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 was funded in 2014 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 2014 the EMPART group had four professors including one FiDiPro professor, 17 senior research fellows and post-doctoral researchers and 16 doctoral students. The unit is highly international: 41% 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 Finnish Academy of Technical Sciences in recognition her independent creative research work and the associated remarkable advancing research of technical sciences and technical and economic development in Finland.

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. LTCC micro modules and printed electronics devices 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,
The research achievements of the group are presented through examples covering selected doctoral theses in 2014 and the FiDiPro (Finnish Distinguished Professor) project. These are linked to the EMPART research areas in materials science, manufacturing processes development and electronics applications.

Electrical Phase Transitions and Future Cooling by Relaxor Ferroelectric Materials

*(Doctoral thesis by Jani Peräntie: Electric-field-induced dielectric and calorific effects in relaxor ferroelectrics)*

In this thesis work, dielectric and thermal behavior due to the application of dc electric fields were experimentally studied in single and polycrystalline relaxor ferroelectric \( \text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})_{1-x}\text{Ti}_x\text{O}_3 \) (PMN-PT) and \( \text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})_{1-x}\text{Ti}_x\text{O}_3 \) (PZN-PT) solid solutions of great technological importance.

In contrast to conventional materials, where for example electrical voltage and mechanical stress induce direct responses in the form of electric current and mechanical strain, ferroelectric-based materials tend to show strong additional indirect and smart responses. A large dielectric polarization enabled by the structure of ferroelectric-based materials can be modified by various external stimuli, such as temperature, electric field, light, and pressure, which lead to strong couplings between the material’s different properties.

The ferroelectric-based PMN-PT and PZN-PT materials studied in the thesis show extraordinary strong piezoelectric, pyroelectric and electro-optic effects. These phenomena are widely utilized, for example, in pressure sensors, actuators, thermal cameras, and optical switches. In addition, recent research results indicate that these materials show unusual electrocaloric effects, which offers a potential pathway for realizing more efficient cooling of future electronic devices. Most importantly, all these effects are strongly linked to the material’s structure and changes within, and a better understanding of the underlying phenomena is essential, especially for developing new and enhanced applications.
Directly measured electrocaloric effect in PMN-PT single crystal as a function of electric field and temperature [J. Peräntie et al. (2010), Phys. Rev. B 82:134119].

The results of the thesis help to improve the understanding of the structure and behavior of relaxor ferroelectrics in general and especially when under the influence of an applied electric field. These results play a part in the development of the existing application as well as helping more directly in estimating applicability for future solid-state cooling applications.

Applications of Carbon Nanotubes

(Doctoral thesis by Jani Mäklin: Electrical and thermal applications of carbon nanotube films)

The excellent mechanical, electrical and thermal properties of carbon nanotubes (CNT) suggest several applications such as mechanical reinforcement of composites, electrical interconnects, electrodes, field effect transistors, add-on devices for thermal management, piezoresistive pressure gauges and chemical sensors among many others. The major challenges for practical applications are associated with the integration of these nanomaterials into macroscopic systems with proper electrical, mechanical and thermal interfacing.

The main objective of this thesis therefore was to study various types of carbon nanotube architectures (random networks of single-wall and multi-walled CNTs, and aligned films of multi-walled CNTs) that are integrated in Si and ceramic chips, and to explore their suitability for gas sensing, electrical interconnects/electrodes and thermal cooling applications.

Stable aqueous dispersions of carbon nanotubes were prepared and applied on ceramic and Si chips by the means of drop casting and inkjet printing to demonstrate sensing elements for nitric oxide (NO) gas and to study the linear (ohmic) and nonlinear (Schottky type) current–voltage characteristics of the micropatterned thin films suitable for electrical interconnects as well as for semiconducting channels in thin film field effect transistor devices.

Aligned multi-walled CNT films (forests) mounted on brass cantilevers by soldering were applied as novel high-performance brush-type electrical contacts. The soft, viscoelastic contact brush structures were shown to outperform conventional bulk copper-carbon composite materials when applied as sliding contacts to commutators in electrical motors. The stable, low-noise and low contact resistance operation of the solder mounted aligned nanotube films is expected to open new routes towards the integration of CNTs in a number of different related fields.

Stable aqueous dispersions of carbon nanotubes were prepared and applied on ceramic and Si chips by the means of drop casting and inkjet printing to demonstrate sensing elements for nitric oxide (NO) gas and to study the linear (ohmic) and nonlinear (Schottky type) current–voltage characteristics of the micropatterned thin films suitable for electrical interconnects as well as for semiconducting channels in thin film field effect transistor devices.

The thermal diffusivity/conductivity of aligned CNT forests was measured and they were then applied as finned cooling structures by solder mounting them on ceramic test chips. The heat transfer coefficients of 42 Wm⁻²K⁻¹ and 150 Wm⁻²K⁻¹ under natural convection and forced cooling regimes indicate that CNT based coolers may be reasonable solutions for thermal management in microelectronics packages.
Microwave Based Dielectric Characterization of Powdery Substances

(Doctoral thesis by Marko Tuhkala: Dielectric characterization of powdery substances using an indirectly coupled coaxial cavity resonator)

Dielectric properties of materials have a very significant role in electronics and optoelectronics applications. These dielectrics may be used not only as solids but also in powder form for composites, coatings, and printed electronics. In addition there are several other industrial areas that utilize materials in powder format, as for instance the pharmaceutical and food industries. The properties of powder particles can affect the manufacturing process and have a direct effect on the properties of the final product, e.g., flowability, shelf life, mechanical, chemical or electrical properties.

The main objective of the thesis was to research and develop a sensitive microwave based characterization method for dielectric powdery substances which could be utilized in various industrial and research fields. This was achieved by simulations and multiple experiments with an indirectly coupled coaxial resonator together with commonly used dielectric powders and using classical mixing rules. In addition to the dielectric properties of these materials in powder form, it was also demonstrated that surface coating of the particles by surfactant or moisture adsorption may be evaluated by this method. Even very small degrees of moisture adsorption (0.1 - 2.5 vol.%) affected the permittivity of the powder and the effect was found to be more pronounced when measuring dielectric loss tangents. With stearic acid treated powders it was seen that changes in extrinsic loss factors such as particle morphologies and boundaries can significantly affect the complex permittivity of powder inclusions. Furthermore, the method was proved to be accurate in the determination of molar ratios of MgTiO₃ and CaTiO₃ powder composites.

The researched novel characterization was shown to be a useful method for measuring the dielectric properties of powders and detecting changes between modified and unmodified powders. In addition, the research provided solutions and gave valuable additions to knowledge in the field of the dielectric properties of powdery substances. Thus, the method could be utilized in various applications, e.g., in quality monitoring including phase transitions, purity and the homogeneity of larger master samples. Furthermore, the method can give new information for material development, e.g., in core-shell and nanoparticle applications. One company in the UK has already purchased contract service for their materials utilizing this method.

Bulk Components to Improve the Performance of Piezoelectric Structures on LTCC

(Doctoral thesis by Maciej Sobocinski: Embedding of bulk piezoelectric structures in low temperature co-fired ceramic)

In this thesis, methods for integrating bulk piezoelectric structures with Low Temperature Co-fired Ceramic (LTCC) through gluing and seamless co-firing were investigated.

Over the last 30 years LTCC has evolved from simple multilayer substrates to a sophisticated packaging method with buried passive components, microfluidic channels, sensors and actuators. Employing the piezoelectric effect has also added to the broad spectrum of applications. However, thick and thin film piezoelectric layers on LTCC have proven to be troublesome due to the low temperatures of sintering, lead diffusion, high constraining, degradation of performance or large surface roughness. On the other hand modern piezoelectric bulk components such as energy harvesters, sensors
and actuators require packages that enable not only mechanical protection and means of mounting but also provide sophisticated electrical connections and signal processing. LTCC technology provides the possibilities for all the above while additionally enabling hermetic encapsulation and resistance to harsh environments, thus creating advanced “systems-in-a-package”.

The thesis presented a novel method of introducing piezoelectric devices to LTCC structures through co-firing of bulk components, which greatly enhances the behavior of piezoelectric structures in LTCC. Laser-shaped samples, in the form of advanced designed piezoelectric structures cut from commercially available disks with thick film silver electrodes, were placed between the layers of “green” LTCC, laminated and sintered to form robust structures with excellent performance.


At the same time, adhesive bonding was investigated as an alternative for applications where co-firing cannot be used, i.e. in microfluidics.

Several structures were manufactured for different application areas to test both methods of proving the feasibility of bulk piezoelectric components in LTCC structures.

The results of this work expand the application areas of LTCC by providing an excellent method for the packaging of piezoelectric bulk components.

**Cell Clinic: CMOS Chip Designed for Capacitance Sensing Applied for Cell Adhesion Detection in Evaluating the Cytotoxicity of Nanomaterials**

(Part of the FiDiPro project, contributed by Niina Halonen et.al.)

The aim of this on-going research project is to develop a “cell-clinic” device to evaluate the health effects of nanoparticles on the cellular scale. The cell-clinic is a lab-on-a-chip concept utilizing a fully differential CMOS-based IC chip designed for capacitance measurements to sense the attachment of cells on top of the chip as an indication of cell viability after exposure to nanoparticles.

Nanomaterials are marketed to consumers in increasing amounts but the knowledge of their health effects is insufficient. Health effects are typically evaluated by animal testing and cytotoxicity assays. The first method is often ethically controversial while the traditional marker-based cell study is expensive and time consuming. The health effect evaluation of nanomaterials is also complicated since the EU has banned animal tested ingredients in cosmetics.

This research project introduces an alternative method to evaluate the cytotoxicity of nanomaterials; a CMOS IC chip designed for fully differential capacitance sensing of cell adhesion on the top of the sensor chip. Adherent cells normally spread out on the surface on which they are cultured, but stressed cells “ball up” after exposure to a harmful substance. This change in attachment can be sensed via a change in capacitance.

The capacitance sensor chips are produced by a commercially available CMOS technology. The IC chips comprises capacitance sensor arrays and readout circuitry. The sensor chip is packaged in a LTCC module integrated to a PCB and the measurement system is software controlled.
Layout of the IC chip with capacitance sensor arrays and readout circuitry.

Prototype of the LTCC package for the capacitance sensor chip.

Adherent epithelial human lung cells (BAES2B) were cultured on the LTCC module with a dummy chip, and the cells adhered and proliferated properly.

Normal proliferating human lung epithelial cells (BAES2B) cultivated on LTCC package.

At the moment the reliability and biocompatibility testing of the LTCC module is proceeding under cell cultivation conditions, which are very harsh on electronic components due to the high humidity and elevated temperature. The next step in the project will be to integrated a real sensor chip, cultivate adherent cells on it, expose the cells to TiO$_2$ nanoparticles and nanowires and then compare this data to previously made reference data gained with a commercial cytotoxicity kit (LIVE/DEAD® Viability/Cytotoxicity Kit, Life Technologies Corporation), and a cell proliferation kit (CyQUANT® Cell Proliferation Assay, Life Technologies Corporation).

This FiDiPro project is implemented in collaboration with the University of Maryland (the capacitance sensor IC chip development), the University of Oulu (Microelectronics and Materials Physics Laboratories, development of sensor chip package; Faculty of Biochemistry and Molecular Medicine, the cell tests) and Linköping University (development of measurement software).

### Personnel

<table>
<thead>
<tr>
<th>Role</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>professors</td>
<td>4</td>
</tr>
<tr>
<td>senior research fellows</td>
<td>6</td>
</tr>
<tr>
<td>postdoctoral researchers</td>
<td>11</td>
</tr>
<tr>
<td>doctoral students</td>
<td>16</td>
</tr>
<tr>
<td>other research staff</td>
<td>2</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>39</strong></td>
</tr>
<tr>
<td><strong>person years for research</strong></td>
<td><strong>11</strong></td>
</tr>
</tbody>
</table>

### External Funding

<table>
<thead>
<tr>
<th>Source</th>
<th>EUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academy of Finland</td>
<td>340 000</td>
</tr>
<tr>
<td>Tekes</td>
<td>990 000</td>
</tr>
<tr>
<td>domestic private</td>
<td>200 000</td>
</tr>
<tr>
<td>international</td>
<td>1 150 000</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>2 680 000</strong></td>
</tr>
</tbody>
</table>

### Doctoral Theses

- Juntunen E (2014) From LED die to a lighting system: performance improvement in LED lighting by means of thermal management and smart control. VTT Science 64.

### Selected Publications


