# PARYLENS

## PARYLENE based artificial smart LENSes fabricated using a novel solid-on-liquid deposition process

**Final Report**

**1 Oct 2010 - 30 Sep 2013**

**Final publishable summary report**

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The research leading to these results has received funding from the European Union Seventh Framework Programme.

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## 4.1 Final publishable summary report

### 4.1.1 Executive Summary

All deliverables could be fulfilled in the project PARYLENS. The project deals from bringing to value applications that are protected by the patents WO/2006/06395 and US 0892892 on solid on liquid deposition technique (SOLID).

The project packages droplets. This has the potential creating ideal lenses that share properties of droplets which tend to minimize their surface leading to perfect shapes. Apart from the SOLID technology that is highly innovative, the package (Parylene) had to be chemically modified allowing mechanical deformation of the lens. There was a tradeoff to be worked out that consists in optical power variation of a hermetically sealed lens of about 14 diopters of a sealed lens where the boundary conditions are determined by the choice of the liquid (index of refraction), its thickness (optical power range required) and the compressibility of the liquid and the elasticity of the package. Promising liquid organogels could be synthesized having an index of refraction that can be tailored for better adaption to optical systems. Looking at lens manufacturing only strong un-isotropic lenses could be realized due to delays in the synthesis of the precursors and the final manufacturing of the device.

The compressibility of the liquid is a weak contribution since deformation must not need strong forces. For intraocular lenses the typical forces that are available for accommodation are typically the force that the ciliary muscles can afford.

For consumer electronics, similar rules are valid in order to obtain a long autonomy for the power supply. For consumer electronic applications, high-voltage solutions could be worked out using electrostatic forces that are applied using transparent compliant electrodes. In this field the project could present a large variety of solutions; PEDOT: PSS thin film layers allowed depositing layers of less than 1 kOhm / square. Another solution consisted in the insertion of ITO nanoparticles by sonochemistry treatment ending in a resistivity around 50 kOhm / square. Sonochemistry was also successful applied for antibacterial post treatment of the lens surface using ZnO or $MgF_2$ nanoparticles. It was found that a relatively low surface coverage of these particles may already have a strong antibacterial effect. Furthermore, sonochemistry acts on the entire surface of the object that is put into the ultrasonic bath; it can be considered that it can be considered as conformal surface treatment, well compatible to Parylene technology.

Promising for future scenarios was also grafting of Carbon nanotubes (CNs) and Graphene layers using Thiophene and Carbazol linkers via TEOS precursors, hereby values in the range of 1 MOhm could be synthesized.

Elastic Parylene could be synthesized with a Young's modulus of one tenth (400 MPa) of standard Parylene C that has typical values of 4 GPa; an alternative could be also worked out using a composite lens structure whereby one liquid enclosing wall consisted of high elastic RTV-23 silicon rubber with 1 MPa Young's modulus. Looking at industrial manufacturing of intra-ocular lenses and consumer electronic lenses, an important issue is automatic manufacturing because imperfections during manual assembling are not the exceptions but the rule. In this regard, a big effort must still be made.

As another objective of the project, flexible bi-stable displays for electronic books were manufactured using sacrificial templates. The templates consisted of Polystyrene honeycomb structures that can be loaded with liquid crystals (LC) and sealed with Parylene. The LC's in the micro-wells (pixels) are incompressible allowing that the entire displays can be folded and rolled without affecting the on or off state of the pixels. During the project, prototypes of mono-stable displays could be manufactured. Direct deposition of Parylene on the LC did not yet allow to fix the charge that is necessary stabilizing the opposite state. In the future chargeable states at the interface LC / Parylene may be created either by post-treatment using UV activation or by pre-polarization of the device during the deposition of Parylene.

### 4.1.2 Summary description of project context and objectives

The project aims to bring to value the results of the previous FP6 Project MULTIPOL where a polymer thin film (Parylene C, a paracyclophane also known as dichloro-di-para-xylylene) is directly deposited on liquid surfaces hermetically sealing the liquid without any measurable mechanic deformation.

Inspired by the shape droplets of liquid take in the nature, several applications such as finely shaped lenses come to mind. Therefore, manufacturing lenses that make use of the fact that the liquid surfaces are perfect is the centre of interest of the PARYLENS project.

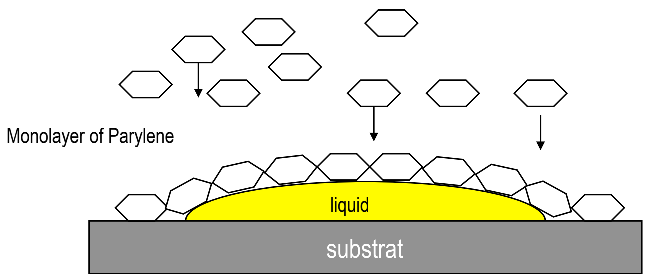


Fig. 1: Concept of Solid on Liquid deposition (SOLID)

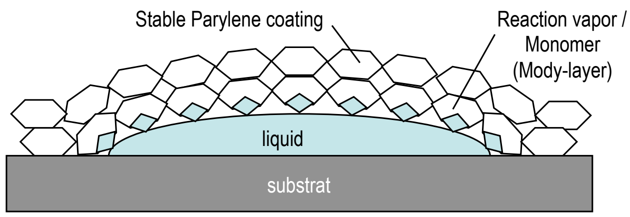


Fig. 2: Concept of Parylene functionalization from FP6 project MULTIPOL

Different lens-based applications are hence promising:

(i) Intra-ocular lenses in the field of biomedical engineering are one field where the focal lengths can be modified
(ii) Tuneable lenses for consumer applications such as cameras in mobile telephones.
(iii) Following the concept of insect facet eyes, the vision of flat flexible displays comes up.

Flexibility is a key issue, meaning **for intraocular lenses** that an external force is able to deform the Parylene sealed liquid, resulting in a modification of the focal length. In the simplest case the patient's own ciliary muscles will deform the lens. In a more complex case, actuators have to be integrated either using Coulomb interaction between two adjacent transparent conductive electrodes, or so-called EAPs (electrically activated polymers). External actuators are rather preferred for **tuneable lenses** used in **consumer opto-electronic devices**.
For **flexible displays**, liquid crystals are embedded in a transparent polymer template structure made of microscopic cavities. Each of the miniaturized containers is incompressible, thus image and colour changes due to macroscopic folding or other deformations of the display can be avoided.

Obtaining flexibility is a difficult issue to be solved since the polymer (Parylene) that is not at all stretchable (Young's modulus of 4 GPa). Together with perfect encapsulation of a liquid, this produces a quite rigid structure. One of the crucial scientific objective of the project is the creation of a degree of liberty that allows to change the focal length of the lens in a way that accommodation is feasible either driven by the ciliary muscles, or by an electro-active driver. There are four approaches that will allow solving this issue:

(i) Making Parylene elastic (0.5 GPa).
(ii) Making the body of the lens (liquid) compressible.
(iii) Allowing partial (reversible) delamination from a substrate.
(iv) Fixing the geometry but tune the index of refraction.

Note the other favourable properties of Parylene such as high chemical inertness, pin-hole free packaging of the liquid, biocompatibility, high optical transparency (no opaque colour effects, etc.), must be conserved. The solution for issue (i) will be worked out using co-polymerization of the vapour of Parylene together with gases that are injected into the reaction chamber. For the establishment of the technology a variety of liquids must be looked at for being coated (one of the liquids fulfils best the

properties). Due to the fact that the classic Gorham Process for Parylene deposition is carried out at pressures as low as 1 Pa, the low pressure CVD process must be converted into atmospheric pressure CVD (APCVD) whenever aqueous solutions have to be coated.
For issue (ii) and (iv) hydrogels are very promising as the index of refraction can be modified and compressibility can be achieved. For issue (iii) the lens can be anchored onto a substrate as in Fig. 4.

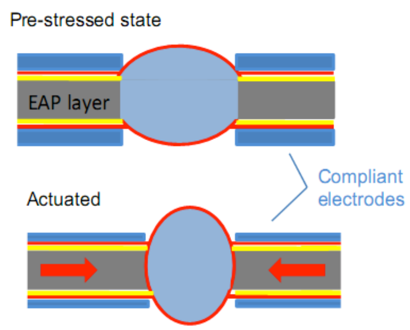


Fig. 3: Concept of electrical actuation for changing the focal length of SOLID-based lens.

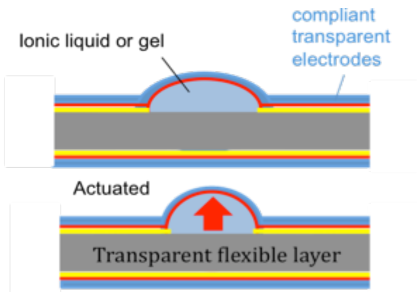


Fig. 4: Concept of changing the focal length of a SOLID-based lens by changing its volume.

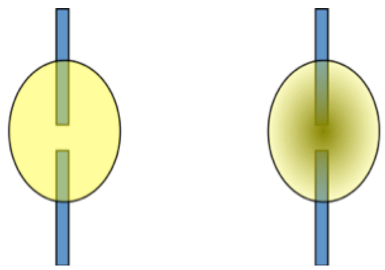

Fig. 5: concept of changing the focal length by changing the refractive index.

Flexibility for the variable focal length devices means also that the area contact for the actuator must be transparent and simultaneous conducting. Typically TCOs (Transparent conducting oxides) have these properties, however they are ceramics and very brittle and end in crack formation that interrupts the current path. In the simplest case a very thin gold layer can partly solve the problem, however the thickness must be kept sufficiently low for avoiding too strong absorption. Better solutions promise conducting or semiconducting polymers that have in general lower Young's moduli as ceramics. Other solutions are tested using implanted conducting nanoparticles that give rise to percolation as soon as the density is sufficiently high. Such transparent compliant conductive layer are also needed for the flexible displays because they allow the reorientation of liquid crystals that are embedded using SOLID technique by external electrical fields.

### 4.1.3 Main S & T results/foregrounds

#### 4.1.3.1 Chemical understanding and Parylene elasticity

Looking at the lacking flexibility of Parylene the degree of deformation for a required optical power is brought to evidence in work package 1 (WP1). It is obvious that the higher the index of refraction of the optically active medium (liquid) the less deformation is required. It was further shown that at the required optical deformation of non-modified Parylene, the polymer surface degradation during stretching is acceptable (wave-front error (WFE) used as monitor). In this part of the project this aspect was brought to evidence for all projected application of the partners from industry by setting up a list that correlates the degree of stretching of the modified Parylene and the optical power modification.
The test structures were cast PDMS probes whereby the test lens system is connected with a channel to a chamber that allows pressure variations for deformation of the lens, as shown in Fig. 6.

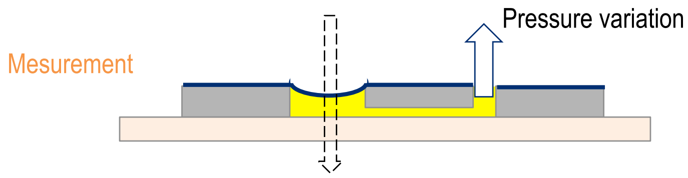


Fig. 6 Principle of controlled deformation variation for SOLID-based lenses.

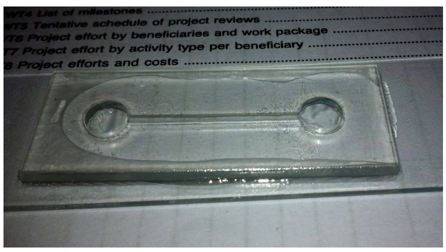

Fig. 7 PDMS cast for realization of test devices as shown in Fig. 6.

In order to be able to respond on these optical power requirement, the standard Parylene reactor using the Gorham process had to be modified allowing as much as possible co-polymerizations, so as to achieve elastic Parylene. A typical reactor is shown in Fig. 8 containing the following features:

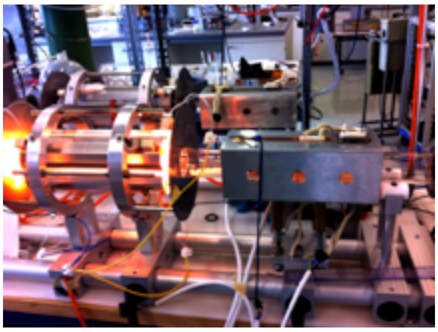

Fig. 8: LPCVD reactor for Parylene co-deposition containing two crucibles for two substances.

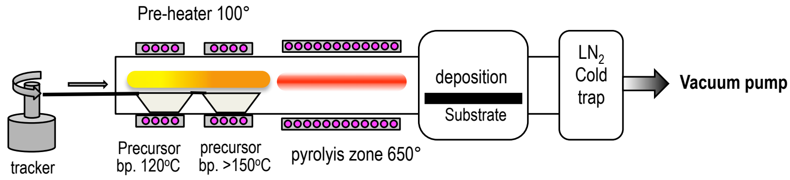


Fig. 9: Sketch of the modified reactor; the deposition can be controlled by the tracking speed of the substances in the two crucibles.

The reactor was further modified allowing gas-supply from the left from independent is co-evaporators. In another configuration, plasma assisted the creation of radicals allowing an almost infinite variety for co-polymerization. An example of successful co-polymerization is shown in Fig. 10 and 11.

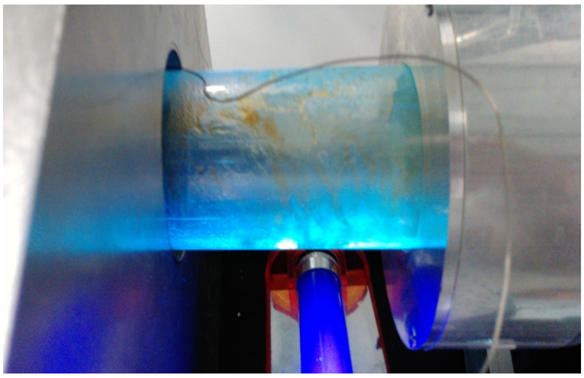

Fig. 10: Vinyl formation in an APCVD reactor.

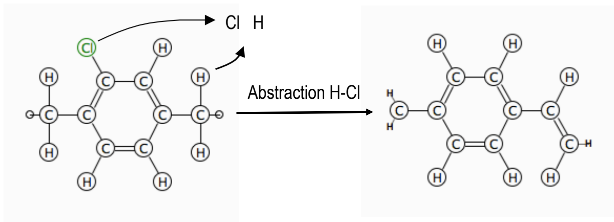


Fig. 11: Mechanism of Vinyl creation in the APCVD reactor.

In this configuration, the mechanical properties of Parylene could be reduced. The ad-molecule was evaporated in the second crucible and by its volume, collision rate reduced crosslinking occurring due to the fact that the molecule acted as a "placeholder" avoiding strong cross-linking. The synthesis of these molecules was carried out at ISMAC and deposited at HESSO. The best results showed Parylene with a Young's modulus of 300 MPa instead of 4 GPa (pure Parylene C).

The chemical understanding of the project was strongly supported using molecular simulation in order to understand the effect of increasing elasticity.

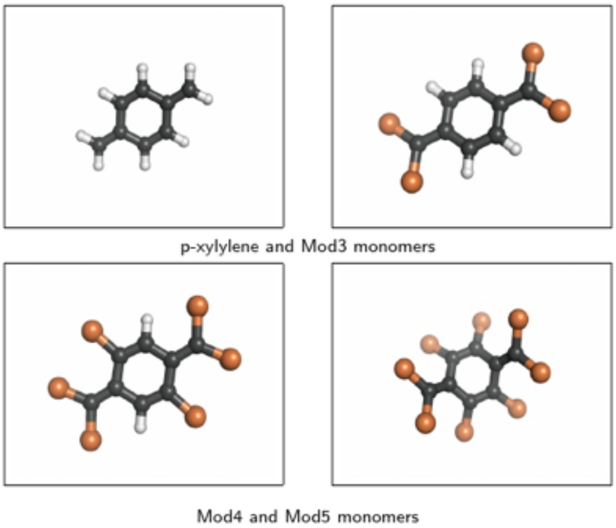


Fig. 12: P-xylylene-modified monomers.

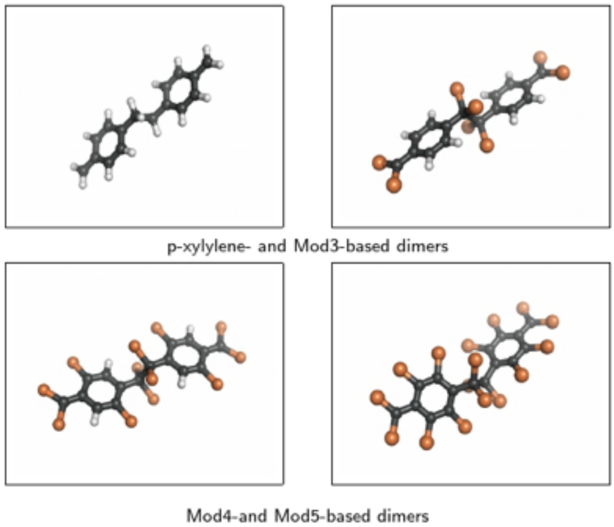


Fig. 13: First dimers after the initiation reactions.

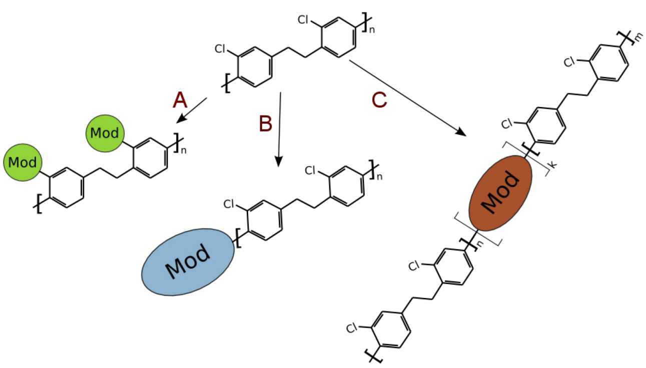


Fig. 14: Various possible chemical ways of Parylene modification. Route A leads through a pre-processing changes, i.e. the polymerization involves modified Parylene-like units. Route B involves deposition on active substrate, like it was shown above. Route C leads to copolymers, like it was found in the case of Parylene-vinyl copolymerization.

Fig. 15: Coarse-growing concept for increasing the predictions for larger molecular units being assumed to be representative for molecular growth.

### 4.1.3.2 Shaping of the lenses

Real close-to-implant biconvex lenses were prepared that should bring to evidence that bubble-free packaging and shaping can be carried out and the optical power can be adjusted. The tuneability of such lenses will be explained in the next chapter.

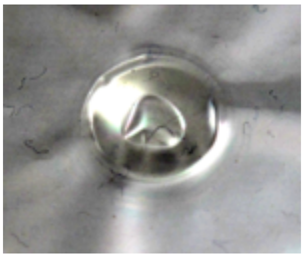

Fig. 16: Defect due to thermal shrinking at higher substrate temperature.

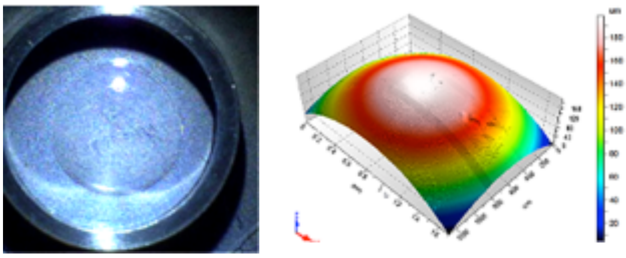

Fig. 17: Perfect ready-to-measure biconvex SOLID lens; left: lens, right: Confocal micrograph of upper part of the lens.

Fig. 18: Sample of lenses for attachment to ciliary muscles.

The base of the lenses is prepared using a mould that is first coated by a de-moulding agent. As next step the bottom Parylene layer is grown. The liquid is then trapped by the mould and coated by a top Parylene layer. All lenses are simultaneously released (Fig. 22) and diced by laser.

Fig. 19: Glass plate with RTV23 silicon moulds for trapping the liquid.

Fig. 20: Lenses as Fig. 21

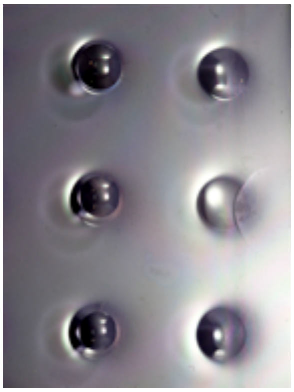

Fig. 21: PMMA moulds trapping liquid prior to Parylene deposition.

Fig. 22: Lenses ready for dicing by laser.

Another way to shape the lenses, trying to solve the issue of making the body of the liquid lens compressible, was to use sol gel technique. One of the crucial advantages is the fact that, using hydrogels, the index of refraction can be tailored. Note that a high index of refraction means a smaller lens deformation can still cover the range for the needed accommodation. In Fig. 23 the actual state is represented, where water loss from the hydrogel leads to pronounced local deformation of the lens. This will be avoided in future work.

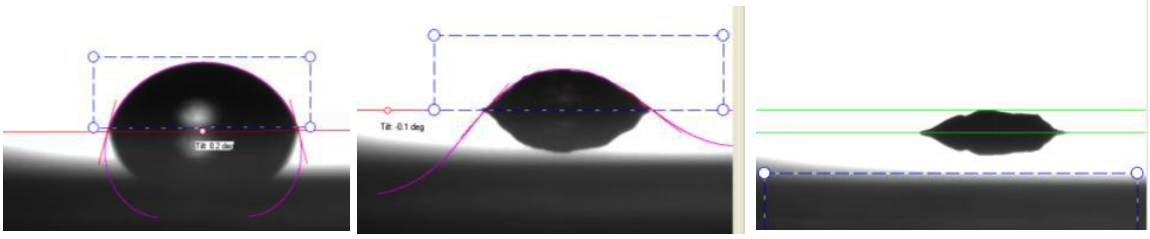

Fig. 23: Digital pictures of a single gel droplet during vacuum treatment. (AJL)

#### 4.1.3.3 Tunability and EAP

As first and simple approach that did not need the developments carried out in the other WPs, an electrostatically activated tuneable lens was projected having similar dimensions of either typical single lens devices, and intra-ocular lenses. A schematic cross-section of the test device containing all layers is represented in Fig. 24.

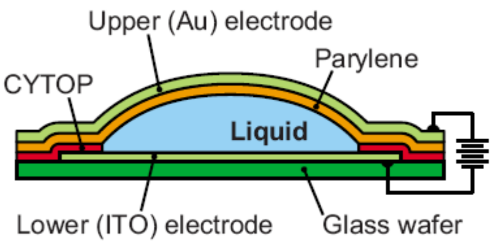


Fig. 24: Model device for first tuneable lens approach containing: ITO-coated transparent bottom-electrode on glass substrate, CYTOP-pattern for liquid area definition, Parylene for encapsulation of the liquid and transparent compliant electrode as top contact (IMEC).

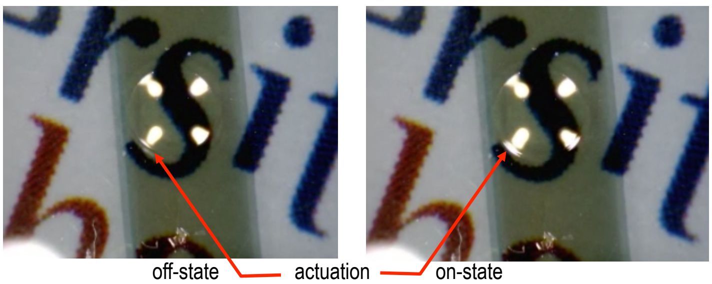


Fig. 25: First working model device as sketched in Fig. 12 in operation monitored by the light reflection as indicated by changing from the off-state to the on-state.

After the creation of biconvex lenses with non-modified Parylene on top and bottom of the lens (Fig. 20-23), the bottom-layer of the biconvex lens was replaced by a highly elastic silicon rubber layer (Neukasil RTV23); meaning the bottom layer could be easily stretched upon mechanical stress. This concept allows the construction of mechanical drivers for deformation of the lens either using a pneumatic or an EAP (electrically actuated polymer) principle. The concept is shown in Fig. 26.

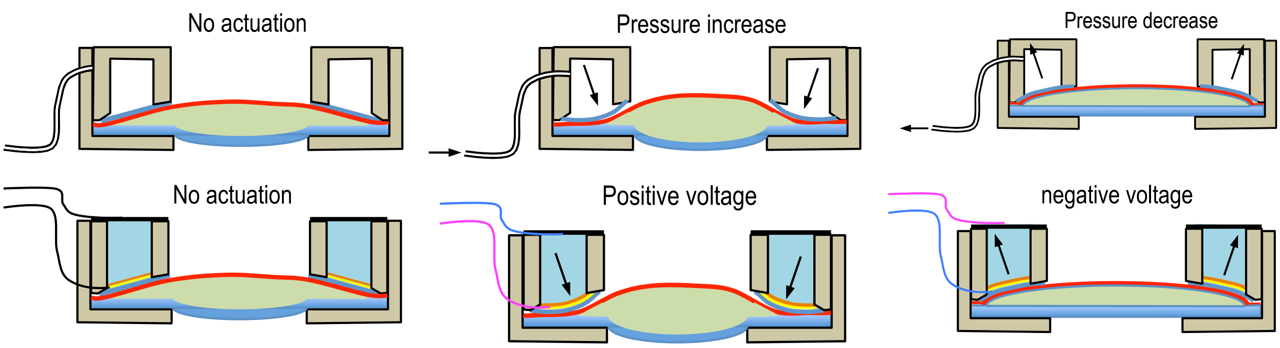


Fig. 26 Principle of pneumatic (up) and EAP-based actuation of an SOLID-based lens

The principle of EAP-based actuation was worked out in WP2.1. The ionic EAP is working as shown in Fig. 27.

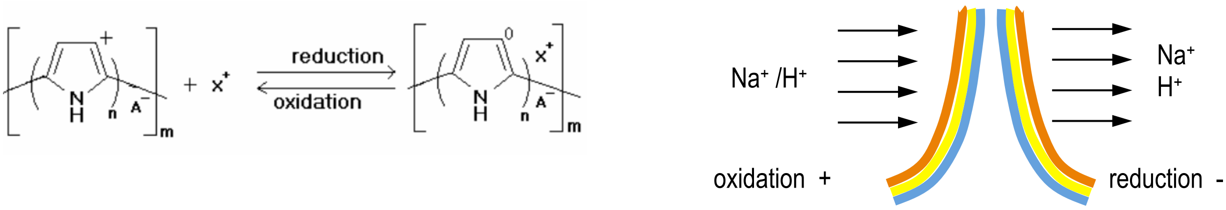


Fig. 27: Working principle of the IOL EAP: when oxidation occurs, the polymer matrix compensates the charge. The adsorption and release of ions leads to a volume modification, resulting in a bending.

A sequence of in EAP based on Polypyrrole on gold and RTV23 silicon rubber is shown in Fig. 27 whereby an electrical potential was applied between a counter-electrode in the liquid and the Polypyrrole. The active rubber will be placed in Fig. 28 series below:

Fig. 28: IOL / EAP deposited on a Parylene layer in a Parylene / gold / Polypyrrole structure at work. The immersed sheet in the 1 M NaCl solution: the bending from the left to the right is about 180°.

#### 4.1.3.4 Tunable lenses

##### EAP-driven lenses

The method for transferring the results as presented in Fig. 28 to a driver concept shown in Fig 26 followed two ways: first using a pneumatic actuation, second arranging the EAP (Polypyrrole) on a membrane as shown in Fig. 26 down. Results on EAP drivers are shown in Fig. 29.

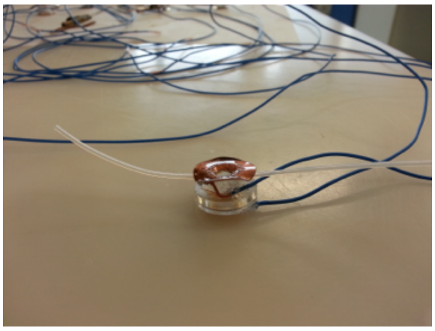

Fig. 29a: top view on a prototype of EAP driven actuator with contact wires and liquid supply system

Fig. 29b: Bottom view on a prototype of EAP driven actuator with contact wires

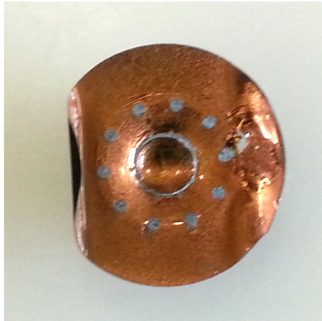

Fig. 29c: view through the membrane of the EAP prototype.

All manufacturing steps for completing the lens and the driver could be carried out, however the driver did not work in the few prototypes that could be realized. More care must be taken in sealing the membranes and contacting the thin-films. The assembling procedure needs a lot of delicate hand-made manufacturing steps in a way that initially a very low yield (<10%) must be assumed, hence at least 20 prototypes must be realized for having the chance that ne will work as it was projected.

##### Pneumatic lenses

The concept follows fig. 26 upper sketches; a membrane holding volume was constructed using PMMA and the entire lens was either glued onto the carrier or the membrane was pasted onto the carrier and the lens was finished with the carrier system:

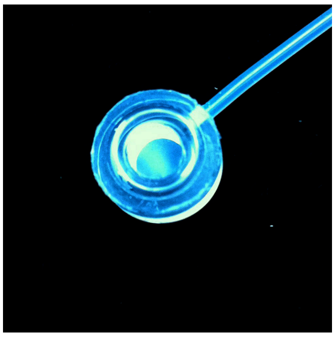

Fig. 30a: compressed membrane

Fig. 30b: depressed membrane

Fig. 30c assembled lens + driver

Fig. 31: pneumatically actuated tunable lense in two different focalizations

#### 4.1.3.5 Biocompatibility

##### Carcinogenesis

Looking at the context of biomedical product such as implantable intraocular lenses, biocompatibility and inertness is always a fundamental issue. For a permanent implant such as an intraocular lens on going active protection from bacteria and unwanted protein accumulation increases the security. To this end nanoparticles that are known from their anti-bacterial behaviour were deposited using sonochemistry onto the surface. Fig. 32 shows the successful reduction of biomass creation due to ZnO nanoparticle exposure.

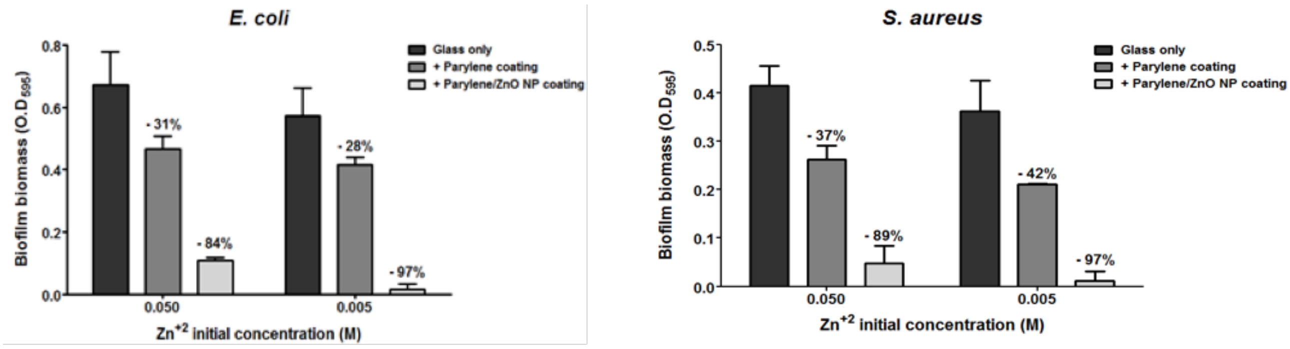


Fig. 32: Biofilm biomass formation resulted after 24 hours of treatment with pure glass slides, glass slides coated solely with Parylene and glass slides coated with Parylene and ZnO nanoparticles. (BAR-ILAN).

Proteinaceous spheres containing Tetracycline were further inserted into the Parylene C layer, again using the sonochemical method. The size distribution of incorporated spheres into the Parylene C layer ranged between 25-130 nm. Although the suspended proteinaceous spheres loaded with Tetracycline have shown antimicrobial activity, the Parylene surfaces with deposited spheres caused no killing of tested bacteria.
The nanoparticles of antibiotic and anti-inflammatory drugs were prepared and subsequently embedded into the Parylene C layer. The size distribution of obtained particles ranged between 40-70 nm. The drug NPs is homogenously dispersed onto the surface of Parylene C without damage to the structure of the polymer.

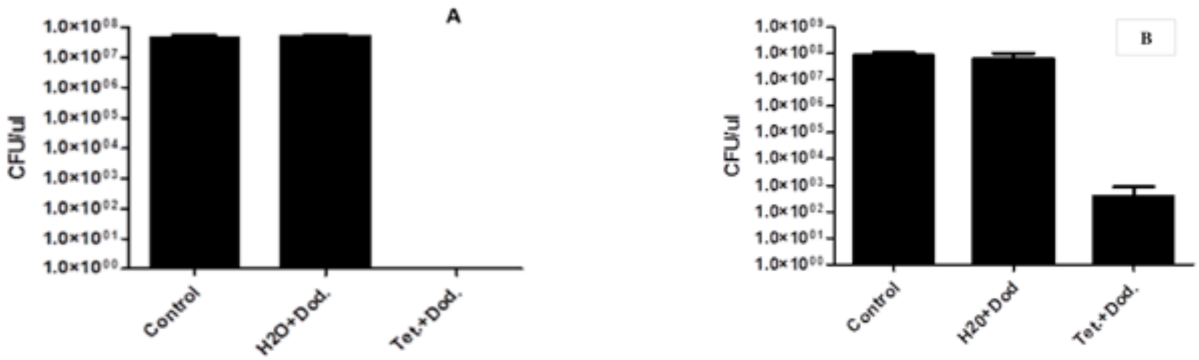


Fig. 33: Antibacterial activity of Tetracycline NPs- coated Parylene surfaces. *E. coli* (A, left) and S. aureus (B, right)

##### Cytotoxicity

Modified Parylene films were exposed to laminin to allow the cells to adhere and grow. Cultures of human neural cells (Rencells) were seeded directly on sterilized (ethylene oxide) substrates. Viability test kit (live/dead) was used containing different fluorescent marker for dead cells (Propdium Iodide staining) and alive cells (Vital Calcein staining). Test devices were incubating in 1.5 ml at 37oC at 5x104 cells/well.
Imaging of cultures was made after 24, 48 and 72 hours. For some experiments imaging was made up to 1 month. Positive control plates coated with laminin were used.

Imaging of samples of Parylene C film deposited on Falcon wells.
Parylene C film show a good adhesion, survival and proliferation of neural cells grown onto surfaces after 24, 48 and 72h.
Imaging of samples of Parylene C modified with dioctyl-paracyclophane
Parylene film modified with dioctyl-paracyclophane shows good adhesion, survival and proliferation of neural cells grown onto surfaces after 24, 48 and 72h. Coating indicates a good growth of the neural cells and a good survival even after one week in culture as shown in Fig. 34.

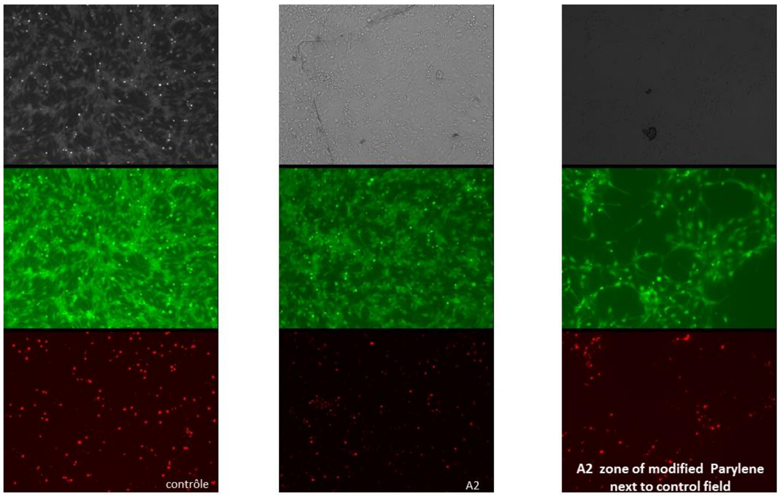


Fig. 34 Sample (d) Parylene C is copolymerized with dihexyl-paracyclophane after 1 week in culture

Qualitative and quantitative in-vitro tests for cytotoxicity studies were made in accordance with ISO 10993-5 for Parylene C films and Parylene C films modified with co-monomer dihexyl-paracylcophanes also for Parylene films modified with co-monomer dioctyl-paracylcophanes .
Tests shows for all samples a negative result, which indicates that the materials are free of harmful extractables.

#### 4.1.3.6 Flexible bistable displays

In this field small templates with microscopic cavities were filled with liquid crystals and successfully sealed with Parylene. The fundamental technology of the devices could be realized and all basic issues are solved. A first prototype could be realized whose performance needs further to be improved with respect to increasing its contrast ratio. More development and training in manufacturing further prototypes are promising to further improve the efficiency of the devices.

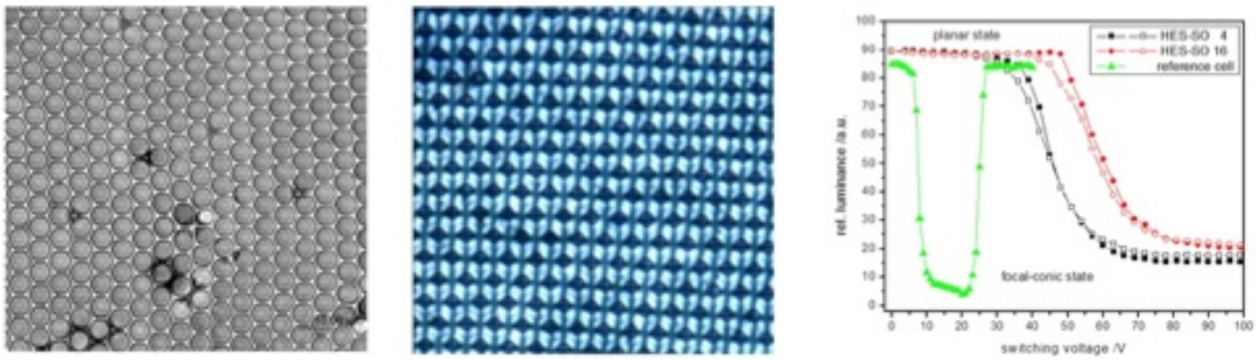


Fig. 35: Micrographs of empty and LC filled micro-voids on flexible polymer foils (ISMAC, left and center). Electro-optic characteristics (EOC) of two Parylene encapsulated LC samples with a thickness of 1,5 µm (HES-SO 4) and 2,4 µm (HES-SO) Parylene, together with a LC in a reference glass cell (FhG PYCO, right).

The results of the first prototypes using an all Parylene encapsulated template structure loaded with LC is shown in Fig. 36.

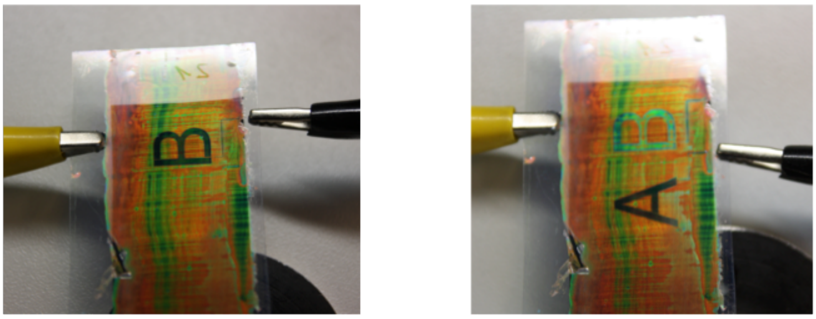


Fig. 36: Prototype of the first bistable display demonstrators involving truly parylene-encapsulated cholesteric LCs.

#### 4.1.3.7 Parylene functionalization

During the project important research platforms could be established allowing functionalization for Parylene layers with other molecules:
• Both strong hydrophobic and Van der Waals interactions have been successfully exploited to physicochemically adsorb various hydrophobic nanomaterials such as non-oxidized and oxidized polyCOOH SWCNTs/MWCNTs onto hydrophobic Parylene C coatings. Beyond the aspect of pure functionality issue introduced onto the surface on such a non-functional polymeric coating, these specific carbonaceous nanomaterials might be a quite powerful entry to obtain 2D conductive parylene coating:

• Same non-covalent hydrophobic/Van der Waals interactions have been also successfully used for the strong adsorption of various functional silicates that enabled the formation/growth from the surface of parylene C coatings of a silica-based adlayer that has been strongly adsorbed useful for 2$^{nd}$ step functionalization.
• Various UV-photoreactive materials, i.e., hybrid silica nanoparticles and polycarbazole polymeric microspheres might be UV activated for covalent attachment onto non-functional parylene C coatings. That innovative way of surface functionalization will be a strong entry to UV patterned parylene C films (activity Bar-Ilan).

### 4.1.4 Potential impact and main dissemination activities and exploitation results

Tunability (accommodation) of lenses is the most important feature that is demanded from both intra-ocular (bio-medical) lenses (IOL's) applications and consumer electronics, such as mobile phones, and camera supervision / inspection systems needing an auto-focus facility. Tunability of lenses makes PARYLENS solutions attractive for exploitation and therefore special care was taken to fulfil this requirement. Apart form the electro-wetting approach pioneered by partner VARIOPTIC new alternatives are demanded and were explored in this project.

The project PARYLENS could be finished in time and all deliverables could be fulfilled, however some of them needed more time as foreseen in the DOW. This is certainly due to the high degree of innovation that is always closely connected with high risk of failure, and particular efforts to be carried out in research. The strong delayed deliverables can be identified as part of the key challenges "par excellence" of the project that makes up its certainly being exclusive.

The first challenge is the **creation of elastic Parylene** that could be achieved at the end of the project; the success of increasing the original Youg's modulus of Parylene from 4 GPa down to 0.4 GPa. The second challenge is the surface treatment of polymers (Parylene) in order to obtain **transparent compliant electrodes**. The third consists in creating a kind of **motorized driver system for changing the focal length** as soon as a deformable lens that can be obtained.

#### 4.1.4.1 First challenge– elastic Parylene

The **first challenge** of obtaining **elastic Parylene** needs a threefold impact:

1. Theoretical prediction of the mechanism leading to elasticity and the molecule shape that must be added to the Galxcyl C (trade name of the dimer precursor, di-Chloro [2.2] paracyclophane).

2. Synthesis of the most promising precursors based on 1. allowing be co-evaporated together with Galxyl C at similar temperatures.

3. Co-deposition of the new molecules developed in 2. together with standard Galxyl. The enhanced work on this issue made it possible to modify the concept beyond what was planned in the DOW.

A further concept could be proposed and successfully carried out is by replacing one Parylene-based limitations of the bi-convex lens by a highly elastic silicone (1 MPa). SOLID technology allowed then finishing encapsulation in the usual way. The structure of this composite lens was submitted as foreground patented. This paves the way for one of the end-users that are foreseen in the project for manufacturing variable lenses to facilitate exploitation. This technology is not only for intra-ocular lenses but also for any kind of tuneable lens application.

#### Potential IMPACT

The major impact can be seen in those activities in the development of the elastic Parlene. Looking at the large varieties of industrial application of Parylene coatings, elasticity is missing and can be applied for all those devices that contain mobile components such as hinges and flaps, valves etc. Independently form this project, as soon as flexible Parylene is at hand, one can think about all these applications.

#### 4.1.4.2 Second challenge - transparent compliant electrodes

**The second challenge** on the way creating tunable lenses is the creation of transparent compliant electrodes, for such devices where deformation of the lens is carried out using electrostatic forces. It was decided at an early state of the project that such driver concepts for electrostatically deformation of a lens can be carried out only be applying high voltages (100 V) that are not compatible for IOL's. The compliant electrodes must conserve their conductivity in the case of deformation of the substrate (tunable lens) Hereby the PDOT:PSS technique turned out to be promising as well as nanoparticle insertion using sono-chemistry, and carbon nanotube / graphene grafting using double functionalized Silica- carbazol linkers. In contrast to conventional thin film layers, these three technologies avoid application of a separate conducting layer (such as ITO) that cracks upon macroscopic external stress from deformation. Two of three concepts have the advantage that the grafts have a molecular structure that binds covalently to the surface and easily follow elastic deformations without crack formation because they are also polymers and the conductivity is due to conjugation. The other very promising approach is the insertion of conductive nanoparticles; it could be found that sufficient conductivity (<100 kOhm) and close to 90 % optical transmission can be obtained. In the latter case a "kind" of percolation via nanoparticles under the polymer surface occur; however the extrapolated density of particles under the surface level is much less as one would expect for the case that percolation would be the dominant transport mechanism. The effect is surprising and open explications of the effect are looked for. All techniques were identified, looking at optical transmission and electrical conductivity, as suitable solutions for later production. After some initial drawbacks these tress solutions could be pushed in parallel; a platform was created allowing a larger space for optimization at later industrial level.

#### Potential IMPACT

Highly promising is the grafting of graphene layer based on graphene-oxide reduction; even if the process could not be optimized, the fundamentals could be established looking at the grafting mechanisms. Large area uniformity as lateral contacting of the layers are big challenges that are assumed to be further explored in Horizon 2020. Flexible displays and electronic paper need such layers at large area.

#### 4.1.4.3 Third challenge - motorization of the lens deformation

The **third challenge** consists in a **motorization of the deformation** using driver systems. For IOL's such drivers must be highly miniaturized and flexible for insertion and operating at low voltages. A tunable flexible IOL system was mounted on lens layout that is usually used by partner AJL. This IOL system looks like a conventional IOL, however the focal length can be modified upon peripheral deformation. In a later purely life-science oriented project the possibility of grafting this lens to the ciliar muscle system in order to bring the tunability to application by the patients own accommodation mechanism.

If this accommodation mechanism fails, externally powered driver systems must be at hand. A tube-like torus around the lens was tested as a pneumatic driver and showed the best results of all tested approaches. The way to apply pneumatic pressure t the system must be solved in another project. More elegant is the solution using EAP's (Electrically Actuated Polymers). As most promising candidate the ion activated thin-film Polypyrole was identified to be the most promising. The technology could be fully developed for cantilever samples in a liquid bath. Complete systems with an encapsulated ionic liquid allowing the application of a peripherical force to the lens could be manufactured but not successfully brought to function yet.

The research work on the lenses and the development of assembly scenarios brought clearly to evidence that hand-made manufacturing is always accompanied by imperfections looking at optical quality. Gluing and pasting needs robot-controlled application of the paste in order to conserve the perfect round shape of the lens. Further, several optical liquids that are suitable for filling the lenses must be mixed and polymerized using automatic routines prior to UV polymerization. Best exploitation can be achieved by complete working out all manufacturing steps looking for precise automation for obtaining highest optical quality.

#### Potential IMPACT

All glass based accommodative optical system can potentially be replaced by such kind of optics allowing highest precision based on the perfection of natural-driven surface finishing that makes use of surface reduction due to energy minimization. It has been shown that the range of lens systems that can be manufactured using SOLID technique ranges for micro-lenses up to conventional macroscopic lenses. There is a large range of different liquids that can be used in function of index o refraction, together with the curvature the optical power can be chosen and adapted. For consumer electronic application SOLID on liquid-based lenses are easy to be recycled.

#### 4.1.4.4 Other challenges - Biocompatibility

In a separate work package the issues **of biocompatibility** were addressed. As a favourable feature all initially used were close to the Parylene chemistry; well known as highly biocompatible polymers and all already used for bio-medical purposes. The activity that aims developing flexible Parylene for tunability had to modify both the chemical structure and composition of the precursor that had to be added for co-polymerization to the conventional Galxyl C. In general it must be feared that the biocompatibility is the price that has to be paid for elasticity and hermeticity. In a separate test for cytotoxicity it could be brought to evidence that full biocompatibility could be conserved.

In an additional tests, again using ultra-sound treatment of nanoparticles such as $MgF_2$ or ZnO in aqueous medium, pronounced antibacterial behaviour of the surfaces could be found. The special advantage of this method is its full isotropy for any even complex surfaces that are put into the ultrasound bath. This particular result that could be worked out in the project is assumed to be a universal way of treating any bio-med surface e.g. such as wound bandages.

#### Potential IMPACT

The results confirm full conformity of this treatment that can be extrapolated not only for anti-bacterial nanoparticle treatment of any surfaces but also for anti-corrosion, surface energy and even decorative purposes. The deposition of catalytic sites at small large surface areas comes close to vision.

#### 4.1.4.5 Other challenges - Bistable flexible displays

Bi-stable flexible displays development was a major challenge of the project. Microscopic templates based on polystyrene were assembled in a micro-mold of honeycomb structure. Filling with liquid crystal and subsequent Parylene deposition onto the LC are considered as well suitable to bring solid on liquid deposition technique to value. In this case the Parylene layer represents the interface to the liquid allowing depositing transparent conducting layers such as ITO for contacting the device. This device is highly flexible and could be manufactured in all projected states. As a special feature, even the styrene templates could be completely dissolved such as sacrificial templates. As result, the device showed only mono-stability due to the fact that probably the Parylene-LC interface did not allow attaching charges upon external polarity creating bi-stability that is able to conserve the polarization state.

#### Potential IMPACT

Large-area flexible displays for applications such as low energy consuming e-paper, tags and mall area low-cost signs can be manufactured. If the contrast can be increased and the bi-stability can be achieved, these displays have an advantage looking at ecological aspects in comparison with other technologies, because extremely low quantities of organics together with liquid crystals have to be recycled.

#### 4.1.4.6 Dissemination

Several publications are submitted and in preparation; the topics are publications on the molecular chemistry on elastic Parylene synthesis; further on results of elastic Parylene manufacturing. The EAP actuator that converts the movement of a cantilever into a linear displacement for deforming a lens will be submitted to the journal Sensors and actuators Parts of the research on tuneable lenses was carried out by totally tree bachelor students at HESSO, and the subject of nanoparticle insertion by sono-chemistry, and the grafting of CN nanoparticles and graphene layers were a parts of PhD thesis at Bar Ilan University. The results of the project were presented at the inauguration event for the nanotechnology building at Gdansk University. The concept where enhanced deformation of the lens could be achieved by the use of one elastic side-wall was submitted as a patent.

#### 4.1.4.7 Exploitation

The main exploitation tracks are foreseen to be followed by the project partners for Economy; AJL for ophthalmology, Varioptic / Parrot for consumer electronic devices. For COMELEC's main activity in general Parylens coatings the enhanced demand from potential end-users will increase the total business. The task of the project are settled in the field of high risk and partially in the field of Biomedical engineering, her closest to product achievement was the implantable tunable IOL. It is well known that medical tests, despite of the use of biocompatible materials and antibacterial treatments, last several years of testing. This activity, together with finding way how to attach the lens to the ciliary muscles in a way that accommodation can be carried out, must be the objective of a new project that focuses the perfection of such lenses in terms of optical quality, optical power and range of tunability. The focus will be then on manufacturing techniques allowing respecting precisely the lens geometry throughout all handling steps. This can not be carried out just in an laboratory environment.

### 4.1.5 Address of project public website and relevant contact details

**Public website**: http://www.parylens.eu

**Coordinator contact**:

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