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Glasses for solar energy conversion systems☆

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Abstract

Solar technologies are projected to increase tremendously over the next 10 years. Glasses are playing an important role as transparent materials of photovoltaic (PV) cells and concentrating solar power (CSP) systems. Glasses are materials of short energy payback time and environmental compatibility suitable for sustainable energy concepts. The paper reviews recent solar applications. Surface structuring and coating of glasses are shown to improve energy efficiency for solar conversion systems substantially. Encapsulated glass-to-glass PV modules and solar photocatalytic glass surfaces are identified as elements of a green architecture combining renewable power generating and destruction of air pollutants of urban environments. Emerging solar technologies for power generation, including transparent PV modules, solar chimney and thermoelectric systems may become significant areas of future solar glass applications.

Keywords: Solar glass; Solar reflector; Solar glass receiver; Solar photocatalytic substrate

1. Introduction

Progressive growth in world energy demand is projected through 2030. Worldwide marketed energy consumption is projected to grow by 57% between 2004 and 2030, according to the International Energy Outlook 2007 (IEO2007) released by the US Energy Information Administration (EIA). IEO2007 shows the strongest energy consumption growth in developing countries outside the Organization for Economic Cooperation and Development (OECD), especially non-OECD Asia (including China and India), where robust economic growth drives the increase in energy use. Energy use in non-OECD Asia nearly triples over the projection period.[1]

In recent years, atmospheric concentrations of carbon dioxide, one of the most important greenhouse gases in the atmosphere, have been increasing at a rate of ≈0.5% annually. Because anthropogenic (human caused) emissions of carbon dioxide result primarily from the combustion of fossil fuels for energy, energy use has emerged at the centre of the climate change debate. World carbon dioxide emissions continue to increase steadily in the IEO2007 reference case, from 26.9×10^{12} kg in 2004 to 33.9×10^{12} kg in 2015 and 42.9×10^{12} kg in 2030, an increase of 59% over the projection period.[1]

Supply of energy via sustainable carbon-neutral processes is one of society's most important challenges. Solar energy is the largest carbon-neutral source of energy of global disposability. More energy from sunlight strikes the Earth in 1 h (6.3×10^{20} J) than all the energy consumed on the planet in a year (4.7×10^{20} J in 2004). The current exploitation of renewable energy is ≈7% (2004) of global energy consumption. The huge gap between our present use of solar energy (0.04%) and its enormous undeveloped potential defines a grand challenge in future energy research and materials technology.[2]

Glasses offer a high level of participation on combating climate changes due to their energy saving functions. Despite the relative high energy demand for batch melting and the generation of CO_2 during glass production, energy efficiency of glass technology has been increased in the last decades substantially via the use of recyclable post consumer waste glasses and reduced weight of glass products, e.g. container glasses by 25% (≈300 kg CO_2/1000 kg glass). The energy saving function of glass products, including low-emissivity double glazing in buildings, mineral wool and foam glass for insulation and continuous filament glass fibre for production of wind turbines,

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lighter vehicles, etc. compensates several times during service life for the energy consumptions of their production. Thus, the replacement of single with double-glazed windows will save 60 kg CO_2/year due to heat insulation compared to approx. 25 kg CO_2/m^2 emissions of manufacturing, i.e. the energy payback time is 5 months.[3]

Among the variety of engineering materials glasses offer superior optical properties and environmental compatibility preferred for solar energy conversion systems. Solar applications can be divided into different categories such as solar electricity, solar thermal systems, and solar chemical reactions.

1.1. Solar electricity

The development of PV cells, which convert solar energy in electricity, is driven by reducing the ratio cost/watt of delivering solar electricity. SEU2005[2] raises the factor of approx. 5–10 to compete with fossil and nuclear electricity and by a factor of 25–50 to compete with primary fossil energy. It is projected that these numbers will decrease substantially in the next years due to commercialisation of new cell concepts and progressively increasing cost for fossil energy. We will focus on the contribution of thin glass sheets and glass coatings to increase energy efficiency of PV cells including anti-reflection, light trapping and encapsulation.

1.2. Solar thermal systems

Developments are faced with cost-effective conversion of solar energy into thermal energy. The solar heat is then used to operate a conventional power cycle, such as a steam or gas turbine, or a Stirling engine. Solar heat collected during daytime can be stored in concrete, molten salt, ceramics or phase-change media. At night, it can be extracted from the storage to run the power block. Concentrated solar power (CSP) systems consist of solar collectors focussing and concentrating solar energy to a receiver or reactor unit. Besides power generation, high solar concentration temperatures above 1000 °C enable the efficient chemical production of fuels from raw materials without expensive catalysts. However, thermo-stable materials, like ceramics are needed to drive applications of this technology. At concentration temperatures below 1000 °C solar heat drives turbines that produce electricity mechanically with greater efficiency than the current generation of solar photovoltaic.[2]

Silica glasses are suitable materials for hot transparent devices. Also borosilicate glasses are used for insulation of heat pipes and as evacuated tubes in hot water panels. Beside glasses for hot applications the environmental performance of silvered glass substrates as reflecting material for the focusing systems are visited in this paper.

1.3. Solar chemical reactions

Solar UV-radiation induces abionic catalytic processes on synthetic and natural surfaces.[4] The photocatalytic effect of semiconductor metal oxides like TiO_2 has received much attention in the fields of purification and treatment of polluted water and air. The role of glass in solar catalytic processes is projected to expand in the next years due to environmental regulations. Currently, only a side effect, i.e. hydrophilicity, as the "self-cleaning" property of flat glass surfaces is exploited and commercialised. The catalytic properties of TiO_2 nano-particle doped porous glass layers and semiconductor thin films on transparent glass substrates for, e.g. destruction of urban air and liquid pollutants are mostly at the research and development stage. Results of a recent approach will be presented.

This paper addresses the different applications of glass in solar technologies with emphasis on coatings and surface modifications. It is intended to highlight recent material developments in the area. Therefore, it has only an introductive character which may open the way for a detailed study and future applications. Those 'bulk glass' applications that require specific optical, thermal and chemical properties are reviewed in a separate paper in these Proceedings.[5]

2. Glass for photovoltaic cells

Solar or photovoltaic (PV) cells convert solar energy into electricity by the photovoltaic effect. Assemblies of cells are used to build solar modules, which may in turn be linked in PV-arrays. Four generations of solar cells can be identified, which verify the fast evolution of device technology from the wafer-based silicon cells to composite photovoltaic systems. Still for terrestrial applications first generation solar cells, which consists of a large area, single-crystal, single layer p–n junction diode made of silicon wafers accounting for >86% (2007) of the solar cell market. Due to reduction of processing costs of bulk Si-materials, i.e. reduction of the amount of light absorbing material, a second generation of solar cells is developed which use thin-film techniques to deposit a thin epitaxial layer of semiconductor on lattice-matched wafers. Semiconducting materials include amorphous (a-Si or a-Si:H), polycrystalline and microcrystalline (poly-Si or μc-Si) silicon, cadmium telluride (CdTe), gallium arsenide (GaAs), copper indium selenide (CIS) and substitution for some of the indium with gallium (CIGS) for single or multiple p–n junctions.[6] Also thin-film crystalline silicon on glass (CSG) solar devices are developed which represent a balance between the low cost of thin films and the high efficiency of bulk silicon.[7] Second generation cells now comprise a small segment on photovoltaic market but a boosting of their shares is expected due to their good cost/efficiency performance. Third generation of PV cells is operating with modified concepts on the traditional p–n junction including photoelectrochemical, polymer, and nano-crystal solar cells, which are in the research and laboratory phase. A fourth and emerging generation of solar cells are discussed to consist of a composite photovoltaic technology such as e.g. nano-particles and polymers mixed together in a single multi-spectrum layer.[2]

Presently, solar cell energy conversion efficiency for commercially available μc-Si cells is in the range from 15% to 20% (Fig. 1).[8] The energy payback time of a modern photovoltaic module, assuming a working lifetime of around 40 years, is currently anywhere from 1 to 20 years. This depends on the type of PV panel used, the grid connection availability as well as the

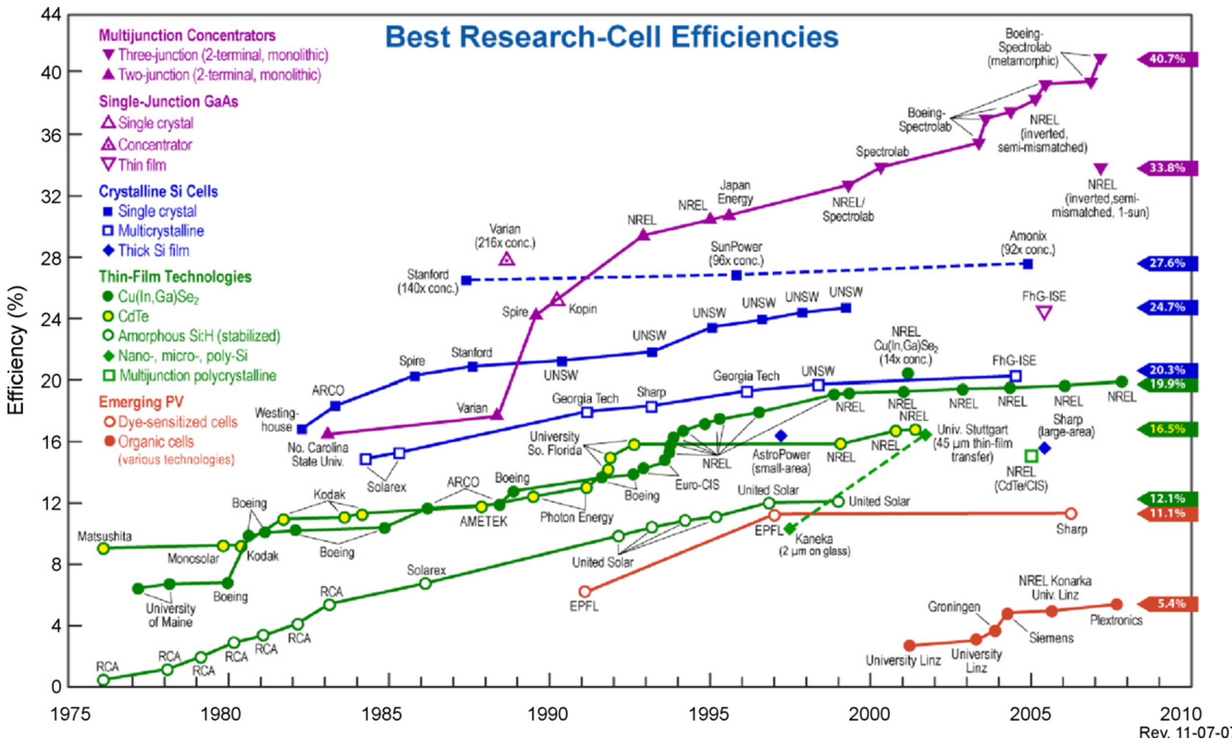

Fig. 1. Temporal development of best PV cell efficiencies, Courtesy of L.L. Kazmerski, National Renewable Energy Laboratory (NREL).

feed-in tariffs for electricity into the grid. Thus, solar cells can be net energy producers, i.e. they generate more energy over their anticipated lifetime than the energy expended in producing them.

Glass plays a mayor role in most of the different PV cell concepts preferentially as cover, substrate, and light trapping material. The use of glasses is attributed to their beneficial properties, i.e. excellent transmittance of photon energies required for the photovoltaic process, multifaceted coatability (AR and TCO), together with exceptional weathering and UV-resistance.[9] To meet material demands white soda-lime-silica glasses (float glass and cast glass) of low iron content are used, but also white borosilicate glasses are assembled.[7,10]

2.1. Light trapping and anti-reflecting

Light trapping via back-reflecting of photons at external glass surfaces and multiple reflections (scattering) of photons at internal glass/Si interfaces is part of present solar cell design. Additionally, modified AR glass/air surfaces to couple efficient light into the cell are used (Fig. 2).

To back-reflect sunlight structured faces and high profiles of front glasses are produced for crystal silicon cells by hot embossing or patterning under roller.[11] Usual pyramidally textured surfaces are used which trap back-reflected light inside the cell.[12] Draw back of figured glass, which has template patterns on the surface is the potential of dirt accumulation from environment and corrosion fostering non-uniform water films due to capillary forces. Alternative concepts of thin-film crystalline silicon on glass (CSG) texture the inside glass surface via a combination of sand-blasting and subsequently HF-etching. The two-stage treatment results in a μm-scaled hilly surface used for direct deposit of silicon.[7] The textured surface can be shifted into transparent conductive oxide (TCO) materials, e.g. ZnO:Al, by rf-sputtering on glass and subsequent texture-etching in diluted acids.[10,13]

Besides structuring of the glass surface, an AR coat at the outside glass/air surface is used to improve cell efficiency by interference and index matching. The AR coat consists typically of, e.g. a sequence of three or four deposited SiO_2, Si_3N_4 layers.[14] AR can be achieved also via etching of a demixed borosilicate cover sheet to produce a nano-porous silicate-rich

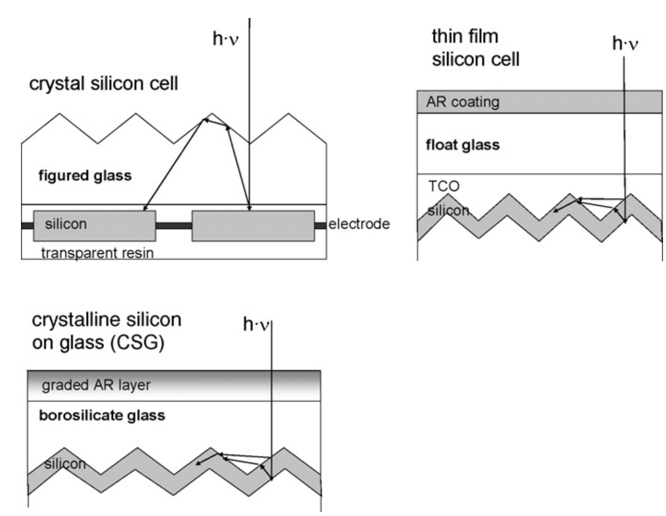

Fig. 2. Coated and figured solar glasses as part of crystalline silicon, thin-film silicon and crystalline silicon on glass cell concepts. Arrows indicate paths of multiple reflections.

surface layer of an effective refractive index below 1.46.[7] Gradient refractive index AR coatings produced by etching of the glass substrate result in beneficial optical properties and good chemical durability.[15] Porosity based on etched structures of demixed glasses are however limited to suitable compositions, e.g. borosilicate glasses.[16] A low effective refractive index is also evident for nano-porous quarter wave AR coatings synthesised by sol–gel technology.[17,18] In this route, which goes back to the invention of Moulton,[19] the sol consists of colloidal silica particles of ≈20 nm size.[20–24] Measurements under standard test conditions (STC) show a current gain of 2.65% with the AR glass, whereas an additional current gain is obtained at high light incidence angle.[25] Besides the sol–gel route, a double-layer porous SiO_2 AR coat on float-glass is produced by plasma-enhanced chemical vapour deposition (PECVD) which increases the spectral transmittance weighted by the AM1.5G spectrum in the 400–1150 nm wavelength region from 91.6% to 99.4%.[26]

2.2. Encapsulation

The encapsulation of thin-film solar cells is made by a vacuum lamination process using an encapsulating copolymer (mostly ethylene vinyl acetate, EVA) and a sheet of glass as front, back, and both sides cover material, latter also finalised as, e.g. laminated safety glass with a PVB foil.[27] The lamination of copolymer encapsulating foils and glass sheets assure lower deflection, low creep, impact and structural performance over a wide temperature range and superior post breakage properties. Problems of this encapsulating technology are seen in the high weight and due to the glass/polymer interface at the edges where moisture and gas can enter into the photoactive layers and cause degradation.[28] Alternative concepts for flexible thin-film solar cells, which can be adapted to non-planar surfaces, i.e. a standard integrated part of construction components, use a multi-layer encapsulation system including an adhesive sealing layer, a barrier system against water vapour and gases and an outside layer for weatherability. Solutions are almost glass-free but the use of a roll-to-roll coat of an organically modified sol–gel-glass for the barrier system was reported.[29] However, long-term stability of polymer PV cells is a major issue to be resolved. Defect characteristics of encapsulated PV modules are induced by accelerated life time tests (damp-heat exposures) where glasses with reduced sodium content, e.g. by adequate SO_2 treatment, show reduced delamination and increased adhesion strength.[30]

2.3. Building integrated photovoltaic (BIPV)

Building integrated photovoltaic (BIPV) is one of the fastest growing segments of the photovoltaic industry. Architectural glasses can be functionalised with encapsulated PV modules for facade, roofing and overhead glazing.[31] Lamination and encapsulation of solar cells, primarily as crystalline silicon but presently also as a-Si and thin-film CIS/CIGS between glass sheets bring additive value to architectural elements.[32,33] When glass-to-glass encapsulated thin-film PV modules are integrated into a building during construction, the incremental costs of the system are reduced while a significantly reduced demand for peak electricity, reduced transmission losses and the ability of back-up power is provided. Translucent or patterned panels which offer an aesthetic effect are produced.[34] Different types of transparent modules are used as glazing, most common crystalline silicon as single glazing or double (low *U*) insulation glass. The transparency rate is defined by distance between solar silicon cells which are patterned, e.g. produced by laser drilling.[35] They can be also a part of shading devices (shadowvoltaic systems) whether movable or not.[36] Further development searches for higher transparent modules as electricity generating windows, by the use of silicon nano-powders which enhance the power output of conventional solar cells by up to 70% in the ultraviolet light range and 10% in the visible.[37]

3. Glasses for solar thermal collectors

Different devices are designed to absorb and transform solar energy into heat. Solar thermal collector systems consist of a reflector, a fluid heat transfer circuit, and a storage system including a heat exchanger. Systems can be used in a variety of ways, mostly for domestic application as warming domestic hot water (solar hot water panels), heating water for a radiator or floor-coil heating circuit, but also for industrial use including dryer and evaporation systems.[38]

Solar power plants use various types of thermal collectors, such as parabolic reflectors and solar towers with surrounded heliostats to generate electricity in a power station by heating water to produce steam and driving a turbine connected to the electrical generator. In the first concept a trough-shaped parabolic reflector is used to concentrate sunlight on an insulated tube or heat pipe, placed at the focal line, containing a coolant which transfers heat from the collectors to the boilers in the power station. Also single dish-shaped parabolic reflectors are designed in combination with a positioning system, which tracks the sunlight. In solar tower plants the heliostat mirrors align themselves via dual axis to focus sunlight on a receiver at the top of the tower; collected heat is transferred to a power station below. Presently, the generation of power in solar thermal plants is a fast growing market, thus U.S. Department of Energy estimates that by 2020 more than 20 GW of concentrated solar power (CSP) alone will be online in the United States.[39,40]

Glasses are used for central components of domestic solar collecting systems (flat plate or evacuated tube) such as transparent cover material and as evacuated tubes to reduce conducted heat losses of solar hot water panels.[41] For solar power plants mirror substrates are mostly flat (heliostats) or bended (parabolic) float glass sheets which are silver metallised at the back surface,[42] but also high transmission glasses for heliostats are developed.[43] Receivers consist of a glass to metal seeded borosilicate cover tube. The surrounding glass insulates the coated pipe from weather effects (wind) and reduces convective and conductive heat loss.[38] High-temperature pressurised volumetric receivers for solar thermal tower plants are covered by a cooled silica window to keep operating temperatures <800 °C.[44,45]

Solar chimney technology is being proposed. Air is heated underneath a large-scaled glass structure (collector roof), and passes up a chimney through a wind turbine near the base as it rises.[46]

3.1. AR coating and heat insulation

The receiver of a trough concentrator is typically a metal absorber surrounded by a glass tube. The absorber pipe is lowE coated to permit incoming radiation in the visible range, and to decrease emittance (or radiative loss) in the infrared wavelength. Temperatures at the absorber pipe can reach up to 400 °C. Borosilicate glass tubes are used due to their low thermal expansion and superior environmental resistance. The gap between the absorber tube and the inside of the glass is sized to minimize heat loss across the air gap. Glass is also a radiation barrier to infrared light so it reduces heat loss due to radiation. Since the light from the parabola must first pass through the glass before it hits the absorber, the glass reflectance losses at the outside and inside glass/air surfaces, and absorption losses in the glass itself have to be minimised. Therefore, glass tubes are coated with an AR layer to minimise optical losses due to reflectance.

An industrial breakthrough was achieved by inventing an adherent AR coating on borosilicate glasses via the cost-effective (vacuum-free) sol–gel technology.[47,48] Traditionally, broad band quarter-wave AR-coatings are found to be suitable for passing through incident radiation efficiently from UV to infrared wavelength.[49,50] Effective refractive indices between glass (1.5) and air (1.0) are achieved in these coatings by porous media (nano-porous SiO_2 sol–gel coating) and by periodic or stochastic sub-wavelength surface-relief structures via embossing in organically modified sol–gel and acrylic materials.[51,18] However, former porous SiO_2 coatings were shown to display insufficient adhesion strength and wiping resistance on borosilicate glass, i.e. coated glass tubes will loose their AR effect shortly during operation. Helsch et al.[52] found that phosphoric acid enhances adhesion of a porous silica coating considerably when added to the dipping solution of the sol–gel process. They developed a quarter-wave (≈110 nm) thick and porous (≈35%) silica-rich layer with an interface, after firing at 500 °C, accumulated on sodium and phosphorous ions.

Taking all AR factors into account, the peak optical efficiency of a parabolic trough receiver is in the range of 70–80%. Since thermal losses from the receiver are relatively small and increase only moderately as operating temperatures increase, at peak conditions, a trough can be expected to deliver at least 60% of the radiation incident on the collector even when taking into account heat losses in the solar field piping.

In tower receivers, which are exposed to the concentrated solar radiation of the heliostats, temperature can reach more than 1000 °C allowing in principle higher efficiency rates of energy conversion. To compensate for reflectance losses of window materials of a volumetric receiver AR coatings based on porous SiO_2 are developed (Fig. 3). Extremely low sintering rates for the operating temperatures of the window assure long-term stabile AR of quarter wave thin-films based on porous silica.[50]

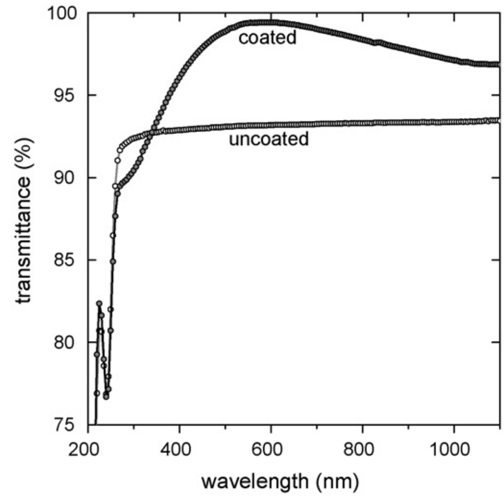

Fig. 3. Spectral transmittance of a cover glass for a high-temperature cavity receiver of solar tower plants: silica glass (4 mm) and coated with porous SiO_2-bearing sol–gel layer.

3.2. Environmental compatibility and degradation

Environmental variables have an important effect on the reliability of many solar products such as coatings and polymeric composites on glass.[53] Long-term prediction of their performance must take into account the probabilistic/stochastic nature of the outdoor weather. Thus, degradation of functional materials and consequently a loss of performance is a crucial factor for the economic viability of solar systems.

The use of silver as an optical thin-film material on glass for production of elements for regulating solar energy transmission, especially for highly reflecting mirrors of solar thermal devices, requires appropriate environmental protection. The poor compatibility with environment is based on mechanical and chemical properties of silver. Consequently, silver can readily be abraded and an impairment of optical properties occurs due to corrosion if the silver mirror is exposed without protection against the environment. For this reason the silver layer of solar mirrors is located on the back of the substrate and covered with a protective coating which usually comprises a copper layer as well as varnishing in a stacked layer system produced by combination of thin and thick film techniques.[42] Materials are selected for the optical properties and by the necessity of increasing the resistance of the silver layer relative to environmental influences. Solar mirrors can be stabilized on the back of the silvered glass substrate by an additional sheet of glass, metal, or glass fibre reinforced polymer. By using inorganic glass as substrate of the solar mirror, service life of 20 years and more is projected even under extreme climatic conditions. The glass substrate, in general a thin (3–4 mm thickness) high transmission float glass of significantly lower iron content than normal float glass and in contrast to organic substrates, is not requiring any protection against the UV content of the solar radiation. However, the viability of solar thermal systems depends on a durable low-cost reflector. Thus, comparative assessment of solar concentrator materials, including anodised sheet aluminium, thin-film coated anodised aluminium, and lacquered rolled aluminium are performed.[54–56]

4. Glasses for solar chemical reactors

Besides water heating and power generation, solar collectors can be used for heating chemical processes including the generation of (i) energy carrier media, e.g. hydrogen, synthesis gas, ammonia, methanol, aluminium, (ii) primary materials, e.g. calcination of limestone, reduction of ores, desalination of water, production of carbon fibres, of nylon, of vitamin D, (iii) radiation induced reactions, e.g. the treatment of surfaces (alloy formation), decomposition of toxic substances. Latter category applications, i.e. photocatalytic processes, are currently a vital field of development since, in principle, a solar collector system is dispensable and the area of non-shaded surfaces in residential and industrial architecture is enormous.

4.1. Photocatalysis

Photocatalytic oxidation (PCO) is based on the photochemical production of an electron–hole pair in a solid semiconductor under irradiation by light of energy greater than its optical band gap. Among the many semiconducting materials, titanium (IV) oxide (TiO_2) has proven to be the most suitable photocatalyst. Suggested applications can be divided into the area of environmental photocatalysis and into the area of photoinduced hydrophilicity, which involves not only self-cleaning surfaces, but also antifogging ones.[57] The types of photochemistry responsible for photocatalysis and hydrophilicity are completely different, even though both can occur simultaneously on the same surface.

"Self-cleaning" glass, which is produced by many of the major glass manufacturers are products based on the photoinduced hydrophilicity of TiO_2. Fundamental to these products, due to its optical and electronic properties, chemical stability, and low cost, is a thin film (typically 15–20 nm) of crystalline anatase grown by chemical vapour deposition (CVD).[58,59] On laboratory scale TiO_2-based photocatalytic films on glass for self-cleaning purposes are prepared also via sol–gel.[60,61]

Besides hydrophilicity the applications of photocatalytic TiO_2 for solar purification and treatment of polluted water and air are emerging.[62] Further, numerous studies have demonstrated disinfective effect of PCO, including the destruction of chlorine-resistant micro-organisms.[63] Various air borne volatile organic compounds (VOCs) have been investigated related to industrial, traffic, and indoor pollutants. Latter are part of solvents which are present in indoor air in the form of paint, binders, or glues. Their slow release in small concentrations from walls, furniture, and so forth can pollute the indoor air over years.

Glasses are often used as catalyst carriers due to their relative chemical inertness, the absence of harmful metal-support interactions and their ability of facilitating the action of promoters.[64] Both high surface area as well as low surface area can be achieved of glass catalyst carriers. The efficiency of the catalyst often changes with the substrate properties; therefore research is focused on discovering suitable substrate materials (Fig. 4).

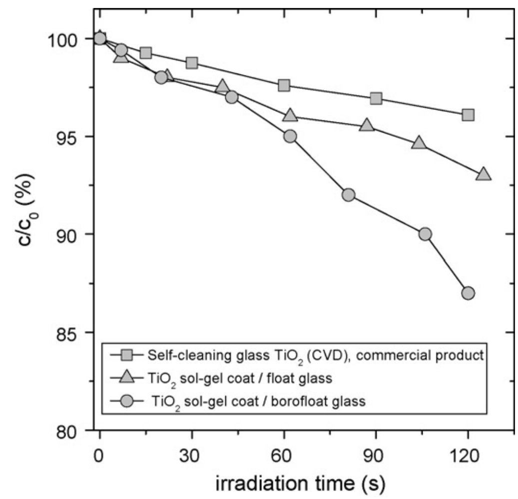

Fig. 4. Degradation of dichloroacetic acid ($c_0 = 5\ mmol\ l^{-1}$) as a function of UV-A irradiation time (thin-film reactor, $60\ W\ m^{-2}$ UV-A) of $0.024\ m^2$ sized samples of commercial self-cleaning glass (TiO_2-CVD coat), soda-lime-silica float glass (TiO_2 sol–gel coat), and borofloat glass (TiO_2 sol–gel coat).

Most gas phase applications are based on surfaces of constructions and architectural elements available without additional costs (e.g. building fronts, windows, sidewalks). Thus, the costs for the PCO are the differences between the active and the non-active materials which are comparable small (approx. 10–30%). Nevertheless, beside the hydrophilicity the activity of these coated materials compared with powder photocatalysts for water treatment is extremely small. Aqueous phase PCO is not established in the market so far. Two issues are essential: photon transfer limitations and mass transfer limitations.[65,66] Practical applications of solar PCO have so far been limited to ceramic tiles,[67] concrete paving blocks or sound-proof walls for NO_x-reduction.[68]

Additionally, TiO_2 with its absorption edge below 380 nm has photoactivity only under UV-light, utilize only a small fraction (2–3%) of the solar energy. Newly developed catalysts which are tailored to use visible light such as transition metals doped, nitrogen- and sulphur-doped TiO_2 or reduced band-gap catalysts will make more photons from the sun accessible and will reduce the investment costs in the same ratio as they enlarge the photon source.[69–72]

5. Outlook

Emerging nano-structured thermoelectric materials, in the form of nano-wires or quantum dot arrays offering a promise of direct electricity production from temperature differentials with efficiencies of 20–30% over a temperature differential of a few hundred Kelvin, require new glass solutions for reflector and concentrator devices. Solar power generation via chimney technology requires flat glass roofs with tailorised surface properties. Novel PV cells concepts require compatibility with glasses for architecture and mobility. The short list may reflect the wide range of future solar energy applications. Cost-effective glasses produced for these techniques may represent an opportunity to bring novel solar conversion systems to reality.

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