PROJECT FINAL REPORT

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TREASORES - EXECUTIVE SUMMARY

The TREASORES project (Transparent Electrodes for large Area, large Scale production of Organic Optoelectronic Devices) has largely succeeded in its aims to develop and scale-up alternative electrode technologies that outperform widely used Indium Tin Oxide (ITO) conductive oxide layers deposited on plastic foil. Barrier materials incorporating such electrodes were scaled-up and shown to be suitable for organic large-area electronics. The Consortium composed of 9 industrial partners, 6 technology development institutes as well as 3 key universities demonstrated that such materials can be used for pilot-scale roll-to-roll production of Organic PhotoVoltaic (OPV) solar cells and Organic Light Emitting Diode (OLED, see Figure 1) light sources with commercially viable efficiencies.

Figure 1 Large area OLED devices fabricated by roll-to-roll process on a barrier electrode from the TREASORES project

During the project almost two thousand square meters of impermeable transparent barrier material were made and coated with electrodes - this combined production of barrier and electrode layers is a novelty of the TREASORES project that reduces production costs and enables thinner more flexible devices. OLED and OPV devices of up to 15 x 15 cm^2 were produced in quantity by roll-to-roll techniques, and the production of serial modular OPV devices several meters long has been demonstrated.

Four types of electrode material have been improved within the project (nanowires, nanocarbon, thin-silver and woven metal), and three of these have been made at pilot scale or larger using roll-to-roll processes and are expected to become commercially available in 2016. The fourth approach (using silver nanowires) has been protected by several patents from the project and license partners are sought. These new transparent and flexible electrode materials offer lower prices AND higher performance than the widely used ITO foils for the application areas targeted by the project.

The project has scaled-up and improved the hybrid organic-inorganic transparent barrier materials and demonstrated reproducible results using pilot-scale facilities. The performance of the best commercially available transparent barrier materials has almost been reached, but with production costs estimated to be an order of magnitude lower. It has been shown that organic electronic devices with useful lifetimes can be made using these barrier materials from the TREASORES project. Furthermore, an approach to barrier materials or pre-encapsulation layers on devices using Atomic Layer Deposition (ALD) has shown to be very promising (patent applied for).

The project has recognized a paucity of standards for flexible electronics, and sought to improve upon this by developing equipment and test procedures, and by active engagement in several standards committees, culminating in a pre-normative report under the auspices of the Versailles Project on Advanced Materials and Standards (VAMAS).

TREASORES – SUMMARY DESCRIPTION

Energy and lighting-panel technologies are dominated by inorganic technologies that have shown tremendous advances in the last decades. Solid light-emitting devices (LEDs) have reached excellent white light efficiencies well above 100 lm/W and silicon photovoltaic (PV) modules reach 20% at competitive prices[2]. Organic optoelectronic devices lagged behind these achievements until organic light-emitting diode (OLED) displays recently started to takeover important parts of the market[3].

Organic materials, however, present unique properties which can challenge traditional technologies. Above all, they can be easily coated onto flexible foil substrates, which means that high throughput processes such as roll-to-roll coating can be applied in the fabrication process - very low costs per square meter should result from this approach. Optoelectronic devices require at least one transparent electrode and it is clear that such an electrode must withstand the complete coating process. A further constraint comes from the fact that the ultrathin organic layers (less than 1% of the width of a human hair) and electrode interfaces are prone to chemical degradation upon exposure to ambient atmosphere. It is therefore mandatory to protect the devices using airtight encapsulation techniques. Ideally devices are encapsulated by glass lids, which is the present technology used for most OLED devices[4]. Such brittle barriers however prohibit roll-to-roll production of large area devices, which is seen as the only way to produce large area optoelectronics at a very low cost.

The TREASORES project (Transparent Electrodes for large Area, large Scale production of Organic Optoelectronic Devices) has sought to develop substrates incorporating barrier layers and electrodes that can withstand the stresses imposed by roll-to-roll manufacturing. Not only does the substrate have to be flexible enough to adapt to the curvature of the rollers, but it also has to withstand stretching and heating. Since polymer foils are the most industrially promising flexible transparent substrates (due to their low price and ready availability) they were used as the base substrates in TREASORES. The glass transition temperature of plastic foils such as PET is typically below 100°C which therefore limits the temperature in the process steps accordingly. Advantageously, the necessity for low processing temperatures also means lower production costs.

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[2] OSRAM press release 28.03.2014, “OSRAM constructs the world’s most efficient LED lamp; Prog.Photovolt:Res.Appl. 2015;23:1–9

[3] Z.R. Lee. (ed.), “Organic light-emitting materials and devices”, CRC Press, Boca Raton, 2015

[4] R. Martens (ed.), “The OLED handbook”, Ron Mertens, 2015.

To achieve its goals, the TREASORES consortium combined 9 industrial partners, 6 research and development institutes and 3 key research universities (see partner Logos in Figure 1).

Figure 1 Partner Logos of the TREASORES project

Most industrial partners operate roll-to-roll machines able to coat electrodes (Rowo Coating Gmbh, Canatu Oy, Sefar AG), barrier layers (Amcor Flexibles GmbH), organic solar cells (Eight19 Ltd) and organic light emitting devices (Osram AG and Fraunhofer FEP). Industrial partners Quantis Switzerland and Amanuensis were involved in life cycle analysis and project administration, respectively. Two technology partners were implied in the synthesis of barrier materials (Fraunhofer ISC) and coating, lamination and characterization of permeability (Fraunhofer IVV), respectively. CIC Nanogune developed barrier technology together with Osram AG. Fraunhofer ISE contributed to electrode development and organic solar cell characterization. Other technology providers such as Empa and the National Physics Laboratory (NPL) were involved in characterization of electrodes and optoelectronic devices. Finally the key universities mainly contributed in the development of electrode technology (Aalto University, Technische Universität Dresden PC department) as well as light-emitting electrochemical devices (University of Valencia) and organic solar cells (Technische Universität Dresden IAPP).

Together, these partners developed new substrates with integrated barrier and electrode and demonstrated the suitability of these materials for the fabrication of organic optoelectronic devices by a roll-to-roll process. The consortium gathered expertise in barrier coatings on polymer foils and electrode technologies using different approaches as well as device manufacturers capable of roll-to-roll fabrication. The large breadth of expertise within the TREASORES project allowed it not only to assess the new functional substrates in depth, but also to pinpoint the particular suitability of electrode technologies for specific applications. The ambitious goals set for the project required a dynamic interplay between TREASORES partners in barrier development, electrode development; device fabrication and roll-to-roll manufacturing (see **Figure 2**). Additionally, two partners were also active in life cycle analysis and standardization.

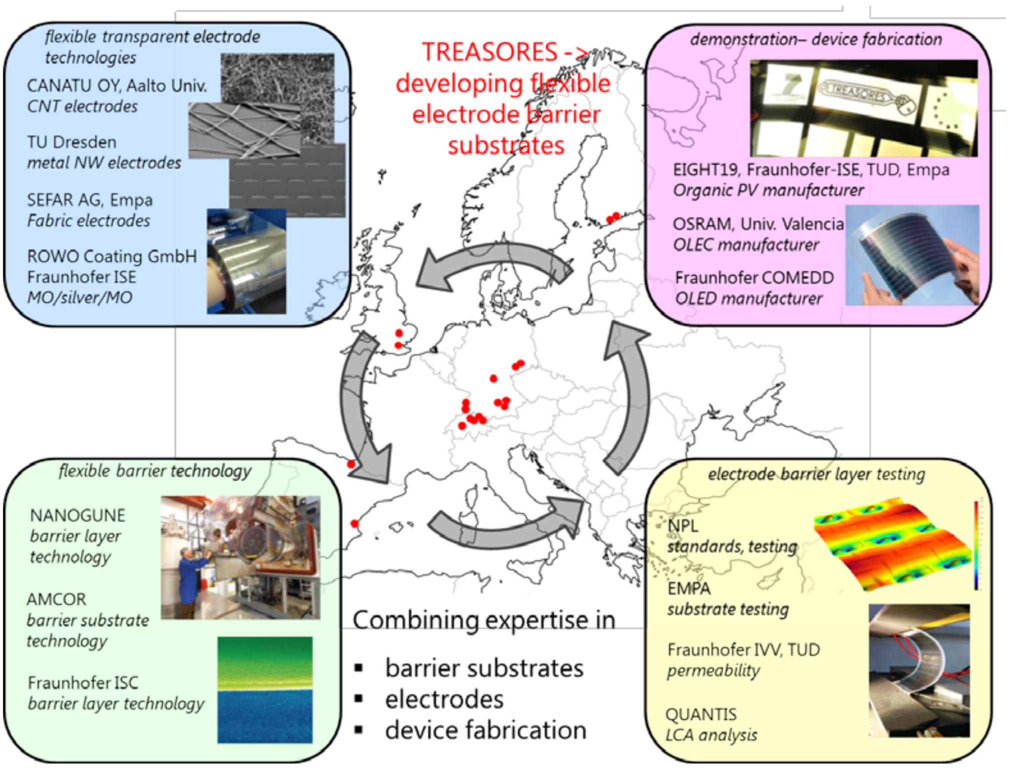

Figure 2 Collaborative effort in the TREASORES project showing the workflow used in the development of barrier electrode substrates. Partners are indicated in the Figure as well as their expertise.

The main goals of the project were as follows:

- Develop barrier substrates via roll-to-roll processing with low oxygen and water permeability and low fabrication cost

- Develop and scale-up roll-to-roll production of ITO-free electrode technologies with competitive prices including thin silver films (TSE), carbon nanotubes (CNT), fabric electrodes, silver nanowire electrodes (AgNW)

- Combine barrier substrates with electrode technologies and demonstrate roll-to-roll scale-up of such integrated barrier electrode substrates

- Assessment of electrodes and integrated barrier-electrode-substrates using optoelectronic devices. Demonstration of large area roll-to-roll fabrication of OLEDs, OLECs and OPV devices with high efficiency and lifetime

Quantitatively, TREASORES set very ambitious goals combining high technical performance with low costs. All thin film technologies were planned to be scaled-up at the end of the project therefore roll-to-roll production runs on kilometer scale had to be planned at the industrial partner's premises.

BARRIERS

Barrier development included two main developments.

a) CERAMIS® and ORMOCER® technologies

Solid production know-how of CERAMIS® and ORMOCER® stacks on PET was already available to the partners (in particular through the German Fraunhofer society alliance POLO®). It was known that robust large-area low-cost barrier stacks could be achieved by laminating two such stacks together via an adhesive (so-called face-to-face laminate) exposing the PET substrate at the outer surfaces of the laminate foil. In TREASORES the goal was to explore other laminate possibilities such as back-to-face laminates which expose one barrier stack as one of the outer surfaces of the substrate (TRE64). The advantage of this architecture is that the electrode and the active device are deposited directly onto the barrier; moisture and oxygen trapped in the polymer substrate can not leak out into the active optoelectronic device layers. The project's barrier performance target was for a water vapor transmission rate (WVTR) $< 10^{-4}$ g m^{-2} day^{-1}. Further improvement in the second half of the project was expected by combining this approach with ALD in order to achieve ultra-barrier properties with device lifetimes of a decade or more.

b) Development of ALD deposition process and atmospheric inline fabrication

Deposition of ALD barrier layers requires the use of highly volatile and reactive precursor chemicals. Part of the work of the TREASORES project was to investigate the effect of these chemicals when using polymer foils as substrates. For example, infiltration may occur, which is not observed for dense substrates. Once deposition parameters had been worked out on laboratory scale, TREASORES set out to construct a pilot line for the deposition of ALD barrier layers in a continuous roll-to-roll process at atmospheric pressure instead of under a vacuum. The target was to achieve a homogeneous ALD coating using the custom built inline coating equipment. The permeability target was set to $< 10^{-4}$ g m^{-2} day^{-1} for water vapour and $< 10^{-4}$ g m^{-2} day^{-1} bar^{-1} for oxygen.

TRANSPARENT AND FLEXIBLE ELECTRODE TECHNOLOGIES

This task encompassed four different technologies which can potentially compete with the present reference technology, i.e. ITO coated PET foils (sheet resistivity of 50 ohm/square, price range 30-50 €/m^2). These four technologies were thin silver electrode (TSE) films sandwiched between two oxide layers, carbon nanotubes also called carbon NanoBuds® (CNB), fabric electrodes, and silver nanowire electrodes (AgNW). As a general requirement for these novel electrodes a sheet resistivity of less than 10 Ohm/square and an optical total transmission of the electrode films greater than 90% were targeted. Additional targets were set during the progress of TREASORES for smoothness and mechanical stability of the layers. It was learnt that the electrodes have to be exceptionally smooth and clean (with roughness of the order of tens of nanometers or less) in order to get a satisfactory yield of devices.

a) TSE technology

The task was set in TREASORES to optimize TSE deposition parameters to achieve an optimum optical transmission/sheet resistivity ratio. Transfer of these parameters to a large scale roll-to-roll deposition plant operated by an small company was carried out in order to provide the consortium partners with roll material. Furthermore an inline optical inspection tool was installed in order to control the quality of electrode deposition during the process.

b) Carbon nanotube electrodes

Two development objectives were set in TREASORES. The first one concerned optimization of the dry CNT deposition process onto polymer substrates. The second one aimed to scale-up the method for a continuous roll-to-roll deposition process.

c) Fabric electrodes

This peculiar type of electrode consists of a woven fabric using primarily polymer fibers, but replacing some of these fibres by metal wires. An important goal in TREASORES was to planarize (i.e. to smooth) the electrode surface to an acceptable level for organic optoelectronic devices. Additionally it was foreseen to scale-up production using the partner's roll-to-roll facility. Organic semiconductors have low charge carrier mobility and therefore it is mandatory to introduce a conductive layer between the metallic wires in order to collect charge carriers. During the progress of TREASORES various combinations of fabric electrodes and the other electrode technologies were addressed.

d) Silver nanowires (AgNW)

The TREASORES tasks focused on ink development and deposition processes. Not only silver but also copper nanoparticles were foreseen. During the project, further tasks were set, in particular to reduce surface roughness, ameliorate conductivity and avoid high temperature annealing steps. Since no TREASORES partner was involved in scaling-up of AgNW electrodes, the main focus was to demonstrate flexible electrode films by industrially relevant methods.

BARRIER-ELECTRODE SUBSTRATES

The development and production of large quantities of polymer substrates incorporating a barrier and an electrode was mandatory for demonstrator fabrication at the TREASORES end-user’s premises. It was therefore an important objective in TREASORES and the choice on barrier and electrode technology was fixed at mid-term. The choice made was to use a version of the face-to-back laminate without an ALD layer, incorporating a TSF electrode. A major achievement was to produce a 400 m length of this roll material with consistently good barrier and electrode properties. In order to inspect such large areas of material (even longer lengths were produced during development) an existing automated system at the Fraunhofer FEP institute was refined and used.

ROLL-TO-ROLL PRODUCTION OF LARGE AREA OPTOELECTRONIC DEVICES

A final goal in TREASORES concerned the demonstration of roll-to-roll fabrication of near-market devices. Very challenging device performance parameters had been set by the TREASORES team, the most important ones being high efficiency and homogeneity of the devices. For LECs and OLEDs the efficiency target was set to 25 lm/W (compared to 15 lm/W for a tungsten filament bulb), while for OPV solar cells a power conversion efficiency target of 5% was fixed.

MAIN SCIENCE AND TECHNOLOGY RESULTS/FOREGROUNDS

INTRODUCTION

Results and foreground in TREASORES can be both attributed to efforts of individual partners, as for example regarding the development of electrodes or production equipment. On the other hand, an important proportion of the TREASORES results must be attributed to the collaborative effort between partners. In the field of optoelectronic device fabrication this poses some practical challenges, since barriers and electrodes must be shipped to other partners without damage. Another challenge arises from the cleanliness of the partner’s laboratories, which in few cases possess clean rooms facilities, but still have to deal with the transfer of simples from one environment to another. Organic optoelectronic devices comprise active layers of only a few 100 nm and therefore a few large surface defects or dust particles can be detrimental to the devices. A fortiori, large device surface areas are extremely critical with this respect. Ideally, all processing steps should therefore be carried out in dust-free environment. Roll-to-roll processing alleviates this condition somewhat. When winded up, the foil in the roll is protected against dust and mechanical solicitation, and can therefore be shipped to a partner’s site without the risk of contamination.

BARRIER FILMS

Organic optoelectronic devices pose very stringent requirements with regard to water and oxygen permeability through substrate and encapsulation. TREASORES developed a cost efficient large area barrier substrates in a twofold way. First it used its known CERAMIS® and ORMOCER® technology in a back-to-front laminate exposing the barrier on one surface of the laminate structure (TRE64) as schematically shown in **Figure 3**.

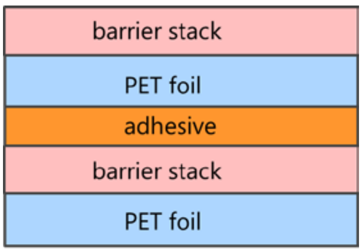

Figure 3 Barrier stack laminate optimized in TREASORES. Electrode deposition is subsequently carried out on the top barrier stack.

This hinders moisture and oxygen being trapped in the polymer foils to leak out into the active device layers after fabrication of the device. Water vapor transmission rates (WVTR) of $4{\cdot}10^{-3}$ g m^{-2} day^{-1} were achieved at tropical conditions scaling to 10^{-3} g m^{-2} day^{-1}at ambient conditions. Even though the project goals of < 10^{-4} g m^{-2} day^{-1} could not be attained by this barrier, it presents the advantages of roll-to-roll fabrication and low prices; these barrier substrates are cheaper by a factor of ten with respect to competing technologies. Two larger batches of barrier laminates were manufactured during the second half of the project. The last batch (TRE 64) was fabricated on a 1000 m scale.

Second, ALD deposition processes were developed which reached $2{\cdot}10^{-3}$ g m^{-2} day^{-1} for a single barrier layer on PET foil at tropical conditions scaling to a permeability of $5{\cdot}10^{-4}$ g m^{-2} day^{-1}at ambient conditions. Although not yet scaled-up, the patented technology is very promising and could potentially be used in combination with above barrier. Efforts to integrate ALD barriers within the robust CERAMIS®/ORMOCER® stack were not conclusive and still need more development. Additionally, an atmospheric ALD process was developed and roll-to-roll equipment manufactured to produce continuous ALD layers in an industrially relevant way (**Figure 4**). First such barriers on PET foil showed oxygen transmission rates (OTR) of $5{\cdot}10^{-3}$ cm^3 m^{-2} day^{-1} bar^{-1} produced by roll-to-roll. This corresponds to an OTR of $6{\cdot}10^{-6}$ g m^{-2} day^{-1} reaching the objectives of the project set in roll-to-roll ALD coating.

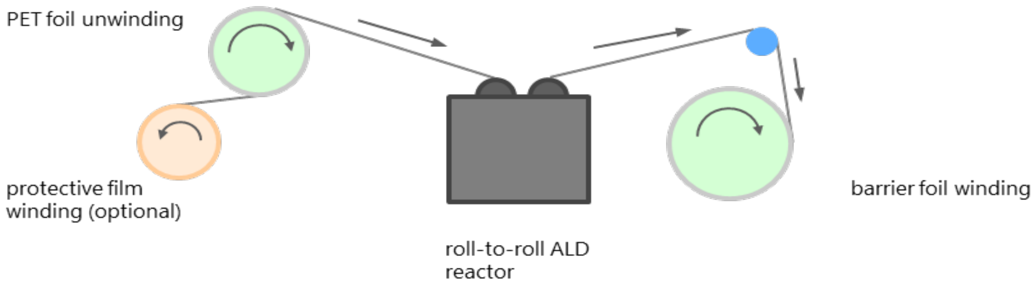

Figure 4 Schematic drawing of the inline roll-to-roll fabrication equipment developed in TREASORES.

ELECTRODE TECHNOLOGIES

The consortium reached its goals in electrode fabrication already during the first period, but needed to substantially improve surface roughness and defect density in order to avoid shunts in large area optoelectronic devices. As shown in Table 1 average roughness could be significantly reduced down to a level, where it becomes comparable to sputtered ITO electrodes on PET foil. **Figure 5** shows an example of the optimization effort carried out by the fabric electrode manufacturing partner.

Table 1 Summary of the figures of merit of ITO free and flexible electrodes developed in TREASORES. All electrodes are coated on PET substrates, except for AgNW where the substrate is PEN. The optical transmission value in bracket means that a bare PET foil reference was subtracted.

Electrode type	Optical Transmission (visible spectrum)	Sheet Resistivity Ohm/sq	Roughness (RMS) nm	Roughness (peak to valley) nm	Bending 1000 cycles r= 5mm Ohm/sq
ITO reference	80 %	50	1.4	40	+0.6
TSE	84 % (87 %)	7.5	4.4	72	+0.07
Fabric	87 %	0.02	2	21.1	+0.02
Fabric + TSE (no wires)	81 %	7.5	23	157	+0.24
CNB	83 %	34 4pt	11	97	-7
AgNW	80 % (PEN)	16	25	100	not tested

This activity of improving electrode performance and reducing surface roughness led to a dozen scientific publications, which are technologically interesting, since they describe low temperature processes to reach flat electrodes[5]. Electrode technologies were also combined during the second half of the project. This is of particular importance to woven fabric electrodes which conduct electricity by means of metallic wires, but which are insulating in between the wires. Low mobility organic materials require conductive surfaces to transport charges to the collecting wires, this being the reason why combining fabric electrodes with all other electrode technologies, respectively, has been a task in TREASORES.

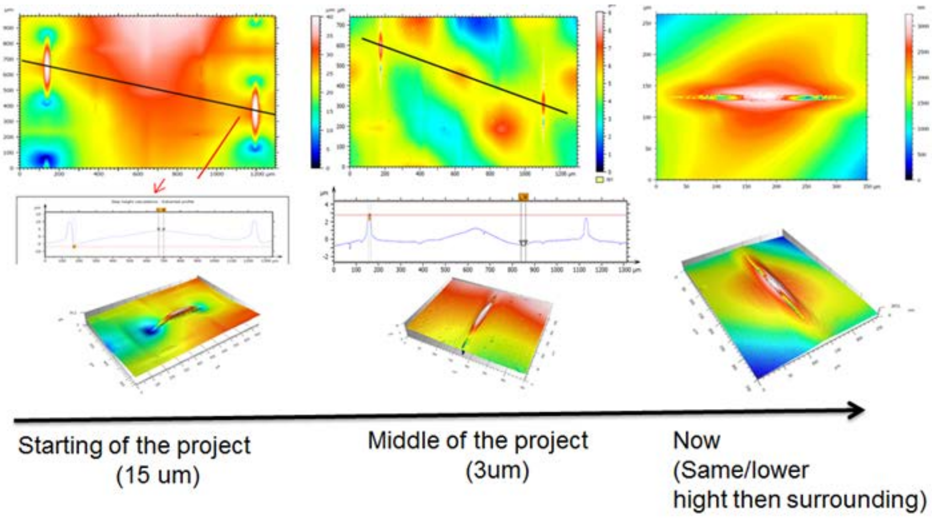

Figure 5 Reduction of surface waviness of fabric electrodes during project progress.

SCALE-UP OF OPTOELECTRONC DEVICES AND DEMONSTRATORS

At the mid-term review meeting the consortium decided to use TRE64 barrier laminates with incorporated TSE for the development of demonstrators. One of the TREASORES goals was to demonstrate large area devices by roll-to-roll fabrication and therefore about 1000 m of barrier foil was required in order to produce the barrier laminate TRE64 and to incorporate the TSF electrode. Four partners were responsible for scale-up using roll-to-roll fabrication. Notably the barrier-electrode substrate retained all its barrier properties after depositing the electrode.

Organic optoelectronic devices were coated on TRE64 with TSE using the roll-to-roll processes available at the end-users premises. Even though this electrode substrate had been tested on laboratory devices, roll-to-roll coating is a big step forward to industrial production of devices. Table 2 shows the efficiency of devices together

[5] Nelli Weiß et al., RSC Advances, **5**, 19659, 2015; K Mustonen et al., Appl. Phys. Lett, 143113, 2015.

with the device area and fabrication method. In terms of efficiency, TREASORES reached its efficiency goal regarding OLED devices using sheet-to roll manufacturing. Devices entirely processed by roll-to-roll had half the efficiency due to limitations in the stack architecture but demonstrate clearly the suitability of TRE64 and TSE electrode substrates. Note that objectives were surpassed the in terms of active device area (see **Figure 6**a).

Table 2 Summary of the organic optoelectronic device efficiencies achieved

Device type	Substrate incorporating electrode and barrier	Encapsulation material	Efficiency	Area (cm^2)	Fabrication method
OLED	TRE64 with TSE electrode	TRE64	25 lm/W	250	sheet-to-roll
	TRE64 with TSE electrode	TRE64	10 lm/W	250	roll-to-roll
OLEC	commercial PET with ITO electorde	commercial	30.5 lm/W	1	spin-coating
	3M barrier foil with TSE electrode	Al backsheet	15.5 lm/W	100	roll-to-roll
OPV	TRE64 with TSE electrode	commercial	2.2 %	800	roll-to-roll
	TRE64 with TSE electrode	commercial	5 %	360	sheet-to-roll

OLECs produced entirely by roll-to-roll showed good performance on TSE coated commercial barrier foils as compared to other production techniques, but are still lagging behind commercial objectives in terms of efficiency. However, as shown for laboratory devices within the project, record high lumen efficiencies above 30 lm/W can be obtained. OPV modules produced on TREASORES substrates convincingly demonstrate the potential of these barrier-electrode foils (see **Figure 6**b. A 20x18 cm^2 module indeed reaches 5% using sheet-to-roll fabrication. In fully roll-to-roll processed photovoltaic modules, however, device performance is still limited by an identified single process step. It is believed that there is no major hurdle to adapt the process in such a way as to reach TREASORES' efficiency target.

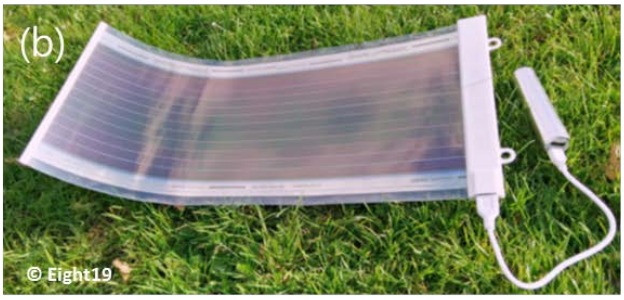

Figure 6 TREASORES demonstrators produced by roll-to-roll fabrication. (a) 10 x 25 cm^2 white OLED device (middle part) from Fraunhofer FEP, (c) 20x40 cm^2 OPV device by Eight19.

POTENTIAL IMPACT

INTRODUCTION

TREASORES was set up with the idea of giving a strong impetus to large area optoelectronic device fabrication in Europe. The worldwide market of organic optoelectronics is only now beginning to develop, with OLED displays at the front of the field with an 8 billion USD market today, about one tenth of the global display market[6]. A summer 2014 market intelligence report[7] forecasts that OLED lighting will be a 3 billion USD market by 2020, based on the assumption that prices will fall to 1000 USD/m2 by 2016, and 200 USD/m2 by 2020. Konika-Minolta announced in late 2014, the start of mass production of OLED lighting devices on plastic foil[8]. More recent announcements in 2015 report on flexible barrier foil activities using either barriers on plastic substrates or flexible glass[9].

All these announcements point to a growing industrial interest in the fabrication of large area organic devices. In this respect TREASORES targeted the technical areas in this emerging market where Europe has a realistic chance of playing a significant role, despite the resources devoted to industrial R&D in other parts of the world. The relatively short project time of three years put a lot of time pressure on the TREASORES goals to reach prototype or pilot scale production of demonstrator devices at the end of the project, but was felt to be necessary to remain in touch.

TREASORES provided direct support to those partners investing in pilot line development to implement processes developed at a small scale at an industrially relevant level. Furthermore TREASORES supported collaborative approaches between industrial partners in the project to develop flexible substrates with integrated barrier and electrode and to manufacture demonstrators. Without financial support from the EU, these approaches would not have been possible. TREASORES has connected different partners together to accelerate development of large area optoelectronic device manufacturing in Europe. Its activities have led to exploitable know-how and to new inventions.

During the project 9 patents were filed, 10 peer-reviewed scientific papers were published (2 further publications were submitted and are still under revision) and

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[6] "Global Display Market by Type, Technology, Application & Geography - Trends & Forecast to 2020", Research and Markets (http://www.researchandmarkets.com/research/lwxcnt/global_display).

[7] http://www.cintelliq.com/oled-lighting/ppccf-2014-q2.html

[8] http://www.konicaminolta.com/about/releases/2014/0318_01_01.html

[9] http://www.oled-info.com/tags/technical-research/frontplane/roll-roll

more than 30 communications were made during conferences or interviews. Academic partners and partners from research and development institutes have greatly benefited from the visibility of the project and have been able to invest in the rising field of large area organic optoelectronics.

We expect the project to have contributed at least to the preservation and creation of a number of jobs in the nascent European plastic electronics industry, and at best to have created a new category of products for a booming global market.

MAIN EXPLOITABLE RESULTS

The list of exploitable results and foreground can be categorized in four categories. The first relates to developments in barrier technologies, the second regards novel electrode technologies with the potential to substitute presently used ITO coated plastic foils. The third category concerns flexible plastic foil substrates incorporating a barrier and an electrode while the forth is related to optoelectronic devices.

a) Barrier technologies

A method was developed to produce highly impermeable barriers on PET foils using ALD precursors. This method, though developed at a laboratory scale, has the potential of being scaled-up at industrial level. It provides barrier properties of $5{\cdot}10^{-4}$ g m^{-2} day^{-1} and $1.3{\cdot}10^{-6}$ g m^{-2} day^{-1} for WVTR and OTR at ambient condition, respectively but is not yet fully optimized. Two TREASORES partners have jointly filed a patent. One of the partners is interested in transferring the technology to third parties and to provide services in this field of development.

A roll-to-roll inline facility for atmospheric pressure ALD deposition was developed by one of the partners. This pilot machine allows to deposit ALD barriers on foils providing an OTR of $5{\cdot}10^{-3}$ cm^3 m^{-2} day^{-1} bar^{-1} (or $6{\cdot}10^{-6}$ g m^{-2} day^{-1}). The exploitation of the results is currently discussed.

Regarding laminated barrier foil development, reliable back-to-face CERAMIS®/ORMOCER® laminates will be available on the market very soon from Amcor. A new barrier adhesive has been synthesized and is available to barrier manufacturers.

b) Novel electrode technologies

Synthesis of nanowire inks and a coating process for the nanowires have been patented and are available to electrode manufacturers.

Transparent carbon nanotube electrodes can now be purchased commercially from the responsible TREASORES partner Canatu Oy of Finland..

A new fabrication technology has been developed for fabric electrodes with greatly reduced waviness. Such electrodes should be available on the market very soon from the Swiss company Sefar AG.

A resistivity tester has been developed by one of the TREASORES partners. Licensing of know-how and design is being envisaged.

Production and knowhow of the thin silver electrode technology is expected to be available on the market very soon from Rowo Coating GmbH.

c) Flexible roll-to-roll substrates incorporating a barrier and an electrode

The development of TRE64 foils with TSE electrodes is likely to rival common standard ITO on PET. Efforts to commercialize this new product will start very soon.

d) Flexible roll-to-roll substrates incorporating a barrier and an electrode

Process know-how from Fraunhofer-FEP regarding OLED fabrication is being made available to third parties.

Manufacture of large area OPV panels as charging unit for e.g. smart phones will be available on the market very soon. Two patents relating to production processes have been applied for.

Table 3 Published patent applications from the TREASORES project.

Reference	Title
WO/2016/012046	Method for producing a barrier layer and carrier body comprising such a barrier layer
WO2015090395 A1	Transparente Nanodrahtelektrode mit funktionaler organischer Schicht
WO2015091783 A1	Verfahren zur Herstellung einer Nanodrahtdeckelektrode für optoelektronische Bauelemente sowie deren Verwendung
WO2015043850 A1	Prozesskammer für einen chemischen Reaktionsbeschichtungsprozess und Verfahren zum Beschichten eines optischen Objekts mittels eines chemischen Reaktionsbeschichtungsprozesses
EP2790196 A1	Elektrisch leitfähiges Substrat für eine optoelektrische Vorrichtung

PRACTICAL EXPLOITATION OF TREASORES RESULTS AFTER THE PROJECT

The progress and innovations of the TREASORES project are expected to have both immediate and longer term impacts on the European and global markets for flexible electronics. For example, the British project partner NPL Ltd has developed new testing procedures and equipment for flexible electrodes that have been proposed to form the basis of a new worldwide test standard, although this will take several years to be completed. Three of the project partners expect to immediately begin marketing and sales of transparent and flexible electrodes which use technology developed within the project. These are:

- Rowo Coating (Germany) - very flat, thin silver electrodes suitable for all types of organic electronics that do not need very low sheet resistance (e.g. organic photovoltaic devices). This type of electrode can be applied directly to impermeable membranes (i.e. barrier foils).
- Sefar (Switzerland) - fabric electrodes with very low sheet resistance that are especially suitable for large area lighting applications with OLEDs. For some applications these would be combined with an area-filling electrode layer such as that from Rowo Coating. In addition, Sefar intend to cooperate with the Fraunhofer Society's Institute Organic Electronics, Electron Beam and Plasma Technology on further development of advanced flexible OLED devices.
- Canatu (Finland) - flexible, stretchable electrodes made from carbon nanotubes that are well suited to shaped touch sensors.

Each of these companies expect to attain global market shares in their targeted markets of at least few per cent within a few years. Canatu have already made small-scale sales of electrodes for touch sensors, but are investing in 2016 in their production facilities to increase throughput and further improve surface quality (with a view to diversifying from touch sensors to other application areas). Rowo will be ready to produce commercial pilot quantities (i.e. kilometres of electrode material) in 2016, but will continue to develop their process in conjunction with customers. Sefar are also able to produce commercial pilot quantities from 2016, but plan to invest further in their production equipment to allow higher throughput and more flexibility for customer demands.

Furthermore, the impermeable and transparent 'barrier foils' developed within the project will be commercialised by Amcor Flexibles. Scale-up development continued in 2015 after the end of the project, and pilot commercial production is expected from early in 2016.

The promising technologies involving the use of atomic layer deposition of aluminium oxide both to manufacture barrier foils and to provide a temporary protection layer during device manufacture will be taken further by the Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer IVV). Shortly after the end of the project, Osram and Fraunhofer IVV agreed to transfer the technology developed by Osram within the TREASORES project to Fraunhofer IVV, who intend to make this ground-breaking technology available for co-development and innovation to any European company.

Finally, the British company Eight19 will incorporate materials and production processes established during TREASORES into their pilot scale production line, leading to higher yields of larger solar cells, with better efficiency and fabricated at lower cost. Eight19 is already developing specific solutions for customers and expect to begin full commercial production within two years.

DISSEMINATION OF TREASORES RESULTS

PRESS RELEASES ETC.

The project public website, http://www.treasores.eu, summarises the goals of the project, lists the project partners and has an educational section that seeks to explain the technologies developed by the project team. There are links to the publications from the project. The website also has a regularly updated news section which flags selected issues relevant to the production and use of large area organic electronics.

Press releases were issued at the start of the project by Empa and NPL and the institutional websites of EMPA, NPL, AMAN and UVEG as well as many independent international websites also reported the start of the TREASORES project (including: www.sonnenseite.com, www.erneuerbareenergien.de, www.drillingsraum.de, www.derecho.com (Valencia), benasque.aragob.es (Aragon), www.southeastip.co.uk, wwww.myscience.ch, www.zol.ch and www.swissinnovation.org).

Shortly after the start of the project, radio interviews were given by the coordinator, and later a television interview was aired on Swiss television in in connection with the result of the Swiss referendum on 'Masseneinwanderung" (Mass immigration) (Einstein programme, 27th February 2014).

A second press release summarising the project's progress was prepared for use by all partners (in English, German and French) in Spring 2015. As a result of this press release the project was contacted by a businessman interested in opening an OPV factory in India (he was referred to partner EIGHT19), Fuji film contacted the project with an offer to try out their barrier foil materials, and the US journal 'Foreign policy' (2.4 million monthly online readers, and a print run six times per year of about 361,000 copies), requested further information about the TREASORES OPV work. The press release was used by several media outlets, including an article in the Swiss free commuter's newspaper '20 Minuten' with a print circulation of over 2.1 million copies.

The project coordinator was interviewed for the Swiss science television programme 'Einstein' in 2014 concerning international research collaboration in Switzerland. An interview with the project coordinator regarding advances in TREASORES and the possible uses of OPV panels is expected to be broadcast on Swiss regional cable television channels (and the world-wide web) by *homegate TV* soon (as of October 2015). Another video about the project (made by the project itself) has been made available to the public by streaming from YouTube.

PEER-REVIEWED PUBLICATIONS

Table A1 lists all eleven manuscripts from the project that have been published by, or submitted to, peer-reviewed journals. The focus of the publications is on the new electrodes from the project and their use with devices, which are the most academically novel (and therefore publishable) parts of the project work. The equally important work on scale-up of electrodes, barriers and devices is less academically suitable, and also because of the near-future commercial applications there is less desire to make the details public.

In addition to the publications and manuscripts listed in Table A1, four further publications from the project are in preparation, or planned:

#	Provisional Title	Lead partner	Planned journal	Open access?
1	In-situ electrical characterisation of the mechanical stability of electrodes for flexible electronics	NPL	Advanced Materials	Maybe
2	In-situ environmental degradation studies of light emitting electrochemical cells in water and oxygen rich atmospheres	NPL	Organic Electronics	Maybe
3	Life cycle analysis and cost estimation of a novel OPV system	QUANTIS	Solar Energy	Maybe
4	Lifetime study on highly efficient, flexible, ITO-free cascade solar cells	TUD	Advanced Energy Materials	Maybe

CONFERENCE PRESENTATIONS

Table A2 includes a full list of all thirty-one conference presentations made concerning the TREASORES project. All aspects of the project (ultra-barriers, electrodes, scale-up, OLAE devices, green power) have been presented to audiences both of scientists (industry and academic) and policy makers, in Europe, the USA and Japan. Conference presentations serve not only to show-case the project, but provide a means for the project partners to make new contacts (especially with prospective customers) and to gauge the market interest in their results.

STANDARDISATION ACTIVITIES

Flexible, plastic electronics including OPVs OPV's are so new that standards are still emerging. Therefore, in early 2014, EIGHT19 and NPL joined a new working group of the Organic Electronics Association (OE-A): the Organic Electronic Energy Workgroup, with the aim of participating in setting new standards.

NPL have written and distributed a report on the landscape of standardisation efforts in organic electronics for the Versailles Project on Advanced Materials and Standards (VAMAS) that is expected to influence further pre-normative work (through Technical Working Area 36 "Organic Electronics"), and has been downloaded more than one hundred times so far. The procedures for mechanical-electrical testing developed by NPL during TREASORES will be at least partially included in upcoming standards for testing of flexible OLEDs, after presentation of results during the meeting of Technical Committee 119 Printed Electronics of the International Electrotechnical Committee (IEC).

For barrier layers, the existing standards for measuring oxygen and water vapour transmission rates are still applicable.

CONTACTS WITH OTHER ACTORS

- The TREASORES project has provided information to the "Innovation Portal" of the European Factories of the Future Association (EFFRA), and has access to this portal to make updates
- TREASORES has been represented at meetings of the EC-organised Factories of the Future Impact Workshops in 2013, 2014 and 2015. These workshops have sought to promote links between projects through clustering. Through these workshops, the TREASORES project made contact with the Flex-o-Fab

project (funded in the same FP7 call as TREASORES), but commercial considerations make co-operation effectively impossible.

- The FP7 GLADIATOR project is concerned with scaling up CVD graphene production for use as a transparent electrode, and includes work on barrier materials for compatibility with graphene transfer. Common ground with TREASORES exists for standardising measurements of transparent electrode parameters, and contact between the two projects has been established (both through shared partners F-COMEDD and AMAN, and through direct contact between the GLADIATOR project and TREASORES partner NPL).
- Through common partners, TREASORES remains aware of progress from over ten other EC research projects including the SUNFLOWER (FP7), CELLO (FP7) and Clean4Yield projects, but the outcomes of these projects mostly have no direct impact upon TREASORES. (Although in some cases the aims are similar, the technical approaches are different). Similarly, the outcomes from TREASORES will have no direct impact on these projects (which anyway mostly finish before TREASORES).

TABLE A1 LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT

#	Title	Main author	Journal title	Issue	Publisher	Place	Year	Pages	ID	Open access?
1	Flexible high efficiency perovskite solar cells	Cristina Roldán-Carmona et al.	Energy and Environmental Science	7	Royal Society of Chemistry publishing	London, UK	2014	994-997	doi: 10.1039/c3ee43619e	No
2	ITO-Free, Small-Molecule Organic Solar Cells on Spray-Coated Copper-Nanowire-Based Transparent Electrodes	Christoph Sachse et al.	Advanced Energy Mateials	4(2)	Wiley-VCH	Weinheim, Germany	2014	1-6	doi: 10.1002/aenm.201300737	No
3	Highly conductive silver nanowire networks by organic matrix assisted low-temperature fusing	Franz Selzer et al.	Organic Electronics	15(12)	Elsevier BV	Amsterdam, the Netherlands	2014	3818-3824	doi:10.1016/j.orgel.2014.09.030	No
4	Hybrid Carbon Source for Single-Walled Carbon Nanotube Synthesis by Aerosol	Anoshkin	Carbon	78	Elsevier BV	Amsterdam, the Netherlands	2014	130-136	doi:10.1016/j.carbon.2014.06.057	No

	CVD Method									
5	Humidity assisted annealing technique for transparent conductive silver nanowire networks	Nelli Weiß et al.	RSC Advances	5	Royal Society of Chemistry publishing	London, UK	2015	19659-19685	doi: 10.1039/C5RA01303H	No
6	A spray-coating process for highly conductive silver nanowire networks as the transparent top-electrode for small molecule organic photovoltaics.	Franz Selzer et al.	Nanoscale	7(6)	Royal Society of Chemistry publishing	London, UK.	2015	2777-2783	doi: 10.1039/C4NR06502F	No
7	Laminated fabric as top electrode for organic photovoltaics	Roland Steim et al	Applied Physics Letters	106(19)	American Institute of Physics	Melville NY	2015	19331	doi: org/10.1063/1.4919940	No (but free for 30 days)
8	Uncovering the ultimate performance of single-walled carbon nanotube films as transparent conductors	K Mustonen	Applied Physics Letters	107	American Institute of Physics	Melville NY	2015	143113	http://dx.doi.org/10.1063/1.4932942	No (but free for 30 days)
9	Flexible light-emitting electrochemical cells	L Martínez-Sarti	Organic Electronics	30	Elsevier	Amsterdam, the	2016	36	10.1016/j.orgel.2015.12.011	No

	with single-walled carbon nanotube anodes					Netherlands				
10	Doped Hole Transport Layers Processed from Solution: Planarization and Bridging the Voids in Noncontinuous Silver Nanowire Electrodes	L Bormann et al	Organic Electronics	28	Elsevier	Amsterdam, the Netherlands	2016	163	DOI: 10.1016/j.orgel.2015.10.007	No
11	Dry functionalization and doping of single-walled carbon nanotubes by ozone	A Nasibulin et al.	Journal of Physical Chemistry C	119	American Chemical Society	Washington DC, USA.	2016	27821	10.1021/acs.jpcc.5b08832	No
12	Electrical limit of silver nanowire electrodes: Direct measurement of the nanowire junction resistance	F. Selzer et al.	Applied Physics Letters		American Institute of Physics	Melville NY	*submitted 2015*	-	-	No (but free for 30 days)

TABLE A2 LIST OF DISSEMINATION ACTIVITIES

#	Type	Leader	Title	Date/Period	Place	Type of audience	Size of audience	Countries addressed
1	Talk	AMAN	The TREASORES project	11th-12th March 2013	FoF Impact workshop Brussels, Belgium.	FP7 participants and bureaucrats	150	EU and FP7 associated countries
2	Talk	TUD	Alternative, Transparent Electrodes for Organic Photovoltaics	13th-15th May 2013	8th International Symposium on Transparent Oxide and Related Materials for Electronics and Optics Waseda University, Tokyo, Japan.	Technical	≃120	International meeting in Japan
3	Poster	F-IVV	Transparent high barrier films for flexible organic electronic devices	11-13 June, 2013	5th Large-area Organic and Printed Electronics Convention (LOPE-C)	Technical	1800	International: attendees from 40 countries
4	Talk	TUD	Colloidal nanocrystal architectures for efficient energy and charge transfer	22-27 September 2013	DPG Summer school on physics "Innovative Concepts in Photovoltaics2	Technical (academic scientists and research sudents)	49	Attendees from Germany and other EU countries.
5	Poster	F-ISE	"Sputtered Transparent Silver	8th - 10th October	Plastic Electronics 2013 conference, Dresden,	Technical	5000	International meeting in

			Electrodes with AZO for Organic Solar Cells"	2013	Germany.			Germany.
6	Poster	AMAN	The TREASORES project	22nd October 2013	Ecological and Economical Impact of PV Energy Dübendorf, Switzerland.	Technical	100	Switzerland (international speakers)
7	Talk	TUD	Spray coating process for highly conductive silver nanowire networks as transparent top electrode for small molecule organic photovoltaics	15-20th March 2014	DPG (German Physics Society) Spring meeting 2014, Dresden, Germany.	technical	50	German
8	Talk	AMAN	discussion (no presentation at the meeting, but text for slides given beforehand)	24th-25th March 2014	FoF impact workshop Brussels, Belgium.	FP7 participants and bureaucrats	150	EU and FP7 associated countries
9	Talk	TUD	Highly-conductive silver nanowire networks via purposeful wire functionalization as transparent top electrode for organic photovoltaics	14-17th April 2014	SPIE Photonics Europe 2014, Brussels.	technical	1200 presentation s	international (European)

10	Talk	UVEG	Flexible high efficiency perovskite solar cells	21st to 25th April 2014	Materials Research Society (MRS) Spring meeting, San Francisco, USA	Technical (80% academic 20% industrial)	500	International
11	Talk	UVEG	High Performance Metal Oxide Free Perovskite Based Solar Cells	11th-14th May 2014	International Conference on Hybrid and Organic Photovoltaics (ICHOP), Lausanne, Switzerland	Technical (80% academic 20% industrial)	600	International
12	Talk	F-COMEDD	OLED on flexible Glass from Sheet-to-Sheet to Roll-to-Roll Fabrication	26th May, 2014	6th Large-area Organic and Printed Electronics Convention (LOPE-C)	Technical	>2000	
13	Conference presentation and publication	F-COMEDD	Roll-to-Roll OLED fabrication on transparent barrier film	June 2014	ICCG10, International Conference on Coatings on Glass and Plastics Dresden	Technical	1800	International
14	Conference presentation and publication	F-COMEDD	Roll-to-Roll OLED fabrication on flexible glass and barrier films	June 2014	AIMCAL (Association of International Metallizers, Coaters and Laminators)	Technical	60	International
15	Report	EMPA	TREASORES Transparent electrodes for large	summer 2014	2014 report of the Swiss government *Bundesamt für Energie* on photovoltaics	Policy makers	Printed report and open access	Swiss national

			area, large scale production of organic optoelectronic devices		"Programm Photovoltaik Ausgabe 2014"		online	
16	Info to EFFRA innovati on portal	AMAN	-	June 2014, last updated October 2015	internet	industry and policy makers	web-based. EFFRA may be able to reveal number of page hits	International
17	Poster	UVEG	Flexible light-emitting electrochemical cells	31st August - 3rd September 2014	10th International Conference on Electroluminescence and Optoelectronic Devices (ICEL.10), Cologne, Germany	technical	300	international
18	Talk	UVEG	Flexible light emitting electrochemical cells	28th August to 4th September 2014	Koln, Germany.	Technical (80% academic, 20% industrial)	100	International
19	Talk[10]	NPL	Environmental Stability of Organic Semiconductors for Use in	8th-10th September 2014	4th World Materials Research Institute Forum: Young Scientists Meeting, Boulder, USA	technical	40	International

[10] George Dibb from NPL won the 2014 WMRIF Young Scientist Award for his talk

			Optoelectronic Devices					
20	Invited plenary Talk	UVEG	High Performance perovskite solar cells	22nd - 26th September 2014	EU PV SEC, Amsterdam, Netherlands.	Technical (40% academic, 60% industrial)	2000	International
21	Talk	UVEG	Solar Cells Containing Evaporated Perovskite Layers Sandwiched in between Organic Charge Transporting Layers	29th November to 4th December 2014	Materials Research Society (MRS) Fall Conference, Boston, USA.	Technical (80% academic, 20% industrial)	500	International
22	Poster	EMPA	Electrode materials and barrier foils for organic electronics – an overview on the R&D activities within the EU funded project TREASORES	16-17th March 2015	13th National Photovoltaic days 2015	technical and policy makers	550	Swiss
23	Poster	EMPA	Electrode materials and barrier foils for organic electronics – an overview on the R&D activities within the EU funded project TREASORES	3.-5. March 2015	LOPEC 2015, Münich, Germany.	technical	2300	International

24	Poster	ROWO	Novel Transparent Silver Electrodes on flexible Substrates as Alternative to ITO	3.-5. March 2015	LOPEC 2015, Munich, Germany.	technical	2300	international
25	Contribution (interview) to Swiss ETH Report	EMPA	'Internationality of research' in ETH Geschäftsbericht 2014 (i.e. the annual report of the body responsible for the Swiss national universities and research institutes.)	April 2015	http://www.ethrat.ch/sites/default/files/ETHR_GB2014_D.pdf (see p33, in German only)	Policy makers	few hundred plus website	Swiss
26	Report	NPL	Current landscape of standardisation efforts in organic and printed electronics 2015 - a VAMAS review.	April 2015	Published by NPL (report MAT 73, April 2015) under the auspices of the Versailles Project on Advanced Materials and Standards (VAMAS) http://www.npl.co.uk/content/ConPublication/6568	Technical (metrology and standards)	>100 downloads	international
27	Talk	TUD	Alternative transparent electrodes for OPV	April 6-10th 2015	2015 MRS Spring Meeting, San Francisco, USA.	technical	large	international
28	Poster	TUD	Spray-Coated Silver	April 6-	2015 MRS Spring Meeting,	technical	large	international

			Nanowire Top-Electrodes and Annealing-Free Bottom-Electrodes for Small Molecule-Based Organic Photovoltaics	10th 2015	San Francisco, USA.			
29	Invited talk	AALTO	Directly dry deposited SWCNTs for record high performance transparent conductive films	6th-10th April 2015	Materials Research Society (MRS) Spring Meeting, San Francisco, USA.	technical	5000 attendees at conference	International
30	Invited talk	AALTO	The effect of SWNT bundling on the growth during FC-CVD synthesis	April 10th-14th, 2015	7th Single Wall Carbon Nanotube Workshop, Rice University, Houston, TX, USA.	technical	70	international
31	Invited talk	AALTO	Novel Nanocarbons to replace Indium in Flexible Devices	17th April 2015	The Corning Glass company, Corning, NY, USA.	commercial	50	USA and international
32	Invited talkApri	AALTO	Carbon Nanotubes to replace Indium in Flexible Devices	16th April, 2015	Columbia University, New York, NY, USA.	technical	100	USA
33	Presentation	EMPA	Workshop on Impact of the Factories of the Future PPP	29-30 April 2015	EC, Brussels	Technical, industry and policy makers	200	international
34	Invited	F-ISE	Silver based	5th-7th	Power Electronics for Plasma	Technical	50	international

	talk		transparent electrodes for applications in OPV, OLED and flexible electronics	May 2015	Engineering (PE^2), Ditzingen, Germany			
35	Invited talk	NPL	Needs for standardisation in organic electronics	11th May, 2015, London, UK.	VAMAS/BSI technical workshop 'Materials Meet Standards'. 40th Steering Committee meeting of VAMAS	standards	30	international
36	Talk	EMPA	Funktionelle Materialien und Substrate für die Plastikelektronik	11th June 2015	Kick-off meeting for 'Flat Systems' focus group, Nano-Cluster Bodensee (NCB), St Gallen, Switzerland.	technical	50	Swiss
37	Plenary talk	NANOG	ALD for Technologies Beyond Electronics: Chances and Challenges	29th June 2015	AVS ALD conference. Portland, USA.	technical	>700	international
38	Invited talk	EMPA	Electrode materials and barrier foils for organic electronics – an overview on the R&D activities within the EU funded project TREASORES	6-9th July 2015	ISFOE 2015/Nanotexnology	technical	200	international

39	Talk	TUD	Polymer-facilitated low temperature fusing of spray-coated silver nanowire networks as transparent top and bottom electrodes in small molecule organic photovoltaics	8-13th August 2015	SPIE Optics and Photonics, San Diego, USA	technical	4,537	international
40	Invited talk	EMPA	Functional films for optoelectronics and mechatronics applications	7th September 2015	Visit to Holst Centre (Holland) and the coordinator of the Flex-o-Fab FP7 project	technical	20	Netherlands
41	Poster	NPL	In-situ mechanical testing of transparent electrode materials for organic electronics	29th September to 1st October 2015	International Summit on Organic and Hybrid Photovoltaic Stability (ISOS-8), Rio de Janeiro, Brazil	technical	80 at ISOS, 2000 at poster session open to B-MRS	international
42	Talk	NANOG	Highly efficient encapsulation of organic opto-electronic devices utilizing ALD	28th-29th September 2015	13th International Baltic Conference on Atomic Layer Deposition (BALD), Tartu, Estonia.	technical	200	international
43	Poster	EMPA	Electrode materials and barrier foils for	1st-2nd October	Swiss ePrint – The Swiss Conference on Printed	technical	160	national (Swiss)

			organic electronics – an overview on the R&D activities within the EU funded project TREASORES		Electronics and Functional Materials.			
44	TV interview	EMPA	Topic: Switzerland and international research collaborations	27th February 2014	'Einstein', a prime-time TV program about science from the Swiss broadcaster SRF	The public (free national television, and video on SRF website)	1.8 million	national (Swiss German)
45	TV interview	EMPA	R2R OPV and applications	repeated showings from 8th June 2015	Homegate TV, a private cable TV channel in Switzerland	The public (subscribers	>100,000	national (Swiss German)international
46	video	AMAN	the project	from October 2015	video about the project	The public (available from YouTube)	c. 100 downloads	

WEBPAGE AND CONTACT

TREASORES webpage: http://treasores.eu/

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