1. Publishable executive summary

The aim of MULTIPRO was to develop **new multifunctional material for opto-electronic devices** based on solid state lighting sources (SSLS), addressed to several applications (automotive head-up displays and lighting, public information displays and general lighting) and contemporarily, an integrated reactive packaging technology suitable for the material developed and cost effective for the application addressed.

In particular, the performance of solid-state optoelectronic devices such as flat panel displays, imaging sensors, photonic circuit, and light-emitting diodes (LED) can be improved by applying a transparent high refractive index coating (>1,65) onto the light emitting or light sensing portion of the device. Coupled to these properties, due to the process and service conditions generally encountered thermal and chemical stability are required to materials for optoelectronic. Further, special functionalities such as wavelength conversion properties are required (typical example are white LED).

During the MULTIPRO project the consortium has developed **polymeric resins in which nanoparticles, of different nature, are embedded or built in**, in order to reach multifunctional material with new and improved properties. The specific material properties has been controlled and tailored by changing nature, size, composition, and concentration of the nanoparticles, according to industrial and technological request.

In particular, the project aim was to obtain the following functionalities from the material:

- **optical functionalities** (high refractive index and wavelength conversion property) for LED encapsulation, and
- **thermal and electrical conductive functionalities** for conductive layout realization also on transparent substrates.

During MULTIPRO project new nanoparticles synthesis route has been developed and the following nanoparticles have been produced:

- Nanoparticles for enhancement of the refractive index: Titania nano-crystals in the 4-5 nm diameter range have been synthesised in acidic media with good colloidal stability and high concentration.
- Nanoparticles for wavelength conversion properties: Fluorescent core/shell quantum dot particles consisting of a CdSe core covered by a shell of graded composition composed of CdS, CdZnS and Zns. The optimized route allows to obtain yellow emitting QDs with fluorescent quantum yield around 45%.
- Nanoparticles for electrical conductibility: Metal nanopowders of two main types were prepared: silver with copper (Ag/Cu alloy, 2.5%w/w and less) and pure silver.

Nanoparticle embedding into polymeric matrices has been studied and the following multifunctional material has been synthesized:

- Transparent composite materials with controlled, high refractive index were obtained by combining semiconductor nanoparticles (zinc sulphide or titania) with a silica-based matrix.
- Hybrid matrix material obtained through sol-gel processing of glycidoxypropyltrimethoxisilane and titania nanoparticles, obtaining thin films with easily tuneable refractive index in the 1,5 - 1,89 range. Wavelength conversion functionally from blue to yellow was added by embedding fluorescent core/shell quantum dot semiconductor nanoparticles.
- Conductive inks based on Ag/Cu and Ag nanoparticles with viscosity and the surface tension suitable for M3D printer were synthesized. After application in M3D and laser sintering the conductivity of 1/4 times of that of bulk silver was achieved.

MULTIPRO responds to the concept of the **"tailor to made",** which means that the functionalities above described respond to specific needs of the application addressed. **Molecular modelling** has been the enabling technology to tailor the material in terms of components necessary for the properties desired. MULTIPRO project has developed modelling procedures and dedicated software to simulate each step of materials development, from the pure components structure, to reactive models, up to final materials from which properties can be argued, in particular developing:

- an atomistic simulation protocol for epoxy based polymers forming 3D networks through chemical bonds

- a reactive mesoscale simulations of polymer/nanoparticle systems to predict system morphology, and mobility and clustering of nanoparticles in polymeric matrices.
- a reactive mesoscale simulation engine with graphical user interface.

As the process aspects are concerned, traditional technologies often are difficult if not impossible to adequate to new multifunctional materials. This aspect represents a great obstacle to the commercial exploitation of multifunctional materials and nanotechnology in general, especially for application with high and very high volume production.

In the framework of MULTIPRO project a **3D mesoscale maskless direct writing process** has been implemented for the deposition of multifunctional materials. In particular, The main results in process development has been:

- development of process parameters for conductive inks and hybrid optical multifunctional materials,
- deposition of different conductive inks for printing conductive paths, successful printing and sintering of conductive paths for LED application also on transparent substrate for the realization of luminous head-up display,
- deposition of different multifunctional materials for LED encapsulation. The printed materials consist of different matrixes and different nanoparticles and could successfully deposited by using Aerosol Jet® technology.

The approach used in the project represents a breakthrough in multifunctional electronic packaging because foresees a **complete integration between material preparation, processing and assembling of the final device**.

As final result, the feasibility to integrate M3D deposition technique in Chip On Board process has been demonstrated.

Technology exploitation and validation with the realization of four demonstrator in the field of solid state light (LED) by realizing two head-up display, a general lighting device and an automotive lighting function.

The four demonstrators produced in the framework of MUTLIPRO project as been evaluated, according regulation where present, the main results has been achieved are:

- transparent automotive head-up display satisfied the specification of luminance reaching a value higher then 10000 cd/m^2, where the request of automotive application is > 5000 cd/m^2;
- the luminous pattern of the general lighting device satisfied industrial requirements and can be used for domestic or commercial use;
- the luminous pattern of DRL lamp is quite close to the automotive regulation one; the difference is probably due to the manual and inaccurate assembly of the lenses on the LED-sources. In the worst cases the error is of about 20%, but the average discrepancies automotive regulation values are around 10%.

Finally, important results have been achieved in terms of performances of new material developed in MULTIPRO project for the application to solid state lighting devices.

OPTICAL MATERIAL:

- the application of the new multifunctional material (DpHTiA) developed in MULTIPRO project contribute to an increase of the light extraction from LED of about 20% to respect standard encapsulants.
- wavelength conversion has been achieved and multifunctional materials developed during the project can be successfully used for the realization of white chip-LED sources.

CONDUCTIVE MATERIAL:

- electrical 2 point measurements of printed layout showed electrical resistance ranging from 3 to 35 ohms; these results are in line with project objectives of electrical resistance (< 30-50 ohms).