SIXTH FRAMEWORK PROGRAMME PRIORITY:
IST FET Open

MEGAFRAME
Million Frame Per Second, Time-Correlated Single Photon Camera

Deliverable 2.1 (public version)

MEGAFRAME Design: From Concepts to Requirements

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Abstract

In this preliminary phase of the MEGAFRAME project all partners were involved in the refinement and definition of the technical specifications of the final system, by means of intense communications via meetings, audio-conferences and e-mail exchanges.

This deliverable presents an abridged version of these activities' results, starting from an update of the work carried out by each partners before the official project start, followed by a general update of the state-of-the-art and competitor analysis.

Executive Summary

Since the submission of the proposal, most partners have continued to pursue their SPAD related research programmes. Most of the corresponding developments, which have not yet been implemented in the same target technology as MEGAFRAME nor led to performance measures comparable to the MEGAFRAME target, are briefly summarised in Section 2.1.

A new and refined search on recent scientific articles, other developments of potential interest and an extensive patent search have been carried out by each partner in the respective domains of competence. Although the field of single photon based arrays and imagers is attracting increased attention, no new element has emerged that may impair the adequacy and the timeliness of the proposed developments (for example, there is little obvious patented activity on high speed imaging and no patents on integrated imaging systems based on SPADs).

The previously described information has been used by the partners to revise the design specifications. Most of the original approaches were confirmed as viable, and the corresponding performance as adequate.

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1 Methodology

The WP2 general structure and work organization was presented and agreed upon at the MEGAFRAME Kick-Off Meeting (EPFL, Lausanne, 12/06/06). After that, each partner contributed to the drafting of this deliverable along the following lines, as defined early on in the WP and with clear responsibilities for each sub-section.

- Update on work carried out by each partner (WP 2.1.1)
- State-of-the-art and IP update, competitor analysis (WP 2.1.2)
- Agreement on hardware specifications (WP 2.2.1)
  - Sensor Specifications,
  - Pixel Specifications,
  - Optical Concentrator Specifications,
  - Technology Characteristics,
  - System Functionalities.
- Agreement on software specifications (WP 2.2.2)
  - Preliminary Functionalities,
  - System Functionalities.
- Agreement on experimental setups (WP 2.2.3)
- Refined tape-out dates (WP 2.2.4)
- Revised Planning before M3 (WP2.2.5)
- Website organisation details.

Work was carried out under the supervision of ITC (WP leader) and with the support of EPFL. Bi- and tri-lateral meetings and audio-conferences were organised to keep momentum. These activities culminated in the WP2 Final Meeting held at ITC, Trento, on the 31/8/2006.

2 State-of-the-art Update

2.1 Update on work carried out by each partner (WP2.1.1)

Each partner has contributed with a brief summary of the research activity of potential interest to MEGAFRAME and carried out before its start, including any published or submitted papers.

EPFL:

Since the submission of the proposal, EPFL has vigorously pursued its SPAD related research programme as follows:

1. A SPAD array was used to detect bio-reactions emitting a very small number of photons. The approach was based on a confocal setup which required a microscope (see microTAS reference).
2. An event-driven readout approach was implemented in 0.8μm CMOS technology. This led to the largest monolithic SPAD array to date (see ESSCIRC reference).
3. An event-driven readout approach was implemented in 0.35μm CMOS technology. This led to the first published and characterized SPAD array in this technology (see SPIE and DATE references).
4. A sensitivity of $1.3x10^{-3}$ Lux was measured for an older SPAD array (see S&A reference).
5. An overview of architectural considerations for large SPAD arrays was generated. No development was involved (see ASICON reference).
6. An entire optical channel (TX and RX) was first implemented in CMOS using SPADs. Logic gates were also demonstrated (see IEDM reference).

Most of these developments are of potential interest to MEGAFRAME, although none of them has yet been implemented in the same target technology nor led to performance measures comparable to the MEGAFRAME target.

The previously mentioned papers are available from the lab's Website (http://aqua.epfl.ch/).

ITC:

Since the submission of the proposal, the ITC research activity related to SPAD sensors has continued through the characterization of the latest designed sensors. In particular, a new test chip containing SPAD structures with embedded read-out electronics for bio-imaging applications has been fully tested, confirming the validity of the SPAD approach for this kind of applications. In parallel, the use of SPAD for 3D measurement applications has been investigated, particularly looking for fast and precise punctual distance sensors based on Time-of-Flight (TOF).

Moreover, some papers have been published or accepted for publication, including on the design and characterization of a linear array of 64 SPAD-based pixels (Stoppa *et al.*), and the design of a sensor using SPAD aimed at time-resolved fluorescence detection (Mosconi *et al.*). (Although of relevance to MEGAFRAME, these two sensors were respectively fabricated in 0.8μm and 0.35μm CMOS technology, and neither of them is a 2D array. Furthermore, the data throughput reached in MEGAFRAME will be much higher than the one provided by the two sensors just discussed.)

UNIPV:

Since the submission of the MEGAFRAME short proposal in August 2005 and up to the time being, the UNIPV Group has continuously monitored the literature on Optical Concentrators and related topics. The corresponding conclusions are reported in the following section.

UNIED:

The UNIED activity up to the project start date was as follows:

1. Collaboration with EPFL on a 0.35µm CMOS SPAD chip for fluorescence detection. The chip measuring 4.1mmx2.4mm was taped out on May 8th 2006 and is currently under test. A number of SPAD in-pixel counting techniques are being evaluated. Several publications are expected.

2. Software modelling of SPAD firing events for time-of-flight applications. This modelling activity will feed into WP6. A time-domain, single-photon SPAD simulator is expected to be developed. Initially this is being developed in C/C++ with mapping of detection algorithms to RTL at a later stage. A paper has been submitted to the VLSI SOC conference in Nice (Oct. 2006).

3. Trial measurements of fluorescence lifetime at COSMIC with EPFL.

This allowed us to become familiar with the existing equipment and detectors for FLIM available in the COSMIC lab. The instrument response function (IRF) and uniformity of a 32x32 array of SPADS in 0.8µm CMOS technology were determined.

4. Support for EPFL in design of test chip in the MEGAFRAME target technology with SPAD device test structures. This chip was taped out in Jan 2006 and became available in May 2006. It is currently being evaluated and results presented at the WP2 meeting.

Internal References (work carried out before the start of the project):

EPFL:

2006

M. Gersbach, Y. Maruyama, C. Niclass, K. Sawada, and E. Charbon, A Room Temperature CMOS Single Photon Sensor for Chemiluminescence Detection, to appear in microTAS, Nov. 2006.

C. Niclass, M. Sergio, and E. Charbon, A CMOS 64x48 Single Photon Avalanche Diode Array with Event-Driven Readout, to appear in ESSCIRC, Oct. 2006.

C. Niclass, M. Sergio, and E. Charbon, A Single Photon Avalanche Diode Array Fabricated in Deep-submicron CMOS and based on an Event-Driven Readout for TCSPC Experiments, to appear in SPIE Symposium on Optics East (Advanced Photon Counting Techniques), Oct. 2006.

C. Niclass, A. Rochas, P.A. Besse, R. Popovic, and E. Charbon, A 4µs Integration Time Imager Based on CMOS Single Photon Avalanche Diode Technology, to appear in Sensors and Actuators: Physical, June 2006.

E. Grigoriev, A. Akindinova, M. Breitenmoser, S. Buono, E. Charbon, C. Niclass, I. Desforges, R. Rocca, Silicon Photomultipliers and their Bio-medical Applications, EuroMEDIM, May 2006.

C. Niclass, M. Sergio, and E. Charbon, A Single Photon Avalanche Diode Array Fabricated in Deep-Submicron CMOS Technology, IEEE Design and Test in Europe, Mar. 2006.

2005

E. Charbon, Techniques for CMOS Single Photon Imaging and Processing (INVITED), IEEE ASICON, Shanghai, Oct. 2005.

M. Sergio and E. Charbon, An Intra-Chip Electro-Optical Channel Based on CMOS Single Photon Detectors, IEEE International Electron Devices Meeting (IEDM), Washington, DC, pp. 837-840, Dec. 2005.

ITC:

D. Stoppa, L. Pancheri, M. Scandiuzzo, L. Gonzo, G.-F. Dalla Betta, A. Simoni, A CMOS 3D Imager based on Single Photon Avalanche Diode, accepted for publication on IEEE Transaction on Circuit and Systems Vol. I.

D. Mosconi, D. Stoppa, L. Pancheri, L. Gonzo, A. Simoni, CMOS Single-Photon Avalanche Diode Array for Time-Resolved Fluorescence Detection, to be presented at IEEE European Solid-State-Circuit Conference, ESSCIRC 2006.

D. Mosconi, D. Stoppa, M. Malfatti, M. Perenzoni, M. Scandiuzzo and L. Gonzo, A CMOS Sensor based on Single Photon Avalanche Diode for Fluorescence Lifetime Measurements, IEEE Instrumentation and Measurement Conference 2006.

UNIED:

R. Henderson, B. Rae, D. Renshaw, E. Charbon, Oversampled Time Estimation Techniques for Precision Photonic Detectors (INVITED), to be presented at VLSI-SOC 2006, Nice, Oct. 2006.

2.2 State-of-the-art Update, Competitor Analysis (WP2.1.2)

A new and refined search on recent scientific articles presented in international journals and conferences as well as other developments of potential interest has been carried out by each partner in the respective domains of competence. The results can be summarised as follows:

Applications (Bio-imaging state-of-the-art update):

The following developments in commercial bio-imaging instrumentation have been noted recently:

1. SensL paper on SPAD readout circuitry and ingestible fluorescence analyser (2006) [1].
2. Cooke Corporation Ultraspeed camera system, 2MHz frame rate, 4-8 images, 7e- read noise based on CCDs (June 2006). (http://pco.orange8.ch/cooke/php/products/index_1-en__01030201&view=detail&cam=28.html)
3. Horiba Jobin Yvon TCSPC/confocal microscope, PMT+deep UV nanoLED sources. Lifetimes between 100ps and 100µs (http://www.jobinyvon.fr/frdivisions/products.htm).
4. BD Biosciences automated confocal imaging BD Pathway 425 Benchtop system with 100fps and a cooled 14-bit CCD camera (http://www.atto.com/products/pathway/).
5. Andor Technology Revolution 488 confocal microscopy system 1000fps EMCCD. (http://www.andor.com/products/microscopy_systems/)
6. Diagnostic Instruments EMCCD BT1900 128x128 24µm pixels at 500fps, at -100 °C. (http://www.diaginc.com/camBT.shtml)
7. Hamamatsu photon counting units 50Hz DCR, 16x18mm. USB interface. (http://sales.hamamatsu.com/en/products/electron-tube-division/detectors/accessories/photon-counters.php)
8. SensL PCMPlusX photon counter USB2, 2.5ns time binning (http://www.sensl.com/).
9. IdQuantique id100-50 50µm avalanche photodiode 20MHz, count rate, 40ps timing resolution, 50Hz DCR, 45ns dead time (http://www.idquantique.com/).

Broadly these activities can be divided into: (1) extension of the capabilities of existing microscopy techniques based on CCD cameras and PMTs by specialised scientific equipment vendors, and (2) SPAD based sensor commercialisation. In the latter category, companies SensL and IdQuantique are offering performant, single device modules for photon counting with convenient interfaces. Of particular relevance to this programme is the stated intention of SensL to develop large imaging arrays of SPADs. A recent paper [1] shows a very efficient readout structure for SPADs based on DRAM techniques.

Device and Systems:

In our initial proposal we overlooked some references we were not aware of. Miyagawa and Kanade, for example, were the first to apply gating to CCDs [2] previously thought to have been first implemented by Lange [3]. Another work we unintentionally overlooked was the lifetime imaging setup implemented with non-CMOS SPADs in 1983 by Cova [4].

Among new developments we noticed some activity at SensL [5], where work on device modelling and design has been performed and published this year. We are also aware of activities at MIT, where Brian Aull's group is continuing to expand SPAD arrays mostly from the technological perspective [6],[7]. A meeting took finally place in February 2006 and views were exchanged on the future of Geiger mode sensing.

Another interesting friendly "competitor" will soon be Ken Shepard of Columbia University. He has done interesting time-correlated imaging work in the past [8] and is currently looking at SPADs in CMOS.

Stellari has published a work in IEDM on circuit analysis in chips in operation to discover the causes of malfunctions [9]. This work is relevant to MEGAFRAME since it has used SPADs for detection.

Finally, we have also become aware of the NANOSPAD STREP project (http://www.nanospad.eu/, FP6 Action Line NMP-2004-IST-NMP-2 "Bio-sensors for Diagnosis and Healthcare"), started at the end of 2005 and aimed at the development of a highly sensitive system, which includes a SPAD array, for rapid analysis of protein microarrays. Some of its partners are already well known to the Consortium, and its developments will be closely followed.

Optical:

The literature on optical elements/concentrators has been constantly monitored. A few interesting papers have been identified, spanning from applications of concentrators to solar cell optical systems and to organic display brilliance enhancement to the description of some new detail of fabrication of the micro-concentrator or micro-optical elements [10]-[13]. From this literature, no new element has emerged that may impair the adequacy and the timeliness of the optical concentrator proposal.

In particular, the approach of optical concentrators (either imaging or non-imaging) is confirmed as viable, and its description as well as its performance are deemed adequate.

The literature analysis does also confirm that the micro-optics approach attracts a considerable interest, and therefore its technology, though still in the very early stage, is undergoing a useful development.

The following have also been searched:

- **Optical Simulation Software** for modelling of concentrators: a few commercially available ones have been found, and are currently being evaluated.
- **Suppliers of Micro-optical elements** (e.g. prisms and lenses): a few have been identified, but with capability limited to large size (100 μm typ.).
- Labs and Companies capable of **manufacturing a micro-optical array**: one has been found in Germany (Univ Berlin), and one in Taiwan (Nat Taiwan Univ.).

References:

[1] http://www.sensl.com/Technology/01References--Journal_Papers.html

[2] R. Miyagawa and T. Kanade, CCD Range-Finding Sensor, IEEE Trans. On Electron Devices, Vol.44, N. 10, pp.1648-1652, Oct. 1997.

[3] R. Lange, 3D Time-of-Flight Distance Measurement with Custom Solid-State Image Sensors in CMOS/CCD-Technology, Ph.D. Thesis, ETH-Zürich, 2000.

[4] S. Cova, A. Longoni, A. Andreoni, R. Cubeddu, A Semiconductor Detector for Measuring Ultraweak Fluorescence Decays with 70ps FWHM Resolution, IEEE Journal of Quantum Electronics, Vol. 10, N. 4, pp. 630-634, Apr. 1983.

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[6] B. F. Aull *et al.*, Geiger-Mode Avalanche Photodiodes for Three Dimensional Imaging, Lincoln Lab. J., Vol. 12, N. 2, pp. 335-350, 2002.

[7] B. F. Aull *et al*., Laser Radar Imager Based on 3D Integration of Geiger-Mode Avalanche Photodiodes with Two SOI Timing Circuit Layers, ISSCC, pp. 304-305, 2006.

[8] G. Patounakis, K. Shepard, R. Levicky, Active CMOS biochip for time-resolved fluorescence detection, Symposium on VLSI Circuits, pp. 68-71, 2005.

[9] F. Stellari et al., Testing and Diagnostics of CMOS Circuits Using Light Emission from Off-State Leakage Current, IEEE Trans. on Electron Devices, Vol. 51, N. 9, pp. 1455-1462, 2004.

[10] A. Y. Yi and L. Li, Design and fabrication of a microlens array by use of a slow tool servo, *Optics Letters*, vol. 30, July 2005, pp. 1707-1709

[11] F. Nakamaru, Y. Matsumoto, A. Nakazono, Novel High-Efficiency Concentrator for Optical Fiber Communications, *IEEE Photonic Techn. Letters*, vol 14 (2002), pp.953-955.

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[13] M. Ferstl, G. Devendra R. Grunwald, M. Bock, Lithographically fabricated micro-optical array beam shapers for ultra-short pulse lasers, *Paper JThC98., Proceedings CLEO 2006*, Long Beach, 21-26 May 2006.