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PROJECT FINAL REPORT

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Project acronym: POINTS

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Project website Error! Bookmark not defined. **address: http://www.points-fp7.eu/**

4.1 Final publishable summary report

Executive summary

Points was set to make break-through advances in printed electronics in terms of new low-temperature printable materials with enhanced performance. This was achieved through combining the best properties of organic and inorganic (metal-oxide) materials into hybrid structures at both the molecular and at structural-interface level. In particular, the project focused on semiconducting and dielectric materials based on (i) molecular precursors, (ii) nanoparticle composites and (iii) hierarchically structured materials. Furthermore, expertise of the consortium in cost-efficient mass fabrication processes was coupled to the materials development to obtain optimum performance and processability. Industrial relevancy of the work was assured by selected demonstrators of industrial interest for ICT applications. Focused materials included IZO, GIZO, IO and GZTO for semiconductor and Al_2O_3, AlOOH, HfO, and novel high-k oxide/PMMA nanocomposites for insulator. Spin coating as well as inkjet, gravure and flexo printing were utilized for solution processed TFTs and circuits. Sputtering was used as fabrication method for reference devices and in materials selection.

The main results of the project were:

- Several alkoxide precursors were under detailed studies for low-temperature decomposition.
- Nanoparticle synthesis was improved for controlled composition for ternary materials.
- Nanoparticle processing into homogeneously thin, dense, and smooth films required for functional device stacks has been achieved.
- Semiconductor curing was achieved at 180 °C combined with FUV illumination resulting in mobility of the order of 3 cm^2/Vs. For 200 °C annealing, the mobility reached 7 cm^2/Vs with solution processed semiconductor and dielectric.
- Gravure-printed nanoparticle-based dielectrics were tested in capacitor structures. The results consistently reached a capacitance density of about 100 pF/mm2 and a leakage current density of 1 µA/mm^2 as obtained at an electric field of 3 MV/cm. Best project dielectrics reached 1 nA/cm^2 leakage current.
- Flexo printed TFTs reached a 4 cm^2/Vs mobility performance on plastic.
- Statistical circuit simulation models were developed for the Aplac circuit simulator and those were used in circuit design.
- Simple logic flip-flop circuits, ring oscillators and LED drivers were implemented using the project materials. Those components were used to construct functional card demonstrators that were taken to the LOPE-C 2014 conference exhibition.
- The achievements of the project have resulted in 9 journal articles, 5 conference papers, contributions in 1 book, 1 doctoral dissertation, 2 publications in university series, 57 conference presentations (including the demonstrators exhibited at the LOPE-C 2014 conference) and 2 patent applications.

It is expected that the results will enable and catalyse development of printed electronics within the next couple of years.

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Multivalent, Promethean Particles, Stora Enso Oyj, Bayer Technology Services GmbH, University Dunarea de Jos of Galati, IGCatalysts

Summary description of project context and objectives

Printed electronics is an emerging disruptive technology which has made impressive progress in the last 10 years. In particular, (i) the field-effect mobility of solution-processed, organic TFTs has increased to levels exceeding that of thin-film amorphous silicon TFTs, (ii) the performance of polymer LEDs is surpassing that of fluorescent tubes, and (iii) the efficiency of printed organic solar cells is constantly improving. However, it has also become clear that significant further improvements in performance and reliability of materials and devices are needed to enable meeting real-world application requirements for a range of demanding ICT applications such as ambient intelligent labels, radiofrequency identification tagging, intelligent packaging, integrated sensor systems, etc. A potential approach to achieve these is to not restrict oneself to organic materials but also incorporate inorganic materials. This is because (i) inorganic semiconductors with three-dimensional covalent or ionic bonding tend to exhibit significantly higher charge carrier mobilities than organic semiconductors, (ii) printable inorganic conductors, such as metal nanoparticle inks, achieve much higher conductivities than conducting polymers, and (iii) the dielectric properties and breakdown characteristics of the best inorganic insulators are superior to those of polymer dielectrics.

Metal oxides is a class of inorganic materials that has recently attracted significant attention for use in thin film transistors (TFTs), conductive electrodes, capacitors, optoelectronics, sensors, and electrochromic devices. Through use of vacuum-based sputtering techniques at room temperature, a great variety of conductive or wide-band-gap semiconducting materials with binary, ternary or quaternary composition, such as ZnO, ZnSnO, SnGaZnO, InSnO, InGaO and InGaZnO, are accessible. Since for these materials, the electron conduction band is formed by overlap of the metal cations' spherical s-orbitals, they can exhibit excellent electronic properties for non-crystalline films. For conductors, Al-doped ZnO (AZO) and F-doped SnO2 are potential candidates for transparent materials to replace indium tin oxide (ITO) for which cost efficiency is limited by the shortage of indium. Recent results for insulating inorganic-organic composites have demonstrated relative dielectric constants over 100 thereby outperforming organic dielectrics.

To make use of the superior properties of inorganic materials while retaining the processing benefits of organic materials (compatibility with low-temperature solution processing and printing on plastic/paper substrates as well as good adhesion properties) hybrid organic-inorganic materials are essential. To achieve sufficient solution processability, the inorganic elements need to be attached to organic ligands and/or mixed with organic binders that either are eliminated during thin film processing, e.g. by thermal, laser, UV or electrical annealing or remain in the structure for enhanced operation. The objective of this project was to develop low-temperature solution processing approaches to a broad range of high-performance hybrid organic-inorganic metal-oxide materials. We also explored applications of these new materials in device structures relevant for ICT applications. In particular, we focused on the active semiconducting and gate dielectric layers of TFTs. What is needed in the field is a broad range of oxide materials that can be processed at low temperatures (< 180°C) to be compatible with common plastic substrates and that provide tailor-made controllable electronic properties (mobility, carrier concentration, interface states, permittivity) for optimization of device performance and stability. Points was set to make an improvement in this respect.

The Points achievements were valued on the basis of selected devices and application-relevant circuit test structures for ICT usage. Although the focus of the project was fully on ICT applications, we would like to emphasize that the materials developed in this project can potentially also be applied widely outside the applications targeted in POINTS. Such other application areas for the project outcomes are in displays, lighting and photovoltaics to implement the active light-emitting/absorbing layers, charge-transport layers or transparent electrodes.

The project had the following objectives:

- Develop high-performance solution-processable organic-inorganic metal-oxide semiconductor and dielectric materials. The main performance characteristics of special attention to be monitored during the project included:
    - Semiconductor charge carrier mobility to exceed $\underline{10\ cm^2/Vs}$.
    - Dielectric leakage current under $\underline{1nA/mm^2}$ at electric fields of $\underline{3MV/cm}$.
    - Low temperature processability at $\underline{150°C - 180°C}$.
    - Bias stress stability of $\underline{\Delta V_T < 3V}$ after $\underline{10^5\ s.}$
    - Relative dielectric constant over $\underline{10.}$
- The material approaches included:
    - Molecular precursor routes to metal oxides.
    - Use of metal-oxide-based polymer-encapsulated nanoparticles dispersed in a liquid.
    - Organic ligand/polymer encapsulation of the semiconducting inorganic nanoparticles.
- Develop and upscale new formulations of printing inks for oxide-based semiconductors and insulators.
- For preparation of reference devices and to guide the materials selection, RF sputtering was used.
- Validate and optimize the developed materials for the processing steps that are needed for low-cost mass production of the project target applications on paper and plastic substrates.
    - Pre-processing such as substrate treatments
    - Printing in sheet-fed and roll-to-roll compatible processes
    - curing (oven, laser, UV, electrical)
    - post-processing such as lamination
- Develop high-performance printed thin-film transistors (TFT) utilizing the new materials.
- Develop circuit-level models for the components to be available for further work in the field.
- Proof the industrial relevancy through application-specific circuit prototyping such as:
    - Elementary logic devices such as inverters and flip-flops.
    - Ring oscillator
    - Switching multiplexer for memory addressing.
- Disseminate results into public knowledge and IPR, for example, through scientific articles and patents, through European and international conferences and workshops, through participation in industry associations such as the OE-A, using The POINTS project web site.

Description of the main S&T results/foregrounds

SEMICONDUCTORS

Precursor approach for solution processing

The main approach in the project for semiconductors was metal oxide chemical precursors that turn into the desired semiconducting film after deposition by thermal or other annealing methods. Especially two classes of precursors were focussed on namely alkoxide and nitrate precursors. The nitrate precursors are considered below in more detail in connection to the zinc tin oxide (ZTO) results (new precursors to replace indium and gallium usage) and in connection to low temperature UV annealing results. Here we present investigated alkoxide precursors as published by partner UCAM. The alkoxide approach is presented in Figure 1[1]

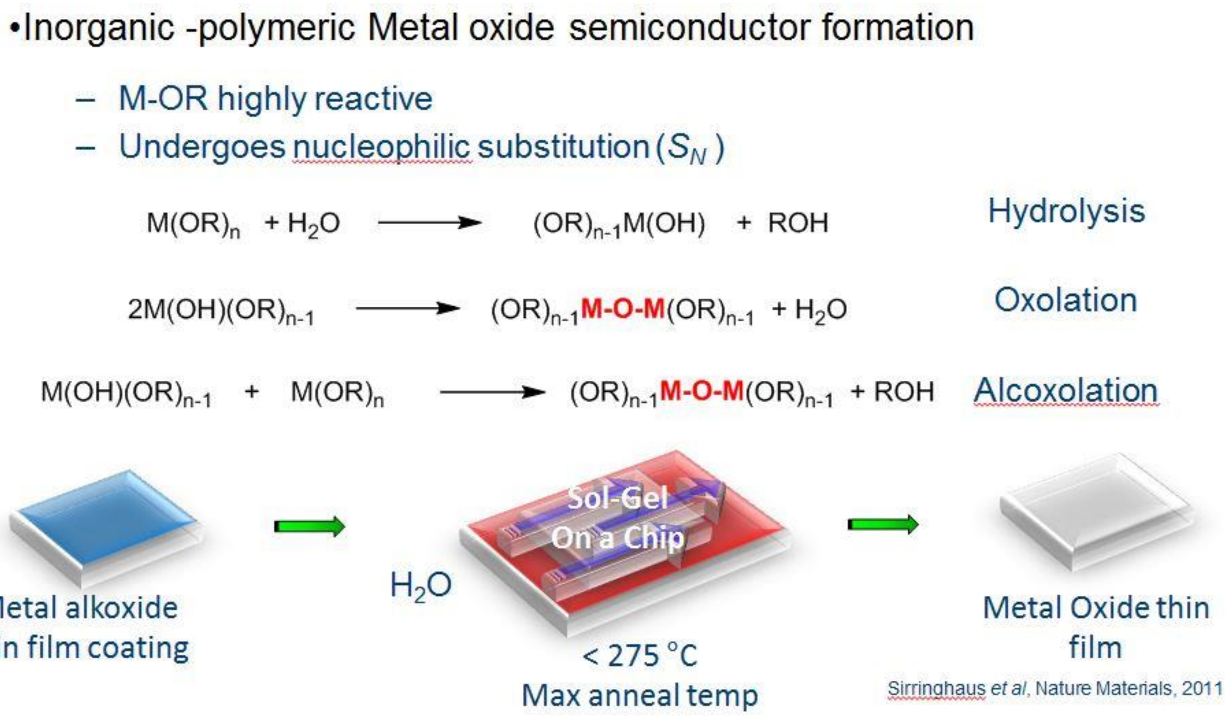


Figure 1: Alkoxide route to semiconductors (UCAM).

Using the alkoxide route, UCAM achieved replacing gallium in the indium gallium zinc oxide (IGZO) semiconductor by strontium or barium such that enhanced stability characteristics were obtained. TFT characteristics are shown in Figure 4[2]. The devices are spin coated on an oxidized silicon wafer that acts as the bottom gate and gate insulator. For high performance of mobility up to 26 cm^2/Vs, the devices were annealed at 450 °C while with low temperature annealing at 200 – 225 °C still good mobility of 4.4 cm^2/Vs was obtained. Bias stress stability results are shown in Figure 3. An improvement in the stability is found as compared to IGZO.

[1] Sirringhaus *et al*, Nature Materials, 2011
[2] Sirringhaus *et al*, Chem. Mat. 2014; K. K. Banger, IMID Meeting Daegu 2014

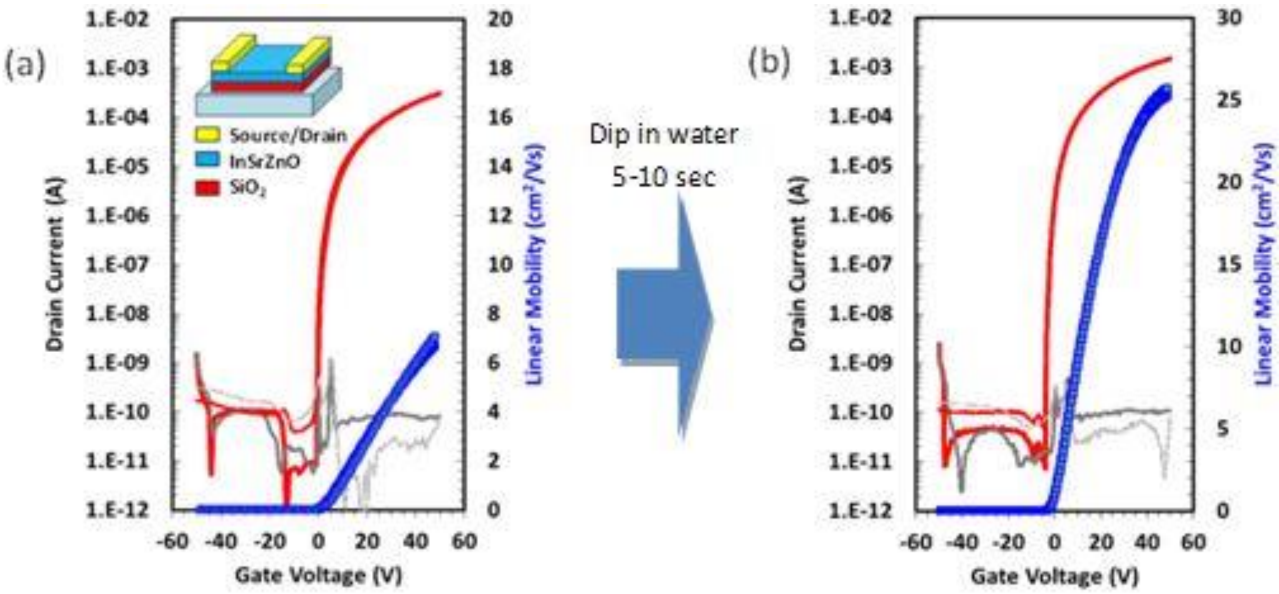


Figure 2: ISZO TFT characteristics before and after the last processing step of rinse in water (UCAM)

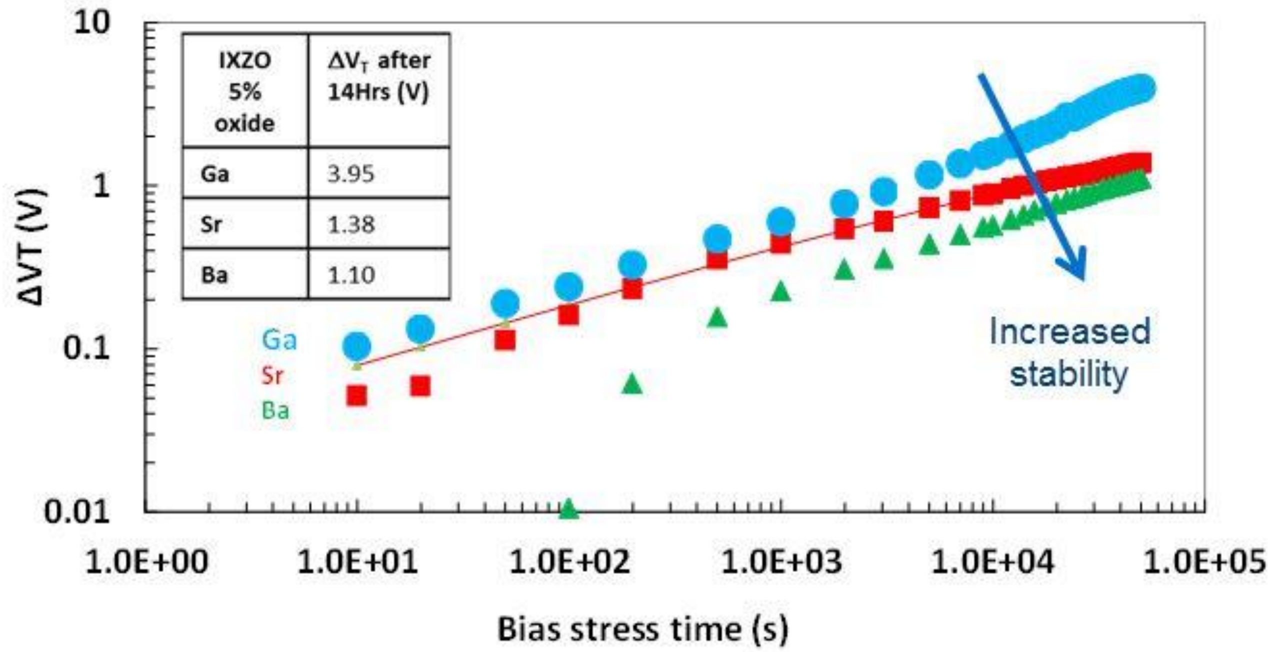


Figure 3: Bias stress measurements of ISZO and IBZO as compared to IGZO (UCAM).

IZO nanoparticles

POINTS partners Promethean Particles and Fraunhofer IISB developed recipes for ternary metal oxide nanoparticles and improved formulations for layer processing by spin coating and ink-jet printing into thin semiconducting layers (Figure 4). The development along the value chain from synthesis through to integration into electron devices was guided by physico-chemical and electrical analysis in the involved labs.

Based on a unique reactor design that offers maximum variability for controlling hydrothermal, solvothermal,and mixed-solvent reactions, Prometean Particles developed routes for the preparation of InO and IZO particles. In the chosen approach a downstream of solvent heated to the reaction temperature meets an upstream of the room temperature precursor mixture (indium isopropoxide from POINTS partner Mulktivalent/Ig catalysts) and particles are formed and ligand coated in the mixing zone. The reactor design thus enabled the combined synthesis and formulation of particle-based inks, that were processed further at partner IISB.

Improvements to the ink formulation were achieved by variation of synthesis temperature; nature and concentration of particle capping agent; and the post production concentration steps. These variations were implemented in the production of second generation ink samples which were once again processed, applied and analysed at IISB. In this case, the inks could be applied to substrates by spin coating or inkjet printing and to give more homogeneous thin films of IZO nanoparticles.

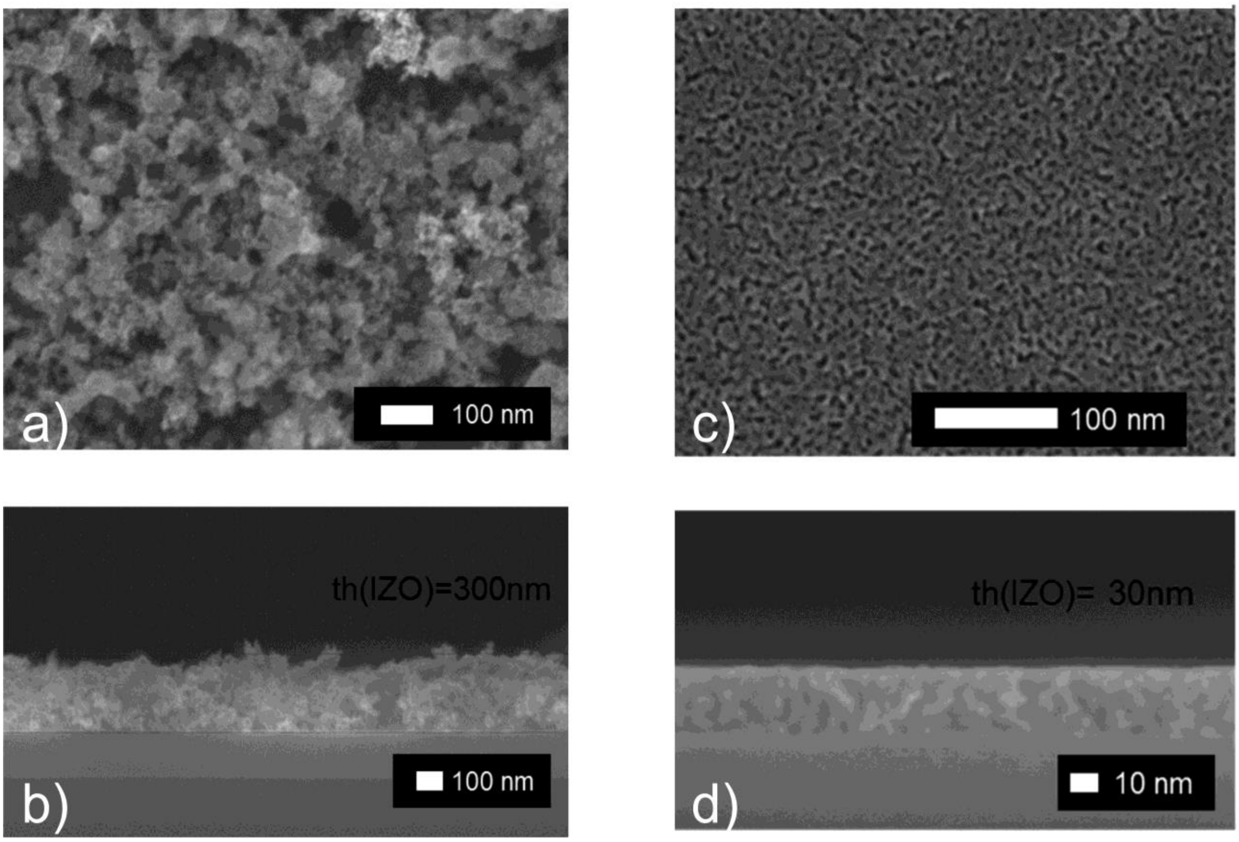


Figure 4: Integrated development of ultrathin semiconducting films by well-matched synthesis, formulation, and thin-film deposition (spin-coating). SEM top view (a) and cross cut (b) show layer quality before, (c) and (d) after optimization.

Figure Figure 5 shows the respective output and transfer characteristics for TFTs built on oxidized silicon substrates where the p-doped silicon acts as gate electrode while the 200 nm thick SiO_2 delivers the gate dielectric. The semiconductor in these samples is spin-coated IZO (from the reference batch (#Zn21), roughly 30 nm in thickness and annealed at 350°C in air, whereas the source and drain electrodes were deposited from an aluminum source through a shadow mask yielding a channel length of 120 µm and width of 3000 µm. The devices show mobilities between 0.2 and 0.5 cm^2/Vs at considerably high negative threshold voltages which is attributed to high levels of free carriers. Furthermore, for fast and high volume materials screening we have applied simple TFTs that avoid patterning of both the semiconductor and gate electrode layer. The resulting high leakage currents are suppressed by chosing a rather thick dielectric layer that in turn increases the absolute value of the threshold voltage.

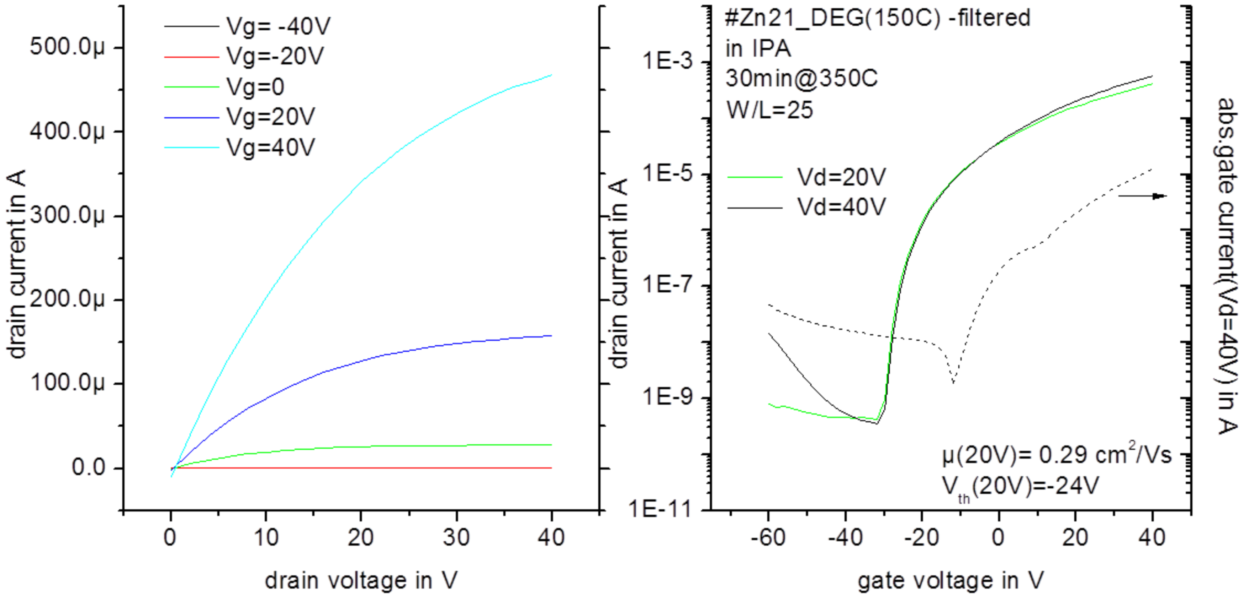


Figure 5: Output and transfer curves of staggered bottom-gate TFTs employing nanoparticle-based IZO semiconductor.

The formulation optimized by Promethean Particles allows for the transfer of the device fabrication to ink-jet printing at minor modifications. In detail only an additional filtering step with a 0.2 µm syringe filter has to be performed before or while filing the ink into the ink jet cartridge. Figure Figure 6 shows the SEM top view and cross cut of the devices that are built on the identical gate/dielectric base and is finalized by ink-jet printing of silver electrodes. The output curves of these devices show a good linear behaviour around the origin suggesting the absence of any barrier for injection of electrons to or from the semiconductor (Figure 6) as well as a good saturation behavior. The transfer curves reveal a desirably high ON/OFF ratio as well as low gate leakage achieved by patterning the semiconducting layer. Interestingly, the extraction of the saturation mobility of the ink-jet printed TFTs delivers values similar to those achieved for the spin-coated devices. This observation is in alignment with the morphological appearence of the semiconductor films that can be evaluated comparing Figure 4 and Figure 6. By applying proper deposition and drying routines, both deposition techniques yield dense, crack-free, and smooth semiconductor layers.

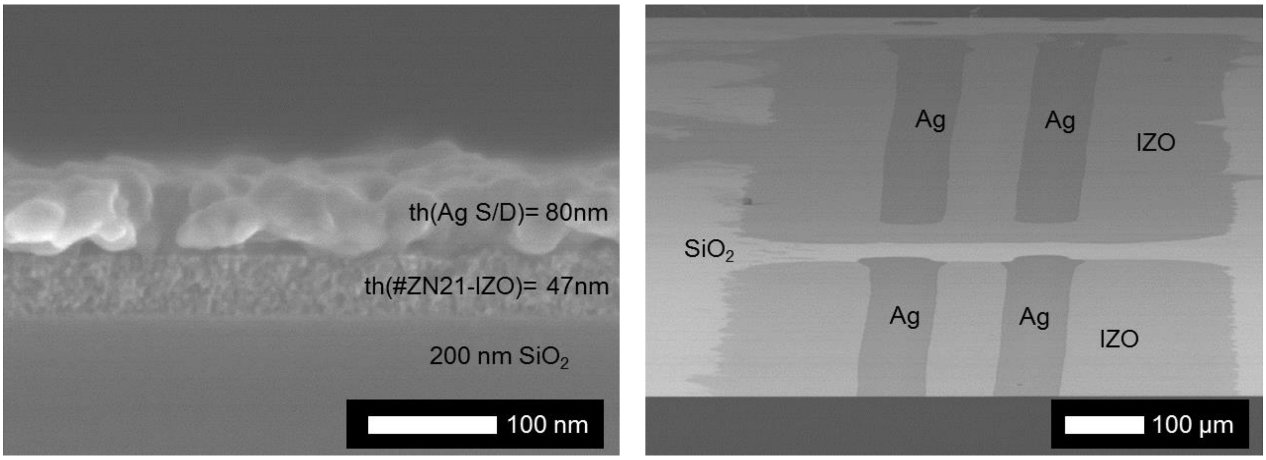


Figure 6: Solution processed semiconductor and S/D electrodes in bottom gate TFTs on Si/SiO_2 substrates (gate stacks). SEM of cross cut (left) and top view (right).

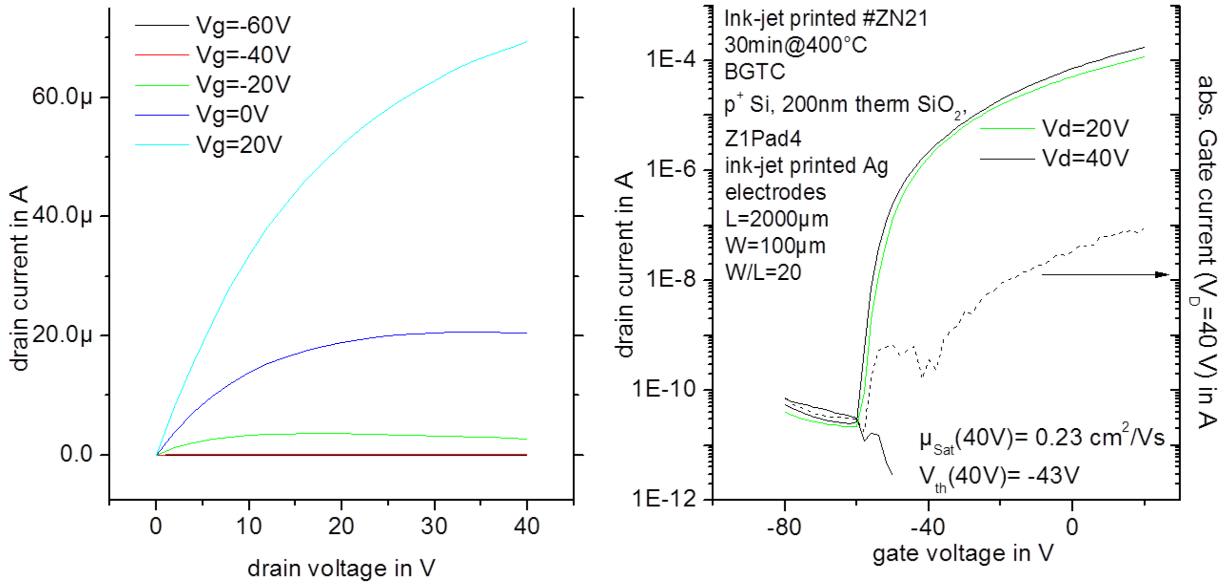
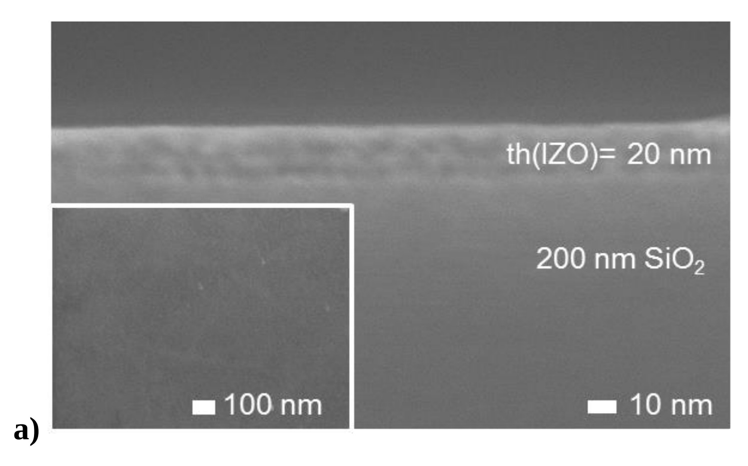


Figure 7: Output (left) and transfer (right) characteristics of staggered BG TFTs with printed semiconductor and S/D electrodes.

Precursor development for spray pyrolysis

A facile, fast, and low-cost precursor route for the formation of binary and ternary metal oxide thin films was developed at IISB and verified by the preparation of thin-films transistors. The processing uses only non-toxic solvents and can be done in ambient air. Post deposition annealing temperatures are as low as 250°C (Thin Solid Films 553 (2014) 114–117).

The precursor is based on the reaction of dissolved Zn^{2+}-ions with dissociated hexamethylene tetramine (HMT) in the presence of hydroxide ions, forming stable tetraammin zinc complexes avoiding precipitation. Formation of ternary and higher metal oxides is achieved by simple mixing of metal salt educts. Thus, ZnO deposition resulting in highly crystalline films delivering saturation mobilities of 0.1 cm^2/Vs could be improved by adding indium nitrate to the precursor improving the performance to μ_{Sat} of 14 cm^2/Vs.



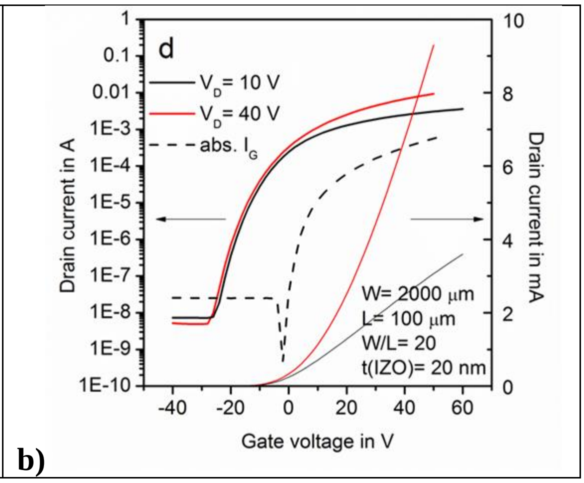


Figure 8: Film formation (a) and electrical characteristics of TFTs (b) based on spray pyrolysis of IZO. The non-toxic precursor can be handeled and processed in ambient air and is post-annealed at low temperatures.

ZrO_2-PMMA Hybrid dielectric

Hybrid materials combining controlled nanoscale structures of inorganic and organic constituents, characterized by combined properties of the organic polymers (flexibility, elasticity, adhesion to substrate, facile processing) with those of the inorganic compounds (optical, electrical and thermal properties) can simultaneously satisfy all the requirements of the gate dielectric for use in transparent and/or flexible electronics. The hybrid materials open the way to obtain new materials with high dielectric constant ("high-k") that underlie the development of a new generation of electronic devices based on thin film transistors (Thin Film Transistor -TFT).

UDJG and IISB aimed to develop a new class of hybrid "high-k" dielectric films based on tantalum oxide, zirconium oxide, hafnium oxide and silicon oxide in the PMMA polymer matrix. According to the materials development approaches of this project, metal (Zr, Hf, Ta, Si)-organic molecular precursors (alcoxyde type) and organic monomer (MMA) together with an organo-silane ligand were used to obtain high-k hybrid thin films based on in situ generation of metal oxide nano-building-blocks.

Molecular alkoxide with high potential for the formation of dielectric films, namely triterbutoxi silanol $Si(OH)(O(C(CH_3)_3)_3)$, tritertbutoxialuminiu $(Al(OC(CH_3)_3)_3$, ethoxide, hafnium $(Hf(OC_2H_5)_4)$, tantalum ethoxide $(Ta(OC_2H_5)_5)$ and zirconium oxoethoxide have been investigated as precursors for in situ generation of dielectric metal oxide components of the hybrid films. The thermal decomposition of the molecular precursors and hybrid systems, resulting by combining and treating them in diferent experimental conditions were investigated by mTGA- mDSC modulated thermal methods in the range from ambient temperature up to 600 °C, under pure (5.0) nitrogen, synthetic air or air enriched with O_3. The composition of gaseous products arising during pyrolytic decomposition was analyzed by infrared spectroscopy (FT-IR) and mass spectroscopy (MS)[3]. Based

[3] V. MUŞAT, E.E. VÂLCU (HERBEI), T. LEEDHAM *"Thermal behaviour of complex precursor for sol-gel preparation of dielectric tantalum oxide-PMMA hybrid thin films"* XVII INTERNATIONAL SOL-GEL CONFERENCE 2013, Madrid, 25-30 August 2013

on these results, plus X-ray photoelectron spectroscopy (XPS) data, the methods for obtaining dielectric hybrid films using molecular precursors and organic MMA monomer were developed and optimised. The optimal post-deposition treatment of the as-deposed gel thin films was estimated at 160°C followed by UV exposure.

Good and very good dielectric behavior was obtained for the most of the hybrid films, allowing futher investigation for their integration in TFT transistor structures. The best dielectric properties were obtained for Ta_2O_5:MPS:PMMA and ZrO_2:MPS:PMMA films[4]. The last ones are in the same time very stable dielectrics, due to a very homogeneous smoth surface morphology and homogeneous phase composition, including in situ formated ZrO_2 nanocrystals. Figure 9 shows the layer structure of spin coated hybrid dielectric films on top of a silicon wafer and the corresponding capacitance measurement results are shown in Figure 10. The temperature budget was 160 °C.

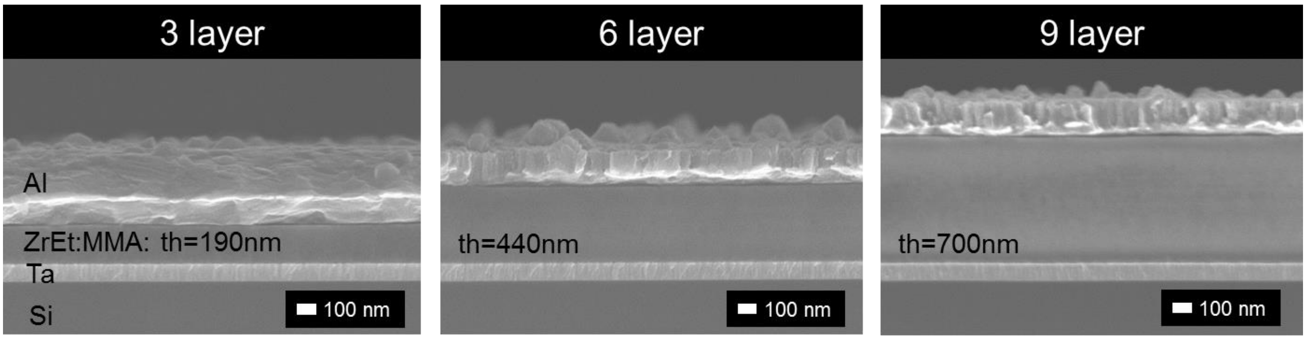


Figure 9: Cross section SEM images of the hybrid dielectric (IISB).

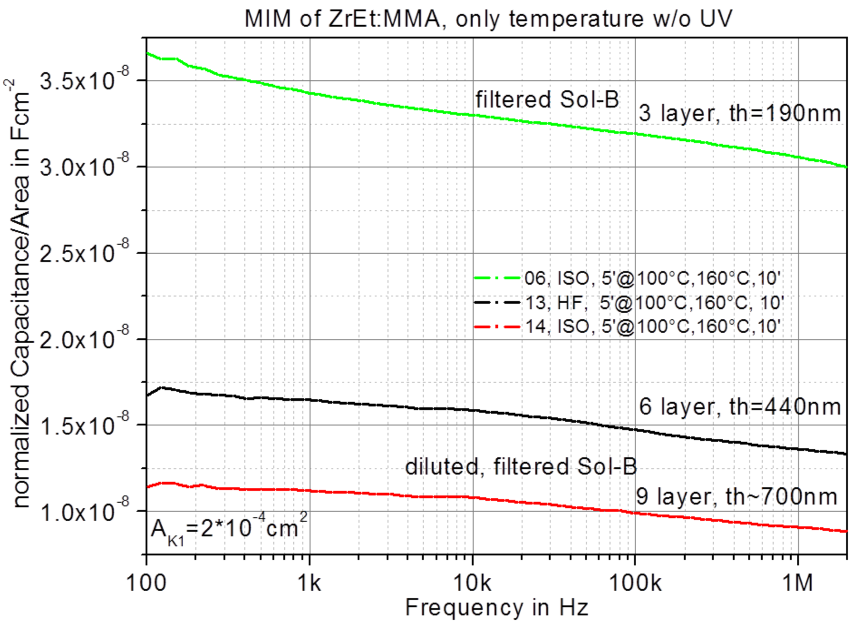


Figure 10: Capacitance measurement results of the hybrid dielectrics (IISB).

[4] E.E. VÂLCU (HERBEI),V. MUŞAT, M. JANK, S.OERTEL, P. ALEXANDRU, T.LEEDHAM *„Hybrid dielectric materials obtained by sol-gel method for thin film transistors"* **XVII** INTERNATIONAL SOL-GEL CONFERENCE 2013, Madrid, 25-30 August 2013 B; E. E. VÂLCU (HERBEI), Viorica MUŞAT, Susanne OERTEL, Michael JANK "*Sol-gel preparation of ZrO_2-PMMA for thin films transistor*" Revista de chimie (CHEMISTRY MAGAZINE), 65/Nr.5 (2014), 574- 577 (ISI, IF =0.53)

ZTO combustion synthesis

The development in solution processed inorganic metal oxide semiconductor materials for high-performance thin film transistors (TFTs) are generally focused on gallium indium zinc oxide however there is a need for alternative semiconductor materials that rely on abundant and non-toxic elements. Zinc tin oxide (ZTO) is a promising indium and gallium free alternative and has been developed as channel layer for TFTs in the POINTS project by FCT. Combustion synthesis was chosen as a method to diminish processing temperature for both ZTO semiconductor and AlOx solution based dielectric. Ethanol was explored as a more environmental friendly solvent than typically used 2-methoxyethanol.

The low temperature solution combustion synthesis has been reported for multicomponent oxides thin films [3–6]. This combustion synthesis takes advantage of the chemistry of the solution precursors as a source of energy for localized heating (Figure 11). The precursor solutions are obtained by dissolution of the desired metal salts, usually nitrates, which provide the metal ions and an organic fuel, usually urea, in an organic solvent, 2-methoxyethanol (2-ME) [3–6].

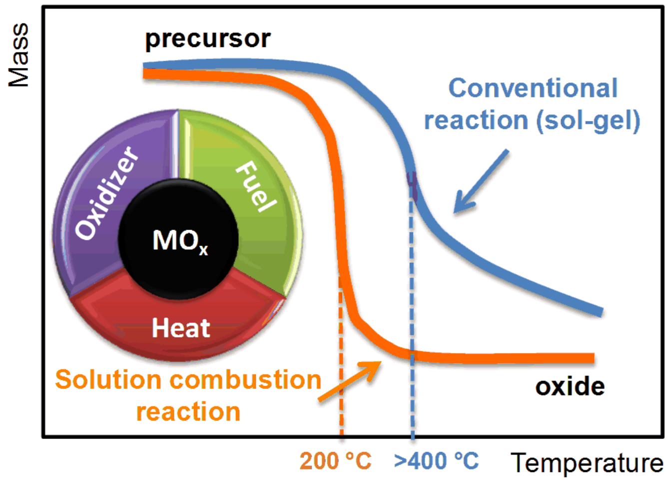


Figure 11: Schematic representation of the decomposition profile of a precursor solution of combustion synthesis reaction compared to conventional sol-gel synthesis.

ZTO precursor solutions with 0.05 M concentration were prepared in 2-methoxyethanol and ethanol using zinc nitrate and tin nitrate as metal ion source and oxidizer, and urea as fuel. AlOx precursor solutions with 0.1M concentration were prepared in 2-methoxyethanol and ethanol using aluminium nitrate as metal ion source and oxidizer, and urea as fuel.

The TFTs were produced in a staggered bottom-gate, top-contact structure by depositing solution based AlO_x dielectric thin films onto p-type Si substrates (1–10 Ω cm) followed by deposition of ZTO semiconductor thin films. hotplate annealing at 350 °C for 30 min was performed after each deposition. Source and drain aluminium electrodes (100 nm thick) were deposited by e-beam evaporation via shadow mask onto annealed films

Thermal analysis of precursor solutions was performed to investigate the decomposition behaviour of the metal oxide precursors. TG-DSC measurements show expected exothermic peak of the oxide formation reaction. Using ethanol as solvent did not significantly affect the reaction mechanism.

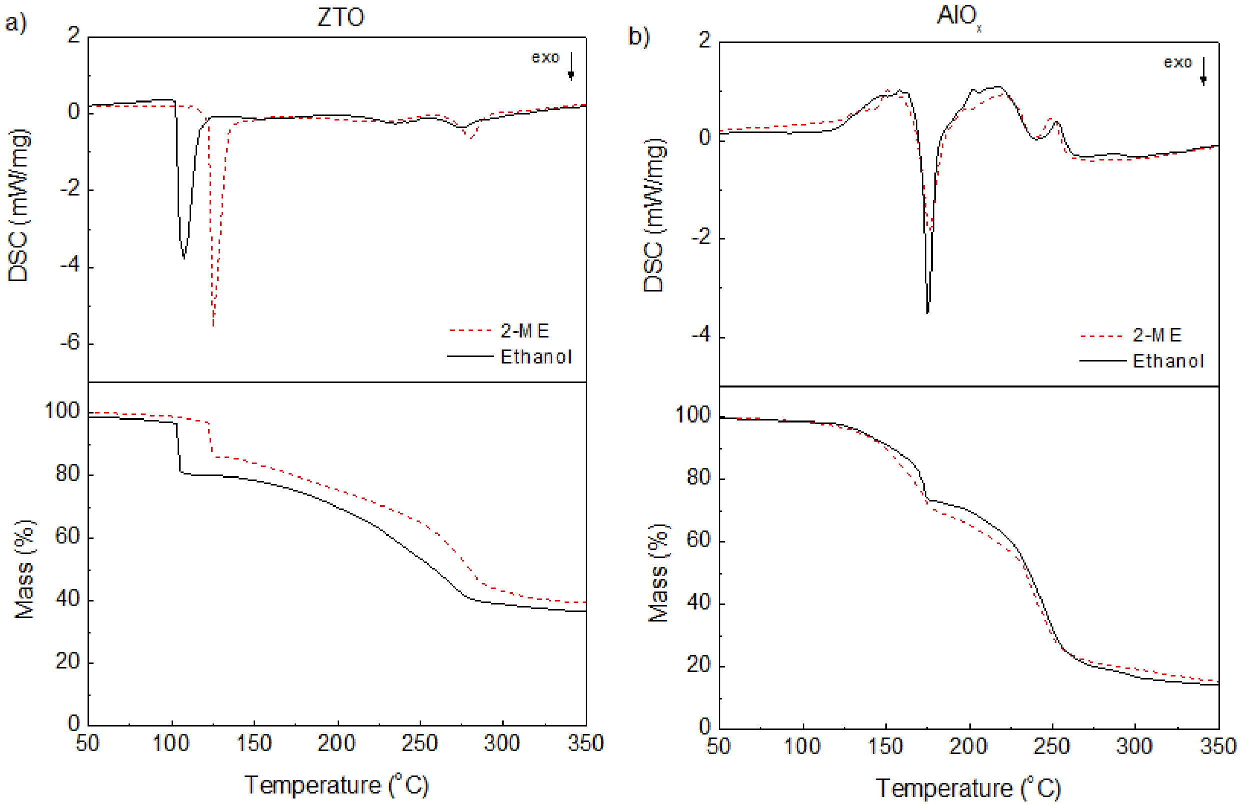


Figure 12: TG-DSC analysis of ZTO (a) and AlO_x (b) based precursor solutions using 2-methoxyethanol (2-ME) and ethanol as solvent.

Electrical characterization of solution processed AlOx capacitors and ZTO/AlO_x TFTs (Figure 12) was performed.

The capacitance obtained for ethanol and 2-ME based AlO_x at 100 kHz was 92 nF/cm^2 and 149 nF/cm^2, respectively and the leakage current density was bellow 10^{-5} A/cm^2. The calculated relative permittivity was 4.2 and 6.7, respectively. The permittivity values are lower than expected for Al_2O_3; ~9 however these are in agreement with reported values for solution processed aluminium oxide Al_2O_3; ~6-7.

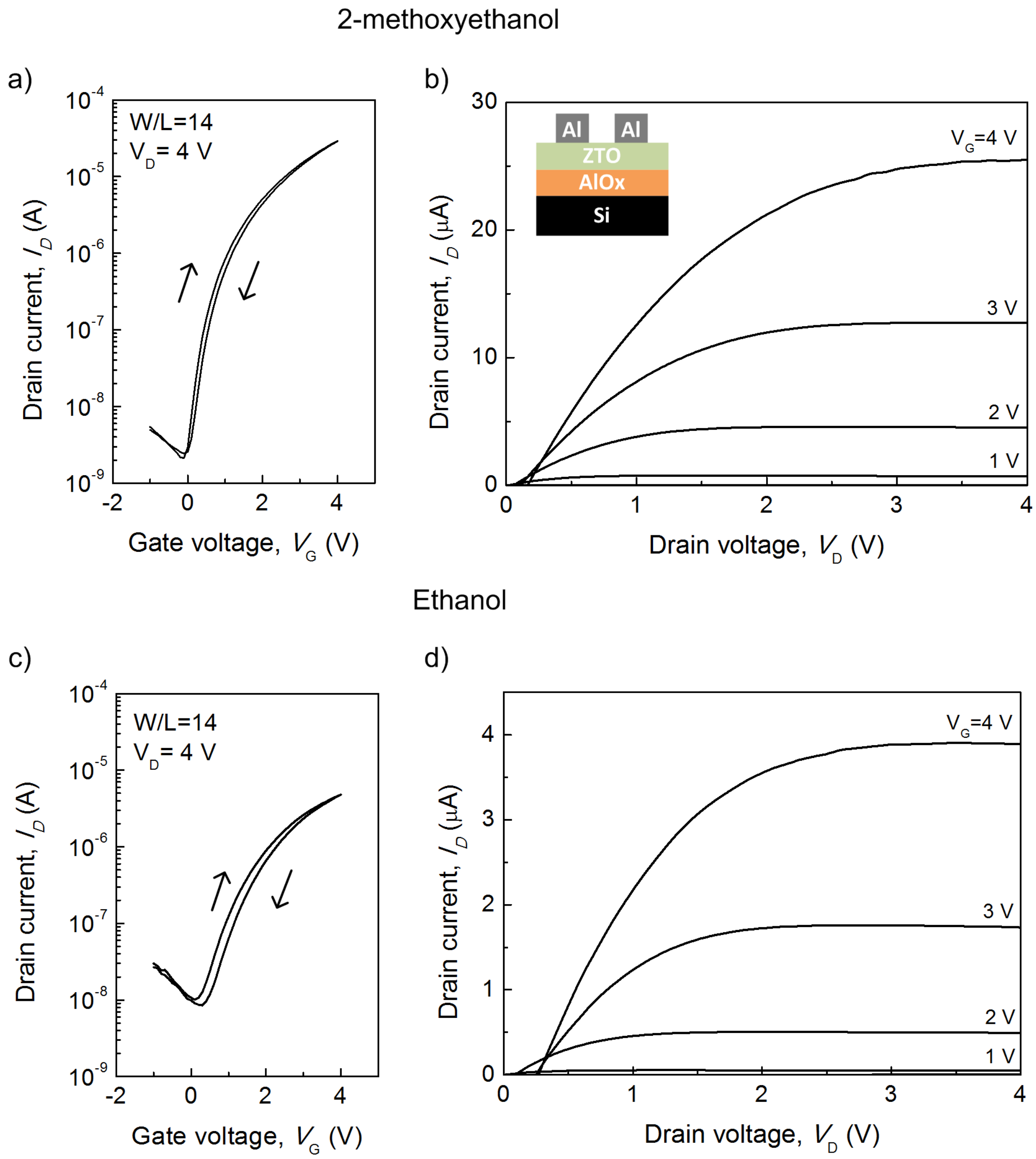


Figure 13: Electrical characterization of bottom gate 2-methoxyethanol (a, b) and ethanol (c, d) based solution processed ZTO/AlO_x TFTs produced on highly doped p-Si (gate); transfer (a, c) and output (b, d) characteristics. 100 nm thick aluminium source/drain contacts were used in all devices. The inset shows a schematic representation of the TFTs structure.

Successful drain current modulation with gate voltage is obtained for all TFTs as demonstrated by the transfer characteristics (Figure 13a, c).

Generally both ethanol and 2-ME based ZTO/AlO_x TFTs show low hysteresis, close to zero V_{ON} and low V_T.. The use of a thin layer of high-κ dielectric allows for a high capacitance, and consequently very low operation voltages (over 3 orders of magnitude of drain current increase with only 4 V of gate voltage) which is highly advantageous when compared to the minimum of 40 V that are required when a thicker SiO_2 gate dielectric is used [3,4]. Output characteristics exhibit saturation behaviour for the applied gate voltage range, as required for reliable operation on a broad range of circuits. TFTs where ethanol was used have a slightly higher clockwise hysteresis ($\Delta V = 0.23$ V) and subthreshold swing (0.62 V dec^{-1}), and lower saturation mobility ($\mu_{SAT} = 0.8$ cm^2 V^{-1} s^{-1}) when compared to 2-methoxyethanol based devices (ΔV = 0.12 V; S = 0.25 V dec^{-1}: μ_{SAT} = 2.6 cm^{2} V^{-1} s^{-1}). These differences in device performance are attributed to trapped charges in shallow trap states at the semiconductor-insulator interface as consequence of the films' composition and rougher morphology. These issues can be minimized with solution processing optimization when using ethanol as solvent, such as solution pH control to improve solubility and Zn:Sn ratio adjustment to account for Sn losses during processing. Nevertheless, the ZTO/AlO_x TFTs here presented show already promising results for application in disposable, low cost and environmental friendly electronics.

INSULATORS

AlOOH-GPTS hybrid nanocomposite

Sol-gel derived nanocomposite gate dielectrics based on commercial aluminum oxide (Al_2O_3) and aluminum oxohydroxide (AlOOH) nanoparticles and 3-glycidyloxypropyl trimethoxysilane (GPTS) were developed in the project[5]. We investigated the possibility to use GPTS as a dispersant but also as a binder for the aluminum oxide and boehmite nanoparticles. In such a role, the low solubility of formed cross-linked alkoxide derived –O-Si-O- network allows the freedom to use various different solvents in other TFT layers. In addition, the epoxy functionalized side chain in GPTS are capable to form a poly(ethylene oxide) network providing the required toughness and flexibility of printed dielectric films. The synthesis process and a schematic of the materials structure for the AlOOH-GPTS ink is shown in Figure 14.

[5] T. Kololuoma et al., LOPE-C 2012 proceedings; T. Kololuoma et al., J. Materials Chemisty C, submitted.

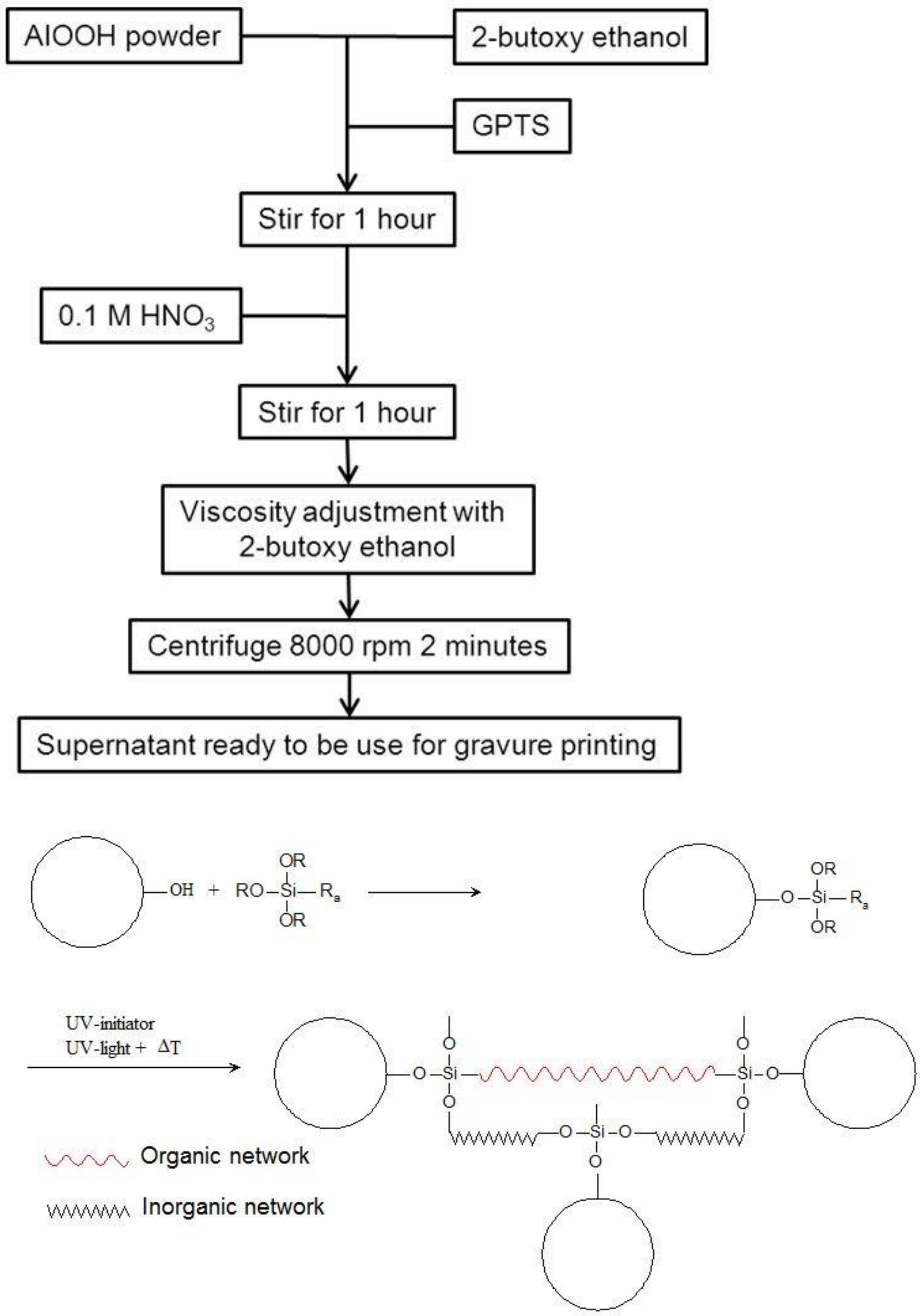


Figure 14: AlOOH-GPTS ink synthesis of VTT (top) and the structure of the material (bottom).

The ink were gravure printed using the Schläffli labratester on a Mo-coated PI substrate. The printing achieved films with average roughnesses of the order of few nm and maximum roughnesses of the order of few tens of nm. The film thicknesses varied from 450 nm to 1400 nm depending on exact composition of the ink. To measure the dielectric properties of the inks, evaporated Au contacts were used on top of the gravure printed insulator on the Mo-PI substrate to complete a MIM structure. Depending on the fraction of the nanoparticles in the composite, the relative dielectric constant reached 11.2 in the best case and the leakage current could be suppressed to 1.1 $\mu A/cm^2$ at 0.5 V/cm field.

LOW-TEMPERATURE PROCESSING FOR PRECURSORS

UV annealing was developed in the project by UCAM and VTT to enhance the decomposition of an oxide precursor into a semiconducting film for the TFT channel layer[6]. Indium and zinc nitrates were considered as the precursors for indium oxide (IO) and indium zinc oxide (IZO) amorphous semiconductors. Figure 15 shows the measurement setup used for the combined thermal and UV annealing. The TFT devices were fabricated on top of oxidized Si wafer and evaporated aluminium was used for the S/D contacts for the bottom-gate-top-contact device structure. Ink chemistry and device fabrication is described in Figure 16. The method of combined thermal and UV annealing was first published in 2012[7] for deep-UV (DUV) wavelength and in this project the method was optimized for the shorter far-UV (FUV) wavelength with advantages in process efficiency.

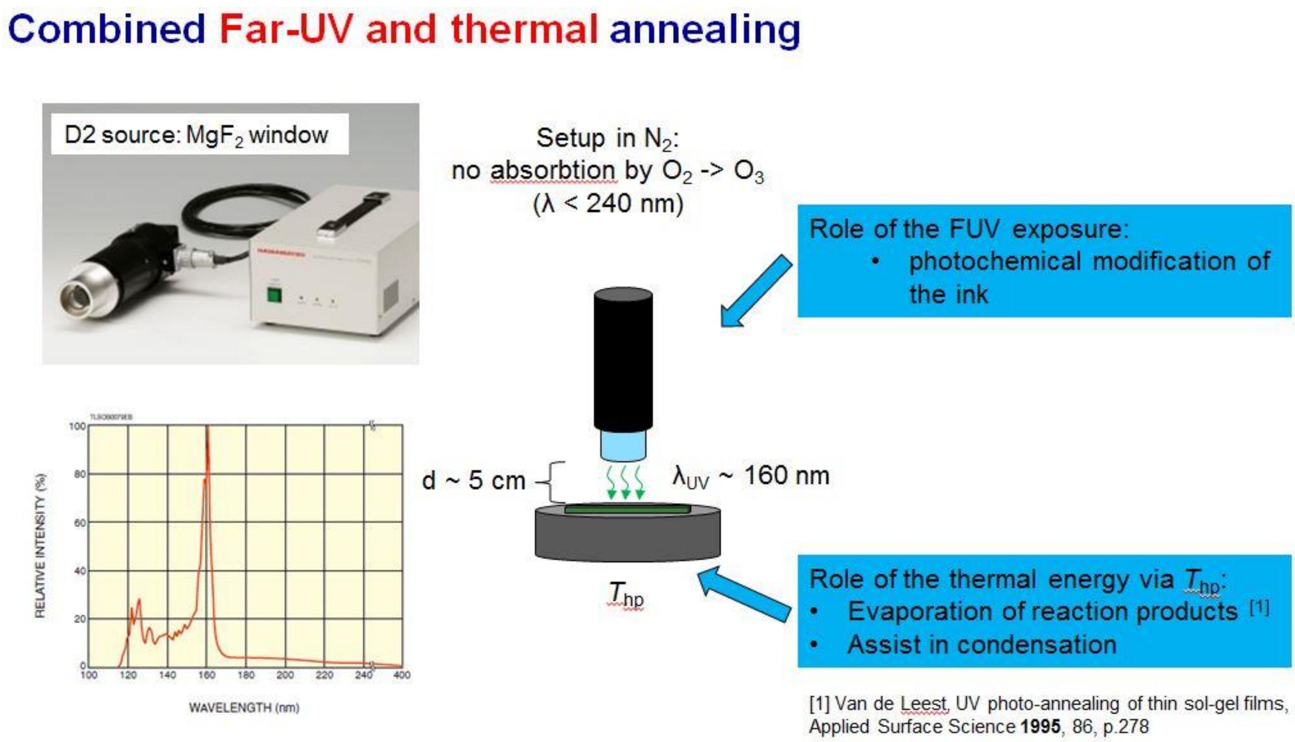


Figure 15: UV setup of VTT for metal oxide annealing.

[6] J Leppäniemi et al., Applied Physics Lett. 105, 113514 (2014); H. Majumdar et al., ESTC2014 proceedings

[7] Y-H. Kim *et al*. Nature 2012

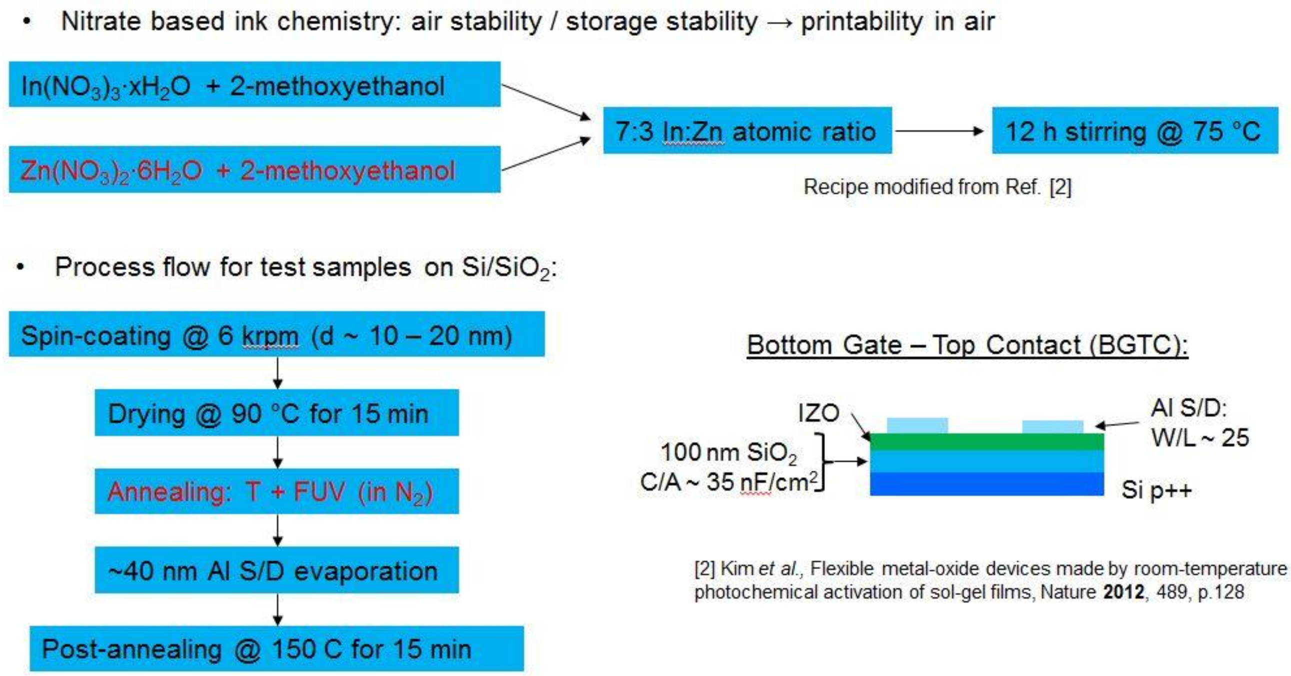


Figure 16: Nitrate ink synthesis and device fabricatin for the UV curing**.**

Figure 17 shows results of UVA ($\lambda \sim 320 - 390$ nm) annealing for indium-oxide TFTs. The effect of the added UVA illumination is quite limited. Namely, compared to thermal curing without UVA (a) the temperature could be lowered by 50 °C but associated with a reduction in electron mobility by a factor of two. The curing is much more efficient when FUV ($\lambda \sim 160$ nm) is used together with thermal energy. As shown in Figure 18, the same level of performance is reached at 200 °C with FUV than at 300 °C without UV (Figure 17 (a)). Furthermore, the annealing temperature could be lowered to 180 °C resulting in the same performance as for UVA at 250 °C. At 250 °C with FUV one can further reduce the curing time to 5 minutes (not shown in the picture) but still get a mobility of 1 cm2/Vs. Reducing the curing time together with the curing temperature is of importance in mass production of printed electronics because short curing times are needed in roll-to-roll production to have reasonable web speeds and oven lengths. For more information, see the references cited.

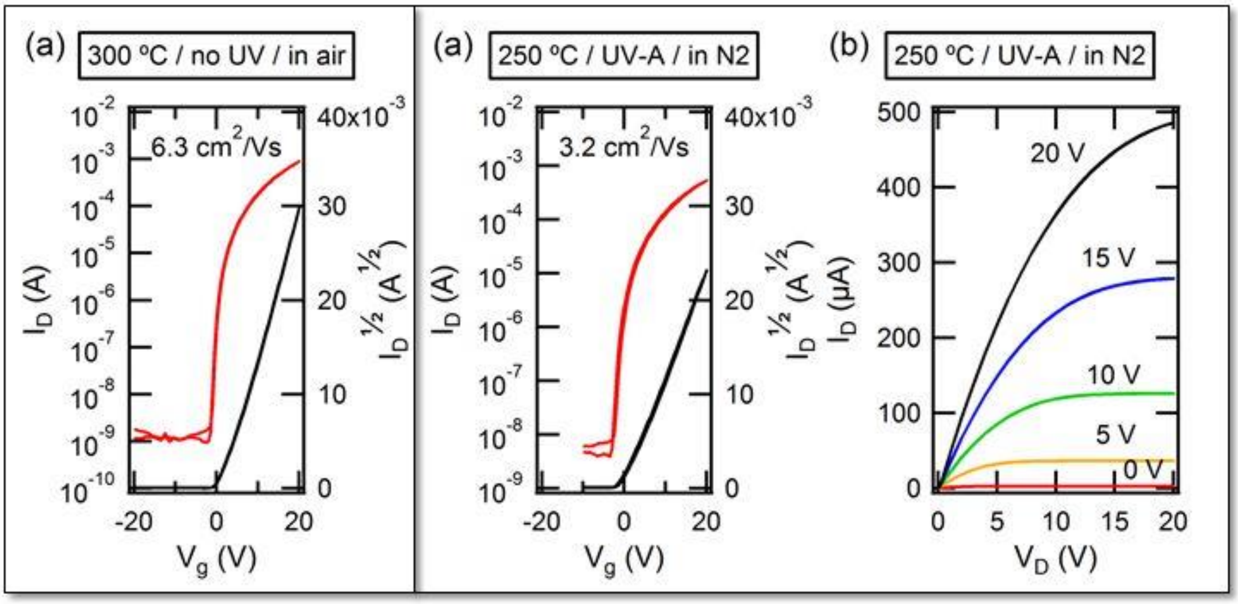


Figure 17: UVA annealing results of IO TFTs**.**

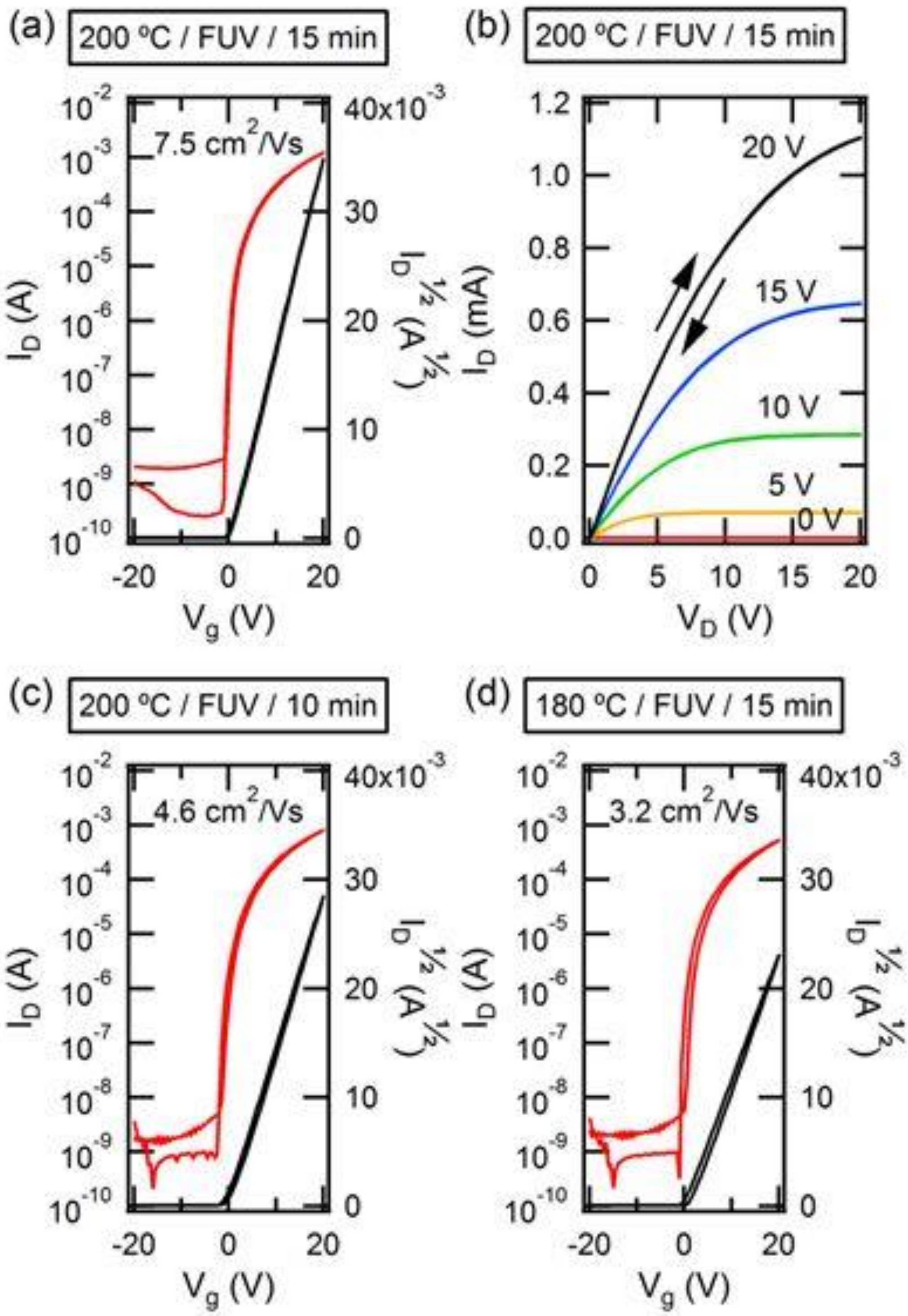


Figure 18: FUV annealing results for IO TFTs**.**

TFT MODELLING

Following[8] for an n-type oxide TFT and under the usual assumptions of (i) no short-channel effects, (ii) majority current carriers only, (iii) DC steady-state conditions, (iv) uniform current across the channel width (W), (v) current confined to the direction between the source and drain, (vi) monotonic function for the potential along the channel and (vii) ideal saturation, the TFT drain-source current (I_{DS}) can be written as

$$I_{DS} = \frac{C_{ins} W}{L} \int_0^{V_{DS}} dV \mu_{avg} (V_{GS} - V)(V_{GS} - V - V_{on}),$$

where C_{ins} is the gate capacitance density, W is the channel width, L is the channel length, V_{DS} is the drain-source voltage, μ_{avg} is the average mobility of current carrying electrons, V_{GS} is the gate-source voltage and V_{on} is the gate voltage at the onset of I_{DS} in the transfer measurement. For the electron mobility, we use the simple exponential function that is often used for oxide[9] as well as for organic[10] TFTs and that can be physically derived based on trap-limited and percolation conduction mechanisms[11]:

$$\mu_{avg} = \alpha (V_{GS} - V_{on})^{\beta}$$

Consequently, we obtain for the drain-source current:

$$I_{DS} = \frac{W C_{ins} \alpha}{L(\beta+2)} \left[(V_{GS} - V_{on})^{\beta+2} - (V_{GS} - V_{DS} - V_{on})^{\beta+2} \right]$$

The saturation current is found from by setting $V_{DS} = V_{GS} – V_{on}$ that leaves only the first exponential term in the parenthesis.

In the Aplac circuit simulator, the TFT model is implemented as a voltage-controlled current source (VCCS) with the drain-source current and its derivatives with respect to the control voltages V_{GS} and V_{DS} in linear and saturation regimes. In addition, (i) the off-state current is modelled by a resistance between the drain and source electrodes representing, for example, the bulk resistance of the semiconductor, (ii) the gate leakage current is modelled by a gate-source resistance, (iii) contact resistances are included at drain and source electrodes and (iv) the AC properties are modelled by gate-source and gate-drain overlap capacitances as well as by a direct capacitance between drain and source. A corresponding circuit schematic is shown in Figure 19.

[8] R. L. Hoffman, Solid State Electronics 49 (2005) 648
[9] K. Abe, et al., IEEE Trans. Electron Devices 58 (2011) 3463; J.-H. Shin, et al., Thin Solid Films 520 (2012) 3800
[10] O. Marinov, et al., IEEE Trans. Electron Devices 56 (2009) 2952
[11] S. Lee, et al., Applied Physics Letters 98 (2011) 203508

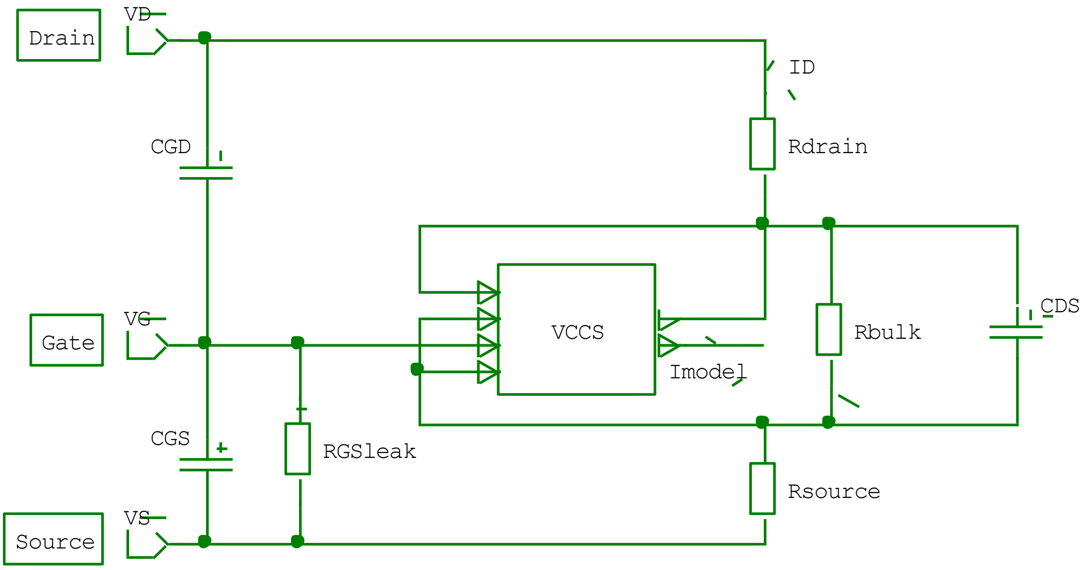


Figure 19: Aplac circuit schematic for the TFT model**.**

The TFT model of Figure 19 was used in a hierarchical circuit design, for example, for the on-off switch flip-flop circuit of Figure 20. The model parameters for the different TFTs and their statistical variations for a Monte Carlo simulation can be independently defined to address circuit yield. The device variations come from ink fluctuations (density / composition variations, impurities) as well as from processing irregularities (wetting fluctuations, impurities, variation in dimensions due to shadow mask evaporation, registration errors).

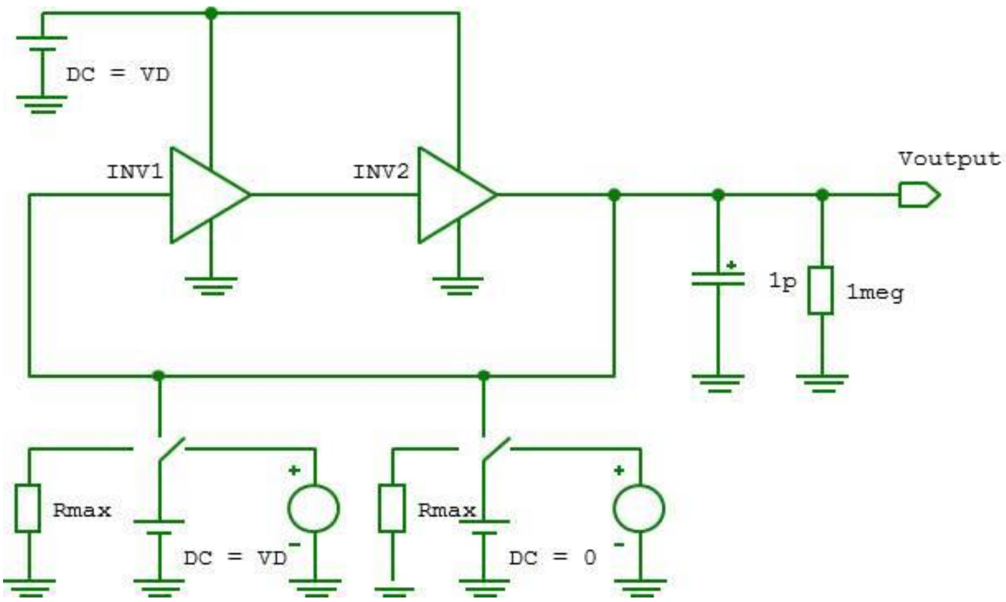


Figure 20: On-off flip-flop circuit**.**

Figure 21 shows measured and simulated output characteristics of a set of TFTs that were used to implement the circuit of Figure 20. The black curves represent maximum-current and minimum-current devices in the set. average values of the TFT model parameters were fit to produce the average TFT behaviour in the measured set and the statistical variations of the parameters were obtained to produce the same current variation in a Monte Carlo simulation as that obtained in the measurements.

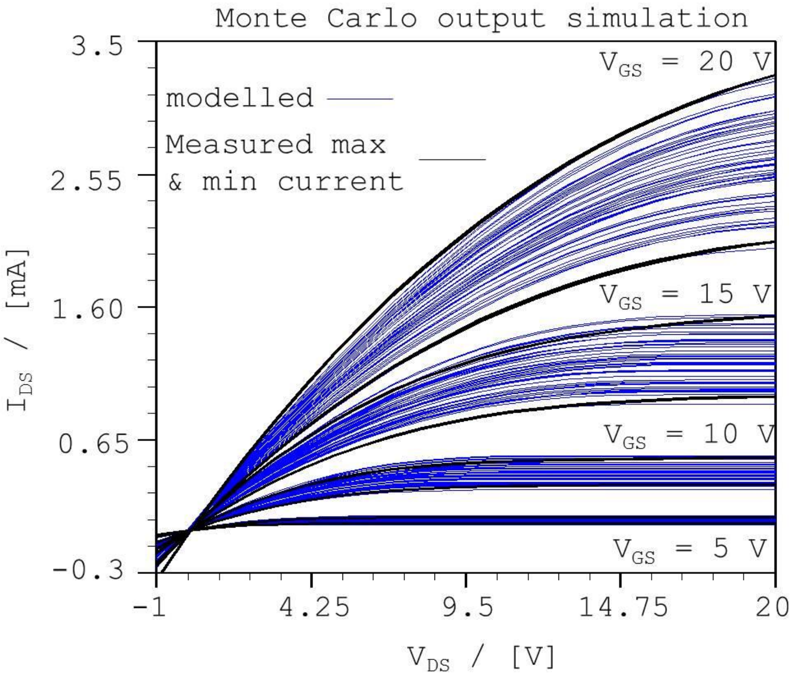


Figure 21: Measured and simulated output characteristics of TFTs used for the circuit of Figure 20**.**

Figure 22 shows measured and simulated output voltages of the on-off circuit of Figure 20. For more details and a video of the circuit operation, see Reference[12]

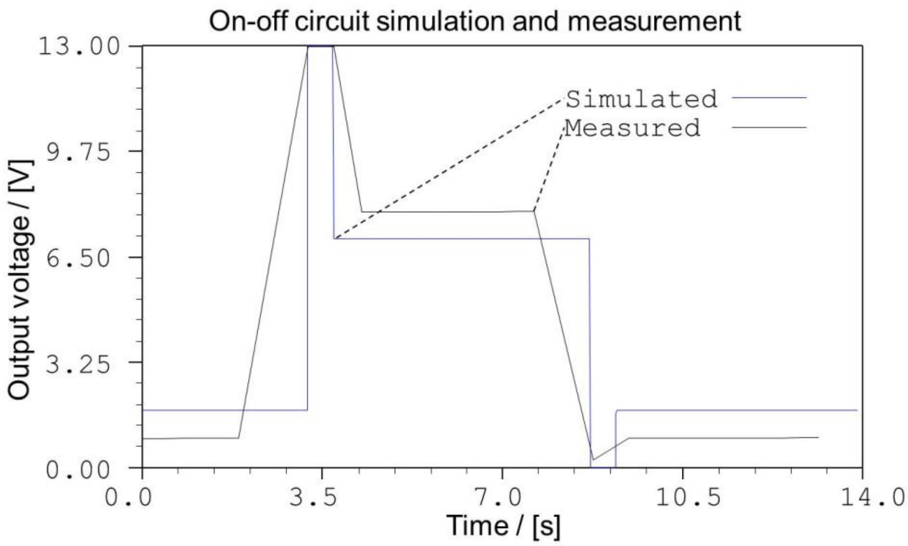


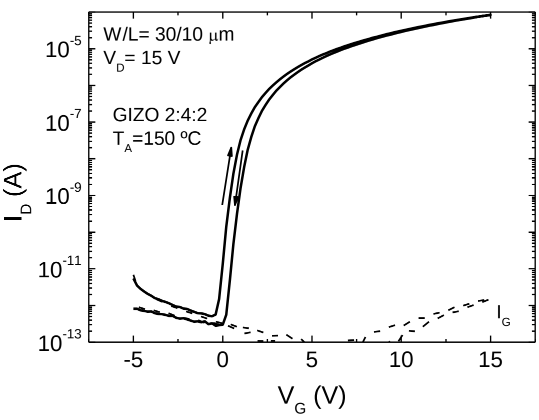
Figure 22: On-off circuit simulation and measurement results. At the time of 3.2 s and 8.7 s, the set and reset pulses are applied, respectively.

[12] Ari Alastalo et al., "Modelling of Printable Metal-Oxide TFTs for Circuit Simulation", ESTC 2014 proceedings; http://youtu.be/yNpF_brcOj4

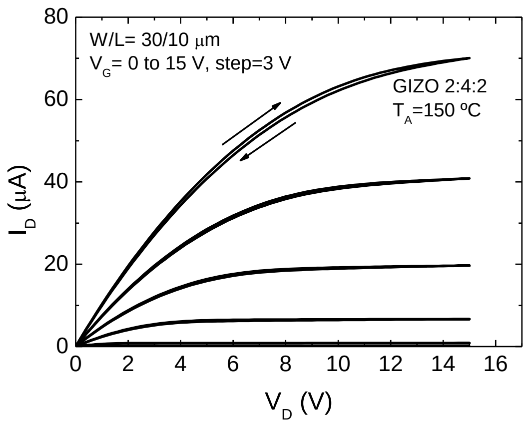
P-TYPE AND N-TYPE REFERENCE DEVICES

In order to establish a baseline for benchmarking the solution-processed oxide TFTs developed within POINTS, reference devices were fabricated at FCT-UNL using r.f. magnetron sputtering. Both n- and p-type TFTs were fabricated, using temperatures not exceeding 150 °C. The devices were patterned using conventional optical lithography techniques, achieving channel lengths down to 2 µm.

N-type oxide TFTs are currently at a more mature stage, with Ga-In-Zn oxide (GIZO) being the standard semiconductor material, as it allows for good electrical performance (μ_{FE}>10 cm^2/Vs) even at processing temperatures below 150 °C, assuring also an excellent uniformity in large areas due to its amorphous structure. At CENIMAT, GIZO (Ga:In:Zn=2:4:2 atomic ratio) was integrated with Ta-based multicomponent/multilayer dielectric and transparent IZO electrodes, both deposited by sputtering[13]. Transfer and output characteristics of these devices are shown in fig. 1. For these devices, after annealing at 150 °C electrical parameters such as μ_{FE}≈13 cm^2/Vs, close to 0 V V_{on}, On/Off ratio>10^8 and S=0.2 V/dec are obtained. Note that devices with transparent IZO or metallic Ti/Au or Mo source-drain electrodes present similar performance for such low annealing temperature, with contact resistance only being relevant for channel lengths below 5 µm.



a)

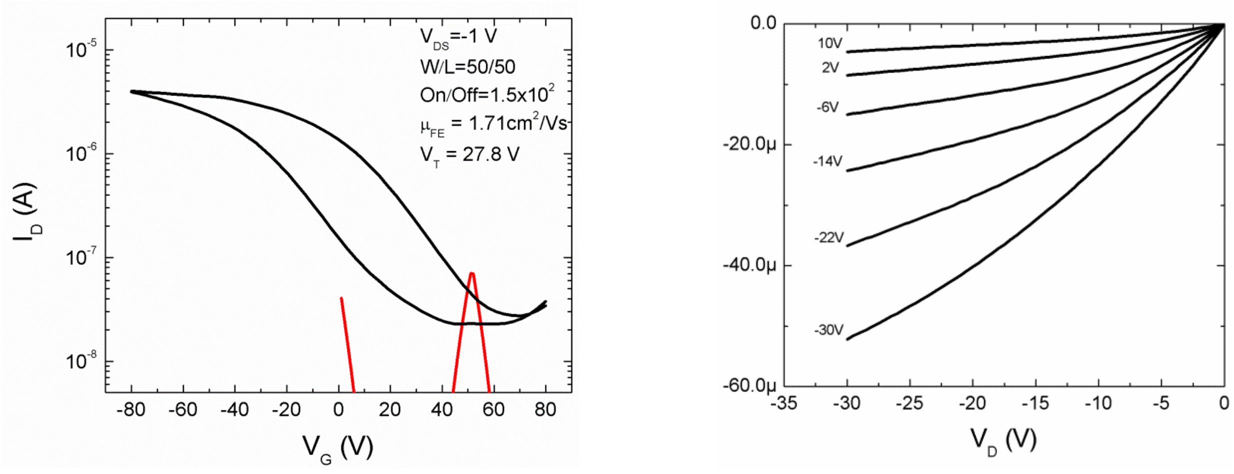


b)

Figure 23 – Electrical properties of reference n-type GIZO TFTs with Ta-based dielectrics: a) transfer, b) output characteristics. Devices annealed at 150 °C.

Regarding p-type TFTs, they are based on Sn and Cu oxides, deposited by reactive sputtering using metallic targets. Best results on these devices were obtained with a commercial high-κ dielectric (ATO, aluminum-titanium oxide), where the added capacitance compensates the large defect density of these oxide semiconductors. After 150 °C annealing p-type operation is achieved, with On/Off ratio>10^2 and μ_{FE}>1 cm^2/Vs.

[13] E. Fortunato, P. Barquinha, and R. Martins, "Oxide Semiconductor Thin-Film Transistors: A Review of Recent Advances," *Advanced Materials*, vol. 24, pp. 2945-2986, Jun 2012.



a) b)

Figure 24 – Electrical properties of reference p-type SnO TFTs with ATO dielectric: a) transfer, b) output characteristics. Devices annealed at 150 °C.

APPLICATION FUNCTIONALITIES AND CONSIDERATIONS

Based on application and market analysis done during the project several application ideas were created and properties of those were analysed. Based on this analysis few different test structure circuits were decided to be produced and analysed.

It was decided that few basic circuits were selected to be produced as test structures to understand better manufacturing challenges and properties of POINTS-materials. Some of these circuits could be used directly in selected applications but they are also general components which could take printed electronics development further also in other application areas.

- Large W/L current driver TFTs
- Ring oscillators
- A hold circuit for storing an external input during power on
- An astable multivibrator circuit
- A RF energy harvesting circuit

Based on these test structures also demonstrator concept was created to be able to test as many test structure circuits as possible in action in real applications.

To be able to demonstrate functionalities of several different test structure components new application concept was created. A “star map” application was selected to be produced as project demonstrator as the same concept could be used in many different applications like packaging, magazines, posters and greeting cards.

The concept uses either printed power sources or energy harvesting to enlighten LEDs inside the card structure. In these applications, LEDs indicate the position of three different stars in the Ursa Minor constellation either automatically, when the circuit is turned on, or when correct button is pushed down.

Figure 25: POINTS application demonstrator (Stora Enso)

In the first demonstrator "star map" card was used to show usage possibilities of printed rectifiers for energy harvesting of radio frequency field of mobile phone's NFC-reader. NFC is rapidly expanding technology for near field communication between electronic devices like mobile phones and other physical or printed products. Use of energy harvesting enables powering of batteryless devices like intelligent packaging application to interact with consumer and end user.

The second demonstrator showed how printed logic can be used e.g. in user interfaces and interaction when normally always traditional silicon components have been needed. Simple solution processed circuit is used to turn LEDs on pushing one button and turned off when pushing another button. Video of this application can be found in Youtube with following link: http://youtu.be/yNpF_brcOj4

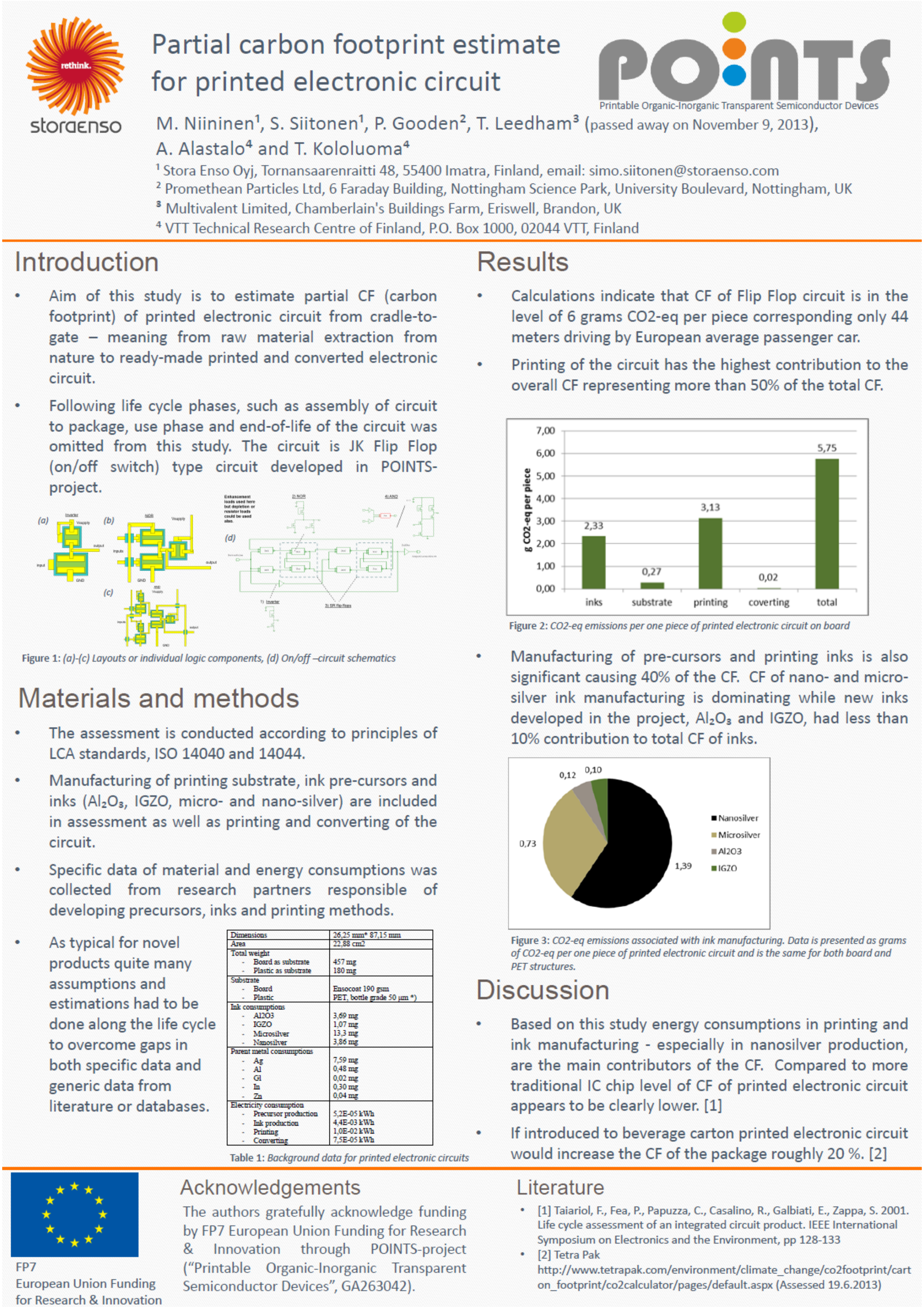
Figure 26: Screen shot of application demonstrator video

Environmental aspects of POINTS materials and application circuits were analysed creating partial carbon footprint assessment for selected circuit. The assessment is conducted according to principles of LCA standards, ISO 14040 and 14044. Manufacturing of printing substrate, ink pre-cursors and inks (Al_2O_3, IGZO, micro- and nano-silver) are included in assessment as well as printing and converting of the circuit. Specific data of material and energy consumptions was collected from research partners responsible of developing precursors, inks and printing methods.

CF results of printed electronic circuits are preliminary and as typical for assessment of novel products include several estimations and assumptions. Based on this study energy consumptions in printing and ink manufacturing - especially in nanosilver production, are the main contributors of the CF. Compared to more traditional IC chip level of CF of printed electronic circuit appears to be clearly lower. If introduced to beverage carton printed electronic circuit would increase the CF of the package roughly 20 %.

Cost analysis preformed in the project show that there are clearly still limitations to get price level very low. First of all printing setup costs are very high and that will affect price per product significantly even in the volumes of 100 000 pieces. Due to long curing time of transistor materials very low printing speed must be used. Effective printing speed is only 0,5m/min which increases printing costs significantly. There is clearly material development needed to improve processability of the materials. One option could be to have additional curing after printing if transistor materials would tolerate this. On line curing for a few m/s production speed would require materials to be curable in few minutes rather than in 30 min – few hours which currently is the case in overall state of the art of the published research.

To conclude POINTS project has provided good starting point for future printed electronics applications development. There is clearly more development needed with materials to improve especially processability and yield but performance levels on transistor level are encouraging. It is also printing process development needed to enable mass manufacturing of circuits to achieve reasonable unit cost levels. And obviously more and more discussion with end users is needed to understand properly what kind of applications could penetrate on markets.



Partial carbon footprint estimate for printed electronic circuit

storaenso

POINTS Printable Organic-Inorganic Transparent Semiconductor Devices

M. Niininen[1], S. Siitonen[1], P. Gooden[2], T. Leedham[3] (passed away on November 9, 2013), A. Alastalo[4] and T. Kololuoma[4]

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[3] Multivalent Limited, Chamberlain's Buildings Farm, Eriswell, Brandon, UK
[4] VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT, Finland

Introduction

- Aim of this study is to estimate partial CF (carbon footprint) of printed electronic circuit from cradle-to-gate – meaning from raw material extraction from nature to ready-made printed and converted electronic circuit.
- Following life cycle phases, such as assembly of circuit to package, use phase and end-of-life of the circuit was omitted from this study. The circuit is JK Flip Flop (on/off switch) type circuit developed in POINTS-project.

Figure 1: *(a)-(c) Layouts or individual logic components, (d) On/off –circuit schematics*

Materials and methods

- The assessment is conducted according to principles of LCA standards, ISO 14040 and 14044.
- Manufacturing of printing substrate, ink pre-cursors and inks (Al_2O_3, IGZO, micro- and nano-silver) are included in assessment as well as printing and converting of the circuit.
- Specific data of material and energy consumptions was collected from research partners responsible of developing precursors, inks and printing methods.
- As typical for novel products quite many assumptions and estimations had to be done along the life cycle to overcome gaps in both specific data and generic data from literature or databases.

Dimensions	26,25 mm* 87,15 mm
Area	22,88 cm2
Total weight - Board as substrate - Plastic as substrate	 457 mg 180 mg
Substrate - Board - Plastic	 Ensocoat 190 gsm PET, bottle grade 50 µm *)
Ink consumptions - Al2O3 - IGZO - Microsilver - Nanosilver	 3,69 mg 1,07 mg 13,3 mg 3,86 mg
Parent metal consumptions - Ag - Al - Gl - In - Zn	 7,59 mg 0,48 mg 0,02 mg 0,30 mg 0,04 mg
Electricity consumption - Precursor production - Ink production - Printing - Converting	 5,2E-05 kWh 4,4E-03 kWh 1,0E-02 kWh 7,5E-05 kWh

Table 1: *Background data for printed electronic circuits*

Results

- Calculations indicate that CF of Flip Flop circuit is in the level of 6 grams CO2-eq per piece corresponding only 44 meters driving by European average passenger car.
- Printing of the circuit has the highest contribution to the overall CF representing more than 50% of the total CF.

Figure 2: *CO2-eq emissions per one piece of printed electronic circuit on board*

- Manufacturing of pre-cursors and printing inks is also significant causing 40% of the CF. CF of nano- and micro-silver ink manufacturing is dominating while new inks developed in the project, Al_2O_3 and IGZO, had less than 10% contribution to total CF of inks.

Figure 3: *CO2-eq emissions associated with ink manufacturing. Data is presented as grams of CO2-eq per one piece of printed electronic circuit and is the same for both board and PET structures.*

Discussion

- Based on this study energy consumptions in printing and ink manufacturing - especially in nanosilver production, are the main contributors of the CF. Compared to more traditional IC chip level of CF of printed electronic circuit appears to be clearly lower. [1]
- If introduced to beverage carton printed electronic circuit would increase the CF of the package roughly 20 %. [2]

FP7
European Union Funding for Research & Innovation

Acknowledgements

The authors gratefully acknowledge funding by FP7 European Union Funding for Research & Innovation through POINTS-project ("Printable Organic-Inorganic Transparent Semiconductor Devices", GA263042).

Literature

- [1] Taiariol, F., Fea, P., Papuzza, C., Casalino, R., Galbiati, E., Zappa, S. 2001. Life cycle assessment of an integrated circuit product. IEEE International Symposium on Electronics and the Environment, pp 128-133
- [2] Tetra Pak http://www.tetrapak.com/environment/climate_change/co2footprint/carton_footprint/co2calculator/pages/default.aspx (Assessed 19.6.2013)

Figure 27: Poster of "Partial carbon footprint estimate"

Potential impact

General

Printed electronics (PE) is an industry experiencing a strong growth towards an annual tens-of-billions – hundred-billion $US market size by 2016 - 2023. Europe has a long-term strategic objective to participate in this growth by having large fractions of product value chains including manufacturing to be established in Europe. This objective is illustrated by the increased focus on the PE market of a growing number of European materials, equipment and application companies as well as research organizations. Within the PE market, the biggest sectors at the moment are displays, sensors and conductive inks. Furthermore, many yet emerging markets, such as logic and memory, power sources, lighting and smart packages, tags, documents and user interfaces are expected to grow rapidly in the next 5 years. Overall, the value proposition of PE is not to replace silicon ICs but rather to enhance existing technologies and enable new applications where characteristics such as large area functionality, flexibility and environmentally friendly materials and processes are needed.

The value creation in the ICT supply chain will be affected by the results of Points and other similar projects at different levels starting from electronic materials, development of active components, assembly services, and final products. The micro/electronics industry is currently centred on fab-based manufacturing which translates to high capital investment, batch processing and limited adaptability in terms of substrate size. Printing-based fabrication of a broad variety of advanced functional materials offers a large advancement in terms of materials, cost efficiency and environmental friendliness when compared with conventional semiconductor processing.

Points brought up new classes of semiconducting and insulating materials for low-cost solution processing of (thin-film) transistors that are the most crucial components in ICT applications. In addition, Points developed low temperature curing techniques to enable usage of plastic substrates for the products and made a significant contribution to the device and circuit modelling of printed TFTs for future product development. Consequently, as circuit performance leaps ahead, printed systems will meet the demands of novel low-cost ICT applications that earlier cannot have been realized using existing technologies.

Strengthening industries

Printed devices and systems will enable new applications and markets for electronics, where electronics up to now found no acceptance due to cost reasons. Materials and processes developed in the Points project are enabling for wide industrial sectors. The targeted printed low-cost applications foster the development and spread of novel products in Security, ICT, Energy, Environment Transportation, Health, and Food, industries. Value-added traditional products such as intelligent packaging, newspaper or cardboard capable of data storage and interaction will lead the way of mature traditional European industries (packaging, print media, textile, retail, entertainment), facing the world-wide challenges of low-cost competition, into knowledge-integrated, science-driven suppliers. This provides them unique selling points. As ubiquitous societies and environments develop and are taken into practise, the true need for systems based on machine-to-machine networks and interaction is realized. The corresponding build-up of infrastructures will also promote complementary knowledge-based fields such as the IT and communications industry. Good examples on applications are brand protection labels, compliance cards and electronic questionnaire cards to probe patient health. In conventional clinical trials, for example, compliance control is followed by a questionnaire and/or diary filled by the test persons while an automatic registration with electronics cards would offer more reliable information. The additional price is well covered by the added value by the automated compliance control.

The impact from the viewpoint of the chemical industry is manifold. Nanotechnology gains an increasing importance for high-tech products in materials science, bioscience and electronics. It shows large influence in material selection and manufacturing processes. Because they often loose market shares for their “traditional” products (e.g. mass polymers, chemicals) to low-wage countries, they have to take this opportunity and not only deliver the raw materials as high-quality nanoparticle or precursor formulations but also have to forward integrate their processes to participate in the value chain. This is an all-European challenge of the “classical” chemical industry in order to safeguard jobs in Europe.

Electronics design and device manufacturing industries adapting the developed technology will generate new jobs requiring specialized expertise in the area of materials development, associated processing technologies (deposition, patterning, integration), and device and application development. A competitive European printed-electronics industry will generate new jobs in the high-tech sector which can at least partly compensate for job losses experienced in the fields of semiconductor and passive components manufacturing, systems design and assembly.

Sustainable products

The Points project addressed sustainable products and related technologies to meet customer requirements as well as growth, public-health, occupational-safety, environmental-protection, and societal values and expectations. Considering the environment, printed electronics is an environmentally friendly technology that uses materials-saving additive fabrication techniques avoiding etching chemistries and enables the utilization of biodegradable or recyclable materials. Novel metal oxides deliver enhanced performance and save resources (e.g. ITO replacement) contributing to the further advancement of green technologies. Moreover, most of the conventional fab-based semiconductor processes that are currently used in electronics production have high temperature budgets. This currently adds a major cost factor that also leads to higher energy consumption and carbon emissions. Printed electronics fabrication can significantly lower such environmental loads.

In addition to the effects on employment and economic wealth, the societal impact is expressed in quality enhancement that people will encounter in their daily life. High-performance printed electronics creates affordable novel types of visible and invisible aids enabling personal information management, mobility, personal healthcare, safety, energy efficiency, environmental monitoring, ambient assisted living, and an overall improvement of ICT usability for pervasive ICT distribution amongst the community. Furthermore, the introduction of environmentally friendly materials with no threat to occupational and consumer health and with lower production costs generate more sustainable electronics devices.

An example of functionalities that printed electronics can bring to simple products such as brochures, information cards and advertisement documents was demonstrated by the project in the LOPE-C 2014 conference in May 2014. A video of the demonstration is available at http://youtu.be/yNpF_brcOj4.

Different business segments

Metal oxide display backplanes have already been commercialized in industry. Sharp has invested in establishing a Gen8 IGZO plant at its Kameyama plant in Japan while LG has also selected IGZO backplanes for its large-sized white OLED technology. At the same time, Chinese companies such as BOE are fast catching up with both prototype and production capacity announcements. IDTechEx estimates that 7 km^2 of metal oxide backplanes will be used in the OLED industry in 2024, enabling a 16 billion USD market at the display module level. The LCD display market will add an extra demand of at least 1 km^2 per year in 2024 for metal oxide backplanes. The flexible display smart phones are expected to hit the market very soon with tablets to follow right after. Laptops and TVs are also expected to follow the trend of smart phones and tablets while OLED based televisions have also been following the same trend, by electronics manufacturing giants Samsung and LG. All these developments have created demand for better and more stable materials to be used in these displays. The use of IGZO (Indium gallium Zinc oxide) is the example of the stable material that is used in the above mentioned displays. Consequently, display industry can be considered a potential future user of Points results. The current oxide backplanes are manufactured on glass and with conventional non-printing deposition processes. The trend is clearly showing that curved and flexible displays are seen in near future and that requires use of flexible substrates like PET or PEN. The current printable oxide materials already have higher electron mobility than amorphous silicon and other incumbent technologies so application in liquid-crystal displays (LCDs) and e-papers to improve the speed, resolution and size of flat-panel displays is a working hypothesis. Application in organic light-emitting diode (OLED) displays is also looking promising.

The key properties and characteristic that might prevail and help bring the material to market are the materials formulation into inks that are cheaper, more energy efficient, more environmentally sound and enable more robust electronic components. As materials developed in Points project have shown capability to be processed on plastic substrates at relatively low temperature, there is clearly potential to commercialize the results in displays industry. When POINTS materials can be combined with printing process, it could enable mass manufacturing cheap display backplanes e.g. for smaller printed OLED devices. This would bring printed OLEDs into our everyday objects like household consumables, packaging etc.

Dissemination activities

The project dissemination activities consist thus far of 9 journal articles, 5 conference papers, contributions in 1 book, 1 doctoral dissertation, 2 publications in university series, 57 conference presentations (including the demonstrators exhibited at the LOPE-C 2014 conference) and 2 yet confidential patent applications. Those that are public are listed below in Section 4.2 A.

Address of the project public website and contact information

The project contact information is as follows:

- project coordinator: Dr. Ari Alastalo, VTT, ari.alastalo@vtt.fi
- project website: http://points-fp7.eu/
- partners since the beginning of the project: VTT Technical Research Centre of Finland, IISB Fraunhofer Gesellschaft zur Foerderung der angewandten Forschung, FCT-UNL Faculdade de Ciencias e Technologia, Universidade Nova de Lisboa, UCAM University of Cambridge, Multivalent, Promethean Particles, Stora Enso Oyj, Bayer Technology Services GmbH, University Dunarea de Jos of Galati, IGCatalysts

Use and dissemination of foreground

Section A (public)

Publications (Peer reviewed publication)

Nº	D.O.I.	Title	Author(s)	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages
1		High-mobility metal-oxide thin-film transistors by spray deposition of environmentally friendly precursors	Susanne Oertel , Michael P.M. Jank , Erik Teuber , Anton J. Bauer , Lothar Frey	Thin Solid Films	Vol. 553	Elsevier	Netherlands	01/02/2014	114-117
2		High mobility and visible–near infrared transparent titanium doped indium oxide thin films produced by spray pyrolysis	S. Parthiban, V. Gokulakrishnan, E. Elangovan, G. Gonçalves, K. Ramamurthi, E. Fortunato, R. Martins	Thin Solid Films	524	Elsevier		01/12/2012	268-271
3		Oxide Semiconductor Thin-Film Transistors: A Review of Recent Advances	E. Fortunato, P. Barquinha, R. Martins	Advanced Materials	24	Wiley-VCH Verlag		12/06/2012	2945-2986
4		Where science fiction meets reality? With oxide semiconductors	E. Fortunato, R. Martins	Physica Status Solidi - Rapid Research Letetrs	5	Wiley-VCH Verlag		01/09/2011	50-53
5		p-Type CuO Thin-Film Transistors Produced by Thermal Oxidation	V. Figueiredo, J. V. Pinto, J. Deuermeier, R. Barros, E. Alves, R. Martins, E. Fortunato	IEEE/OSA Journal of Display Technology	9	IEEE Computer Society		01/01/2013	735-740
6		Performances of Microcrystalline Zinc Tin Oxide Thin-Film Transistors Processed by Spray Pyrolysis	Parthiban, S.; Elangovan, E.; Nayak, P.K.; Goncalves, A.; Nunes, D.; Pereira, L.; Barquinha, P.; Busani, T.; Fortunato, E.; Martins, R	IEEE/OSA Journal of Display Technology	9	IEEE Computer Society		01/10/2013	825-831
7		Rapid low-temperature processing of metal-oxide thin film transistorswith combined far ultraviolet and thermal annealing	J. Leppäniemi, K. Ojanperä, T. Kololuoma, O.-H. Huttunen, J. Dahl, M. Tuominen,P. Laukkanen, H. Majumdar, and A. Alastalo	Applied Physics Letters	105	American Institute of Physics Inc.		19/09/2014	113514
8		Sol-gel preparation of ZrO2-PMMA for thin films transistor	Elena Emanuela VÂLCU (HERBEI), Viorica MUŞAT, Susanne OERTEL, Michael JANK	Revista de Chimie	65	Syscom 18 SRL		01/05/2014	574-577
9		High Performance, Low Temperature Solution-Processed Barium andStrontium Doped Oxide Thin Film Transistors	Kulbinder K. Banger, Rebecca L. Peterson, Kiyotaka Mori, Yoshihisa Yamashita,Timothy Leedham, and Henning Sirringhaus	Chemistry of Materials	26	American Chemical Society		22/12/2013	1195-1203

Project Publications (Paper in Proceedings of a Conference/Workshop)

Nº	D.O.I.	Title	Author(s)	Proceedings	Publication date	Start Date of Conference/Workshop	End Date of Conference/Workshop	Publisher
1		Modelling of Printable Metal-Oxide TFTs for Circuit Simulation	Ari Alastalo, Jaakko Leppäniemi Kimmo Ojanperä, Himadri Majumdar	ESTC2014 Conference	16/09/2014	16/09/2014	18/09/2014	IEEE
2		Effect of UV light and low temperature on solution-processed, high-performance metal-oxide semiconductors and TFTs	Himadri Majumdar, Jaakko Leppäniemi, Kimmo Ojanperä, Olli-Heikki Huttunen, Ari Alastalo	ESTC 2014 Conference	16/09/2014	16/09/2014	18/09/2014	IEEE
3		Gravure-printed sol-gel derived hybrid aluminum oxide dielectric filmsfabricated for TFT applications	Terho Kololuoma, Jaakko Leppäniemi and Ari Alastalo	LOPE-C 2012	19/06/2012	19/06/2012	21/06/2012	OE-A
4		Non-toxic mixed metal oxide precursors for spray-deposition and printing of thin-film transistors	S. Oertel, M. P.M. Jank, E. Teuber, L. Frey	LOPE-C 2013	11/06/2013	11/06/2013	13/06/2013	OE-A
5		Large volume continuous synthesis of IZO nanoparticles and processing into semiconducting thin films	Susanne Oertel, Michael P. M. Jank, Sean Butterworth, Callum Crawshaw, Peter N. Gooden	E-MRS 2014 Spring Meeting	27/05/2014	27/05/2014	29/05/2014	E-MRS

Project Publications (Article/Section in an edited book or book series)

Nº	D.O.I.	Title	Author(s)	Title of the book (series)	Volume	Date of publication	Publisher	Publisher location	Relevant pages	Open access is/will be provided to this publication
1		Transparent Electronics: From Materials to Devices	P. Barquinha, L. Pereira, R. Martins, E. Fortunato	Transparent Electronics: From Materials to Devices		01/01/2012	Wiley		1-295	No

Project Publications (Thesis/Dissertation)

Nº	D.O.I.	Title	Author	Date of approval	Institution name	Institution location
1		Hybrid nanostructured dielectric materials for electronic applications	Elena Emanuela Valcu (Herbei)	01/10/2013	UDJG	Galati, Romania

Project Publications (University Publication/Scientific Monograph)

Nº	D.O.I.	Title	Author(s)	Title of the monograph	Volume	Date of publication	Publisher
1		Thermal Decomposition of Hafnium Ethoxide mollecular Precursor for Hafnia Dielectric Thin Films	Elena Emanuela VÂLCU (HERBEI), Viorica MUŞAT, Timothy LEEDHAM	Annals of Dunărea de Jos University of Galati, Fascicola IX Metalurgy and Materials Sceince	3	01/01/2012	Dunărea de Jos University of Galati
2		High-K Dielectric Inorganic-Organic Hybrid Thin Films For Field Effect Transistors (FETFT)	Elena Emanuela VÂLCU (HERBEI), Viorica MUŞAT, Susanne OERTEL, Michael JANK	The Annals of Dunărea de Jos University of Galati, Fascicola IX Metalurgy and Materials Sceince	2	01/06/2013	Dunărea de Jos University of Galati

Project Dissemination Activities

Nº	Type of activities	Main leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Oral presentation to a scientific event	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	High K Dielectric Polymers For Flexible Transparent Electronics	19/05/2011	UGALnano2, May 2011, Galati	Scientific community (higher education, Research)	100	Romania
2	Oral presentation to a wider public	STORA ENSO OYJ	Recent development in hybrid and fully printed electronics solutions	28/06/2011	3th Large-area Organic and Printed electronics Convention LOPE-C	Industry	50	All
3	Oral presentation to a wider public	BAYER TECHNOLOGY SERVICES GMBH	Intelligent packaging	01/12/2011	"Printed Electronics in Innovative Packaging"-Workshop	Industry	20	Germany
4	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	P-type oxide thin film transistors produced at low temperatures	21/01/2012	SPIE 2012, Conference 8263: Oxide-based Materials and Devices III	Scientific community (higher education, Research)		All
5	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Recent advances in oxide TFTs	30/01/2012	8th International Thin-Film Transistor conference, Lisbon	Scientific community (higher education, Research)	150	all
6	Oral presentation to a scientific event	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Towards large-scale applications of printed TFTs	30/01/2012	8th International Thin-Film Transistor Conference, Lisbon	Scientific community (higher education, Research)	150	all
7	Oral presentation to a scientific event	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE	Low temperature, high performance solution-processed metal oxide thin filtransistors formed by a sol-gel on chip process	30/01/2012	8th International Thin-Film Transistor conference, Lisbon	Scientific community (higher education, Research)	150	all
8	Oral presentation to a wider public	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Enabling logic circuits on and with paper using oxide TFTs	03/04/2012	8th Printed Electronics April 2012, Berlin, Germany	Industry		all
9	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Solution based oxides: from transparent conductive oxides to thin film transistors	16/04/2012	2012 EMN Meeting, April 2012, Orlando, USA	Scientific community (higher education, Research)		all
10	Oral presentation to a wider public	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Gravure printed dielectric films	19/06/2012	LOPE-C June 2012, Munich, Germany	Scientific community (higher education, Research) - Industry	50	all
11	Oral presentation to a wider public	STORA ENSO OYJ	On a way to fully printed Integrated Smart Systems	19/06/2012	LOPE-C June 2012, Munich, Germany	Scientific community (higher education, Research) - Industry	50	all
12	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Transparent electronics: from materials to devices	15/06/2012	Novel conducting oxide materials for energy and optoelectronic applications, Dublin, Ireland	Scientific community (higher education, Research)		all
13	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Transparent electronics	14/06/2012	European Workshop on Nano Transparent Conductive Materials Grenoble, France	Scientific community (higher education, Research)		all
14	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	p and n-type Oxide Thin Fim Transistors	26/08/2012	International Symposium on Compound Semiconductors, ISCS 2012 Santa Barbara, USA	Scientific community (higher education, Research)		all
15	Posters	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Gravure-printed metal-oxide materials for TFTs	01/03/2013	9th International Thin-Film Transistor Conference, Tokyo, Japan	Scientific community (higher education, Research)		all
16	Oral presentation to a wider public	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Printed Electronics made in Erlangen - Nanoscale building blocks for macroscale devices, Cluster NanoMAT	14/01/2013	Cluster NanoMAT – Board Meeting, Karlsruhe, Germany	Scientific community (higher education, Research) - Industry	20	Germany
17	Oral presentation to a scientific event	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	Thin solid films for transparent electronics	02/03/2013	8th International Conference on Materials Science and Engineering, Brasov, Romania	Scientific community (higher education, Research)	150	all

18	Oral presentation to a wider public	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Flexible Ultrathin Electronics for Integrated Industrial and Energy Systems	08/03/2013	Successful Research & Innovation in Europe, Düsseldorf, Germany	Scientific community (higher education, Research) - Industry - Policy makers - Medias	100	EU
19	Oral presentation to a wider public	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Anorganische Elektronikmaterialien aus der Flüssigphase – Prozessierung und Einsatzgebiete	06/03/2013	Etablierte und fortgeschrittene Verfahren in der Druck- und Beschichtungstechnik, Erlangen, Germany	Scientific community (higher education, Research)	25	Germany
20	Oral presentation to a scientific event	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	High-k dielectric inorganic-organic hybrid thin films for field effect transistors (TFFET)	16/05/2013	Scientific Conference of Doctoral Schools from UDJG (CSSD-UDJG), Galati, Romania	Scientific community (higher education, Research)	100	Romania
21	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Alternating Source/Drain Contacts for Ultrashort Gate Length and Non-Symmetric Injection-Controlled Thin-Film Transistors	14/05/2013	INC 9 – The Ninth International Conference on Communication and Cooperation Berlin, Germany	Scientific community (higher education, Research)	200	EU, US, Japan
22	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Printable Organic-Inorganic Transparent Semiconductor Devices – POINTS	14/05/2013	INC 9 – The Ninth International Conference on Communication and Cooperation Berlin, Germany	Scientific community (higher education, Research)	200	EU, US, Japan
23	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Advanced Printed Electronics Based on Inorganic Materials	14/05/2013	INC 9 – The Ninth International Conference on Communication and Cooperation Berlin, Germany	Scientific community (higher education, Research)	200	EU, US, Japan
24	Organisation of Workshops	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Solution-processable low temperature hybrid materials and their application to printed inorganic and hybrid devices	26/05/2013	POINTS Spring School, Strasbourg, France	Scientific community (higher education, Research) - Industry	35	all
25	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	High-mobility metal-oxide thin-film transistors by spray deposition of environmentally friendly precursors	26/05/2013	European Materials Research Society Spring Meeting; E-MRS, Strasbourg, France	Scientific community (higher education, Research)	50	all
26	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Non-toxic mixed metal oxide precursors for spray-deposition and printing of thin-film transistors	12/06/2013	5th Large-area Organic and Printed electronics Convention, LOPE-C München, Germany	Scientific community (higher education, Research) - Industry	500	all
27	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Development of inorganic functional inks	19/06/2013	15. FET-Treffen des Bayerischen Clusters Druck und Printmedien, Ismaning, Germany	Industry	15	Germany, Bavaria
28	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Gedruckte Elektronik – Flüssigphasenprozessierung anorganischer Materialien	04/07/2013	Fraunhofertag "Mikroverkapselung und Partikelanwendungen" Germany	Scientific community (higher education, Research) - Industry	75	Germany
29	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Field effect electronic devices for biosensing	07/07/2013	ERASMUS-IP Program Summer School Transparent Electronics: Chania, Greece	Scientific community (higher education, Research)	40	Greece, Portugal, Germany, UK, Italy
30	Oral presentation to a scientific event	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	Thermal behaviour of complex precursor for sol-gel preparation of dielectric tantalum oxide-PMMA hybrid thin films	25/08/2013	XVII International Sol-Gel conference, Madrid	Scientific community (higher education, Research)	500	all
31	Oral presentation to a scientific event	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	Hybrid dielectric materials obtained by sol-gel method for thin film transistors	25/08/2013	XVII International Sol-Gel conference, Madrid	Scientific community (higher education, Research)	500	all
32	Oral presentation to a scientific event	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Modeling of Solution-Processed Metal-Oxide TFTs for Circuit Simulation	11/09/2013	International Conference on Flexible and Printed Electronics, Jeju, Korea	Scientific community (higher education, Research)	100	all
33	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Thin-FilmTransistors in Current-Driver Applications	21/11/2013	Jahrestagung des Fraunhofer IISB, Erlangen, Germany	Scientific community (higher education, Research) - Industry	70	Germany
34	Oral presentation to a wider public	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Ultrathin Electronics for Industrial/Energy Applications	29/11/2013	EU Brokerage Event on Kets in Horizon 2020, Strasbourg, France	Scientific community (higher education, Research) - Industry - Policy makers	200	EU

35	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Sprühpyrolyse funktioneller Metalloxide für elektrische und elektronische Anwendungen , Verfahren zur Herstellung keramischer Schichten	03/12/2013	Fachausschuss "Verfahrenstechnik" der Deutschen Keramischen Gesellschaft (DKG), Erlangen, Germany	Scientific community (higher education, Research) - Industry	150	Germany
36	Oral presentation to a scientific event	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE	Metal Alkoxide Molecular Precursors towards Solution Processed transparent InGaZnO semiconductors	01/12/2013	13th Royal Australian International Conference, Brisbane, Australia	Scientific community (higher education, Research)	500	all
37	Oral presentation to a scientific event	FRAUNHOFER-GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V	Introduction to Printed Electronics	01/01/2014	Friedrich-Alexander-University of Erlangen-Nuremberg Winter term Germany	Scientific community (higher education, Research)	15	Germany
38	Oral presentation to a scientific event	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Combined far ultraviolet and thermal annealing of metal nitrate precursors for solution processed IZO TFTs	23/01/2014	10th International Thin-Film Transistor Conference, Delft	Scientific community (higher education, Research)	150	all
39	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Thin films transistors based on amorphous Ga-Zn-Sn-O semiconductor by combustion processing	23/01/2014	10th International Thin-Film Transistor Conference, Delft	Scientific community (higher education, Research)	150	all
40	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Aqueous combustion synthesis of Al2O3 for application as gate dielectric in solution-processed TFTs	23/01/2014	10th International Thin-Film Transistor Conference, Delft	Scientific community (higher education, Research)	150	all
41	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Excess oxygen to atomic layer deposition of Al2O3 provided by Cu2O and ITO substrates	23/01/2014	10th International Thin-Film Transistor Conference, Delft	Scientific community (higher education, Research)	150	all
42	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Influence of the multicomponent gate dielectric deposited by ALD on p-type SnOx based TFTs	23/01/2014	10th International Thin-Film Transistor Conference, Delft	Scientific community (higher education, Research)	150	all
43	Oral presentation to a scientific event	THE CHANCELLOR, MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE	Using spectroscopic techniques to understand the effect of annealing temperature and method on IZO TFTs	21/04/2014	Materials Research Society Spring Meeting & Exhibit San Francisco, USA	Scientific community (higher education, Research)	2000	all
44	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Solution-processed TFTs with aqueous based Al2O3 gate dielectric obtained by auto-combustion synthesis	26/05/2014	European Materials Research Society Spring Meeting; E-MRS, Lille, France	Scientific community (higher education, Research)		all
45	Oral presentation to a scientific event	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Hydrothermal Synthesis of GIZO Nanoparticles for Solution-processed Electrolyte-gated Transistors	26/05/2014	European Materials Research Society Spring Meeting; E-MRS, Lille, France	Scientific community (higher education, Research)		all
46	Oral presentation to a scientific event	PROMETHEAN PARTICLES LTD	Large volume continuous synthesis of IZO nanoparticles and processing into semiconducting thin films.	26/05/2014	European Materials Research Society Spring Meeting; E-MRS, Lille, France	Scientific community (higher education, Research)		all
47	Posters	STORA ENSO OYJ	Partial carbon footprint estimate for printed electronic circuit	26/05/2014	LOPEC 2014, Large-area, Organic & Printed Electronics Convention, Münich, Germany	Scientific community (higher education, Research) - Industry	1800	all
48	Posters	PROMETHEAN PARTICLES LTD	Large volume continuous synthesis of metal oxide nanoparticle inks toward inkjet printed TFT devices	26/05/2014	LOPEC 2014, Large-area, Organic & Printed Electronics Convention, Münich, Germany	Scientific community (higher education, Research) - Industry	1800	all
49	Exhibitions	TEKNOLOGIAN TUTKIMUSKESKUS VTT	POINTS demonstrators	26/05/2014	LOPEC 2014, Large-area, Organic & Printed Electronics Convention, Münich, Germany	Industry	200	500
50	Organisation of Workshops	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Solution-processable low temperature hybrid materials and their application to printed inorganic and hybrid devices	26/05/2014	LOPEC 2014, Large-area, Organic & Printed Electronics Convention, Münich, Germany	Scientific community (higher education, Research) - Industry		all
51	Oral presentation to a scientific event	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Modeling of Printable Metal-Oxide TFTs for Circuit Simulation	16/09/2014	ESTC 2014 Helsinki, Finland	Scientific community (higher education, Research)	100	all
52	Oral presentation to a scientific event	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Effect of UV light and low temperature on solution-processed, high-performance metal-oxide semiconductors and TFTs	16/09/2014	ESTC 2014 Helsinki, Finland	Scientific community (higher education, Research)	200	all

53	Posters	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	Nanostructured materials for transparent electronics	24/10/2013	2013 IEEE 19th International Symposium for Design and Technology in Electronic Packaging-SIITME, Gal	Scientific community (higher education, Research)	all
54	Posters	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	Analyzing accomodation phenomena in dielectric hybrid thin films	08/07/2014	7th ISFOE14, 8-11 July 2014, Thessaloniki, Greece	Scientific community (higher education, Research)	all
55	Posters	UNIVERSITATEA DUNAREA DE JOS DIN GALATI	Solution-processing of ZnO-based semiconductors for transparent flexible electronics. From nanoparticles to thin films.	08/07/2014	11th International Conference on Nanosciences & Nanotechnologies (NN14) 8-11 July 2014, Thessaloniki	Scientific community (higher education, Research)	all
56	Videos	TEKNOLOGIAN TUTKIMUSKESKUS VTT	Printed electronics functional card demonstrator	02/06/2014	http://youtu.be/yNpF_brcOj4	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias	all
57	Web sites/Applications	FACULDADE DE CIENCIAS E TECNOLOGIADA UNIVERSIDADE NOVA DE LISBOA	Points	01/06/2011	http://www.points-fp7.eu/	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias	all