and technologies, combining electrochromic and photovoltaic functions to create windows that supply their own power to control transmittance, are now being explored in R&D labs, but they are at the concept stage [Georg, Georg and Krašovec 2004].

A successful electrochromic window should be an “all-in-one” product, covering the range of solar conditions. As a smart window, sensing and independently controlling visible and solar infrared transmittance, energy savings and comfort would be optimized. Fully functional (all-in-one), affordable electrochromic glazing with aesthetic appeal is less likely to appear in the next five years. Current electrochromic glazing will continue to have a position in the overall energy efficiency and design of building as cost and price are reduced due to improvements in manufacturing efficiencies. The real issue with all current EC technologies is that material properties will continue to limit the product’s applications and hence growth, and only incremental performance improvements could be expected. Over the next five years, the focus should be on more intensively exploring alternative systems, and improving manufacturing efficiencies for the current systems to achieve a reasonable price point. But overall, the outlook is more stagnant for EC than it is for spectrally selective glazing. Spectrally selective coatings combined with building information modeling to optimize efficiency will offer an overall better, much less expensive solution for the majority of applications. Table 3 gives a brief overview of some electrochromic technologies, their applications, and current and future status.

**Table 3: Electrochromic Technology**

| | Application | Current Status | Future Status |
|---|---|---|---|
| **Thin Film Inorganic, SPD** | Window glazing, sunroofs | Niche product for direct shading applications | Requires manufacturing efficiencies for price point and growth |
| **Dye Based** | Small Area Applications | Scale up difficult | Small probability for large area commercial product in next five years |
| **Organic** | Low cost, 5 years or less product lifetime | Concept stage | No commercial product in foreseeable future |

## PHOTOVOLTAICS – NEW AND “IMPROVED” PRODUCTS FOR THE GLASS INDUSTRY

The glass industry is now focusing on entirely new product areas arising from the trends in energy savings and the environment. The accelerated growth in the photovoltaic industry will lead to several new or improved products from the glass industry over the next five years in the areas of new glass substrates, transparent conducting electrodes and antireflective coatings which are deposited on the glass surface. Manufacturing processes already in place will be further expanded and upgraded to accommodate the growth of these new products.

**PHOTOVOLTOTAICS**

Glass as a technical material has only recently gained the attention of the PV industry. Although it does not generate power, the efficiency of the PV cell is directly dependent on the properties of the glass and the coatings on the glass surface. Glass also has the durability that other materials cannot match which is important for PV system maintenance, warranty, and lifetime. The PV industry has many rival technologies competing for a dominant position in the marketplace, and there is considerable debate among experts about which one will be the “technology of tomorrow.” In a very simplified view of the PV world, the technologies break down into two areas: crystalline silicon and thin film PV. Each has its strengths and weaknesses, and each has different requirements for a glass product.

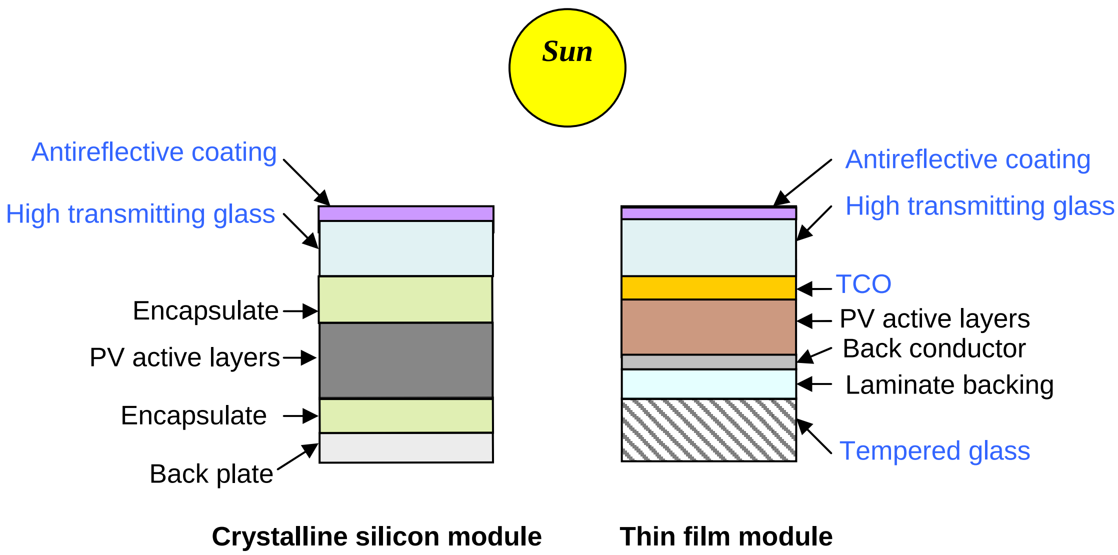


**Figure 6**. Basic schematic of a cross section of a crystalline silicon (left) and thin film module (right). Blue text denotes technologies from the glass industry.

The most important glass requirement for all PV systems is maximum transmittance over a particular wavelength range. To enhance transmittance, iron, the component of glass that is the strongest contributor to absorption and gives glass its characteristic green color, is reduced from over 1000 ppm to less than 100 ppm. An antireflecting coating can be applied to the outer surface of the glass to reduce reflectance losses and to further increase the overall efficiency of the module. Thin film PV systems require the addition of a transparent conductive coating deposited on the interior glass surface as an electrode to transport energy generated in the PV active layer. At the nanoscale level, thin film PV technologies are dependent on the interfaces between the active PV and transparent conducting layers for optimum efficiency. Figure 6 is a schematic diagram showing the basic crystalline silicon and thin film module cross sections, and the locations of the glass technologies (shown in blue) that are incorporated into the module.

Currently, and in the immediate future, crystalline silicon remains the predominant PV technology with about 90% of the global market. The module contains a high transmittance glass cover plate which often has a patterned surface to reduce glare, although this does not increase the efficiency. The next generation of glass products for PV cells will have high performance multilayered antireflective (AR) coating applied to the glass to reduce reflectance losses by 50% or more. One approach for the AR coating consists of using nanometer thick multilayers of metal oxide or nitride coatings which is designed to optimize transmittance in the spectral range for the particular PV system. The process to produce this coating also exploits MSVD technology used to produce spectrally selective coatings.

Because of its lower manufacturing cost, thin film PV technology is rapidly making inroads into the solar cell market with about 45% of the fabrication capacity in the U.S. Like crystalline silicon, thin film PV requires a high transmittance glass and antireflective coating. Thin film silicon and CdTe modules have lower efficiencies than traditional silicon cell modules, but shorter energy payback times because of their much lower manufacturing cost. These thin film PV approaches require a highly conductive transparent electrode on the glass surface in contact with the active PV layer. The coating most often used is fluorine doped tin oxide (SnO:F), a transparent conductive coating which is similar in composition to the Low-E product produced using the CVD process. Thin film silicon calls for a transparent conductive layer designed with a microscopically “rough” surface to more effectively scatter light into the cell, while CdTe, which is currently experiencing an upswing of sales in the industry, calls for a “smooth” transparent conductive electrode to prevent “shorting” of the active layers. Potential transparent conductors for thin film PV include aluminum-zinc oxide (AZO) and indium tin oxide (ITO). Organic PV represents an entirely new type of PV. First noted in publications by Tang [Tang 1979, Tang 1986] with efficiencies of 1%, organic PV’s now have efficiencies approaching greater than 5% in the laboratory [Plextronics 2007, Wake Forest University 2007]. They have the potential to be the lowest cost cell, using conventional printing methods and inexpensive polymer materials to manufacture the cell. There is, however, considerable more basic development remaining, and it is likely to be more than five years before commercialization. A key disadvantage of organic-based devices today, besides UV degradation, is their susceptibility to failure due to water and oxygen ingress into the active layer. Because of its barrier and transparency properties, glass is an ideal packaging material for modules produced with this technology.

Thin film technology PV will require a high transmittance substrate and highly conductive electrodes. Because the different thin film technologies have different performance characteristics, electrodes are needed that are particularly tailored to match up with their active layers to maximize cell efficiency. Thus, it is expected that there will be continuous development over the next five years and beyond.

As costs come down and efficiencies increase, photovoltaic systems are expected to find increasing direct applications in the energy efficiency and design of both residential and commercial buildings. The trend towards self sustaining or “zero” energy buildings is driving the concept of Building Integrated Photovoltaics (BIPV). BIPV will require an across-the-board effort in the building glazing supply chain. The glass industry will become the focal point between the PV suppliers and the glazing contractors, and provide solutions to overall integration of energy efficient and energy producing glazing.

Table 4 shows a brief status of photovoltaic (PV) technology. The matrix shows the critical development areas for the glass technology

**Table 4: Glass Technology Needs for PV Technology Segments**

| PV Technology | Low iron, high T glass substrate | AR Coated Glass | TCO Coated Glass (rough) | TCO Coated Glass (smooth) |
|---|---|---|---|---|
| Crystalline Silicon | ✓ | ✓ | | |
| Amorphous Silicon | ✓ | ✓ | ✓ | |
| CdTe Thin Film | ✓ | ✓ | | ✓ |

## INDUSTRY PAYBACK AND INVESTEMNT FOR NEW PRODUCTS

The success of these products will depend on energy efficiency for the dollars invested, and a net positive effect on the environment. The increasing price for traditional forms of energy and global economic expansion are major factors in determining how fast and to what degree development in these technologies moves forward. The glass industry has already expanded into these technology areas, and continues to make maximum use of leveraging their existing assets to keep cost under control and to accelerate the development and transfer of new products into manufacturing. Additional capital investment will be made in new key areas that are dictated by the macrotrends. But, considering the enormous costs of development and the desire to accelerate progress, partnerships between government agencies and labs, academic institutions, and the glass and core technology industries (e.g., PV) will be necessary in the future to alleviate these costs and reduce the associated risks.

## SUMMARY AND CONCLUSION

By providing solutions through the use of spectrally selective glazing, and development of key components for the photovoltaic industry, the glass industry is addressing the megatrends of energy conservation, the environment and aesthetics. Spectrally selective glazing will become enhanced through the use of coatings and high performance glass and the extensive use of modeling to optimize performance.

Application of Building Information Modeling (BIM) will be critical in understanding glazing combinations in commercial building installations. The development of PV will employ significant glass and coating technology resources for the immediate future and over the long term. Next generation antireflective coatings and highly conductive transparent oxide, and high transmittance glasses will be critical elements in increasing the efficiency of the photovoltaic cell. Electrochromic glazing, which has seen limited growth, will require advances in manufacturing efficiencies if it is to play a bigger role in commercial glazing. Alternative EC technologies should be explored to fully exploit the technology to create the all-in-one window product. Finally, industrial-academic-government partnerships will be necessary to accelerate future progress and alleviate cost of development. One thing is clear, that the glass industry's future path will be different than any time in its history, and the opportunity for growth will be great and driven primarily by energy, environmental, and aesthetic megatrends.

## ACKNOWLEDGEMENTS

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## TERMS DEFINED

<u>Visible Light Transmittance</u> (VLT) measures the percentage of visible light a glass transmits.
<u>Solar Heat Gain Coefficient</u> (SHGC) quantifies the amount of solar energy (heat) that passes directly through or is absorbed into a building through the glass.
<u>Light to Solar Gain ratio</u> (LSG) is derived by dividing a glass' VLT by its SHGC.
<u>U-value</u> is the measure of heat in British Thermal Unit (BTU) passing through the unit per hour (hr) per square foot (sq.ft.) per degree (° F). The lower the U-value the better the thermal insulating value of the unit.

## ABBREVIATIONS

| | |
|---|---|
| BIM | building information modeling |
| CVD | chemical vapor deposition |
| LSG | light to solar gain ratio |
| MSVD | magnetron sputtering vacuum deposition |
| PV | photovoltaic |
| SHGC | solar heat gain coefficient |
| TCO | transparent conductive oxide |
| VLT | visible light transmittance |

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