MEM4WIN

Ultra-thin glass membranes for advanced, adjustable and affordable quadruple glazing windows for zero-energy buildings

Publishable Summary

(m42)

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1 Introduction

Buildings are responsible for 40% of energy consumption and 36% of EU CO2 emissions [9]. According to the Energy Efficiency Plan of the European Commission [9], the largest cost-effective energy saving potential lies in buildings. Directive 2010/31/EU on the Energy Performance of Buildings (EPBD) [10] foresees that Member States should draw up national plans for increasing the number of nearly zero-energy buildings and the Commissions' Lead Market Initiative "Sustainable Construction" [11] aims at the development and growth of the sustainable construction market.

Windows are critical elements to control the energy performance of buildings especially for zero-energy buildings. It is of paramount importance to develop windows which show reduced U-value, weight and costs and certain features to control and harvest energy. Such a window will have a high impact in the window industry and will reduce greenhouse gas emissions as long as the window is affordable, can be used for residential and office buildings in every climate zone, for new constructions or in retrofitting of older buildings.

Therefore

(1) MEM4WIN developed a novel IG-Unit for quadruple glazing containing ultra thin glass membranes dedicated as frameless openable windows for direct application in facades. Due to this approach U-values of 0.3 W/m²K were achieved reducing weight by more than 50% and costs by 20%.

(2) MEM4WIN developed ink-jet printed organic photovoltaics (OPVs) and fully integrated solar thermal collectors for energy harvesting and micro mirrors for energy control and advances day lighting.

(3) Fabrication costs were further reduced by replacing conventional and cost intensive materials used for contacts like ITO and silver by graphene. MEM4WIN developed production methods like transfer printing and ink-jet printing to fabricate contacts for OPVs.

The developed technologies were integrated in a final demonstrated (see below):

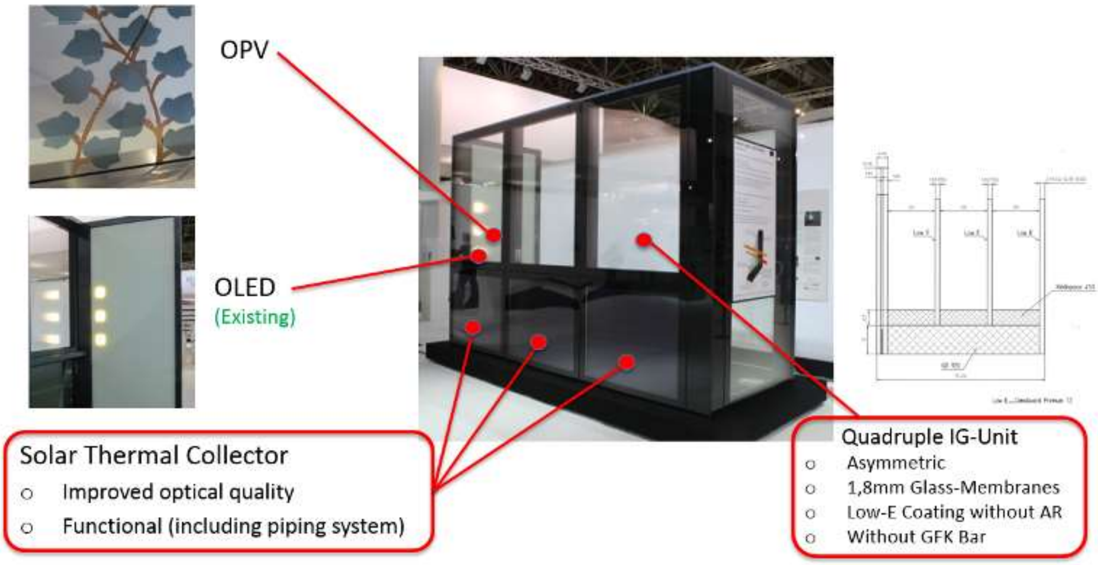

Figure 1: Final demonstrator of MEM4WIN

These single exploitable results of the MEM4WIN projects are described on the next pages:

- Tempered ultra-thin glass membranes
- Frameless, openable window for application in facades
- Novel lamination techniques for fabrication of OPV glass-glass modules
- Quadruple insulated glass unit with novel spacer technology
- Solar-thermal collector (fully integrated in IG-unit)
- Doped CVD Graphene for direct transferred transparent contacts
- LPE graphene ink for printing on organic solar cells
- Micromirror Arrays for Smart Windows
- OPV ink for direct printed organic photovoltaic cells

2 Tempered ultra-thin glass membranes

2.1 The idea behind

The weight of a window could be reduced by 50 per cent through the use of tempered ultra-thin glass membranes as middle or inner pane within a triple or quadruple IG-unit (down to ~0.9mm). But todays tempered glass applications like solar modules or other weight and transmission sensitive applications are based on thinnest commercial available glass – 3.0 mm.

The reason is simply the physical limit on conventional tempering furnaces based on ceramic rollers as transport system; these rollers are arranged in a certain minimum distance but still glass with a temperature close to Tg (at 650 °C) tends to deformation when passing the free space between the rollers, thus creating so-called roller waves in tempered glass, being visible as uneven deflection known from reflecting facades [1].

A new approach of air cushion transportation within tempering furnaces enables tempering of thin glasses without any roller waves, proven today already in glass thicknesses down to 1.8 mm. These thin glasses are used preferably in new solar module applications, enabling weight reduction as well as higher transmission. This technology is patent pending by LiSEC and a few installations within Europe and Asia are already existent.

Tempered thin glass opens up new unparalleled possibilities. Lightweight, flexible and durable glass units without optical distortions and lower stress for the spacer system are ideally suited for use in modern architecture with highly energy-efficient windows/facades. Using tempered thin glass allows for considerably lighter modules with remarkably better thermal insulation values and increased lifespan.

[1] . A. Aronen et al. Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition IMECE2011

2.2 Advantages

Due to the air cushion technology these developments allow to save energy for the tempering of up to 40%. The LiSEC air cushion system is ideal for surface-treated or double-sided coated glass sheets. The required energy is controlled by the air volume and can be immediately adjusted to a wide range of glass properties. (e.g. ultra clear, Low-E, Suncoat, enamel, etc.). No contact is made, which means there is no wear. Ceramic is a highly wear-resistant material. It distinguishes from conventional roller furnaces by

- The glass surface is not touched
- Air cushions are used instead of ceramic rollers
- Maximum convection in the circulation system
- Symmetrical energy input

The utilization of ultra-thin tempered glass membranes within highly energy efficient windows shows following advantages:

- Lower breakage losses due to thin glass sheets of enormous strength and flexibility
- Lower distortions in façade in the event of alternating climate loads due to adjustment of the inner panes to gas volume changes (while the outer pane remains in plane,

because the outer pane is thicker in order to be able to carry the wind loads)

- Lower stress on spacer bars while climatic loads due to flexible tempered thin glass adjustment to gas volume
- Lower loads on fittings and frames due to weight reduction
- Improved working conditions for window construction employees
- Higher transmission (+1% for each mm glass thickness saved) (less absorption through thinner glass)

2.3 Results

With a new air cushion tempering furnace LiSEC demonstrated in experiments that the glass thickness could be reduced down to ~ 0.9 mm. The membrane effect of the flexible tempered thin glass sheet in the unit considerably reduces optical distortions of the thicker exterior glass (thickness regarding wind loads). Even with large temperature changes, the structure compensates for pressure fluctuations occurring in the unit.

2.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
tempered ultra-thin glass membranes	LiSEC	0.9 mm thickness up to 40% energy savings in comparison with conventional tempering furnaces Minimum optical distortions (no roller waves)	From 2 to 8 mm marketable; less than 2mm R&D (test samples possible)

2.5 Contact

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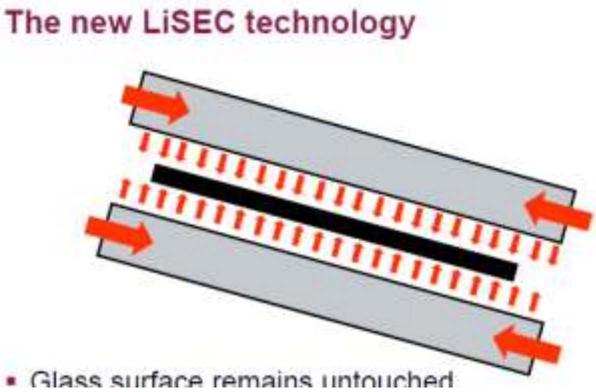
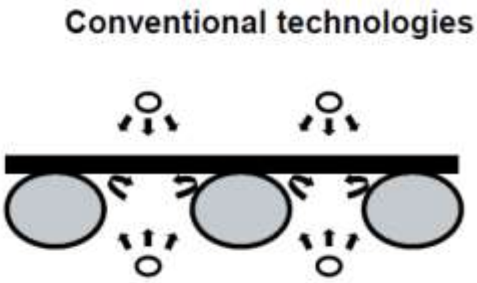
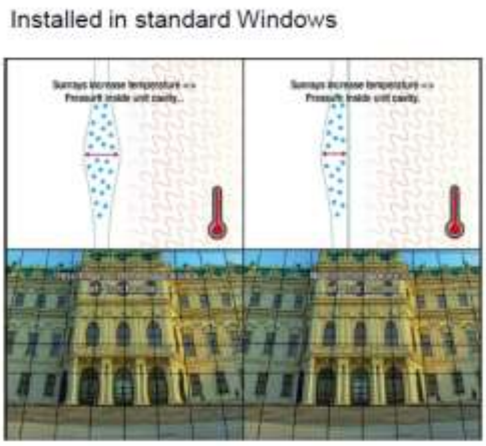
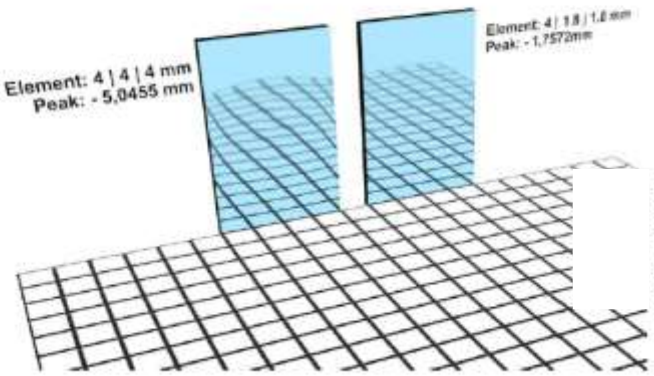
2.6 Pictures

Air Cushion Tempering Maschine









3 Frameless, openable window for application in facades

3.1 The idea behind

A new frameless window design allows reducing considerably the weight of windows as well the visibility of frames in facades. Specially, architects are increasingly giving priority to uniform “reflection” in facades as well as to no visual difference between the glass facades and openable window wings.

Therefore window elements within full glass façade were chosen; only for this application a certain element needs to have this capability, where architectural aspects of uniform “reflection” are preferred and have to be considered.

So a parallel outbound opening was chosen to be useful, incl. motorized drive in order to avoid implementation of manual opening elements.

3.2 Advantages

The output of MEM4WIN will be an advanced, adjustable and affordable quadruple glazing window for zero-energy buildings. Due to the use of ultra-thin **glass membranes** (<0.9 mm) in a **new frameless** window design **weight** is **reduced (50%)**. The new frameless window allows to be integrated in a façade without any visibility of the wing.

3.3 Results

The openable wing is not visible in the façade and there are low distortions in the appearance of the façade due to asymmetric construction of the IG-unit. This was shown with the presented exhibit at the Glasstec 2014 showed.

3.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
frame-less, openable window for application in facades	LiSEC	1. Openable wing not visible in the façade 2. Low distortions in the appearance of the façade due to asymmetric construction of the IG-unit	Certification proceeding in progress

3.5 Contact

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3.6 Pictures

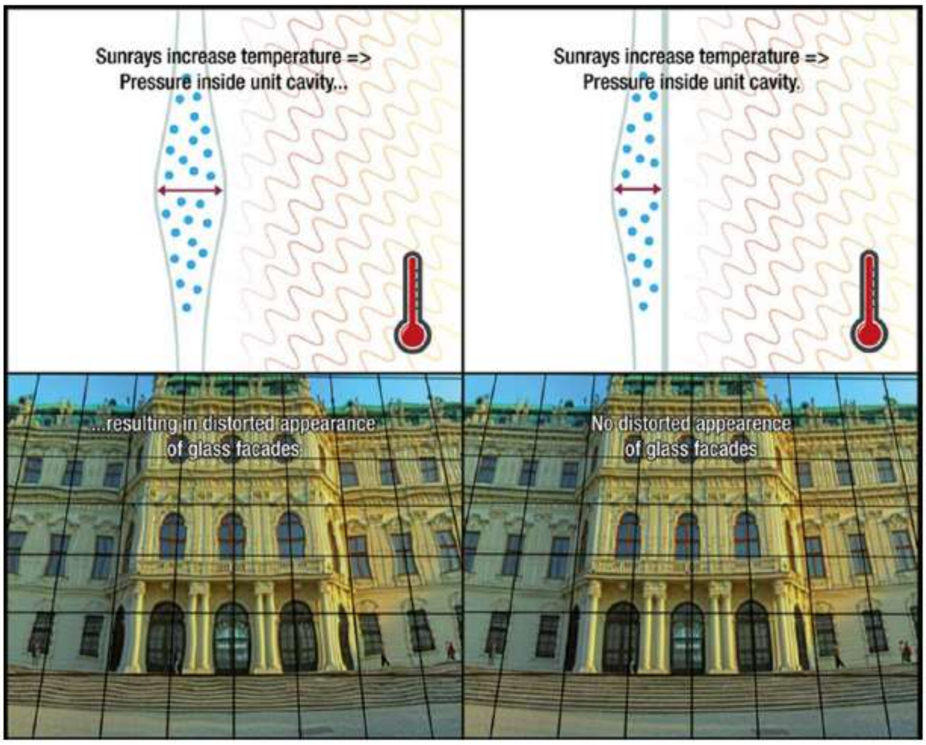

Figure 2: Reflexion

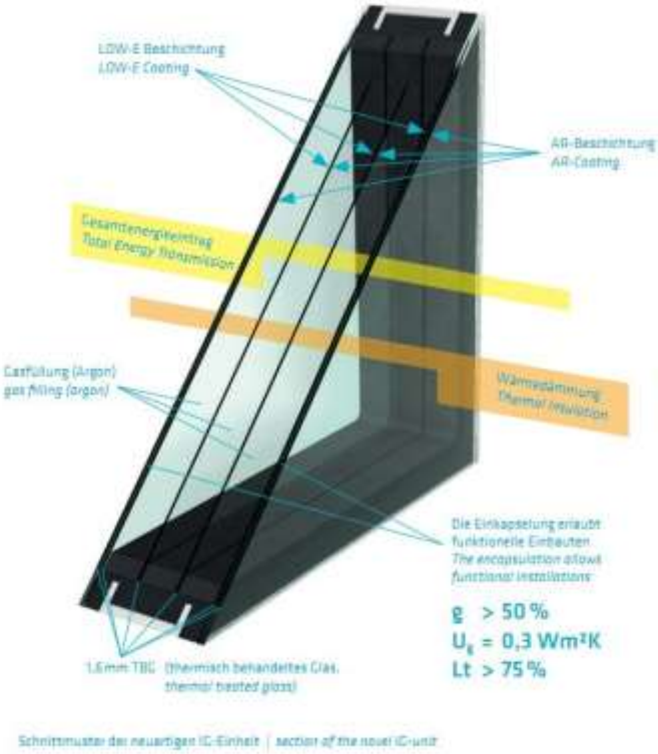

Figure 3: pattern of quadruple IG-Unit

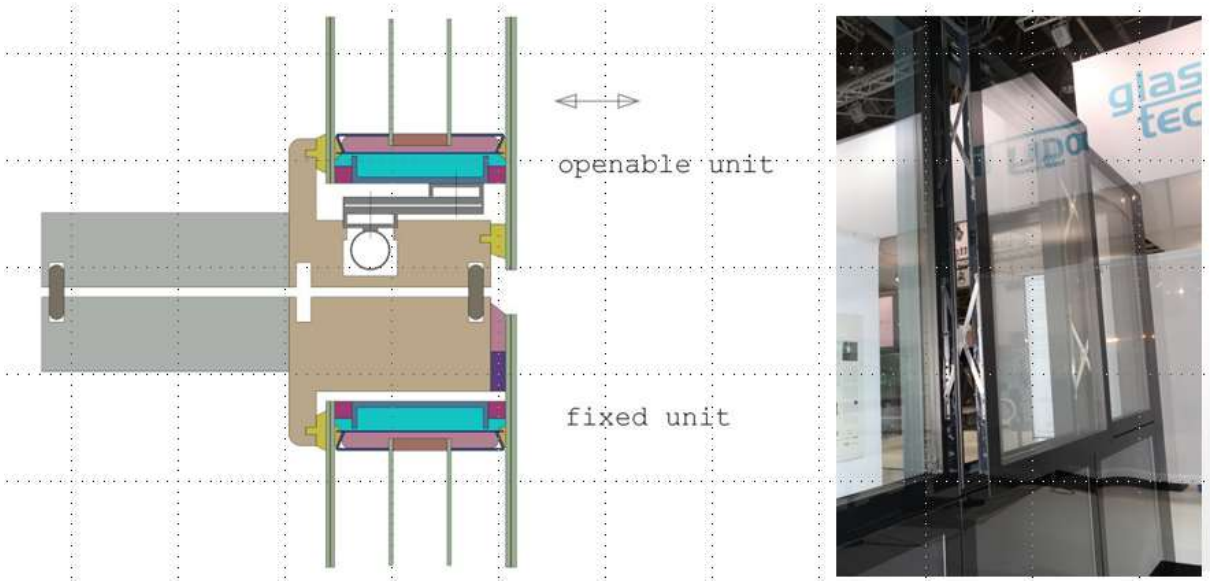

Figure 4: frameless openable window concept (left); openable wing in façade mock-up at glasstec 2014 (right)

Figure 5: illustration of façade mock-up for glasstec 2014

Based on the concept for parallel outbound movement of Siegenia Aubi a first frameless, openable window prototype with quadruple IG-units has been manufactured by LAT

Figure 6: visitors of glasstec 2014 examine the presented prototype of a frameless, openable window in quadruple façade glazing

Figure 7: exemplary mounting of frameless, openable window in quadruple façade glazing

4 Novel lamination techniques for fabrication of OPV glass-glass modules

4.1 The idea behind

Traditional PV technologies are well established in roof top or solar park applications but are not appropriate for integration into facades, shading elements or windows. Lifetimes of more than three years have been demonstrated for flexible modules. Accelerated lifetime tests predict lifetimes of more than fifteen years for glass encapsulated modules. With the new sealing technique which will be developed by LIS during the project we expect to achieve a durability of solar cells up to 30 years since the OPV will be encapsulated 700 times tighter than ever achieved so far.

4.2 Advantages

Integration of solar modules into insulating windows will lead to a mutual benefit: on one hand, the windows will be provided with functionality. On the other hand, OPV modules will be isolated from water and oxygen for up to 30years, which will greatly enhance their stability. The Lisec lamination technology with additional diffusion-tight edge sealing and the Krystalflex encapsulation foil protects OLED very well against environmental conditions.

4.3 Results

The several printed OPV modules produced by Belectric OPV GmbH are directly integrated in a diffusion-tight glass-glass-encapsulation with edge sealing and therefore the modules are perfectly protected against environmental influences. It was produced in a newly developed vacuum lamination process by LiSEC for glass-glass-laminates with edge sealing. Accelerated lifetime tests predict a lifetime of 30 years since the modules have been encapsulated with a water vapour diffusion tightness of 0.01 g/m²day. This value is 700 times better compared with lamination foils of conventional open module edge glass-glass modules.

The novel vacuum lamination technology has been designed especially for PV module encapsulation and is characterised by gentle pressing and extremely short cycle times. Pre-lamination with this vacuum lamination process takes just about 3 to 5 minutes. Since curing is performed in a separate cycle, the laminator no longer is the bottleneck in PV module production.

4.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
novel lamination technology for encapsulation of functional layers in glass-glass modules	LiSEC	< 0.01 g/m²day water vapour diffusion tightness due to additional edge sealing 4 min cycle time Max. size 3500x1700mm	

4.5 Contact

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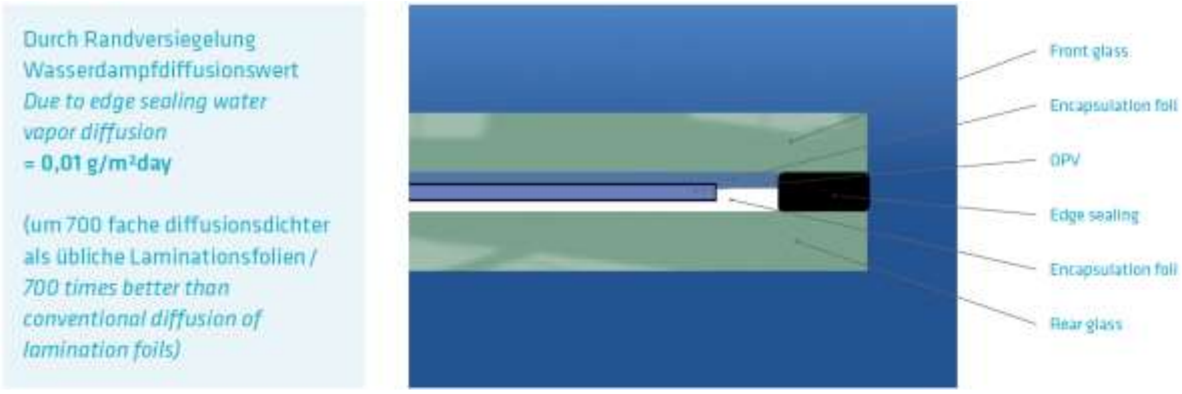

Figure 8 LiSEC modul encapsulation technology

Figure 9 Novel vacuum process laminator

5 Quadruple insulated glass unit with novel spacer technology

5.1 The idea behind

New legislative regulation for further improvements are in progress creating demand for further improved U_g-values, thus new design and manufacturing processes, materials and technologies are required. Since a simple step toward quadruple IG units is not feasible, these new challenges must be overcome like

- increase of weight due to 4 glass layers
- higher heat transition by higher amount of edge materials/sealant
- mechanical instability of edge connection between 4 glass layers
- lower light transmission with each additional glass sheet

5.2 Advantages

MEM4WIN will introduce a novel IG-Unit for quadruple glazing containing ultra thin glass membranes dedicated as frameless openable windows for direct application in facades. Due to this approach U-values of 0.3 W/m²K can be achieved reducing weight by more than 50% and costs by 20%.

The new quadruple insulated glass unit with novel spacer technology reduces weight and costs and lowers the U-value further (down to 0.3 W/m²K)

5.3 Results

The change in glass thickness from 1 mm to 1.8 mm for inner and middle panes is due to current availability of low-e coated glass. In near future availability of 1.3 mm glass will be given and can be considered. As outer laminate 2+2 mm glass laminate was chosen or also thicker glasses depends on the local situation to achieve required windload requirements. New calculations of the U-value show that the spacer filled with Argon gas can be reduced from 22 to 20mm, which helps to fulfill the requirements of profile manufacturers for less broad profiles.

5.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
quadruple insulated glass unit	LiSEC	0.3 W/m²K Ug-value < 0.60%/a gas loss rate	

5.5 Contact

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5.6 Pictures

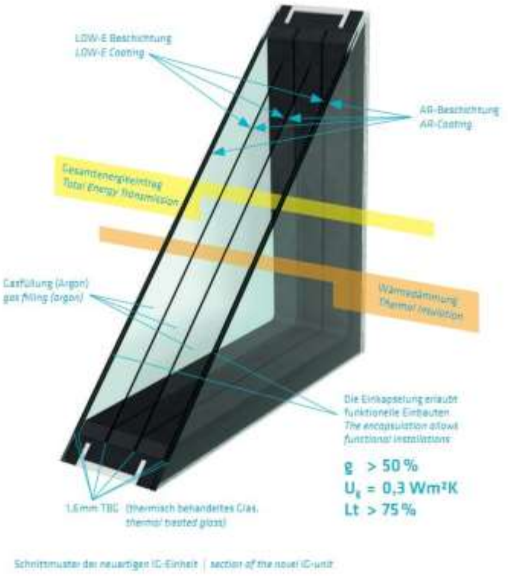

Figure 10: Section of quadruple IG-Unit

Figure 11: IG-unit exhibit @ glasstec

6 Solar-thermal collector (fully integrated in IG-unit)

6.1 The Idea Behind

The idea is to give the insulation not only the function of saving energy, but also to produce energy!

In Europe about 50% of the energy for the heating of buildings to be expended, therefore we want to reduce this demand in the form of solar thermal energy. Solar thermal collectors for energy harvesting are fully integrated in the IG-Unit.

The application in gas-tight insulation provides an ideal prerequisite for this type of collector.

The structures are not thicker than insulating, therefore allows the collector into existing mullion / transom constructions install.

6.2 Advantages

- Low panel thickness compared to conventionally flat plate collectors
- Energy losses reduced by insulating properties (gas-tight and low-e coating)
- Built in the facade 90 degrees with good optical appearance
- Improved energy efficiency in the transitional months

6.3 Results

Energy Glas has produced a gas-tight quadruple insulating glass collector with Lisec technology. The collector works and with improved performance data as a normal flat plate collector. It has better energy harvest in the transitional months and a very good optical properties of the collector for the façade. The insulating collector is gastight and flexible dimensions and special shapes are possible.

Figure 12: Solar-thermal collector (fully integrated in IG-unit)

6.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
solar-thermal collector (fully integrated in IG-unit)	**Energy Glas**	**> 80% optical efficiency > 300 W energy gain (vertical façade integration) < 50mb drop in pressure max. size 1m x 2m Special designs possible Delivery capability for test Installation from 2016**	

6.5 Contact

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7 Doped CVD Graphene for direct transferred transparent contacts

7.1 The idea behind

The objective is to replace indium tin oxide (ITO), which is the common material used as transparent conductive layer in electrical device, by graphene synthesised via chemical vapor deposition (CVD) and the use of a roll to plate process for the transfer. Graphene has a higher transparency than ITO and is a promising candidate for cost reduction, and for overcoming the shortage of indium supplying. Especially the roll to plate process that will be developed within the project is an easy and fast process to transfer CVD graphene from copper foils onto glass and will make it possible to handle graphene layers for mass production. The specific goal within MEM4WIN will be to fabricate large area CVD graphene, transfer it to glass and use it for OPVs, Micro Mirrors and OLEDs.

7.2 Advantages

Graphene layers should be capable of meeting the required minimum conductivities of 10^{-5} $S.cm^{-1}$ (for charge extraction layers) and area conductivities of 0.05 $S.cm^{-1}$ (for electrodes) while still providing transparencies of more than 80% over the whole visible and near infrared region.

7.3 Results

Within the framework of the MEM4WIN project we successfully achieved the transfer on glass plate of CVD graphene grown on copper. The investigation and optimisation works have led to a reliable CVD process for the preparation of defect free graphene. The developed transfer process has enabled the preparation of graphene on glass at lab scale. Four layers of graphene were grown and doped by CNR on glass and showed a resistivity around 25 Ω/□ and a transmittivity above 90%.

To enable large scale applications for graphene, all tools used for material growth and transfer needs to be scaled up. Within the project, a new CVD tool was developed. This new tool allows a significant throughput increase for the production of high quality monolayer graphene. This new equipment is capable of producing $400cm^2/h$ of monolayer graphene. The concept for this new system is fully scalable and could be used to produce very large area graphene > 1x1m.

First integration in OPV cell of graphene transferred on glass was realized. This attempt showed that with CVD Graphene it is possible to make functional solar cells and that the optical density is good. The OPV cell tested consisted of a layer stack of ZnO, P3HT:PCBM, and HIL were coated and a 300 nm Ag electrode was evaporated. The first trial gave 40%FF and 0.8% efficiency, which is very promising. With the optimized transfer process and with graphene doping, a stable sheet resistance of 35Ω/□ at a transparency of 90,2% were obtained with a 4-layer-graphene sample (5x5cm).

7.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
Doped CVD Graphene for direct transferred transparent contacts	CNR	~ 25 Ω/☐ sheet resistance ~ 90% transparency	~ 35 Ω/☐ sheet resistance ~ 90% transparency
CVD Graphene growth equipment	Aixtron	Growth of 6x6" monolayer graphene at a rate of 400cm^2/hr	

7.5 Contact

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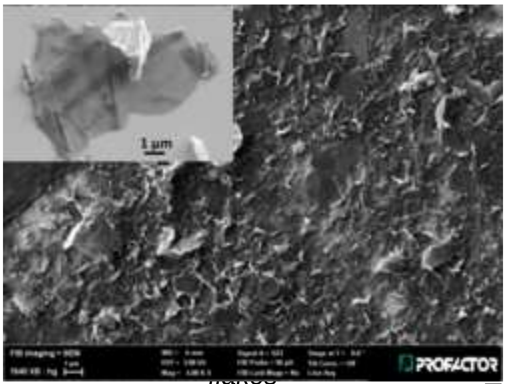
8 LPE graphene ink for printing on organic solar cells

8.1 The idea behind



Graphene can be produced by methods like growth on metal substrates by Chemical Vapor Deposition (CVD) or annealing SiC substrates [1]. However, for industrial applications also Liquid Phase Exfoliation (LPE) is a prominent way for a high-yield production of graphene flakes [2] (Figure 1). In this process a dispersion of graphene in a solvent is obtained that can be used as ink for inkjet printing (Figure 2). The top electrode in organic photovoltaic (OPV) solar cells is usually silver deposited by thermal evaporation [3]. Our goal was to replace the silver grid by an inkjet printed graphene pattern.

Figure 15: Graphene ink

A common solvent for LPE of graphite is N-methyl-pyrrolidone (NMP) [4]. However, it is forbidden to use with most of the print-heads, obviously, due to its high dissolution power. Moreover the reproduction toxicity of NMP can reduce the working place safety.Several suitable solvents for printing were investigated [5]; however, no organic solvent based graphene ink could combine all requirements: stability, compatibility with the substrate and high conductivity. Therefore it was decided to focus on the printing of graphene as hole-transport-layer (HTL). The HTL is the underlaying layer underneath the top electrode (Figure 3) and enables the transport of holes towards the top electrode and blocks electrons due to the favorable energy level.

8.2 Advantages

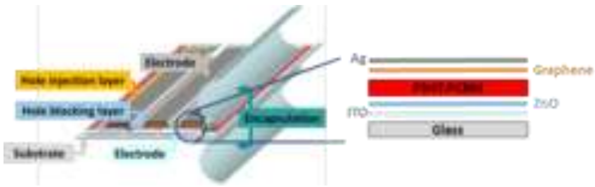


Figure 13: Scheme of organic solar cell

PEDOT:PSS, a transparent, conductive polymer, is widely used as HTL. However, due to its sensitivity to moisture and oxygen its use leads to limited life times even for encapsulated cells [6]. To improve stability we replace the PEDOT:PSS by inkjet printed graphene. Water can be now chosen as solvent since it is compatible with the underlying active polymer in bulk-heterojunction solar cells. Furthermore, water is compatible with print heads, low-cost and ecologically harmless.

8.3 Results

Graphite is successfully exfoliated in water and additionally concentrated to produce a graphene ink with 1 mg/ml. For inkjet printing the graphene flakes have to be smaller than 1 µm and the ink is further optimized for inkjet printing concerning viscosity and boiling point with additives. This is then incorporated into inverted solar cells with an active area of 27 mm² by inkjet printing on Glass/ITO/ZnO/P3HT:PCBM substrates in ambient atmosphere. Silver is used as top electrode. The cells showed efficiencies of up to 1.8 %.

Up-scaling processes and optimization of the ink are currently under investigation.

8.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
LPE Graphene ink	University of Cambridge	**Solvent** Water and organic solvents	Water
		Viscosity range 1-1800 Cp	3-1800Cp
		Solid contents 0.1-9 wt%	0.1-9 wt%
		Flake type Single layer to nanoplatelets	Single layer to nanoplatelets
		Flake size 20- 1000 nm	20- 1000 nm
		Graphene concentration 0.12-5mg/ml	0.12- 5mg/ml
		Deposition methods Inkjet-Screen-Flexo printing	Inkjet-Screen-Flexo printing
		Sheet resistance 100KΩ/sq - 5Ω/sq	4kΩ/sq-10Ω/sq
		Substrate compatibility Glass-Silicon-Paper-Plastic	Glass, paper, Plastic
			2 Patent, license to Cambridge Graphene
Graphite ink	TIGER	Sheet resistance 70 Ohm/square (screen printing)	Sheet resistance 70 Ohm/square (screen printing)
		Sheet resistance 4 kOhm/square (Graphite inkjet ink)	Sheet resistance 4 kOhm/square (Graphite inkjet ink)

8.5 Contact

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[6] K. Norrman et al. J. Am. Chem. Soc. 132, 16883 (2010)

9 Micromirror Arrays for Smart Windows

9.1 The idea behind

Daylighting in general should be preferred above electric lighting. It is free and characterized as a high illuminance with full-spectrum light which gives a perfect color rendering, variable angles of the light incidence, as well as a big variation in intensity and colors, which gives a positive effect on human well-being. Daylight can also offer a favorable thermal energy inside the buildings. However, daylight can also produce uncomfortable solar glare and very high luminance reflections e.g. on display screens, both of which interfere with good vision.

This problem can be met by a flexible system, which can fit the requirements of daylight illumination, glare protection and heat regulation all at the same time. In order to overcome these problems, millions of micromirrors can be implemented in the interspace of conventional insulation glasses, providing efficient transmission control and significantly improved daylight distribution. Such micromirrors have a size of less than 0,1mm², which means about 12 mirror elements / mm² or 12.000.000 mirrors / m².

Figure 16: Open State-Daylight

Figure 17: Closed State-Reflection

9.2 Advantages

Miniaturizing lamella blinds down to micromirrors has some very obvious advantages: Beneath segmentability and the "uncut" outlook, they are protected between the window panes against wind, weather and dirt. Furthermore the miniaturization is beneficial as well to considerably improve the mechanical stability of such devices. The electric field between the mirrors and the electrode upon the pane will make the mirror switch. This makes those mirrors maintenance free for their whole lifetime.

9.3 Results

In principle, the fabrication of micromirrors can be summarized in three steps: deposition of thin-film layers, micropatterning to define the mirror shape and release of the mirror using a self assembling step, in which the mirrors will stand up in a nearly 90º out-of plane position making use of the intrinsic stress of the deposited layers. Within MEM4WIN project, at University of Kassel micromirror arrays of the size of 10 by 10 cm² have been fabricated showing <1 mW/m² power consumption in holding position and at least 75% and 2% transmission (open and closed).

9.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
micro mirror arrays for control of solar radiation and light guidance	University of Kassel	< 0,1mm² mirror area, which means about 12.000.000 mirrors / m² <1 mW/m² power consumption in holding position at least 75% and 2% transmission (open and closed)	not yet marketable

9.5 Contact

Contact Information for	micro mirror arrays for control of solar radiation and light guidance
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10 OPV ink for direct printed organic photovoltaic cells

10.1 The idea behind

Traditional PV technologies are well established in roof top or solar park applications but are not appropriate for integration into facades, shading elements or windows. Solutions based on thin film technologies exist but are merely "building attached" rather than fully integrated into the building components and are thus not competitive, due to high costs and insufficient flexibility. Moreover, the traditional thin film systems do generally not meet the legal requirements for façade integrated systems. Most important, they do not offer any degrees of freedom in terms of design, as they are not easy to be tailored with respect to colour or transparency.
Organic photovoltaics are a promising alternative to traditional PV technologies, as they meet all of the requirements described above.

Figure 18: leaf design for final demonstrator

10.2 Advantages

Organic Photovoltaic Modules are due to their outstanding properties, such as

- semi-transparency
- light weighted
- availability of different colours
- design-freedom,

extremely suitable for the integration in glass and thus for the BIPV (Building Integrated Photovoltaics).

10.3 Results

Several printed OPV modules were produced by BELECTRIC OPV GmbH and integrated directly in a diffusion-tight glass-glass-encapsulation with edge sealing and therefore the modules are perfectly protected against environmental influences. An optimized semiconductor ink was developed by PROFACTOR (lab scale) and Tiger Coatings (upscaling) and OPV modules were inkjet printed with a total active area of 125 cm². In the next step OPV modules will be printed with an industrial inkjet printer, which combines perfect design-freedom with the ability to print very large areas. The industrial inkjet printer was developed by Durst . Apart from the MEM4WIN-Project, OPV Modules from BELECTRIC OPV were already used for the German pavilion at the World Expo 2015 in Milano, where stylised trees integrated with the OPV modules, which are embedded in a flexible film, provide shade for visitors and generate energy at the same time. A second shading system was installed in Addis Ababa for the Peace and Security Building of the African Union in the shape of the African continent.

Figure 20: MEM4WIN Inkjet Printer Prototype.

Printing width up to 160 cm.

10.4 Exploitable Results

Exploitable Results (ER)	Key Partner	KPI (technical possible)	KPI (marketable)
OPV glass-glass module with direct inkjet printed organic photovoltaic cells	Belectric OPV	Freedom of design approx. 30 years lifetime ~ 3% module efficiency with P3HT:PCBM	Freedom of design Lifetime >20 years Around 2% module efficiency with P3HT:PCBM
Industrial large-format inkjet printer for direct printing of active OPV layer on window glass	DURST Phototechnik	160 cm printing width 400 – 1600 dpi resolution up to 20 m²/hour productivity	

10.5 Contact

Contact Information for	OPV glass-glass module with direct inkjet printed organic photovoltaic cells	Industrial large-format inkjet printer for direct printing of active OPV layer on window glass
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