INREP
Towards Indium free TCOs

Develop and deploy valid and robust alternatives to indium based transparent conductive electrode materials as electrodes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641864.

TOWARDS INDIUM-FREE TCOS

High-tech products, including electric and electronic equipment, green energy technologies or extreme applications, contain substantial amounts of certain Critical Raw Materials (CRM). Although the amount of CRM per product in general is very low, the huge number of products manufactured makes the total amounts very impressive. The prices and availability of CRM varies in time. There is therefore a need to find alternative solutions to replace certain CRM in concrete applications, or to diversify the supply of raw materials sources. Substitution of CRMs can also increase the recyclability of waste products, allowing for more efficient processes and reduce environmental impacts.

The goal of the INREP project was to develop and deploy valid and robust alternatives to indium (In) based transparent conductive electrode materials as electrodes.

The present brochure briefly summarises the project context, scope and provides a summary of the scientific and technical results.

13 PARTNERS

7 COUNTRIES

30 RESEARCHERS AND ENGINEERS

3 YEARS
FROM 1ST FEBRUARY 2015
TO 31ST JANUARY 2018

4 APPLICATIONS

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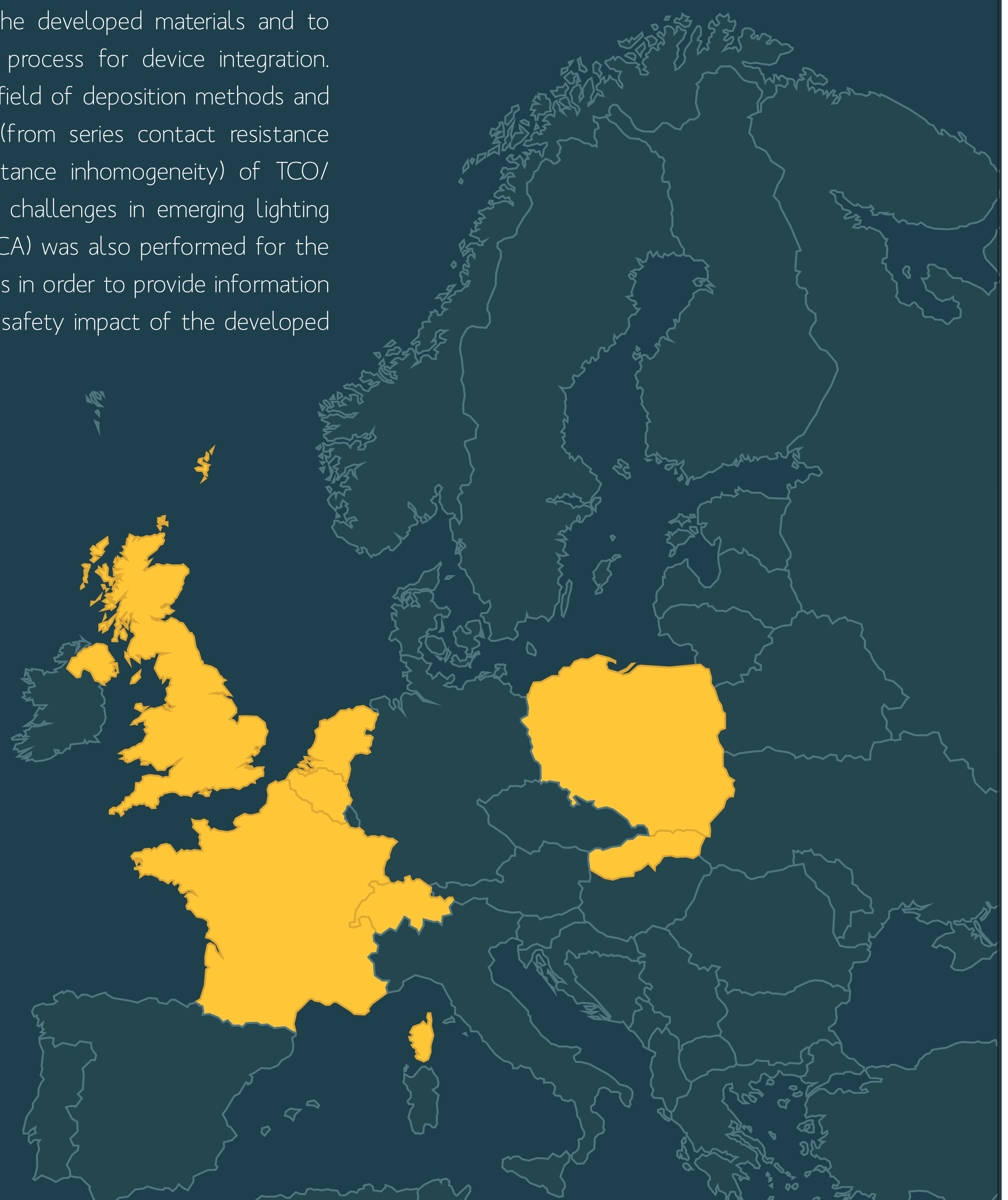
Abbreviations

AFM:	Atomic Force Microscopy	In:	Indium
ALD:	Atomic Layer Deposition	ITO:	Indium Tin Oxide
CoO:	Cost of Ownership	LCA:	Life Cycle Analysis
CRM:	Critical Raw Material	LED:	Light Emitting Diodes
EBIC:	Electron Beam Induced Current	OLED:	Organic Light Emitting Diodes
EL:	Electroluminescence	PV:	Photovoltaic
EPPS:	Extended Planar Plasma Source	SHJ:	Silicon Heterojunction
GaN:	Gallium nitride	SIMS:	Secondary-Ion Mass Spectrometry
HB:	High Brightness	TCO:	Transparent Conductive Oxide

CONSORTIUM

INREP has a large European footprint since the project brought together thirteen partners from seven countries.

The consortium included renown companies working in the TCO value chain from tool manufacturer to end users integrating TCO in their proprietary devices. Academic and research partners provided their large base of material and process know-how for the selected applications allowing to tune on demand the opto-electrical properties of the developed materials and to take into account the whole process for device integration. INREP gathered experts in the field of deposition methods and key characterization methods (from series contact resistance to visualization of diode resistance inhomogeneity) of TCO/GaN interfaces to address the challenges in emerging lighting trends. A Life Cycle Analysis (LCA) was also performed for the proposed material and processes in order to provide information on possible environmental and safety impact of the developed solutions.



UNIVERSITY OF BATH

Expertise: GaN technology; modelling and structural-property correlation; materials design and optimisation from first-principles

imec

Expertise: ITO alternatives, ink formulation, rheology, ink characterization

csem

Expertise: thin films, transparent conductive oxides, sputtering, process optimization, material characterization: TEM, in-situ XRD

PQL Plasma Quest Limited

Expertise: sputtering, TCO coating, HiTUS, low temperature deposition

TU/e Technische Universiteit Eindhoven University of Technology
Where innovation starts

Expertise: plasma surface interaction; plasma chemistry; in-situ diagnostic studies; high-throughput processing; ultrathin film synthesis; novel processing techniques

QUAD

Expertise: printed electronics; capacitive interface design; firmware platform for touch sensors

MEYER BURGER

Expertise: high efficiency Silicon Heterojunction photovoltaic cells; PECVD and PVD deposition techniques for a-Si layers and TCO's; capacity from wafer to cell production line in an R&D environment

STU

Expertise: Complex characterization of semiconducting and optoelectronic device structures; nanoscale I-V, CL, EBIC, EL, AFM, SIMS

plessey

Expertise: technology of light; LEDs design and layout; process integration

L'UP

Expertise: project management, communication, dissemination

Expertise: analysis of products & services complex life cycles ; life cycle assessment (LCA); environmental impact assessment; process optimization

MEYER BURGER

Expertise: high level equipment manufacturing, design, fabrication and integration of injector head in ALD tool

TNO innovation for life

Expertise: plasma-enhanced spatial atomic layer deposition, thin film photo-voltaics, upscaling

CONTEXT

Demand for indium has grown since the 1970s with considerable expansion and diversification in consumption since 1990s.

Today, indium-based materials and mainly Indium Tin Oxide (ITO), are technologically entrenched in the commercial manufacture of components like LEDs (both organic and inorganic), solar cells and touch screens.

Indium has been classified by the European Commission as one of the "critical raw materials" with a high supply-risk and a high economic importance to which reliable and unhindered access is a concern for European industry and value chains. Since a single country is a dominant commercial supplier of indium, it is of strategic importance to find technologies that use Earth abundant alternatives.

PRODUCTION TRENDS FOR INDIUM

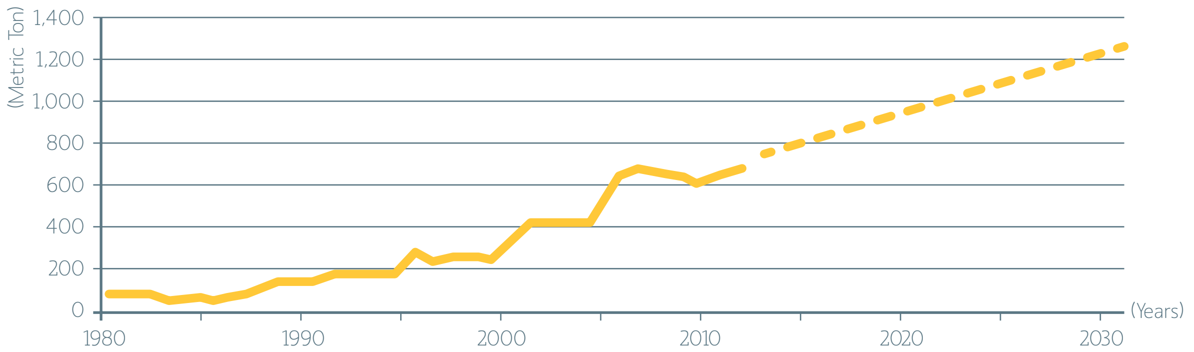


Figure 1: *Production trends for Indium.*
Source: United States Geological Survey, Minerals Information, Indium.

WORLD INDIUM PRODUCTION

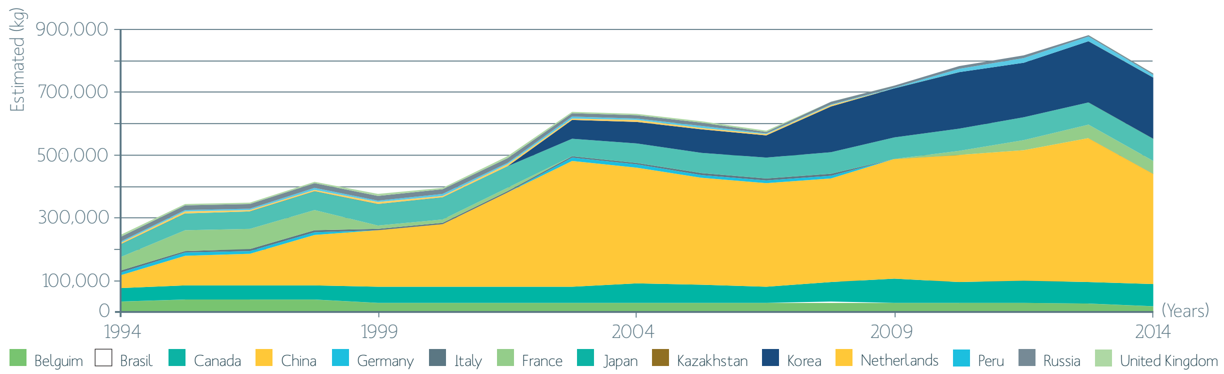


Figure 2: *World Indium Production.*
Source: United States Geological Survey, Minerals Information, Indium.

SCOPE

INREP objective was to develop and deploy alternatives to indium (In) based transparent conductive electrode materials as electrodes in components such as light emitting diodes (LEDs), both organic and inorganic, solar cells and touch-screen displays.

The research extended from the design of novel transparent conducting oxides (TCOs); understanding their electrical and optical properties; advancing methods for their deposition, including equipment development; developing device manufacturing and processing schedules to establish a basis for economic exploitation of the indium-free TCOs in LEDs, solar cells and touch screen displays.

Different TCO deposition technologies (sputtering, atomic layer deposition, chemical vapour deposition, screen printing) were applied to the different component types to be developed with the standardized characterization methods being used to evaluate TCO-device performance.

Procedures developed in the research laboratories were then migrated to component manufacturing schedules with additional measurements of device yield per wafer and lifetime testing performed.

In a particular innovation the INREP methodology extended to evaluating the environmental impact of the developed TCO technologies by devising a robust scheme for Life Cycle Assessment (LCA) and then deploying this methodology to the different TCOs and their deposition methods.

FOUR APPLICATIONS:

/ High efficiency PV cells

/ Organic LEDs

/ GaN based LEDs

/ Touch-screen monitor

+ Develop related processes and up-scaled equipment
+ Perform Life Cycle Assessment (LCA)of the environmental impact of the developed TCO materials and cost of ownership analyses

HIGH EFFICIENCY PV CELLS

For this specific application, the goal of INREP was to replace the indium-based layer of high efficiency photovoltaic cell device by an indium-free TCO while keeping as high as possible the efficiency.

Indium Tin Oxide is state of the art TCO material for this technology, and all indium based TCO have always surpassed other materials in terms of efficiency. The challenge was therefore to minimize the impact on the device performance and to lower the Cost of Ownership (CoO).

More specifically, for the high efficiency silicon photovoltaic application, the developed materials should demonstrate the possibility to tune their carrier concentration between 3×10^{19} cm^{-3} and 3×10^{20} cm^{-3} in combination with an electronic mobility above 20 cm^2 $(Vs)^{-1}$ to be used in front and back contact configuration. Also, the deposition process should not decrease minority carrier lifetime of the cell precursor below 3ms, evidence that the TCO deposition does not degrade the surface passivation in an irreversible way.

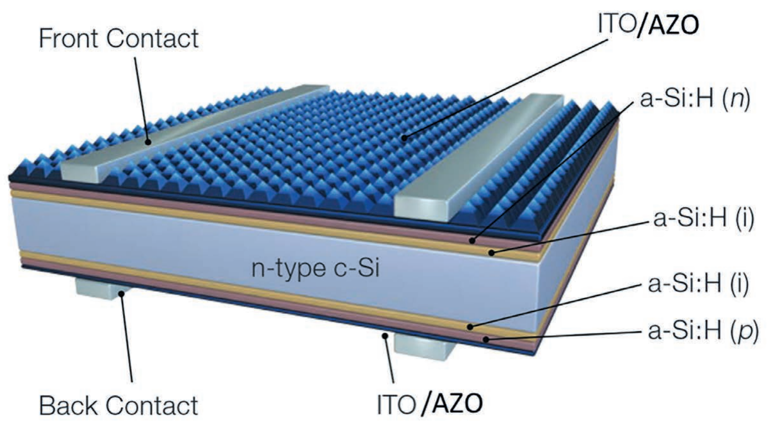


Figure 3: Heterojunction photovoltaic cell device structure.

PARTNERS

MEYER BURGER RESEARCH

PLASMA QUEST

CSEM

It was shown that AZO can make very efficient back reflectors, better than ITO ones, both for front and rear emitter solar cells. This result was demonstrated on sputtering tools.

It was shown that for rear emitter solar cells, AZO offers a viable alternative to ITO front contact, with similar current, fill factor, and VOC.

It was therefore demonstrated at the lab scale that it is possible to make an indium free solar cell using sputtered AZO without compromising the efficiency.

Similarly to sputtered AZO, ALD AZO can make a very good back reflector leading to current gains compared to ITO. However, in the case of front emitter solar cells, it happens at the expense of the fill factor. More generally, it seems that ALD AZO on n-type a-Si:H layers leads to fill factor losses. On p-type a-Si:H however this is not the case, and ALD AZO offers performance increases when replacing ITO at the back of rear emitter solar cells. However, due to reduced fill factors when deposited on n-type a-Si:H, a full indium free solar cell using AZO leads to slightly lower efficiencies.

Figure 4: HELiAPVD Production TCO sputtering tool for HJT cells.

In parallel, other less established at the industrial level deposition methods and novel layer chemistries were evaluated. The path towards their successful implementation in the architecture of the solar cell device definitely requires a longer evaluation period than three years. This is for example the case of atomic layer deposition (ALD) tool. Another lesson learnt is that promising p-type hole selective transport layers such as molybdenum oxide, although proven tuneable in terms of electronic structure, chemical and optical properties, is not yet ready to substitute the consolidated p-type amorphous silicon layer. In both cases, the intermediate step of accurate interface analysis to unravel the causes for losses in solar cell performance is mandatory before future attempts toward implementation in devices.

INORGANIC LEDS

For this specific application, the goal of INREP was to explore new LED architectures and device manufacturing through the use of indium-free TCO materials and deposition techniques developed within the project.

The adoption of transparent conductive AZO layers deposited by sputtering and ALD in organic and GaN-based LED devices involved the challenging task to synthesize TCOs on nitrogen polar n-type GaN and explore new LED architectures. Close collaboration among three complementary expertise in TCO deposition, interface analysis and novel LED architectures has been key to develop low resistance contacts between the TCO and the nitrogen polar n-type GaN upon careful interface engineering via plasma pre-treatment.

GaN is a binary III/V direct bandgap semiconductor material that has a Wurtzite crystal structure and is the main stay material for LED manufacture. The GaN crystal structure has a polarity - the physical alignment of the atoms is different depending on whether the material is "up" or "down" - with the polarity having a profound impact on the material characteristic and device performance. GaN has two polarities referred to as "gallium-polar GaN" and "nitrogen-polar GaN". Gallium polar GaN has traditionally provided robust electrical contacts while contacts to nitrogen polar GaN have traditionally degraded with time and temperature. The usual GaN LED construct requires both the positive (P) and negative (N) semiconductor contact to be processed on the gallium-polar face of the GaN material - as described in the idealised schematic in Figure 5:

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TECHNOLOGY UNIVERSITY OF EINDHOVEN

SLOVAK UNIVERSITY OF TECHNOLOGY

UNIVERSITY OF BATH

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TNO

PLESSEY

Although this architecture provides robust LEDs with a general life expectancy of 50 000 hours, it requires the removal of otherwise light emitting areas to form the cathode via's - reducing the LEDs efficiency - while the via process itself adds cost and complexity to the LED.

Figure 6 describes an idealised LED construct utilising a TCO. The anode contact is formed using a traditional reflective mirror while the cathode is formed with a continuous transparent layer in contact with nitrogen polar n-type GaN. This device structure removes the need for though via's - increasing LED efficiency - while greatly simplifying the process and thus reducing cost.

Initial TCO investigations focused on achieving an Ohmic contact to nitrogen polar n-type GaN. The consortium's different TCO deposition technologies (atomic layer deposition, sputtering and chemical vapour deposition) were assessed using transmission line measurement structures. The partners successfully developed methods for creating low resistance contacts on nitrogen polar n-type GaN for both Aluminium Zinc Oxide (AZO) and Zinc Oxide (ZnO) TCO materials.

Following on from the successful Ohmic contacts, a new LED process was constructed which was compatible with the standard manufacturing LED line, in conjunction with various LED electrode designs and suite of test structures.

The new LED process flow contained approximately 40% less processing steps than an equivalent non-TCO LED.

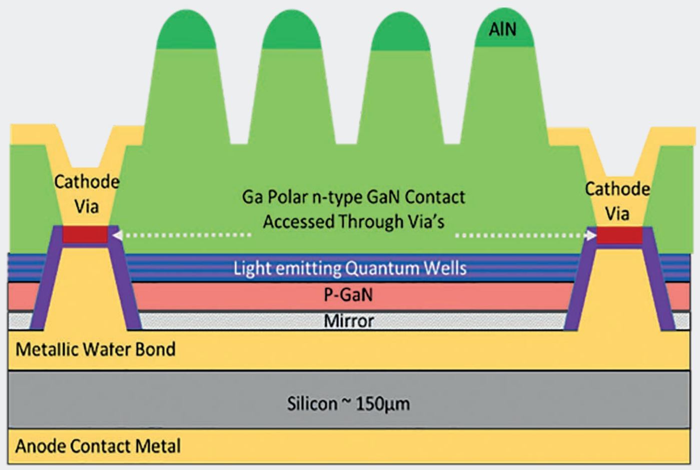

Figure 5: Idealised schematic of HB LED using Gallium polar n-type contacts accessed through via's.

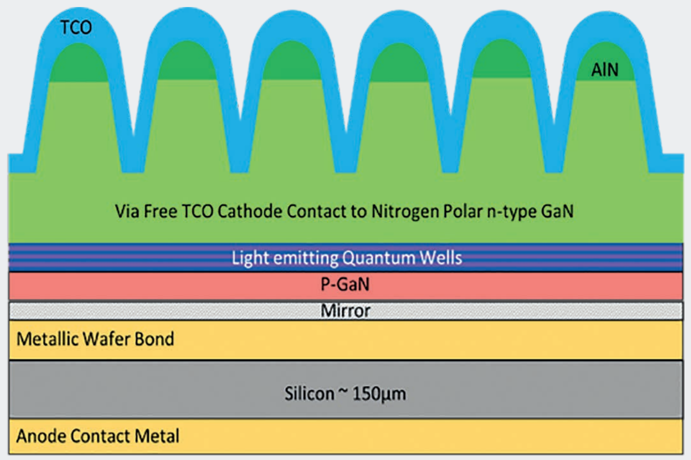

Figure 6: Idealised schematic of novel architecture which can be realised with the INREP TCO material development.

Figure 7 displays three optical images of working LEDs processed during the project. All the LEDs are processed with contacts made to the non-standard nitrogen-polar GaN.

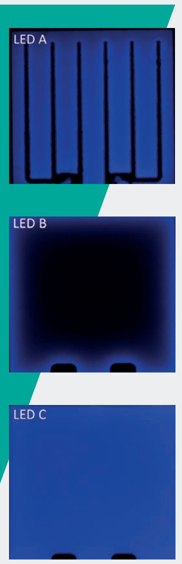

Figure 7: Optical images of three illuminated 450nm nitrogen polar contacted LEDs.

LED A: Illustrates a standard LED design using six absorbing (black) metal electrode fingers. LED A highlights the loss of emitted light within the $1mm^2$ area of GaN.

LED B: Metal electrodes replaced with a perimeter of metal. With the removal of the electrodes, and no application of a TCO layer, the majority LED of the $1mm^2$ area of GaN is dark leading to a large reduction in efficiency.

LED C: Metal electrodes replaced with a perimeter of metal. With the removal of the electrodes and the application of a TCO layer the majority of the $1mm^2$ area of GaN is illuminated leading to an increase of efficiency.

With the tantalising promise of reducing, if not eliminating, absorbing via electrode structures a final design was employed to maximise the potential benefit (Figure 8). The final design was based on Plessey's 12V 3.5mm x 3.5mm HB LED, with a standard non TCO 12V design containing a total of thirty six absorbing electrodes, with the absorbing electrodes covering approximately 10% of the active LED area. Two TCO dependant designs were set with one design containing sixteen absorbing electrodes and the other containing no traditional electrodes at all.

The developed TCO materials have opened a door to new and novel LED device designs enabling increases in efficiency, reduction in manufacturing costs while paving the way for ultra large area GaN applications.

Figure 8: Optical image showing final INREP GaN LED design's prior to TCO deposition.

ORGANIC LEDS

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MEYER BURGER RESEARCH

PLASMA QUEST LIMITED

For this specific application, the goal of INREP was to develop In-free TCOs for use as anode in OLEDs with the same performance as devices with an ITO anode.

Organic Light Emitting Diodes are interesting light emitting devices because in contrast to LEDs, they can provide large light emitting areas, which allows softer illumination and less challenging heat dissipation issues. Combined with flexible encapsulation and substrates, they can provide thinner, flexible large area lighting. Similar to PV devices, a transparent and electrical layer is needed to let the light through and contact the active light emitting layer.

ITO is currently used as material for transparent contacts, but replacement materials are being looked for because of indium's potential scarcity and costs. Also, the need of a post deposition treatment at elevated temperature to improve transparency and conductivity makes it more difficult to use ITO in combination with a flexible polymer device substrate and encapsulation materials. Thus, there is a need in the OLED community for an alternative material to use as transparent electrode.

Candidate electrode materials developed by the project partners were tested by using these as anodes in OLEDs on glass substrate with a small pixel size of 1.5 cm x 1.5 cm. A boundary condition was a deposition (and annealing) temperature below 150°C. Materials included sputtered and ALD aluminium doped ZnO (AZO) layers deposited by sputtering, ALD and S-ALD, stacks of ZnO and silver (Ag) layers as well as silver nano-wire coatings. J-V curves and light output (luminance) were measured. The measurements showed that the relative high absorptance of ZnO / Ag stacks led probably to a lower efficacy than expected on basis of a lower thickness and sheet resistance.

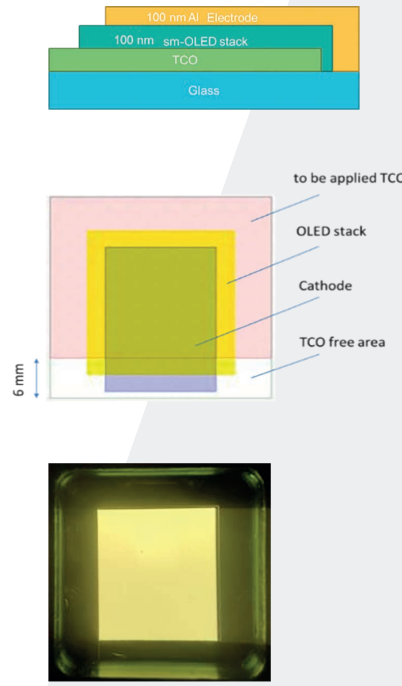

Figure 9: Schematic cross-section (up) and top view (centre) of the test OLED device; 1.5 cm x 1.5 cm OLED test device (down).

Figure 10: *Two 25 mm x 47 mm pixels of an OLED device with an AZO anode*

The test showed that OLED device with sputtered and ALD AZO anodes yielded the highest efficacy (luminance per power) in the tested set of TCO coatings, similar to that of reference devices with ITO anodes (which were not annealed due to the temperature restriction and had hence a relative high sheet resistance). Though the ZnO/Ag stack coatings had a higher conductivity, their relative high absorptance probably led to a lower light-output of the test OLEDs than expected, on basis of their lower thickness and sheet resistance.

In conclusion, the use of sputtered and ALD AZO type anodes resulted in test devices with a performance on par with those with an ITO anode.

The potential of AZO as ITO replacement candidate was further demonstrated by making bottom-emitting OLEDs on glass with six pixels of 25 mm x 47 mm using a patterned sputtered AZO layer as anode, with a performance (in terms of efficacy, luminance, homogeneity) again similar to the used OLED reference with ITO anode. The required patterning of the anode was achieved by means of a shadow mask.

TOUCH-SCREEN MONITOR

PARTNERS

IMEC

QUAD INDUSTRIES

For this specific application, the challenge of INREP was to investigate alternative, screen printable materials for the replacement of ITO as electrode material for transparent touch sensors.

Several touch screen technologies are available on the market, the most widespread being resistive and capacitive touch sensors:

- A resistive touch panel comprises two thin and transparent films separated by a thin space. The top screen has a conductive coating on the underside surface. Just beneath it, we find a similar conductive layer on top of its substrate. When an object presses down onto the outer surface, the two layers connect and a current is measured.

- A capacitive touch screen typically consists of a transparent substrate with a thin-film conductive coating. On top of this, an antiscratch cover is placed. This seals in the sensor electronics and makes the device resistant to scratches. When an object touches the top panel, the electric field across the conductor is disrupted and a change in current is detected.

Typically, the conductive layer is a substantially transparent conducting oxide. Resistive touch systems require sheet resistance between 100 and 500 Ohms per square. The constraint on sheet resistance for capacitive touch systems is relaxed, ranging between 500 and 2500 Ohms per square. As for most applications, the touch screen is integrated on top of a display, the transparency should only cover the visible spectral region (400-800 nm). Within this optical window, the transparency must be at least 85% and preferably higher than 90%. Additionally, a low haze factor below 5% and preferably below 2% is required to guarantee an ideal optical clarity. Currently, ITO is the material of choice for these applications.

The quest for valid replacement to ITO has witnessed the development and testing of transparent conductors deposited by wet chemistry approaches, instead of the previously addressed gas-phase deposition methods. Imomec group of IMEC has developed the silver nanowires (Ag NW) ink formulations. The challenge was to synthesize printing pastes based on silver nanowires with rheological characteristics compatible with transparent touch sensors. A turning point was definitely represented by the switch from PEDOT- to cellulose-based formulation, delivering colourless coatings characterized by a transmittance from 92.8% to 57.3% at 550 nm and a sheet resistance down to 27 Ohm/sq. The opto-electrical properties of these nanowire networks were analyzed in detail by a semi-empirical model, based on the percolation theory in composites.

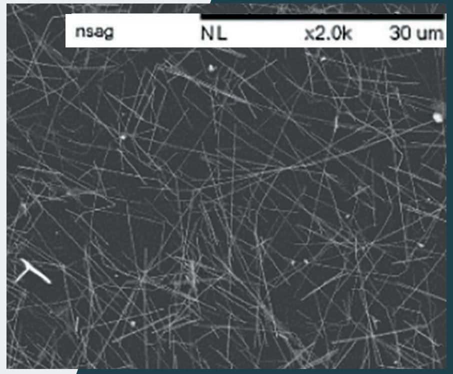

Figure 11: *SEM micrograph of screen printed Ag NWs in a cellulose matrix.*

Different cellulose-based formulations were then applied by Quad Industries in pre-production for touch screen displays applications and compared to corresponding ITO materials performances.

The first demonstrator illustrates the combination of printed touch screen with other printed functionality for a security badge read-out system (NFC read-out; Fig 12), while the second application was an innovative interface for wellness applications which imposes quite challenging environmental conditions due to the presence of extreme humidity or even condensed water droplets at the surface.

The INREP technology has also been applied for the development of printed touch buttons / sliders or other capacitive based sensors, including transparent touch sensor foil for automotive interior parts (Figure 13), integrated sensors for interactive gaming (Figure 14) and innovative liquid sensors for pharmaceutical or industrial applications (Figure 15).

Figure 12: Security badge system, with printed touch screen and printed NFC antenna.

Figure 13: Transparent touch sensor foil, which is typically integrated in automotive interior parts, enabling touch based interfacing.

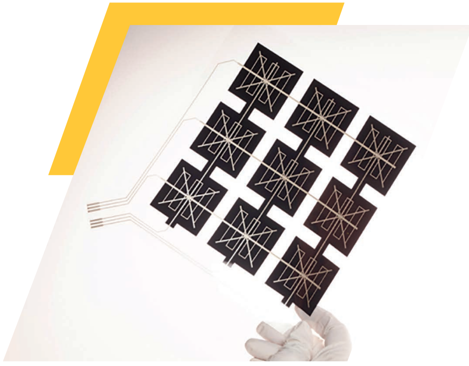

Figure 14: Matrix of printed touch sensors on foil, can be used for interactive gaming

Figure 15: Printed liquid sensor.

RELATED EQUIPMENT

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EXTENDED PLANAR PLASMA SOURCE

As part of INREP, Plasma Quest Limited has developed a large-scale coating source, Extended Planar Plasma Source (EPPS). The patented Plasma Launch System was used to produce small scale high quality TCO coatings. The revolutionary new design enables a spatially confined remote plasma to be focused directly over a planar target. Advantages include very high target utilisation, a stable deposition processes and fast deposition rates to produce superior quality coatings. Coating widths of at least 30cm have been successfully demonstrated and this technology is now ready to take forward to end applications. Furthermore, the novel generation technique that underpins the EPPS is readily scalable. Initial designs are aimed at a 1m width web but the limit is in excess of 3m.

Figure 16: Extended Planar Plasma Source (EPPS).

UNIQUE COATING CAPABILITY:

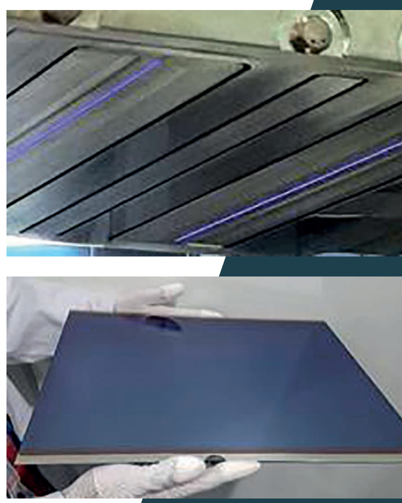
- Scalable technology: available for plate coaters or roll to roll systems.
- High efficiency system: highly directional target sputtering maximises sputtered material usage and minimises power requirements.
- Production capable: minimal maintenance, maximum target utilisation efficiency.
- Peak deposition rates 500 - 1000nm/min for a wide range of materials, including metals, dielectrics and TCOs.
- High performance thin films with low stress (<200Mpa) and high adhesion.
- Low thermal load, compatible with deposition onto organic substrates.
- Suitable for a wide range of target materials, metals, ferromagnetic, ceramics etc.

PLASMA ENHANCED SPATIAL ATOMIC LAYER DEPOSITION

A 30 cm wide injector head with plasma source for an atmospheric sheet-to-sheet (S2S) spatial atomic layer deposition (s-ALD) process, first of its kind, has been built by TNO and Meyer Burger (NL). Test deposition of Al_2O_3 coatings on 325 mm x 400 mm glass plates showed a thickness homogeneity of 98%.

The spatial ALD technology can be used for a wide range of applications, such as highly impermeable barrier coatings, di-electric and transparent electrode coatings with a thickness typically in order of few to a few hundred nanometers. Coatings with a gradient composition over the thickness are possible. The coatings have an unrivalled conformality, enabling complete coverage of surfaces that have high aspect ratios nanostructures such as holes, pillars, trenches and undulations. ALD is a soft deposition technology with minimal impact on the substrate surface. The technologies can be used for sheet to sheet as well as roll-to-roll with deposition rates up to 1 nm/s, depending on the coating, and are up-scalable to a width of several meters.

Figure 17: Injector head with plasma source and glass plate with Al_2O_3 ALD film deposited at 100oC in the S2S-ALD tool.



LIFE CYCLE ASSESSMENT AND COST OF OWNERSHIP

PARTNERS

LODZ UNIVERSITY OF TECHNOLOGY

TNO

It is widely accepted that abundant use of natural resources limits the availability of those reserves for future generations and alternatives leading to more sustainable production must be considered. One of such resources is Indium, which is used extensively in indium-tin-oxide compounds for transparent electrodes in display, solar and OLED devices. Promising candidates for Indium replacement in these TCO layers are widely analysed in terms of layer quality and potential for industrial processing. However, the environmental impact of newly developed layers is unknown and needs investigation. Therefore, some of the activities within INREP were dedicated to analysis of the environmental effect of ITO replacement by other materials, such as zinc oxide (ZnO). To this end, a life cycle assessment was performed, which enables to assess which components may produce smaller environmental impact over the entire period of its life cycle ("from cradle to grave", during manufacturing, operation and waste management).

The INREP partners have selected the following criteria for subsequent choice of the LCA approach:

- The method must follow ISO standards and have a broad number of applications reported, to ensure that the approach was extensively tested.
- The database of materials and utilities related to the method must be very broad to ensure availability of coefficients for all compounds used in the TCO layer deposition process (e.g. Zinc Oxide).
- The method should enable a thorough LCA analysis and include all categories of impact on environment and human health.
- The result of the calculation should be a single score, enabling easy comparison and interpretation.
- LCA calculation tool must enable clear and transparent analysis.

INVENTORY OF MATERIAL AND PROCESS DATA

First of all, the partners collected detailed data for the different TCO materials and TCO layer deposition techniques that were evaluated (physical/chemical vapour deposition, atomic layer deposition). Based on this data, additional mass and energy balances could be calculated and subsequently an impact on environment was quantified. Within the scope of INREP, different promising deposition techniques and material candidates for ITO replacement were analysed and benchmarked against the state-of-the art ITO layer applied by physical vapour deposition (PVD) technique of sputtering

LIFE CYCLE ASSESSMENT RESULTS

Data for ITO and alternative TCO layers deposited by the PVD technique were collected for lab-scale scale equipment. Subsequently, input data for all processes was derived and used for the calculations.

Replacement of ITO by ZnO or AZO proved to be a promising strategy towards minimization of the environmental impact of the TCO layer deposition process.

No.	Compound	Dep. Tech.	Single Score [Pt]	Main impact [%]	CoO per area; (100 = ITO reference)
1	ITO reference case	PVD	3,5E-6	Indium tin oxide 60,9	100
2	ZnO	PVD	1,55E-6	Electricity 95,3	85
3	ZnO:Al	PVD	1,56E-6	Electricity 95	72
4	SnO2	PVD	1,37E-5	Tin dioxide 90,0	93

Table 1. Summary of LCA and CoO results for PVD coatings.

The LCA were accompanied by Cost of Ownership analyses. As input for the latter, the same material and electricity usage per deposited area was used as in the LCA analysis. The material costs were estimated in consultation with the partners as were those of the equipment costs and their assumed throughput (determining the number of tools and hence factory space, personnel).

The PVD processes gave the lowest values. The ranking of their CoO was the same as the costs of the sputter targets. Because of a lower deposition rate for a given power, the latter has to be higher for ZnO and AZO and hence their electricity usage and costs will be higher than for ITO (for achieving the same throughput) but the effect on the CoO was minimal.

The CoO values for the PE-CVD by LP-CVD and ALD processes were one or even two orders of magnitudes higher if input data was used based on the lab scale or experimental tools used in this project. Projecting the effect of re-use of materials, batch instead of single wafer tools and/or multiple injector tools did reduce the CoO usage again enormously, but a significant effort will be needed to implement and validate these improvements (and achieve a TRL of 8 or 9).

As an outlook for further development, we can conclude that sputtered AZO can be recommended as a replacement of ITO from both environmental and cost perspective.

INREP
Towards Indium free TCOs

Contact: contact@inrep.eu

Project website: www.inrep.eu

Project Officer: Dimitrios Biliouris (EC)

Project Coordinator: Duncan Allsopp (University of Bath)

Project Technical Coordinator: Sylvain Nicolay (CSEM)

Dissemination Manager: Peggy Favier (L-up)