ELECTRONICS MATERIALS, PACKAGING AND RELIABILITY TECHNIQUES (EMPART)

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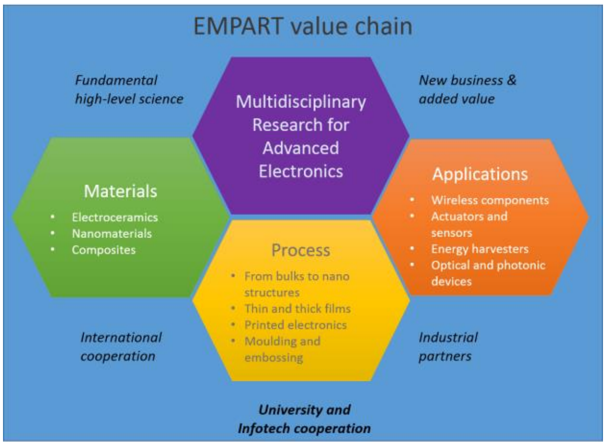
Background and Mission

The EMPART research group is a multidisciplinary research unit. Its main activities lie in micro- and nano-electronics materials and devices. Our overall target is to research and create micro- and nanostructures enabling novel functionality for electronic, telecommunication, energy/environmental and bio/medical devices. The group brings together all the essential know-how required to accomplish the main goal of "embedded multifunctional electronics integrations" based on 1) new, difficult-to-copy hyper-active, high dielectric and optical performance materials, 2) most feasible, cost-aware fabrication technologies for hybrid electronics, and 3) high-end state-of-the-art electronics integrations enabling functional diversification in line with the "More-than-Moore" (MtM) concept of future electronics. The group is the main leader of the More-than-Moore research group that was ranked with the highest score 6 (outstanding) in the Research Assessment Exercise (RAE 2013) of the University by an international panel, aided by a bibliometric analysis made by Leiden University.

The group is funded recently by the European Research Council Advanced Grant (Professor Heli Jantunen), Tekes, the EU, the Academy of Finland, ERA.Net, and by domestic and foreign industry. Global research co-operation is a characteristic feature of the EMPART group, having key roles in several EU and other international projects.

The group is comprised of specialists in electronics, electronic materials, micro- and nanoelectronics, mechanical and process engineering, measuring techniques, and also in chemistry and physics. In 2015 the EMPART group had four professors including one FiDiPro professor, 20 senior research fellows and post-doctoral researchers and 14 doctoral students. The unit is highly international: 48 % of our researchers (professors, doctors, doctoral students) are from abroad.

In accordance with the long-term research targets, we have continued the integration of interdisciplinary topics towards future advanced electronics devices and component implementations. In addition, a wide range of application areas utilizing the generic materials knowledge of the group have been of great importance. In 2014, the group leader, Professor Jantunen, was appointed as a Member of the World Academy of Ceramics and as the Chair of Scientific Advisory Board for Defence (MATINE) in recognition her independent creative research work and the associated remarkable advancing research of technical sciences and technical and economic development.



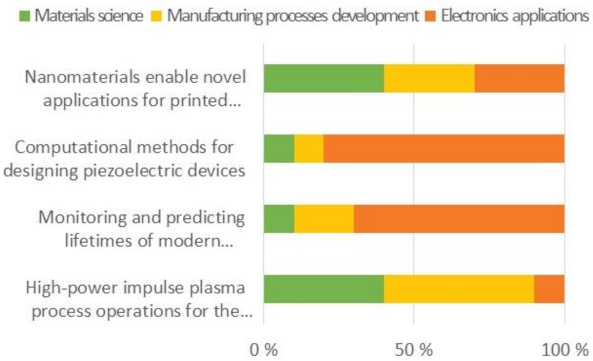
Value chain within the EMPART group with collaboration and driving forces in general.

The EMPART group co-operated in 2015 with several other Infotech Oulu research groups and was a partner in PrintoCent (Printed Electronics and Optical Measurements Innovation Center) having a shared printed electronics laboratory. The group is also a key player in the Center of Microscopy and Nanotechnology of the University of Oulu. The EMPART group is also a seamless partner in the value chain of the Faculty of Information Technology and Electrical Engineering. National and international research and industrial co-operation included common projects and publications, and student, researcher and lecturer exchanges. The group acknowledges Finnish and foreign research and industrial partners for their active participation in the research projects.

Scientific Progress

Materials, components and technologies developed by the group are now widely applied in the electronics industry, especially in wireless telecommunication, sensors/actuators and hybrid microelectronics technology. Piezoelectronic devices and printed electronics applications are important examples of current exploitation, together with recent scientific achievements in nanotechnology with applications. Novel materials, as well as our progress in fabrication, have been utilized in antennas, sensors, ceramic/polymer integrations, filters, micro-pumps, lens and mirror positioning systems, energy harvesters etc.

The research achievements of the group are presented through examples covering selected doctoral theses in 2015 and the EU funded project. These are linked to the EMPART research areas in materials science, manufacturing processes development and electronics applications.



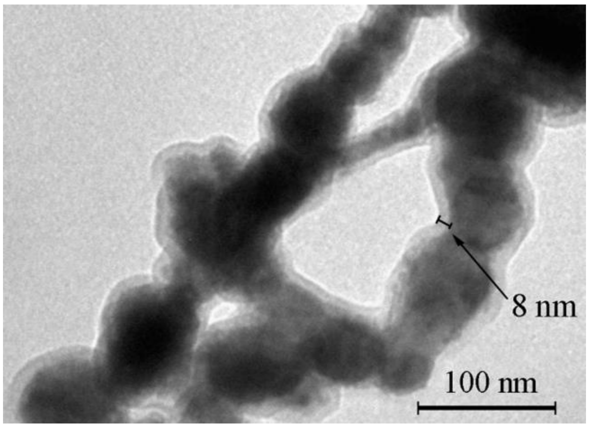
Linkage of the selected doctoral theses and FP7 project in 2015 to the EMPART group's research focus areas in materials science, manufacturing processes development and electronics applications.

Nanomaterials Enable Novel Applications for Printed Electronics

(Doctoral thesis by Mikko Nelo: Inks based on inorganic nanomaterials for printed electronics applications)

In this thesis, novel inks were developed to enable new applications for printed electronics. The inks were based on dry inorganic powders enabling magnetic, piezoelectric and memory resistive (memristive) functionality, to enable RF applications, sensors and memory devices.

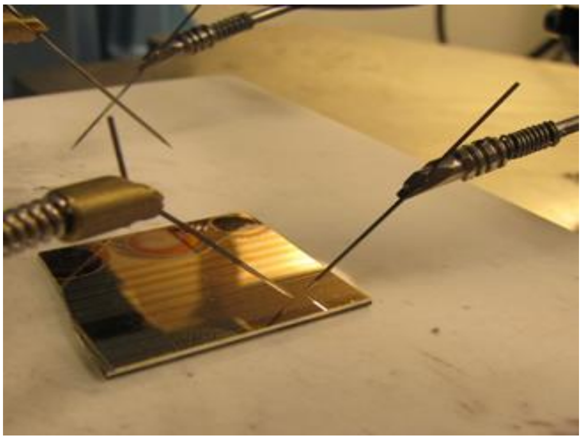
In the first part of the work, low curing temperature screen–printable magnetic inks for high frequency applications based on dry cobalt nanoparticles were developed. Three publications were achieved from this work. The first one concentrated on ink formulation and its process development, the second on the utilization of multifunctional surfactant, and the third on the development of the inks for plastic substrates. The developed magnetic inks were cured at 120 °C. The electrical performance, microstructure, surface quality and mechanical durability of printed and cured layers were investigated. Relative permeability values up to 3 and related loss tangents up to 0.01 were achieved at 2 GHz frequency, as well as a pull–off strength of up to 5.2 MPa. The maximum loading level of cobalt nanoparticles was 60 vol–%, after which the stability of the ink started to degrade. The developed ink was aimed to RF-applications and enabled for example miniaturization of patch antennas.



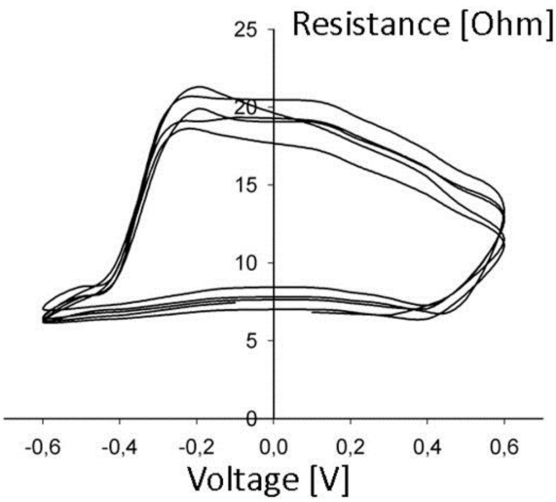
Transmission electron microscopy image of metallic cobalt nanoparticles coated with an 8 nm thick layer of fatty acid surfactant. Utilization of surfactant layer enabled formulation of stable inks from the dry nanoparticle powders [M. Nelo et al., (2010), Progress In Electromagnetics Research 110: 253–266].

The second part of the thesis focused on the formulation of inks based on piezoelectric ceramic particles in powder form and ferroelectric polymers as a matrix material. The performance and quality of the printed inks and cured layers were investigated. The measured pull off –strength was up to 3.25 MPa, relative permittivity was up to 48 at 1 kHz and piezoelectric constant d31 up to 17 pm/V. The printed piezoelectric layer can be utilized for example in pressure sensors.

The development of inks for a novel printed memory component, a memristor, was investigated in the third part of the work. A novel synthesis route was developed for an organometallic precursor solution, which was formulated into inkjet–printable form. The printing tests were carried out in order to find the most feasible layer thickness with memristive behavior. The influence of substrate materials and different thermal treatments on the components' electrical properties, durability of read/erase –cycles and overall lifetime were also investigated. The prepared memristive patterns remained functional for up to 35 days, while the precursor solution remained usable for over a year. The memristive areas withstood up to 30 read/erase cycles and by utilizing heat treatments the shift in resistance value increased by up to three orders of magnitude.



Measurement being done to inkjet-printed memristive pattern.



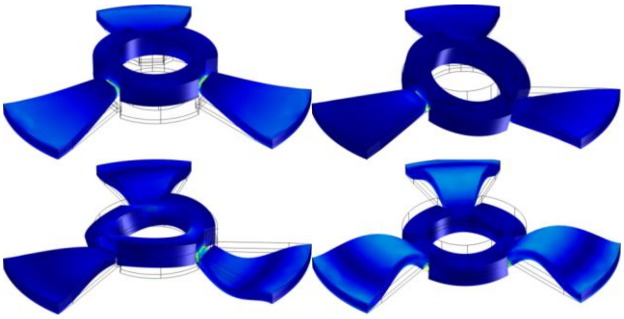
Current-voltage response of a memristor [M. Nelo et al., (2013), Japanese Journal of Applied Physics 52(5): article 05DB21].

Computational Methods for Designing Piezoelectric Devices

(Doctoral thesis by Mikko Leinonen: Finite element method and equivalent circuit based design of piezoelectric actuators and energy harvester dynamics)

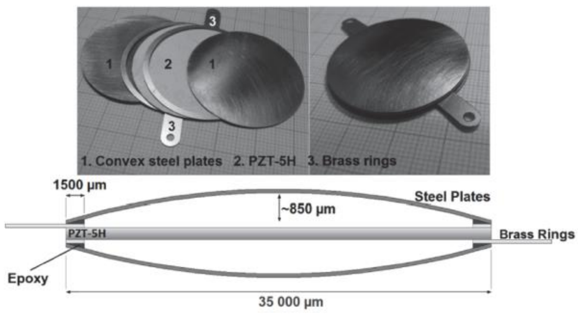
In this thesis, methods to design and tune actuator and energy harvester dynamics were developed. Main methods were the FEM-simulations and equivalent circuits for electro mechanical systems. With these methods, the resonance frequencies of the components were tuned to maximize the power output and bandwidth of energy harvesters. Furthermore, a Fabry-Perot filter was designed with LTCC-technology and its dynamics was characterized and compared with numerical methods.

The Fabry-Perot filter is used in hyper spectral imaging for use in chemical imaging applications. The component comprises of two semitransparent mirrors which have an air gap around 1µm. This air gap is modulated with piezoelectric actuators. Furthermore, the actuators can tilt the mirrors to correct alignment errors occurred in manufacturing. The resonance frequency of this system dictates the speed of wavelength scanning and therefore it is crucial to design the system dynamics to meet the speed requirements. In this thesis, a small signal model was developed for the actuator using FEM-simulations and measurements. This model was used to study the effect of different mirror masses on the resonance frequency of the actuator.



Different resonance modes for FPI-actuator [M. Sobocinski et al., (2012), IEEE trans. on Ultrasonics, Ferroelectrics and frequency control 59(9): 1990–1995].

In second part of the thesis different energy harvester designs were developed. Two wideband designs were realized with multiple beam topology, one PZT-Steel and one PZT-LTCC prototype. In multiple beam energy harvesters, the beams of the harvester are tuned precisely to achieve a wide, relatively flat, resultant power band. The two different manufacturing technologies used in this thesis provided differing manufacturing tolerances and thus different results. The inherently more precise laser processed PZT-LTCC process yielded better bandwidth performance than the more manual work requiring PZT-Steel component. A method to assess the sensitivity of manufacturing tolerances in multiple beam topology designs was presented based on these results.



The cymbal structure and the individual parts of the shoe mounted piezoelectric harvester [M. Leinonen et al., (2014), Journal of Intelligent Material Systems and Structures, 25(4):391–400].

Finally, energy generation from walking was studied with cymbal type piezoelectric component. The component was first manufactured and then tested inside a shoe. This test data was then converted into a force profile to be used in a FEM simulation. FEM simulation model was then developed with real world force signal. This model was used to study the endcap's nonlinear force transmission properties into the piezoelectric material. These results were used to explain the saturation behavior under high loads in cymbal energy harvester.

This thesis provided a plethora of tools for dynamics design in actuators and energy harvesters. The combination of FEM and measurements enabled the parametrization of small signal models, which could be used in transducer design. Furthermore, electrical tuning of piezoelectric components was studied providing low cost methods for high speed modulation of resonance frequency.

Monitoring and Predicting Lifetimes of Modern Electronics Interconnections

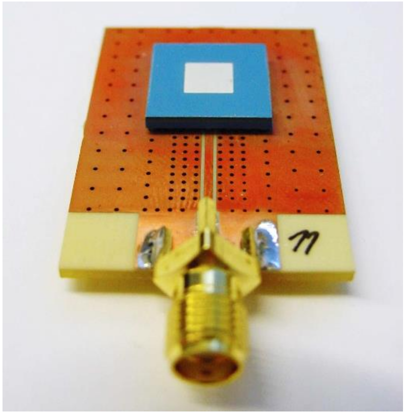
(Doctoral thesis by Jussi Putaala: Reliability and prognostic monitoring methods of electronics interconnections in advanced SMD applications)

Electronic products must endure various stresses during their lifetime. Their interconnections are subjected to perhaps the greatest stresses. Important questions are whether or not the operational capability of a product can be trusted, are there any signs of degradation, and when will the product fail eventually.

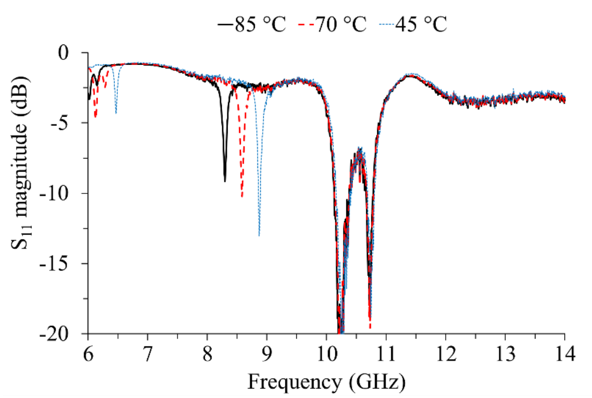
In this work the reliability, electrical monitoring methods, and prediction of the reliability lifetime of modern electronics interconnections were studied. Degradation of interconnections was characterized by means of optical microscopy, X-ray, scanning acoustic microscopy and scanning electron microscopy. Also, monitoring of electrical signals up to 30 GHz were utilized to observe thermal cycling testing (TCT) induced degradation of interconnections. To improve the accuracy of lifetime prediction for ball grid array (BGA) type interconnections, a semi-empirical model, based on Engelmaier's solder joint lifetime prediction model was modified and tested against available data.

The article-based dissertation showed that new solutions such as the use of plastic core solder balls (PCSB) BGA interconnections together with enhanced substrate materials and adequate dimensioning can greatly affect the reliability lifetime. An example of this result was a failure-free lifetime of over 1000 cycles for 10 mm by 10 mm ceramic modules with relatively low BGA sphere size (Ø 500 µm PCSBs), attached on an enhanced printed circuit board and stressed in a harsh TCT range of -40…125 °C.

In another examined case with PCSBs, electrical monitoring performed at high frequencies showed that the signal response was initially affected at some frequencies as short-duration (< 1 s) glitches in the monitored signal when measured during cycling in 0–100 °C TCT. Later on the degradation could be observed in the whole frequency band as TCT was continued. A manufactured antenna assembly used in these tests is shown in figure below, whereas an example of the initially observed, temperature-dependent indication of interconnection degradation, is shown as moving glitches in frequency response in figure below.

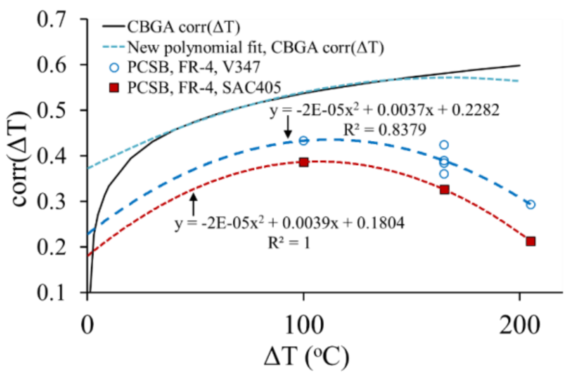


Ceramic patch antenna module (blue) attached on an RF printed wiring board using PCSB BGA interconnections [J. Putaala et al., (2011), IEEE Trans. Compon. Packag. Manuf. Technol. 1:1465].



Effect of interconnection cracks on RF performance of an antenna assembly during shifting temperatures [J. Putaala et al., (2011), IEEE Trans. Compon. Packag. Manuf. Technol. 1:1465].

Development of the semi-empirical lifetime prediction model for interconnections showed the temperature range dependency of the model's correction term to be a second order polynomial instead of a previously observed logarithmic one. For components with PCSB BGA, promising prediction accuracies were achieved which differed from the realized lifetime by less than 0.5% at best. Graphical representations of the achieved correction terms used in lifetime predictions are shown in figure below.



Temperature range dependency of correction terms in modified Engelmaier's model for BGA interconnections [J. Putaala et al., (2012), IEEE Trans. Compon. Packag. Manuf. Technol. 2:994].

This work helps in reaching the goal of increased lifetime electronics with decreased service costs. The results are applicable both in consumer and specialized electronics.

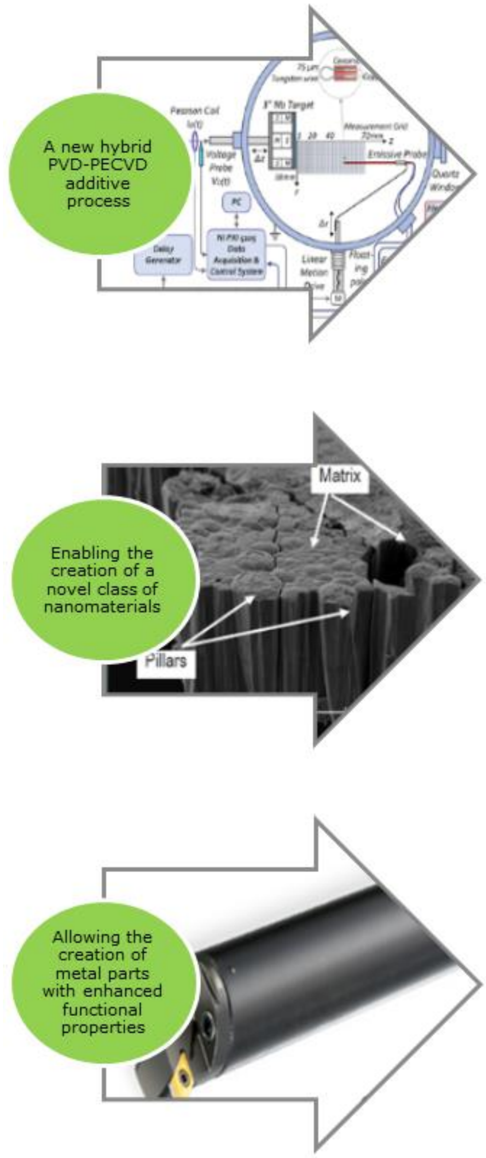
High-power Impulse Plasma Process Operations for the Creation of Advanced Metallic Parts

(Part of the European Commission funded project HIPPOCAMP under FP7, contributed by Geza Toth et.al.)

European industries such as automotive, aerospace and manufacturing have to develop new structural materials and production processes in order to achieve strict emission reduction requirements and improve performance and multifunctionality. However, advanced engineered materials manufactured today with traditional techniques are prohibitively expensive for many applications and generate unwanted by-products and toxic waste. The HIPPOCAMP project focuses on the development of a robust, high-yield, low cost, environmentally friendly manufacturing process to produce nano-composites for products made of engineered metallic material, in particular, structural components for automotive, aerospace, manufacturing and wind turbine applications.

One of the most desired functional property of such components is vibration damping, because vibration and chatter in turbine blades, machine-tools and other industrial components have very significant consequences: decreased performance, higher maintenance costs, shorter service life and ultimately, higher costs. The HIPPOCAMP project develops a novel method to generate a unique carbon-based composite with high dynamic stiffness material, whose effect on vibration damping will prolong the service life of components, reduce their weight and significantly improve the performance of industrial machineries.

Today, there are no standard structural materials that can simultaneously combine high static stiffness with high damping properties at a broad operating temperature and frequency range. Consequently, there are currently no industrially scalable processes for cost-effectively manufacturing high damping components. The HIPPOCAMP project addresses the development of a scalable industrial process enabling, (i) the synthesis of a new class of nano-composite materials, (ii) the production of these nano-composites on metal or polymer parts, to create industrial components with superior vibration damping property. The project has progressed well with its active work packages and had the second meeting already.



Overview of the project process, material and target product.

In the first six month, the consortium has focused to set up internal procedures and started to characterize/test the HIPPOCAMP material. Emphasis was laid on the early development of plasma deposition system. A big effort has been dedicated to characterize experimentally the target industrial cases including internal turning, creping, boring and compressor applications. In this tests, the critical frequencies and the best areas for the introduction of the new material has been defined.

In the second six months, we have finalized the specifications & benchmarking part of the project with the definition of all industrial application scenarios. Other significant workpackages are also started and provided their first deliverables at month 12. The consortium has also worked in an exploitation seminar during the two days project meeting. In the months between month 12 and month 18 the consortium continued the work on the plasma deposition system and produced a number of test batches. The samples were analysed and characterized to have the necessary feedback for further improvements. Our life cycle studies have begun as well. In the period between the midterm and month 24 the consortium has finished building the multi cathode system. Thanks to this, we have started to produce the samples in a much improved pace. Several industrial scenarios were concluded in the first iteration. Most significant results were published in high impact journals.

Personnel

professors	4
senior research fellows	6
postdoctoral researchers	14
doctoral students	14
other research staff	2
total	**40**
person years for research	12

External Funding

Source	**EUR**
Academy of Finland	450 000
Tekes	730 000
domestic private	200 000
international	860 000
total	**2 240 000**

Doctoral Theses

Putaala J (2015) Reliability and prognostic monitoring methods of electronics interconnections in advanced SMD applications. Acta Universitatis Ouluensis. Series C, Technica 521.

Leinonen M (2015) Finite element method and equivalent circuit based design of piezoelectric actuators and energy harvester dynamics. Acta Universitatis Ouluensis. Series C, Technica 532.

Lin J-F. (2015) Multi-dimensional carbonaceous composites for electrode applications. Acta Universitatis Ouluensis. Series C, Technica 534.

Nelo M (2015) Inks based on inorganic nanomaterials for printed electronics applications. Acta Universitatis Ouluensis. Series C, Technica 553.

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