1. PUBLISHABLE SUMMARY

1.1 PROJECT CONTEXT

The MiSPiA **context** is to deploy an enabling technology for the acquisition of scenes at low light levels, at video or higher frame rates, with centimetre distance-resolution. In fact, nowadays the imager market offers a broad portfolio of commercial and scientific-grade cameras, none of them simultaneously offers high-speed and ultra-high sensitivity: CCDs reach sensitivity close to single-photon level, but require cooling and long integration times; CMOS APS imagers provide video-rates, but with limited detection efficiency, thus requiring bright illuminated scenes. The MiSPiA **objective** is to develop imagers for high frame-rates and single-photon sensitivity cameras for 2D "imaging" and 3D "ranging" of rapidly changing scenes, in light starved environments.

The MiSPiA **focus** is on two clearly identified photonics applications, namely:

- high frame-rate (200fps) short-range (<50m) 3D ranging for automotive pre-crash safety systems;
- multi-spectral (300-900nm) long-range (200m-1km) 3D ranging for security surveillance.

The MiSPiA **outcome** will anyhow interest also adjacent markets, like molecular imaging, fluorescence lifetime imaging, biological analysis, confocal microscopy and adaptive optics.

The MiSPiA **technology** is based on solid-state Single-Photon Avalanche Diodes (SPAD), able not only to count single photons ("*photon counting*"), but also to accurately measure their arrival time ("*photon timing*"). The MiSPiA **imagers** consist of arrays of smart-pixels able to provide a full image of the scene. Each smart-pixel contains a SPAD detector and an in-pixel intelligence for processing, at pixel-level, either the 2D intensity-data (from the number of detected photons) or the 3D depth-ranging information (from the Time-of-Flight of each detected photon) of the scene under investigation. The MISPiA **fabrication processings** are a cost-effective CMOS technology, for monolithic planar fabrication of front-illuminated (FRONTSPAD) imagers, and a more complex wafer-bonding processing of two wafers (one for detectors and one for read-out electronics), for back-illuminated (BACKSPAD) advanced imagers.

The MiSPiA **consortium** consists of 7 partners, who are among the leading European research groups in the fields of SPAD arrays and single-photon instrumentation (partner POLIMI), CMOS sensors fabrication and advanced SOI processes (FRAUNHOFER), design and fabrication of microlens arrays and surveillance monitoring (HWU), time-correlated single-photon detection modules and cameras (MPD), safety applications in the automotive field (CRF), security surveillance monitoring (EMZA), and management and dissemination of European projects activities (CFc). Here is their full name, location and contact person:

- **POLIMI** - Politecnico di Milano (Italy), Coordinator, Prof. Franco Zappa (franco.zappa@polimi.it);
- **FRAUNHOFER** - Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung E.V (Germany), Mr. Werner Brockherde (werner.brockherde@ims.fraunhofer.de);
- **HWU** - Heriot-Watt University (United Kingdom), Prof. M.R. Taghizadeh (m.taghizadeh@hw.ac.uk);
- **MPD** - Micro Photon Devices S.R.L. (Italy), Dr. Simone Tisa (stisa@micro-photon-devices.com);
- **CRF** - Centro Ricerche FIAT S.C.P.A. (Italy), Ing. Maurizio Miglietta (maurizio.miglietta@crf.it);
- **EMZA** - EMZA Visual Sense LTD (Israel), Dr. Zeev Smilansky (zeev@emza-vs.com);
- **CFc** - CF Consulting S.R.L. (Italy), Mrs Carla Finocchiaro (carla.finocchiaro@cf-c.it).

The MiSPiA overall **cost** is € 3.400.166, with € 2.632.854 **funding** from the European Union, within the Collaborative project in "Information and Communication Technology", ICT-2009.3.7, in "Photonics", of the FP7 Framework. MiSPiA **leverages** a massive infrastructure worth over 150 M€ existing at the MiSPiA partners' premises that allowed them to request no equipment funding.

The MiSPiA project will last three years, from June 1st, 2010, to May 31st, 2013.

1.1 PROJECT OBJECTIVES

Objective 1 - SPAD smart-pixels with "in-pixel intelligence"

Objective 1 aims at developing the basic building block of the imaging arrays, i.e. the smart-pixels suitable for 2D imaging and 3D depth ranging, based on Single-Photon Avalanche Diodes (SPADs) with beyond state-of-the-art performances. Here are the proposed smart-pixels: **2D "photon-counting" smart-pixel**, able to count individual photons in well-defined time-slots, for providing intensity information of the scene under observation; **3D "direct TOF" smart-pixel**, able to perform accurate "photon timing" of the incoming photon, by means of an in-pixel Time-to-Digital Converter (TDC); **3D "pulsed-light indirect TOF" smart-pixel**, able to extract distance information from the overlapping of a detection time-window, synchronous with the illuminator's optical pulse; **3D "continuous-wave modulated indirect TOF" smart-pixel**, able to measure the phase delay between a sinusoidal illumination and the optical "echo" signal.

The design was led by partner POLIMI, the fabrication of array sensor chips by FRAUNHOFER, the development of the preliminary illuminator for short–range tests by MPD and for microlenses development by HWU. Objective 1 was fully completed in the first year, reaching the new state-of-the-art in CMOS SPAD, in terms of single-photon sensitivity over the 300nm-900nm range, very large active area, low noise, high dynamic range, un-cooled operation and cost-effectiveness.

Objective 2 - Front-side illuminated array chips (FrontSPAD)

Objective 2 aims at fabricating the sensor chips to be integrated in the final 3D camera system, based on the smart-pixels selected from the best performing device (from Objective 1). For the two 3D ranging applications, namely short-range automotive Safety and long-range Security surveillance, two different 3D imagers were designed. Chips have been manufactured in the second year in a planar front-side illuminated (FrontSPAD) fully standard CMOS technology. The fully functionality of the full array and of the in-pixel 3D processing are being characterized and tested in the first month of year three. Suitable microlenses to be aligned, assembled and fixed on top of the silicon chips were conceived and designed. Assembling procedures were studied and are now being implemented and tested with the fabricated chips.

Objective 3 - 3D ranging modules based on FrontSPAD arrays

Objective 3 aims at fabricating two final 3D ranging modules with cameras and illuminators, for the application partners CRF, HWU and EMZA, employing the FrontSPAD chips developed for Objective 2. The ranging modules are divided into the 3D camera (containing the detection head, an FPGA board and a power-supply board) and the corresponding illuminator. The output from the camera is an USB 2.0 link, for parameters download and 2D/3D data upload to a remote computer for further user-specific processing and actuation. The detection head consists of the CMOS FrontSPAD imager and the microlenses packaged together. The FPGA board controls the chip and perform some pre-processing of the 3D depth-information, before uploading it to the external electronics. The power-supply board enables the module to be biased just through the USB link.

Objective 4 - Back-side illuminated array chips (BackSPAD)

Objective 4 aims at fabricating the advanced sensor chips based in a more complex, non CMOS standard, fabrication technology, based on back-side illumination of a silicon-on-insulator (SOI) wafer containing custom SPADs, flipped and wafer-bonded on standard CMOS wafers containing the electronics (see Objective 5). Two major improvements are expected: **higher pixel density**, since BackSPAD detectors are placed on top of the corresponding smart-pixel electronics, instead of being placed to its side (as in the planar FrontSPAD structure); **enhanced spectral sensitivity** in the near-infrared, up to 1µm-wavelength, thanks to the thicker active volume within the SOI detector wafer and to the back-side illumination of the active area.

The first SOI BackSPAD chips were fabricated in the second year and are under testing.

Objective 5 - Assembly and test of the BackSPAD imager

Objective 5 aims at fabricating the wafer containing just the CMOS imager electronics (while SPADs lie on an SOI wafer, see Objective 4), to wafer bond the two wafers together, to dice the chips and to provide standalone BackSPAD sensor chips. The last months of the second year of the MiSPiA project were spent to conceive and design the architecture of the imager electronics in the standard CMOS technology, focused on the: **optimization of "photonic" performance** of SPAD detectors independent of the electronics, due to better SOI layer quality and custom processing; **optimization of "electrical" performances**, independent of SPAD constraints.

The final BackSPAD imager would be easily integrated into the same cameras employing the FrontSPAD cameras (Objective 3), even if this activity was not proposed at the start of the project.

Objective 6 - Integration of the 3D camera into short-range high speed Safety applications

Objective 6 consists in the system integration of the first 3D system into a real automotive vehicle, for the automotive safety applications, and in performing on-field tests in automotive scenarios with short-range high-speed pre-crash Safety intervention. The main activity is to develop all required optics, mechanics and tools and to equip a vehicle and the on-field set-up at the application partner CRF. The last months of the second year were devoted to develop preliminary illuminators for the automotive applications, based on both pulsed-light and continuous-wave indirect TOF approaches. The assembling of the 3D camera and illuminator into the test vehicle will be performed by partner CRF in the third year. All final tests will be performed both in labs and on-field, with dynamic scenes and real automotive environments.

Objective 7 - Integration of the 3D multi-spectral camera into long-range Security application

Objective 7 consists in the system integration of the second 3D system into a real environment, for the security applications, and in performing on-field tests in monitoring scenarios for long-range Security surveillance. The main activity will be to develop the focal plane illuminator for the FrontSPAD 3D ranging module, for single wavelength and multiple discrete wavelengths, in order to exploit the multi-spectral approach. The illuminator will be based on picosecond pulsed semiconductor laser sources and related optics necessary for the collection of light from far-away scenes (hundreds of meters, up to some kms). Then the developed 3D camera, the illuminator and all required optics, mechanics and tools will be assemble into a 3D system that will be characterized in the Security surveillance applications. Also the 2D single-photon imaging feature included in the FrontSPAD (Objective 2) will be exploited to assess the potential advances of the MiSPiA technology in light-starving 2D imaging of long-distance dynamic scenes.

1.2 MAIN RESULTS ACHIEVED IN THE SECOND YEAR

In this second year, many important results have been achieved, important not only for successfully completing the MiSPiA objectives, but also for exploiting novel fields and applications.

1- A first ground breaking outcome being the **assessment of the very good detection performance** of the individual CMOS SPAD detectors (Objective 1). In summary, the performance of MiSPiA single-photon detectors are: Dark-Counting Rate lower than 20cps at 5V excess bias for 20µm-diameter SPADs; Photon Detection Efficiency of 60% at 400nm and still 10% at 750nm; Time-of-Flight precision better than 40ps_{FWHM} at just 5V excess bias. Such SPAD performances really represent a new state-of-the-art not only among CMOS SPADs, but also compared to custom-process SPADs. All these results proved the expertise of partner FRAUNHOFER and the quality of the processing achievable in its silicon foundry. Overall, this data definitely give a much more reliable confidence of the success rate of the development of the smart-pixels for the FrontSPAD imagers (Objective 2) and cameras (Objective 3), and also about the BackSPAD imager (Objective 4) and its CMOS electronics (Objective 5).

2 - A second noticeable result was the **successful test of smart-pixels and mini-arrays for 2D imaging and for 3D imaging**, to be employed in the development of the FrontSPAD (Objective 2). The expertise gained in the development of such smart-pixels and mini-arrays working at the single-photon level allow the MiSPiA consortium to investigate also novel and innovative application fields and exploit MiSPiA technologies. The smart-pixel for direct dTOF, with in-pixel Time-to-Digital Converter able to measure the round-trip time-of-flight of each single photon with 250 ps resolution, can provide a single-shot precision of some centimetres, more than enough in many applications. The smart-pixel for indirect iTOF is just one, and not two distinct as planned. In fact we conceived and developed one “universal” iTOF smart-pixel, able to operate both with pulsed-light excitation and also continuous-wave modulation of the scene, in order to exploit at best the performances even for very different characteristics of the scene (e.g. reflectivity of objects), background (e.g. dusk or sun light), desired resolution and signal-to-noise ratio.

3 - A third important result was the **development of back-illuminated (BackSPAD) SOI SPADs**, to be employed either in the advanced wafer-bonded imager (Objective 4), together with the CMOS wafer of the read-out electronics (Objective 5), or as a novel stand-alone SPAD detector. In the second year of the project, wafer-to-wafer bonding experiments, with the SLID soldering technique, together with backside thinning were performed successfully. Two different designs were developed and fabricated. A first one similar to the recipe employed for the FrontSPAD imagers, in order to stay on the safe side and also to compare detection performances at same cross-sections, but different (i.e. front- vs. back-side) illuminations, different (i.e. CMOS vs. SOI) substrates, and fabrication (i.e. standard CMOS vs. custom) processing. Instead a second one (called HV, high-voltage) was conceived to take full advantage of a complete deep depletion of the SOI layer, aimed at increasing the photon detection efficiency at longer wavelengths (red and near-infrared wavelength ranges) and reducing edge effects and leakages and premature peripheral breakdown. Different SOI test chips with layout variants were designed to investigate the influence of deep trench isolations, as well as shape and distribution of bonding bumbs, on SOI SPAD performance. A full characterization is under way in the first months of year three.

4 - A fourth result is the **development of LED and laser-based illuminators** for the short-range indirect iTOF applications, based on both pulsed-light and continuous-wave light excitation, to be employed in the development of the Front-SPAD cameras (Objective 3). The expertise gained in the design of electronics and optics for the development of illuminator prototypes for laboratory tests, eventually lead partner POLIMi and partner MPD to acquire the know-how to develop the final illuminator for the short-range automotive application, based on the requirements of application partner CRF and its proved expertise. Different light sources (highly efficient LEDs and pulsed lasers) were evaluated and tested, for assessing the best candidates for the short-range automotive (Objective 6) and the long-range security (Objective 7) applications.

1.3 EXPECTED RESULTS AND POTENTIAL IMPACT AND USE

The MiSPiA expected results are novel 3D ranging imagers, based on single photon avalanche diodes, able to provide on-chip and in real-time the 3D mapping of the scene at high frame-rates. Many significant results have already been achieved and validated during this second year of the project (see previous Paragraph 1.2). Dissemination and exploitation activities will deploy MiSPIA components to wider communities and markets, in **Safety** (e.g. environmental surveillance, traffic and workplace safety monitoring, product safety analysis, food and agriculture quality and safety assessment) and **Security** (access control, biometrics, surveillance systems, dangerous agents monitoring, homeland security, fire hazards) applications, but also in microscopy, biology, adaptive optics, gaming, and 2D vision in light starving conditions. Here are some expected impacts.

1- The **state-of-the-art performance** of MiSPiA CMOS SPAD detectors are remarkable when compared not just to other CMOS implementations, but also with custom-process SPADs. Mainly in terms of very-low noise (few tens of counts per second at room temperature), very large diameter (from tens up to many hundreds of micrometers), remarkable photon detection efficiency in the blue and near ultra-violet wavelength range (300-400nm). Individual MiSPiA SPADs can be exploited as advanced single-pixel single-photon detector for many applications requiring large active areas, low noise and easy integration with on-chip CMOS processing electronics. An example is time-resolved breast and tissue imaging through photon migration measurements, where large sensitive area (1 mm diameter would be awesome) and sharp timing response (less than 50ps) are compulsory for achieving high throughput and image contrast.

2 - The **smart-pixels and arrays for 2D imaging** can be used to investigate novel and innovative application fields, where each pixel must count photons, to measure the intensity of DC optical signal and also in those applications requiring a time-resolved information with time-tagging feature down to hundreds of nanoseconds. Demonstrators employing individual single smart-pixels (with SPAD and in-pixel "counting" electronics) and arrays (as the already available 2 x 2 and 16 x 2 chips) have been already conceived and fabricated within the MiSPiA project. The idea is to trigger the interest of potential users working for example in optical spectroscopy, where the cost-effectiveness and low power consumption of the multi-channel chips will dictate the success into products requiring low dimensions, single-photon sensitivities and system ruggedness.

3 - The **smart-pixels and arrays for 3D ranging** can be used also in all those applications requiring a time-resolved information well below few tens of nanosecond, down to very few hundreds of picosecond range. Also in those applications not related to 3D ranging, where no active illumination is needed, but where the useful information is within the arrival time of the photon itself. Demonstrators employing individual single smart-pixels able to perform photon timing and related arrays (as the already available 4 x 4 and 32 x 4 chips) have been conceived and already fabricated within the MiSPiA project. The potential impact will be exploited through already identified industries and research centres, which will be allowed to "play" with these demonstrators, in order to foster dissemination and directly impact novel markets. For instance, the smart-pixel for direct dTOF, with in-pixel Time-to-Digital Converter able to measure the round-trip time-of-flight of each single photon, will be exploited in time-resolved Optical Fluorescence and Spectroscopy setups and applications. The smart-pixel for indirect iTOF with pulsed-light excitation of the scene will be exploited in very-short distance (few meters) applications like gaming and interaction with other electronic appliances (like TV sets), where the movements of an user should be detected with centimetre resolution. The smart-pixel for indirect iTOF with a sinusoidal-modulated light excitation will be used in frequency-resolved Diffusive Optical Tomography setups, where the scattering/absorption info on a biological specimen (like muscles, breast or brain) can be inferred by the "depth-like" information of the delayed photonic echo.

4 - The **back-illuminated (BackSPAD) SOI SPADs** (i.e. just the detectors of Objective 4, without the driving and read-out electronics of Objective 5) will be provided also to other potential users as stand-alone SPAD detectors. The idea is to offer to BackSPAD detector as the more advanced and performing device, compared to the FrontSPAD device, for those applications requiring higher photon detection efficiency in the near-infrared wavelength range. The main limitation of this approach will be the unavailability of on-chip electronics. However partner MPD can easily modify its commercially available modules (actually employing custom SPADs) to fit the new BackSPAD devices. The new module will represent a novel product in the portfolio of the partner and a sure success for the deployment of MiSPiA technologies with large impact on the other partners as well.

5 - The wafer-to-wafer bonding of the **BackSPAD SOI SPADs together with the CMOS read-out electronics** could have an even stronger and more disruptive effect on all those applications requiring state-of-the-art single-photon detection performance together with monolithic integration of many channels or even full 2D imaging / 3D ranging features. To be fair, we will discuss the potential impact only after the characterization of the complete (i.e. Objective 4 and Objective 5) assembly of the BackSPAD wafer-bonded ensemble.

1.4 PROJECT PUBLIC WEBSITE

The MiSPiA **webpage** is www.mispia.eu, with updated information for both scientific community and to general public.