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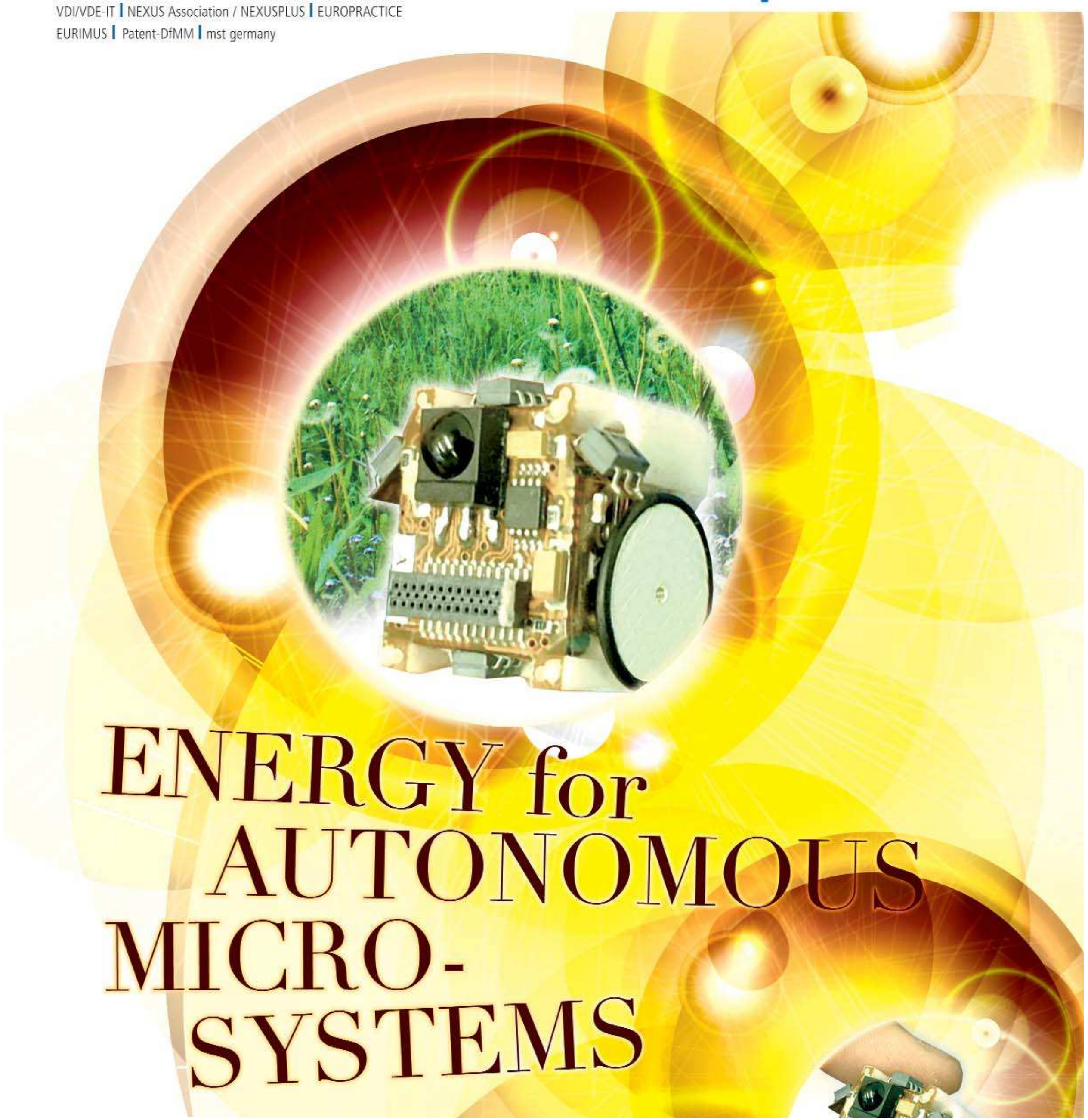

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mstnews 5/05 on "Ambient Assisted Living" in October 2005
This name was given to a initiative, supported by the EC. It covers micro and nano solutions for mobile human health care support and other kinds of assistance in daily life.

Deadline for press releases, short news, event announcements and advertisement orders: Sep 12, 2005

Date of distribution: October 03, 2005

mstnews 6/05 on „Technology Programmes and Initiatives“ in December 2005
Presentation of the efforts to promote and accelerate MST, in particular micro-nano-integration, in Europe on national level (technology policies and programmes, regional clusters) and international level (EC frame programmes, integration of national activities); supplemented by views to Asia and the US.

Deadline for abstracts: August 15, 2005

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Energy-autonomous Microsystems - a Key Technology for a Mobile Future

Manfred Klein and Marco Voigt

Energy-autonomous sensors and microsystems that sense and transmit information wirelessly are a key issue for future mobile applications with small portable products. In the near future - with increasing maturity of the underlying technologies - these highly functional miniaturised systems will enable innovations in many branches.
Low weight, small size, highly reliable devices that operate maintenance-free - realised with integrated power supplies that harvest energy from the environment - are key components for a broad range of application fields like:
health care, consumer electronics, automotive technology, environmental technologies, home and security.

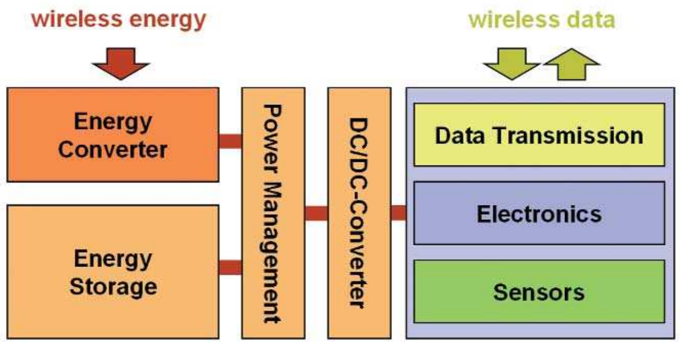

Figure 2: Building blocks of an energy autonomous microsystem

Key technologies for a mobile future

Today's products like laptops, cellular phones, PDAs, etc. follow the trend towards miniaturisation and portability. However, the power requirements of such systems have received less attention - in most cases standard battery-operated electronic systems are used with operating cycles which are often felt to be too short.

Future generations of mobile portable devices or, in more visionary terms, "ubiquitous intelligence" will be based on smart products combining a bundle of challenging technologies. Sensors, electronics and power supplies integrated into tiny, lightweight and flexible systems have to meet high requirements.

Wireless technology is going to revolutionise e.g. the industrial automation world with new operating and surveillance functions realised with self-sufficient wireless communicating components and systems. In addition, these sensor networks

Today, it is mostly small **batteries** that deliver the power to operate modules, which gives rise to two major problems: too short operating cycles and high maintenance costs. As battery-powered (Fig. 1) nodes in networks increase in number or when e.g. the devices are mounted at inaccessible places, the expensive replacement of depleted batteries is not practical.

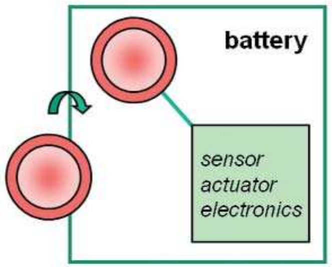

Figure 1: battery-powered system (schematic view)

But fortunately the ongoing progress in CMOS technology towards further reducing size and power consumption allows adequate solution paths: components that harvest their energy ecofriendly from the surrounding "sea of energy". Future research should

- developing efficient "energy harvesting" devices to power
- multifunctional microsystems with low-power sensors, control and transmission electronics and thus
- making the wireless nodes or networks nearly indefinitely self-sustaining.

A schematic view of a complete autonomous microsystem depicted in Fig. 2 comprises subsystems' energy conversion, energy storage and power control, sensors, signal processing, control unit and memory, transmission unit.

In general the energy supply side is split into energy sources (solar energy, mechanical energy, vibrations, low-frequency movements, thermal energy, (bio-)chemical energy, radiation energy - HF, IR), energy transfer (e.g. DC-DC converter), energy storage (batteries, solid state capacitors etc.) and energy management.

A special bio-power generator is described below [1]. Self-sustainable robots are driven by power from Microbial Fuel Cells - devices which are "fed" by plant or animal material and fuelled by the outcome of bacterial metabolism.

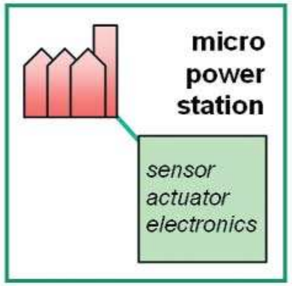

Figure 3: Micro Power Station, e.g. Fuel Cells (schematic view)

The advantage of fuel cell systems lies in their high availability, even after long standby times. In contrast, battery systems usually need to be exchanged after one year. Direct Methanol Fuel Cell developers favour fuel cell hybrid systems with a device-integrated battery charger. With this solution, longer running times can only be achieved if the capacity of the fuel cell is adapted to the average consumption of the application, with (peak) power being supplied by the accumulator battery. In such a hybrid system, fuel cells are continually stressed without major load changes, and the battery additionally functions as an electric buffer. A miniaturisation of the battery may not be possible because the peak power must always be available [4].

Micro power generation with micro gas turbines may produce even more energy: 50 to 100 W/cm³ using turbines spinning with up to 500,000 rpm at working temperatures of about 1200 K [2].

Some typical energies which can be tapped from the sources above and made available for low-power applications at more moderate temperatures are shown in Table 1.

In industrial production lines, vehicles, and for example from people moving around some of these energy sources can be harnessed. A person with an average weight of 68 kg generates about 67 W when walking at 2 steps per second. Piezoelectric converters have been built into heels of shoes

ture will belong to the basic equipment of cars and which are legally required for new cars in the United States. Today four battery-powered tyre pressure sensors are provided for one vehicle - either inflation stem mounted or strapped to the interior of the wheel rim. Taking 17 million new cars registered in Western Europe, this would mean the installation of a total of 68 million coin-cell batteries. To prolong their lifetime special algorithms are used to reduce sampling time and transmission rates. Next generation tyre pressure or tyre condition monitoring may be done with sensors directly embedded in the tyre structure, using e.g. the tyre flexing to drive a piezoelectric converter for energy scavenging.

The energy conversion module is the key element of a self-sustaining

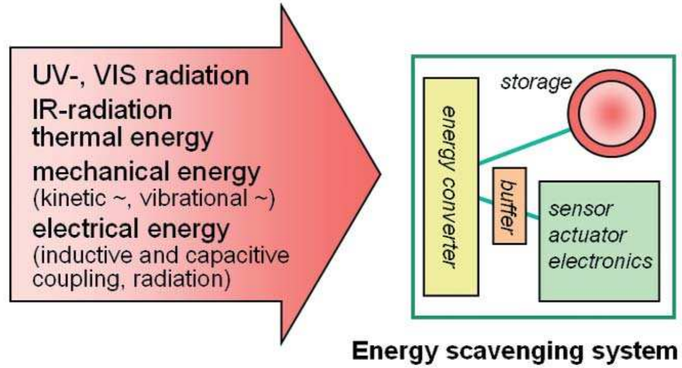

Figure 4: Energy sources and energy management

wireless system but all the other integrated or hybrid subsystems shown in Fig.4 have to be designed to fit the low-power requirements.

Optimised **energy storage** devices with ultra-low self-discharge even at higher temperatures, converters and electronics have to be controlled by a highly efficient power management, e.g. using impedance spectroscopic data to estimate the health and charging status of super caps.

Sensors like capacitive pressure sensors or passive SAW devices are low-power devices per se. Other sensor types have to be redesigned if the sensing principle allows for it in order to fit into the low-power philosophy of the system.

Depending on the distances in the network, **ultra-low power transmission technologies** (optical, acoustical, RF e.g. Bluetooth, ZigBee or inductive coupling) have to be developed or optimised, particularly to achieve reliable transmission results despite often critical signal-noise ratios. As RF power consumption is strongly dependant on bit rates, data protocols and timing has to be adjusted accordingly. An optimised technology for light switches powered with a piezo switch easily covers 10 - 30 m.

	Energy source	Power density [µW/cm³]	
defined level of power generation	**Solar**		
	direct sun	15.000	
	cloudy	150	
	typical office desk	6	
	Vibration		
	piezoelectric conversion	250	
	electrostatic conversion	50	
	Acoustic noise	0,003	*75 db*
		0,96	*100 db*
	Temperature difference	15	*10 °C difference*
	Shoe inserts	330	*elastic deformation*
d amount of ergy stored	**Lithium batteries**	45	*non-rechargeable*
	Hydrocarbon fuel (1 cm³)	333	*micro heat engine*
	Methanol fuel cell (1 cm³)	280	

Typical distances achieved with chip sets developed for transponder applications are up to 50 - 100 cm when operating at 100 - 150 kHz.

Reliability plays a major role for all applications and innovative interconnection and packaging techniques thus have to be used or newly developed in order to assure assembly processes with high yield and reliable devices.

First steps towards intelligent self-configuring wireless sensor networks have been done and with TinyOS a special operating system has been developed at the University of Berkeley, USA. This open-source operating system is designed for wireless embedded sensor networks with its memory constraints. [2]

Key applications for a mobile future

Energy-autonomous microsystems open up opportunities for totally new functions, products and services. The expectations are as high as the challenges to develop them. In the following some of economically interesting applications are listed.

Higher reliability and cost reduction potential through elimination of cables and connectors as well as reduced assembly costs could make this systems of interest for the automotive sector (sensing application powertrain, chassis and e.g. driver condition) and for technical facility services: surveillance and security of facilities (monitoring of air quality, smoke and water detectors, intrusion warning).

An example may illustrate this:
In Germany about 25 million light switches are used in buildings, in Europe more than 100 million. Assuming a mean lead length of about 4 metres, this sums up to 400,000 km of copper wire with PVC insulation that could be saved per year.

Small unobtrusive devices may be carried by persons and e.g. may control personalized access or monigrated sensors, actuators and electronics are no longer a vision of some research labs. First prototypes for health care allow surveillance of relevant vital parameters. A wide range is being opened for further applications - from the mobile control of patients and medical therapy to application in the automotive field. Professional and leisure sportsmen may record their specific detailed strain values. Elderly people may feel more comfortable and safe when in future they have the possibility to use a small device that monitors their actual wellness (heart status, respiratory rate, motion status, etc.) on demand and in case they come into a life-critical situation an emergency call may be released automatically or after pressing a button.

Integrated thermoelectric or piezoelectric converters may act as power supplies for systems dedicated to monitor storage and transportation conditions of goods. Beyond pure identification of goods with electronic labels, active labels with energy harvesting microsystems may measure parameters relevant for condition and quality of goods like temperature, mechanical shock, humidity and log the significant deviations with time stamp in an integrated memory. With regard to increasing routes of transport of many goods, this should be an economically significant contribution to quality assurance.

In order to address and promote this promising research field the VDE/VDI-Gesellschaft Mikroelektronik, Mikro- und Feinwerktechnik (GMM) has launched the research initiative "Energy-autonomous microsystems" and a "kick-off" workshop was held in early February 2004 in Darmstadt.

Many of the applications mentioned above should be realisable on a mid-term scale. For

tonomous microsystems besides industry, smaller and medium-sized companies are addressed. With their technological competence they act as suppliers or manufacturers or use the opportunities of new autonomous systems at the other end of the supply chain to offer e.g. a new service.

References/Links:

[1] I. Ieropoulos et al.; Self-sufficient robots (this issue)
[2] J. Peirs et al.; Micro power generation based on micro turbines (this issue)
[3] www.tinyos.net
[4]M. Voigt, I. Freesen, C. Hebling; European Portable Fuel Cell Study

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Micro Fuel Cell Systems as Device-Integrated Power Supplies

Ch. Hebling, A. Hakenjos and C. Agert

Fuel cells for portable electronic devices have gained an increasing amount of attention within the last few years as a result of some significant intrinsic advantages compared to batteries. Depending on the application and the boundary conditions, small fuel cell systems can be used both as a substitute and as a supplement to batteries. They can be customized exactly according to the power demand of the respective electronic device, the operation time aimed at as well as the geometrical form factor.

Small fuel cells can play an important role in the power supply of portable and remotely located off-grid electronic appliances such as medical appliances, sensors, transponder systems (e.g. RFID), safety engineering, environmental monitoring, global area network components or consumer electronics like the various classes of mobile computing devices, usually categorized as 4C-products (camcorders, cell phones, computers, cordless tools). The major driver for fuel cell systems is the fact that the improvements in the energy density of batteries have not kept pace with the growing power demand of such units, which again is a result of an increase in intelligence (computation), connectivity (band width) and the promotion of ‘always on’. This development can be slowed down a little bit by low-power micro controllers or new kinds of low-power displays (e.g. OLEDs), but the general trend will remain like this.

There are plenty of intrinsic properties of fuel cell systems that make them attractive candidates as a new generation of power sources for electronic mass market products next to batteries. Fuel cells can be laid out exactly according to the power demand of the device and the fuel storage (both hydrogen and methanol) can be dimensioned on the basis of the service time that should be pared to batteries, fuel cells show their greatest benefits whenever small power requirements are combined with a long operation time. Depending on the application and the boundary conditions, small fuel cells can be used both as a supplement to and a substitute for batteries. However, many aspects such as cost issues, technical challenges, fuel infrastructure as well as the need for a different usage and maintenance by the customer as compared to batteries need to be considered as well. If the fuel cell system is to be used as a battery replacement in electronic consumer devices, the safety standards of batteries have to be obeyed.

The major research issues to be addressed in terms of micro fuel cell systems are within the field of material improvements and system technology. One of the key components, the membrane electrode assembly (MEA), for example is a highly complex unit consisting of an ion-conducting membrane covered with a three-dimensional electrode containing the catalyst. Major developments are in the field of highly dispersed electrocatalysts with high activity for oxygen reduction and for high CO and methanol tolerance in case of reformat gas operation or direct methanol operation, respectively. Furthermore, carbon nano-materials such as nano-horns as a substrate for the electrocatalyst and novel membranes with higher operation temperature and low humidity requirements are in the center of interest.

Additionally, for a reliable operation of micro fuel cells, the hydrophilic and hydrophobic properties of the electrode and the adjacent gas diffusion carbon cloth have to be designed and used appropriately in order to remove the emerging water resulting from the overall chemical reaction. Unfortunately, the hydrophobic property of the electrode surface changes as a function of the change in contact angle due to varying wetting behavior can be seen in figs. 1 and 2.

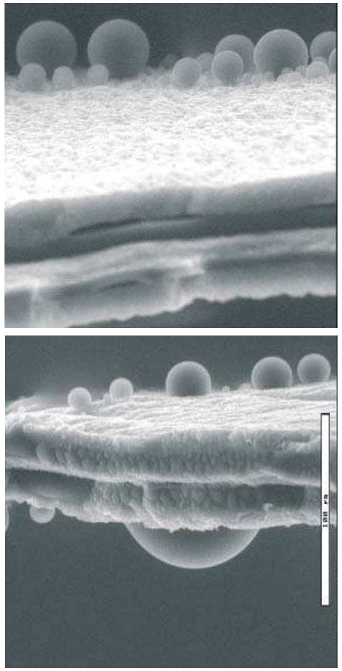

Figure 1 and 2: Change of the contact angle of an electrocatalyst surface in a membrane electrode assembly. The wetting behavior changes due to the degradation of the MEA in the fuel cell under certain operating conditions.

Furthermore, a profound understanding of the time- and spacial-resolved electrochemical, thermodynamic and mass transport processes is necessary in order to set up the appropriate control algorithms for a reliable operation. For that, characterization tools have been developed at the Fraunhofer Institute for Solar Energy Systems to measure in-situ the most important parameters in a single cell. Fig. 3 gives an example of such measurements performed simultaneously in a meander-shaped flow field. Those measurements are accompanied by appropriate multi-scale simulation efforts in order to

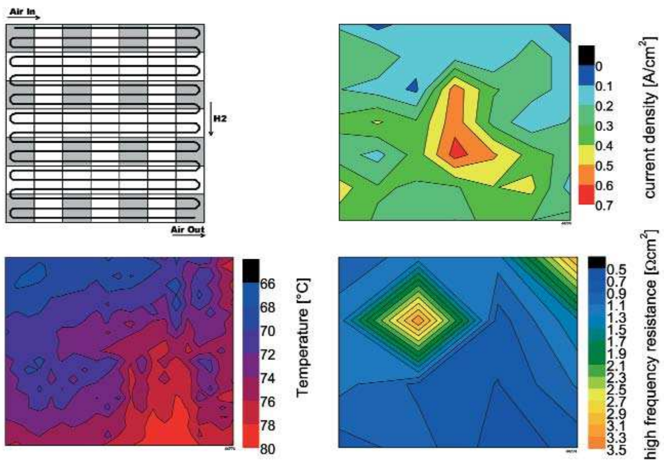

Figure 3: Spatial-resolved in-situ measurements of a single fuel cell under operation. The comparison of the extracted data allows a profound understanding of the electrochemical, thermodynamic and mass transport processes under given boundary conditions.

Concerning the fuel cell system, the most important development tasks are to increase the power and energy density while maintaining the reliability, which should be equivalent to that of batteries. Fuel cells usually operate under ambient conditions. Reliable operation and simple system architecture are contradictory requirements for these applications. Thus, to fulfill these requirements, the main challenges of present and future R&D are ideally to realize a passive thermal and water management as well as a suitable hydrogen feeding and pressure control unit.

This challenge can be solved for stationary fuel cell systems with active components such as compressors, heaters, cooler or humidifier whereas for portable systems a minimum amount of peripheral elements should be used. The most important functions of the peripheral devices for portable fuel cell systems are to start and stop the fuel supply for the fuel cell stack, to ensure a safe pressure regulation and to provide the appropriate air supply for cathode feeding and system cooling. The necessary devices like valves, pumps, fans or pressure reducers have to be miniaturized in size and optimized in power consumption. Automatic operation of such a system requires several components, which, in some cases, are not commonly available and thus need to be developed additionally.

Furthermore, the whole control system has to be developed further and integrated onto a circuit board by means of a micro controller. The benefits of an integrated electronics, although adding complexity, are a perfect match of the various devices, a control of the fuel cell aiming at a highly humidified membrane and simultaneously the least chance of water droplet formation. Additionally, an effective power management needs to be implemented with regard to the adaptation of the fuel cell system to the respective electronic device. Since the profile of the electrical load of electronic devices varies a lot, the fuel cell system must be accommodating to the needs of the respective system. Mobile phones, for example, need only some mW in the stand-by mode, short pulses of higher power demand for contacting the next station (transmitting/receiving), and 2 – 5 W during talk time again with the additional pulses. Such profiles are a challenge for sizing a fuel cell system. A hybrid system combining a fuel cell with a battery or a supercapacitor is considered as an optimal solution for such boundary conditions.

The fuel choice is limited by several factors, such as the volumetric and gravimetric energy density of the fuel, the weight and lifetime of the fuel container, the conversion efficiency of the chemical energy to electricity, the safety of the fuel and fuel container during refueling and transportation and finally the fuel distribution infrastructure. In the small power range, both hydrogen and methanol are very attractive fuels but also chemical hydrides and even the reforming of hydrocarbons are moving more and more into the focus of research activities. Hydrogen has the higher potential in terms of power density whereas methanol fuel cells dominate from the energy density point of view. Meanwhile there are numerous institutes and companies dealing with the development of small fuel cell stacks and systems. The closest to commercialization are free-standing systems as power supply units in the 10 to 100 W range without any geometrical adoption to existing form factors.

The highest development pressure is on device integrated micro fuel cell solutions, such as for cell phones. For such applications, the limited energy density of existing batteries is a major bottleneck for the development of future devices. But as all technical challenges are accumulated for those systems, there is no commercial system in sight at the moment.
Micro fuel cell systems will, without any doubt, have a high impact on the future market as compact and highly efficient energy converters. After a phase of niche market applications, it is expected that they will enter consumer markets where long run times with low power consumption are required.

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Micro-Solid Oxide Fuel Cells as Battery Replacement

A. Bieberle-Hütter, D. Beckel, U. P. Muecke, J. L. M. Rupp, A. Infortuna and L. J. Gauckler

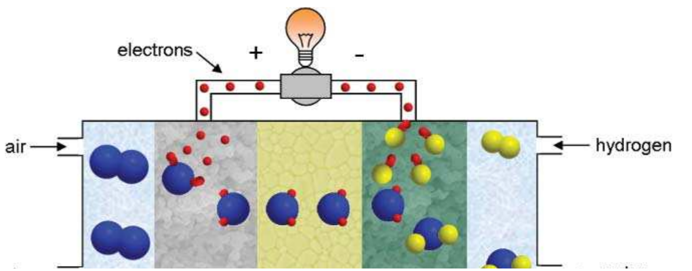
The emerging technology of micro-Solid Oxide Fuel Cells (micro-SOFC) is discussed in this paper with regard to its origin from state-of-the-art SOFCs, its competitors, such as Li-ion batteries, as well as fabrication and characterization issues. A micro-SOFC design for an entire system and, in more detail, for the core SOFC is presented and evaluated in terms of specifications, costs, and safety issues. Micro-fabrication and electrochemical characterization results from thin films deposited by spray pyrolysis prove the feasibility of the concept and provide an insight into the potentials and challenges of this new kind of battery replacement.

Introduction

The operating principle of fuel cells was first discovered in 1839 by Sir William Grove. However, only in the last few decades research and industry started to focus in more detail on this effective principle of converting chemical energy directly into electrical energy without Carnot restriction. Four main fuel cell types are now under investigation and are characterized by the electrolyte material, type of fuel, operating temperature, and anticipated power output range. The mobile devices. The solid oxide fuel cell (SOFC), however, has the highest overall efficiency and is the most flexible one with respect to different fuels. The operating principle of a SOFC is shown in Fig. 1: At the cathode, oxygen is reduced to oxygen ions which can pass through the dense, ionic conducting electrolyte due to an oxygen partial pressure difference between the cathode (high $p(O_2)$) and the anode (low $p(O_2)$). At the porous anode, the oxygen ions react with the fuel gas (hydrogen or natural gas) to form water, electrons, and/or carbon dioxide.

Micro-Solid Oxide Fuel Cells

State-of-the-art SOFC systems are operated between 900°C and 1000°C and are anticipated for stationary application, such as household units with about 1 kW (e.g. Sulzer HEXIS) or as small power plants up to several hundred kW (e.g. Siemens-Westinghouse) power output [1]. However, due to the high efficiency of SOFCs, researcher of a number of universities and institutes around the world, such as ETH Zurich (Switzerland), MIT (USA), ARC (Canada), NIMS (Japan), started to focus on small scale applications, so-called micro-SOFCs. The operating principle is the same as discussed in Fig. 1. “Micro” has a twofold meaning: on the one hand, it signifies chip-sized fuel cell components compared to cm to m sized traditional SOFC components. On the other hand, it implies micro-fabrication and machining techniques common for microelectronic circuit manufacturing. Challenges associated with this new approach are the reduction



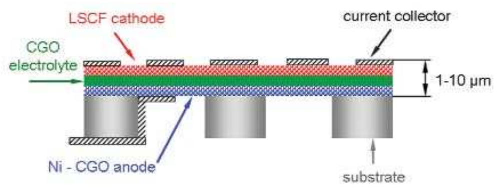


Figure 2: Schematic sketch of a micro-SOFC anticipated to operate at temperatures as low as 550°C.

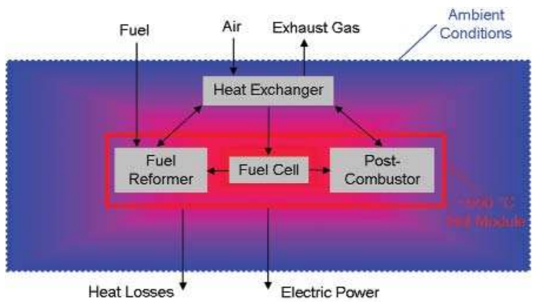


Figure 3: Schematic presentation of the concept of a micro-SOFC system.

in operating temperature down to at least 550°C, the use of new materials and changing of processing techniques to thin film deposition and Micro-Electro-Mechanical-Systems (MEMS) fabrication techniques. Micro-SOFCs are anticipated for battery replacement and should enter the market for power supplies of small electronic equipment, such as portable phones, laptops and electronic handhelds. They are predicted a 3-4 times higher energy density and specific energy than traditional Ni-metal hydride and Li-ion batteries.

The Design

The design of a micro-SOFC test module under investigation at the Institute of Nonmetallic Inorganic Materials, ETH Zurich, is shown in Fig. 2. The electrodes and electrolyte are thin films deposited onto a substrate that can be microstructured. The catalytically and electrochemically active layers have a total thickness of at most 10 µm. Current collectors are added for drawing the electrical current from the device. This design is deduced straightforward from traditional SOFC systems with strict separation between the anodic and cathodic gas rooms. Recently, also so-called single chamber fuel cell designs have been studied, where gas sensitive electrodes allow the operation of the fuel cell in a single gas room [2].

The micro-SOFC in Fig. 2 is the core of a micro-SOFC system consisting of two main parts (Fig. 3): the hot module containing all the elements operating at high temperature and the balance-of-plant elements providing the supplies (air, fuel, power management). The system and module development and integration as well as the thermal management are part of the multidisciplinary project "OneBat" started by 5 research partners from 4 Swiss research organizations and supported by the KTI/CTI, the innovation promotion agency of the Federal Office of Professional Educa-

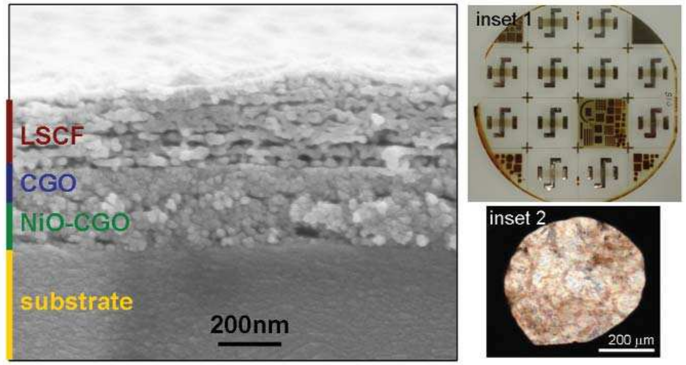
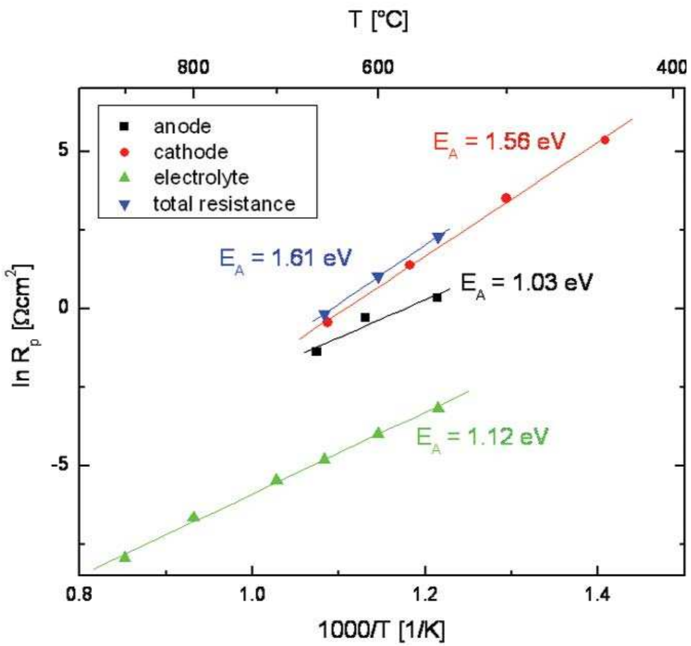


Figure 4: Scanning electron microscope cross-section image of a tri-layer: anode - NiO - $Ce_{0.8}Gd_{0.2}O_{1.95}$, electrolyte - $Ce_{0.8}Gd_{0.2}O_{1.95}$, cathode - $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_{3-\delta}$;
Inset 1: b) Light microscope image of a 4" wafer with several sprayed tri-layers (brownish areas) and Pt contacts (dark rectangles);
Inset 2: Light microscope top view image of a free-standing tri-layer membrane after annealing at 600°C.

tion and Technology (OPET), Switzerland. Within the framework of this project, all hot module components will be micro-fabricated: the micro-SOFC, the key unit of the system, a fuel processor for fuel reforming, and a post-combustor for completion of the catalytic oxidation of the fuel. The heat released by exothermic reactions in the fuel processing and post-combustion will be used to keep the micro-SOFC at temperature in order to guarantee fast start-up from idle conditions. A built-in heat exchanger preheats the incoming air with the exhaust gas to prevent convection heat losses.



Targeted Product Specifications, Costs and Safety

The described micro-SOFC system is targeted to operate in its core at 550°C (external T < 35°C) and to deliver 1 W continuous power with an electrical efficiency of about 30%. To reach an energy density larger than 1 kWh/l (i.e. 3 times greater than the long-term US Dept. of Energy goal for Li-ion batteries), the overall volume is designed to remain below 30 cm^3 with 15 cm^3 liquid fuel in a cartridge, while the overall product shape is as slim as possible. This size corresponds to the upper range of current cellular phone batteries, corresponding to devices integrating large screens and extra functionalities.

Costs are the main factor why SOFCs in general are not yet commercially available on a large scale. Preliminary estimates for a micro-fabricated SOFC indicate that costs lie between 45-15% below the current Li-ion battery technology, indicating the potential of a competitive pricing. With respect to safety issues, it is obvious that a device functioning at 550°C and using hydrocarbons as fuel has to satisfy very stringent certification requirements to find broad acceptance in the public. Hence, the product is designed in a way that the external temperature never exceeds 35°C and due to the small mass of the hot module, no excessive heating of the whole device is expected once the fuel is cut.

Fabrication of a micro-SOFC

The transition from a traditional SOFC to a micro-SOFC implies not only changes of the design, but also modifications in the materials selection and the processing techniques. With respect to materials selection, the main focus lies on the investigation and optimization of materials that allow fuel cell operation with high power output at low temperatures. The electrolyte can be composed of different ionic conducting layers in order to increase the ionic conductivity and chemical compatibility with the electrodes. Electrochemically active electrodes at low temperatures are e.g. Ni-CGO cermet for the micro-SOFCs are thin film deposition techniques, such as spraying, sputtering, and laser deposition. The research results so far are unique as not much experience is available worldwide with respect to processing and properties of such thin films. Very encouraging in terms of performance and costs are the properties of thin films made by spray pyrolysis (Fig. 4). A 4" wafer with contacts is structured into several independent micro-SOFC elements (Fig. 4, inset 1). The brownish areas are the locations where the anode, the electrolyte, and the cathode are subsequently deposited on top of each other. The cross section through one of these tri-layers shows a dense electrolyte film that allows a separation of the anodic and the cathodic gas room, and porous electrodes that allow gas diffusion to proceed easily. All layers are well adherent and the interfaces are clearly visible, which signifies no interface reactions taking place during deposition. The tri-layer is released by etching the rear side of the wafer to result in a free-standing membrane (Fig. 4, inset 2). Even after annealing at 600°C, a membrane as large as 200 µm x 200 µm remains crack-free.

Electrochemical Performance

The electrochemical performances of single thin films of anode, cathode, and electrolyte are shown in Fig. 5. Very low resistances were found for the single elements at temperatures as low as 550°C, namely 0.05 Ω cm^2 for the electrolyte, 1.5 Ωcm^2 for the anode, 8.4 Ωcm^2 for the cathode. The single thin film resistances are added in order to predict the total cell resistance of a tri-layer thin film cell (blue curve). It results today in a power output of 600 mW/cm^2 at 650°C in hydrogen and air (U_{cell} = 0.7 V). This predicted power output is about a factor of 2-4 better than similar state-of-the-art thick film cells in the literature [3]. In order to even increase the performance, it is most promising to improve the performance of the cathode by selecting new compositions and optimizing the thin film deposition parameters.

Summary and Outlook

We introduced the reader to the very growing market of small electronic devices and have the potential to supply the electronic devices 4 times longer with electricity than batteries.

The design of a micro-SOFC test module was presented both for the core SOFC and for the entire system including reformer, post-combustor, and heat exchanger. The fabrication results, namely the free-standing tri-layer of anode, electrolyte, and cathode, fabricated by spray pyrolysis, confirm the feasibility of the new micro-fabricated SOFC basic design requirements. The electrochemical performance of the single thin film SOFC elements is good and an impressively high power output of 600 mW at 650°C is expected for the device. The electrochemical characterization of a free-standing tri-layer micro-SOFC is foreseen for the near future. Pulsed laser deposition will be used as alternative deposition method. Within the framework of the One-Bat project, we will integrate the different module elements to evaluate the feasibility of a micro-SOFC prototype.

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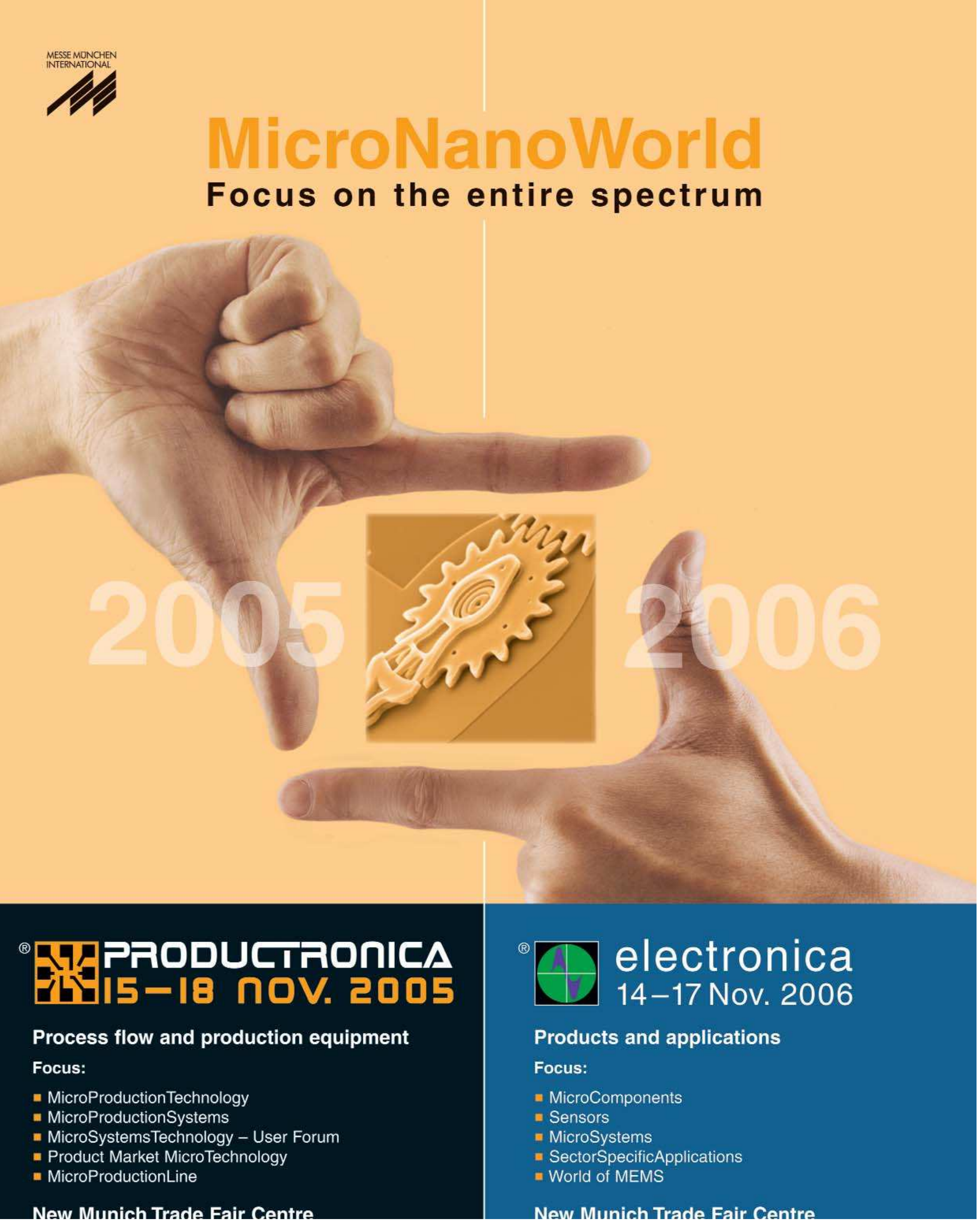
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Miniaturized Thermal Generators

U. Pfeiffer

Thermal generators based on the Seebeck effect do have widespread future applications as an energy source. This article focuses on thermal spring generator applications and markets as well as on possible future developments and applications.

The thermal generator

Initial findings as well as prototype and execution phases suggested that useful results could be obtained with material combinations of silicon and aluminium, the aim being to considerably improve internal resistance and energy efficiency. In order to achieve higher mechanical stability and a larger cooling surface, the oblong solution was given up in favour of a square solution. Two different surface sizes were envisaged to realize this. The realistic size was defined with 3.8mm x 3.8 mm. If it is possible to obtain a higher degree of integration, we can also have samples produced with a size of 2.5mm x 2.5mm. For both versions an integration of 1,600 thermocouples is envisaged. The smallest required structure will be have a resolution of around 1.5 µm and/or 0.8µm.

The thermal generator is now capable of supplying the appropriate sensors and microprocessors with energy and of storing the measured data in the microprocessor. Our thermal generator sensor serves to generate power for the small range (from µW to mW), converting ambient or process heat to energy.

Ranges of application

The applications of the thermal generator are enormous and apply to nearly all applications of sensors, ranging from the medical field, such as data obtained on the human body, the safety of children, women and older people, and of buildings, through the sports clothing industry to the automotive and consumer sectors.

sudden heart failure and to send this information, by radio, to the onboard system so that the vehicle can be automatically brought to a safe halt. The sensors can pick up different data like temperature, the number of revolutions, the position of different actuators and also the status.

In this way one can dispense with a wire inside a vehicle or for inpatients with sensors on the body and transmit the data by radio to the onboard computer or into the nurses' room. As we have pointed out earlier, this can be done with the help of a radio link, observing appropriate time limits in order not to use too much energy for data communication.

Several thermal generators can combine to produce the power needed, thus increasing the power supply. The energy obtained in this way can be used for data transmission, picking up data or controlling actuators and supplying a radio transmitter. In combination with a radio network, the thermal generator is conceivable as a replacement for wire-guided data communication.

If mere data recording is extended to cover control and regulation, the transmitter and receiver modules have to be replaced with transceiver modules.

Potential concepts

For the function of energy production, the thermal generator does need a temperature difference, which depending on the application, is generated by different elements. The temperature difference can be produced by the ambient air, the air inside the vehicle or by the heat of the engine. Sun exposure, inside and outside temperatures in buildings as well as body temperature and room air temperature can also result in temperature differences.

the high temperature difference between the circulating air and the engine. When the vehicle comes to a stop and the engine starts taking on the temperature of the ambient air, there will also be a decrease in the energy of the thermal generator.

After the vehicle has stopped, it must be possible to start it safely again after an extended period of time without dispensing with functions, e.g. by a pre-defined starting position of the actuators. Another possibility would be adding up small energy values of the thermal generator in energy stores such as Goldcaps or Accus.

This is possible because the thermal generator works when temperature differences are still very small. If, for example, the temperature difference is approximately one Kelvin, the thermal generator will start producing several µA. This can be done when the engine is still cold, since the ambient air usually has a temperature deviating from that of solid materials. Here the system benefits from the inertia of a temperature change from solid to gaseous substances.

Thermal generator integrated in a button cell

If thermal generators are being integrated into appropriate button cell housings, the latter may be used for many applications to optimize the heat flow. These devices do not need a "battery change" any more.

The sensor can thus be placed in the button cell housings, with the button cell cover corresponding to the positive pole and at the same time to the cooling surface for releasing the heat energy. The lower surface of the button cell is both the negative pole and the heat accumulator for the supply of the higher temperature to the sensor.

The thermal generator sensor can thereby replace lithium batteries, button cells or small accumulators control units such as function wristwatches, car keys and remote radio control.

Applications in an integrated wristwatch car key allow adding new functions. To open and lock the car door it is sufficient to press a key on the wristwatch. Further data like personal set-points (seating position, interior temperature, favourite radio station), DCF77-radio controlled value and so on can be transmitted to the on-board system.

The wristwatch has now become the fully electronic ignition key, making the ignition lock superfluous. A key is pressed on the steering wheel or on the wristwatch starting the engine. Further applications are likely to be found in the medical and consumer sectors.

Automatic tyre pressure monitoring
Today in most of the newer trucks the tyre pressure is already being monitored by radio through a sensor. In the USA tyre pressure monitoring has been compulsory since November 2003. If additionally a thermal generator is used, the electronics become independent of the lithium battery. The demands made on the lithium battery are very high. On the one hand, an ambient temperature of more than 100°C is needed and, on the other hand, a lifetime of more than 10 years is required. For the extension of the lifetime, the volume to be transmitted is already being kept at a minimum. Today you measure more often than you transmit.

The types of thermal generator sensor setups strongly depend on the applications and the performance required and should be discussed with each customer with a view to their optimization. Here we are faced with the alternative to work with transponders, which, however, from our point of view is substantially more expensive than the thermal generator solution.

What's already on the market?
A good example is the Citizen wristwatch. In this watch a ring was integrated as thermal generator produc-

in miniaturized design with a volume of only 0.2 cm^3 was developed by D.T.S. Further developments of this technology have been advanced by MicroPelt, which can be visited at www.micropelt.com.

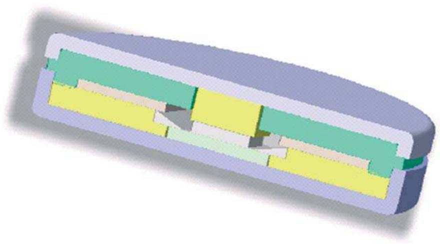

Figure 1: Thermal generator in a button cell

If the efficiency of thermal generators is considered in terms of energy output per area required, semiconductor technology has a higher degree of efficiency than conventional thin-film technology. However, it should be seen that for some applications thin-film technology provides advantages due to a low internal resistance, for which a higher price must be paid.

Possible future developments
Our goal is to obtain a high energy supply from the thermal generator to also activate actuators which require a higher power input. Here there are definitely certain limits that exclude certain actuators. This problem could be solved by microsystem-oriented actuators of the future, since these need substantially less energy. Regarding the optical development of cameras, the IMS (Institute for Microsystems) in Stuttgart has shown that it is possible to reduce power requirements down to 10% through certain chip solutions (personal communication: Prof. Höflinger).

New fixed and flexible materials will be developed and explored and will be examined in terms of higher energy and more inexpensive thermal generators. Additionally, there is the higher degree of integration in the nano range, which allows new horizons of application. We will have, in future, energy recovery in connection with an energy-storage system in the vehicle, as only 10 to 20% of the primary energy for the movement of the vehicle can be converted.

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Low Cost Manufacturing of Foil-Type Micro Fuel Cells

S. Wagner, R. Hahn, R. God and H.-P. Monser

The energy demand of future and emerging electronic products will dramatically increase. These electronic products are usually powered by primary and secondary batteries. Although the battery technology is constantly being improved, it is not keeping up with the demands of handheld equipment. Fuel cells are becoming increasingly popular as candidate solutions for miniature power sources, especially in response to the rapid growth of mobile computing and electronic devices. Fuel cells are well known for high energy density and ease of scaling for application-specific power requirements. At the Fraunhofer IZM (Berlin) a technology for planar micro fuel cells was developed, which is based on wafer level technologies and the use of metal-polymer foils. This technology makes a low-cost mass production possible. Reel-to-reel processing is a well accepted and widely spread concept in the industry. Whenever substrate and materials become very thin and flexible this production technology offers many benefits for efficient and low-cost manufacturing of micro systems. In this article we will present a glimpse ahead for the design and manufacturing of foil-type micro fuel cells.

Fuel cell principles

Fuel cells operate on the same principle as batteries, electrochemically converting energy. But fuel cells are "open" systems where the reactor size and configuration determines the power output while the available energy is determined by the size of the fuel storage. Since a single fuel cell has an operation voltage of ca. 0.5-0.7 Volts, for higher operation voltages a multitude of cells are needed. A fuel cell can be subdivided into three constituent component groups: The Membrane Electrode Assemblies (MEAs), which fulfill the electrochemical function of the fuel cell, the flow field with current collectors and conductive electronic paths, and the Gas Diffusion Layers (GDL), which are inserted between MEAs and flow field to distribute the reactants uniformly. Fuel cells of the air-breathing type use ambient air as an oxidant. PEM fuel cells operate with hydrogen. Direct methanol fuel cells (DMFC) use methanol or sometimes other alcohols. Alcohol-fed fuel cells are more practical than PEM cells for portable applications. The reason is that they have no need for high-pressure hydrogen tanks or other special fueling equipment. But power density of DMFCs is currently three to five times lower than the power of hydrogen-fed systems. Therefore we use a specific approach were the hydrogen is produced on demand in a coin-sized generator.

When relating to the architecture of fuel cells, there exist two different types: the stack and the planar design. The power density of stacks is in most cases higher than that of the planar fuel cell. An important advantage of the planar design is that the open cathode side allows a completely passive, self-breathing operation of the fuel cell. In contrast to this, a fuel cell with stack design needs additional peripherals such as fans and pumps.

But why are micro-systems technologies used for manufacturing fuel cells? The main reason is that the use of new technologies and designs should lead to a significant improvement of fuel cell performance when micro scale phenomena are exploited. However, such benefits can only be realized if the fuel cell devices can be fabricated using available manufacturing techniques. They are in most cases adapted from semiconductor and microsystems technology. Some of these technologies may have the potential to solve problems, which are critical in the conventional stack technology. Another reason is that the majority of research on micro-scale fuel cells is also aimed at micro-power applications. Miniaturiza-

Technology of foil-type micro fuel cells

The micro fuel cells at Fraunhofer IZM are based on thin film and micro patterning technologies and use wafer level and foil processes. Planar PEM fuel cells between 1 mm² and approximately some cm² were developed. The investigations focused on pattering technologies for the membrane electrodes, serial interconnection of single cells in a planar arrangement, laminating and assembling processes. Although wafer technologies were applied, foil materials were used that allow low-cost fabrication in future production. Gas diffusion layers are not necessary due to the micro patterning of channels (see figure 2). Figure 1 shows a micro fuel cell based on foil technology. The foil-type planar micro fuel cell is based on the following key technologies:

- Sandwich laminate of polymer-stainless steel foils
- Lithography and patterning of free standing grid micro-structures
- Micro patterning of flow fields
- Subtractive patterning of MEA-electrodes
- Adhesive sealing and electrical interconnection

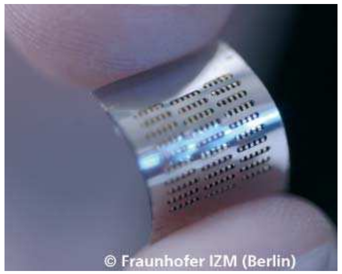
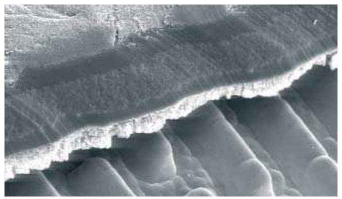


Figure 1: Foil-type planar micro fuel cell



Characterization of foil-type micro fuel cells

Prototypes of self-breathing PEM fuel cells with a size of 1 x 1 cm² and 200 µm thickness were fabricated. V/I curves were measured for many different designs at a variety of ambient conditions. Ambient temperature and humidity have a significant influence on fuel cell performance since power density depends on the water concentration inside the polymer membrane and the removing of water produced by the reaction of oxygen and hydrogen at the cathode.

Fuel cells with 40 mA output current at 1.5 V (= 120 mW/cm², 25°C, 50 % RH) have been successfully demonstrated (see figure 3). In this configuration the three cells are arranged in parallel with a distance of 200 µm and use the same membrane, which simplifies sealing. Cell performance was validated under varying ambient conditions. Stable long-term operation at 80 mW/cm² was achieved. The total performance of the micro fuel cells is in the same range of current and power density compared to the best conventional planar PEM fuel cells. At the same time this technology offers a high degree of miniaturization and the capability for mass production, which is a clear success of our micro patterning approach.

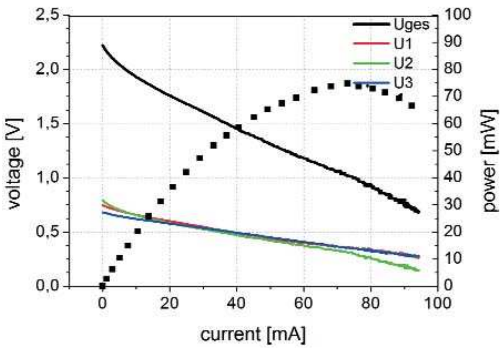


Figure 3: V/I curves of planar micro fuel cell demonstrator. Three cells serial connected (on top) and single cells (below).

Reel-to-reel manufacturing concept

The foil-based design of the fuel cell facilitates an efficient and low cost reel-to-reel manufacturing process. The basic platform used in this process is a high precision pick-and-place equipment, which is well known as chip or die bonder in the semicon-ductor industry.

An endless substrate tape with the anode structure is transported into the machine (see figure 4) and the first process step is the deposit of sealing material onto the anode structure. In a second process step the MEA is accurately placed into the previously formed gasket. The placement is controlled by a sophisticated vision system, ensuring that the micro-structured MEA fits perfectly onto the anode structures of the incoming substrate tape. Finally, a curing process seals together both the substrates, anode and MEA, and the tape is winded onto the take-up spool.

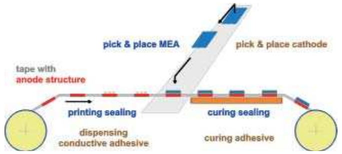
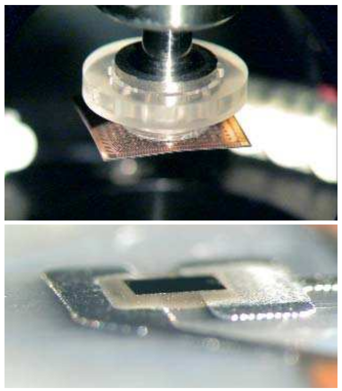


Figure 4: Process flow of the reel-to-reel manufacturing system

Mounting the cathode foil comprises the same production steps as those previously used for the MEA placement, and thus the process flow described above can be applied in a second run for finalizing the foil-based fuel cell package: deposit of conductive glue for fixing and interconnecting the cathode, placing the cathode foil, curing and rewinding the product. In a later aimed mass production the two cycles will be run in two consecutive machine modules, interfaced by a substrate buffer.

The resulting endless belt is ready to be used for further processing. The active area of the fuel cell will be punched out and sealed onto the hydrogen manifold. Electrodes will be interconnected to end up with the final product.

Foil handling and sealing
ASEM GmbH has profound knowledge in handling ultra thin silicon chips at the highest speed. Within a funded BMBF project (www.innosi.de) a die bonder was modified with newly developed process units such thermal die ejection system and miniaturized screen printer.



The thermal die ejection system allows handling of 30 µm or even thinner silicon chips. A heat reactive wafer foil instantaneously ejects the die when treated with heat. For releasing chips individually, a heated needle tip contacts the area of the heat reactive wafer foil below the chip for only a few milliseconds. Immediately the wafer foil decreases adhesion strength down to zero and a pick-up tool can take away the thin piece of silicon.

Interestingly, this handling concept can be transferred to pieces of polymer foil and other foil-type material (see figure 5 on top). Even 7.6 µm thin polymer foil was already successfully handled with the system. With an enlarged heating stamp the releasing speed stays in the 200 ms range, even for bigger pieces of e.g. 10 x 10 mm^2. This ensures a very quick and stable process for high-volume production.

The handling technique will be modified for foil-type micro fuel cells. Instead of using a wafer, the structured foil material will be fed into the machine by an endless tape with heat reactive coating. Pick-up and place of the individual pieces, vision correction during placement and curing will be done in a way very similar to a classical die bonding process.

A challenging process step will be the deposit of the sealing material between the foil layers to form a gasket. Known methods for this process step are dispensing or jetting the glue. Screen printing is another method of choice where ASEM GmbH has a lot of know-how. This process is used for micro-structured and very thin glue deposition in the die bonding process (see figure 5 below). Especially for short process times and highest repeatability and accuracy of the pattern, screen printing is the preferred method.

Figure 6 shows a miniaturized screen-printing device with double squeegee system and material cartridge. It is aimed to achieve very uniform and homogeneous structured sealing by transferring this printing process to

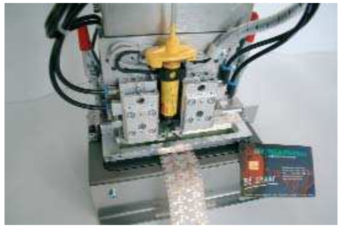


Figure 6: Miniaturized screen printer

Acknowledgement
This development is part of the BMBF project "PROZELL -Produktionstechnologie für Mikroenergiesysteme" (www.pro-zell.de). It is funded within the call Durchgängige Produktionsketten für mikrostrukturierte Teile und Mikroteile, which is governed by the Forschungszentrum Karlsruhe, Bereich Produktion und Fertigungstechnologien PTKA-PFT (www.fzk.de/pft/ncp).

The aim of the project is the development and implementation of a closed manufacturing and production chain of micro-structured functional parts for the production of planar foil-type micro fuel cell system. Within the project consortium the project leader Varta Microbattery GmbH and Fraunhofer IZM are working on the design of the planar fuel cell. Lasermicronics GmbH and the KUZ - Kunststoffzentrum Leipzig are responsible for structuring raw materials. ASEM Präzisionsautomaten GmbH, a Mühlbauer company, and AMICRA Microtechnologies GmbH are in charge of developing production equipment for foil-based micro fuel cells.

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Micro Power Generation Based on Micro Gas Turbines: a Challenge

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Mobile electronic devices require more and more electrical power putting stress on battery technology. As the energy density of most fuel types is about 100 times higher than that of the best rechargeable batteries, fuel-based micro power units could offer an alternative. The micro gas turbine developed by the PowerMEMS project will be in the cm range and will have an output of about 100 W. A first prototype of a turbine driven by compressed air shows that speed is the limiting factor for both power and efficiency. The next step, the development of a complete gas turbine, is many times more difficult, and is not simply the scaling down of larger gas turbines. Major problems are the high rotational speed (> 500,000 rpm) and temperature (> 1200 K), and the efficiency of the components.

Introduction

The current trend towards miniaturization, portability and, more generally, ubiquitous intelligence has led to the development of a wide range of new products such as laptops, cellular phones, PDAs, etc. However, the power requirements of such systems have received much less attention: typically, traditional battery-operated electronic systems are used. Nevertheless, the energy density of most fuel types is still 100 times higher than that of the best rechargeable batteries, which makes the use of a fuel-based micro power unit interesting. Such power units can be based on a wide range of operating principles, ranging from fuel cells and thermo-electric devices to combustion engines and gas turbines. While fuel cells are expected to offer the highest efficien-

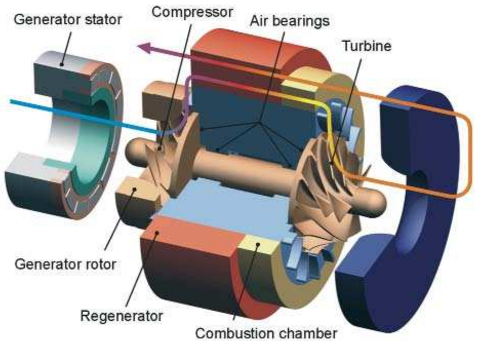

Figure 1: Micro gas turbine layout.

Figure 2: Air turbine, diameter 10 mm.

cy, micro gas turbines are expected to offer the highest power density.

The micro gas turbine developed by the Belgian PowerMEMS project [1] will be in the cm range and will produce a power output of about 100 W. The system basically consists of a compressor, recuperator, combustion chamber, turbine and electrical generator, as illustrated in figure 1.

Air powered turbine

To gather initial experience, a simple turbine driven by compressed air was built first, instead of a complete gas turbine. The rotor has a diameter of 10 mm and is supported by two ball bearings. Figure 2 shows a subassembly of nozzle disc, rotor, and bearings. The turbine is tested for a supply pressure of 0.8 bar. To avoid breakdown of the bearings, the speed is limited to 130,000 rpm, far below the (theoretical) optimal speed of 210,000 rpm. Up to 50 W mechanical power is generated with an efficiency of up to 24%. From the results it was clear that power and efficiency would increase further with speed, beyond the speed limits of the ball bearings. So, a major lesson drawn from this test setup is that speed is the limiting factor for the performance and efficiency of micro turbomachinery. The obtained efficiency may be sufficient to operate an air powered turbine, but lies far below the efficiency required for gas turbine aero-components.

Micro gas turbine

The development of a complete gas turbine is many times more difficult than of an air powered turbine. Surely, it is not simply the scaling down of the components. This requires new concepts for the bearings, electrical generator, recuperator, etc.

Thermodynamic cycle

The main difference between a small and large gas turbine is the amount of gas submitted to an almost unchanged thermodynamic cycle. Velocity and pressure levels remain the same when scaling down a gas turbine. The work exchange between compressor or turbine and fluid is proportional to the peripheral speed, such that the rotational speed should scale inversely proportional to the diameter, resulting in speeds of more than 500,000 rpm for rotor diameters below 20 mm.

Another major problem with the miniaturisation of micro turbines is a large decrease in Reynolds number, resulting in higher viscous losses and lower overall cycle efficiency.
Also the required temperature is a problem. As a pressure ratio of 3 is envisaged, the turbine inlet temperature should be at least 1200 K to obtain a positive cycle efficiency, and higher temperatures would considerably boost the overall efficiency. In large turbines, the blades are cooled by internal cooling channels and protected by thermal barrier coatings. In case of micro turbines, internal cooling of blades a few millimetres in size is unrealistic. Therefore, temperatures of 1200 K and higher can only be reached with ceramic materials.
Another major consequence of the small dimensions is the extreme temperature gradient between the hot turbine and colder compressor. The resulting massive heat flux provokes a non-negligible decrease in both compressor and turbine efficiency.
A gas turbine net power output is the small difference between the large turbine power output and the large compressor energy requirements. This amplifies the effect of the performance reduction of the individual components on the overall efficiency. Therefore, careful optimisation is needed to guarantee a positive output. However, little knowledge is available on aero-thermodynamics at these small scales. There is also no guarantee that the existing flow

Bearings

The bearings must operate throughout the whole domain of possible temperature conditions from start-up to steady state operation. Maximum temperatures between 100ºC and 1000ºC can be expected depending on the exact location of the bearings.

It is clear that conventional ball bearings are not feasible in terms of speed and temperature. Magnetic bearings could offer a solution regarding speed, but the high temperature dissuades the use of permanent magnets as these could demagnetise. Consequently, such bearings should be constructed with electromagnets that consume a considerable amount of electrical energy.

Air bearings seem most suited for this application. Aerostatic as well as aerodynamic ones can be used. Aerostatic bearings can be fed by tapping a small amount of compressed air from the compressor. This results in problems at start-up and moreover decreases the overall efficiency.
Aerodynamic bearings are self-pressurising and therefore need no external supply. However, the phase of dry friction during start-up is a major drawback. Additionally, self-excited instabilities (half-speed whirl) limit the maximum attainable speed.
For the application presented here, aerodynamic bearings are the most promising choice on condition that the issue of instability is tackled.
It is generally known that an unloaded or lightly loaded aerodynamic bearing has a strong tendency towards self-excited vibrations at high speeds. Small-scale systems very often encounter this problem as with miniaturisation rotor mass decreases much faster than bearing load capacity.
Several stabilizing techniques exist, but most promising for this application are bearings with conformable surfaces, more specifically aerodynamic foil bearings. These bearings are virtually immune to half-speed whirl and suffer less from centrifugal and thermal rotor growth.

Compressor and turbine

As stated before, the efficiency of all components is critical. This is especialnumbers obtained for the air driven turbine shown in figure 2. Thus, it is clearly a challenge to obtain the required efficiency despite the low Reynolds numbers, increased heat transfer, and lower relative geometric accuracy of the components. It is not evident to manufacture 3D micro-impellors with sufficiently high accuracy and low roughness in exotic materials.

To cope with the high temperatures, the turbine impellor is made from a Si_3N_4-TiN composite. In the short term, electro-discharge machining is used for prototyping while ceramic powder injection moulding is envisaged for future series production.

Recuperator

Heat recuperation is often used to improve the overall cycle efficiency of standard gas turbines. In small-sized gas turbines this improvement is, however, much more questionable. Indeed, pressure drops are much larger compared to conventionally sized gas turbines. The additional pressure drop introduced by the small channels in the recuperator should not undo the benefits of heat recuperation.

In conventionally sized recuperators, complex, well-designed fin configurations are used to improve the gas-air heat transfer. In order to avoid these costly and difficult to machine fin configurations, alternative recuperator designs are needed for micro-scale applications.

Generator

The generator will operate at much higher speeds and temperatures than conventionally. To withstand the high centrifugal stresses, a solid rotor structure is chosen. Permanent magnets and coils are placed on the stator to avoid damage resulting from high stresses.

The high speed also results in high operating frequencies introducing skin effects in the electrical circuit and eddy currents in the magnetic circuit.

The generator concept is based on a reluctance machine, which also serves as a start-up motor. The necessary magnetic flux can be created with coils or with permanent magnets. The use of coils may be interesting in high temperature environments but causes additional energy consumption. The temperature problem of permanent magnets is bypassed by placing the magnet on the lowest temperature side of the turbine (the compressor side) and by extra cooling with the inlet air.

Acknowledgements

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More information

[1] www.powermems.be

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EcoBot II: Towards Self-sustainable Robots

I. Ieropoulos, C. Melhuish, J. Greenman and I. Horsfield

EcoBot II is a robot that follows the light (phototactic), senses the ambient temperature (thermo-sensitive) and transmits the temperature information wirelessly to a remote base-station. This robot is unique because it does not employ any form of conventional power supply, such as batteries or solar panels; it is solely powered by bacteria that eat dead flies! It also utilises oxygen from free air to stay in (chemical) balance. EcoBot II is therefore the world's first to exhibit some partial form of self-sustainability (a.k.a. energetic autonomy) by utilising raw unrefined substrate as its fuel and oxygen from free air.

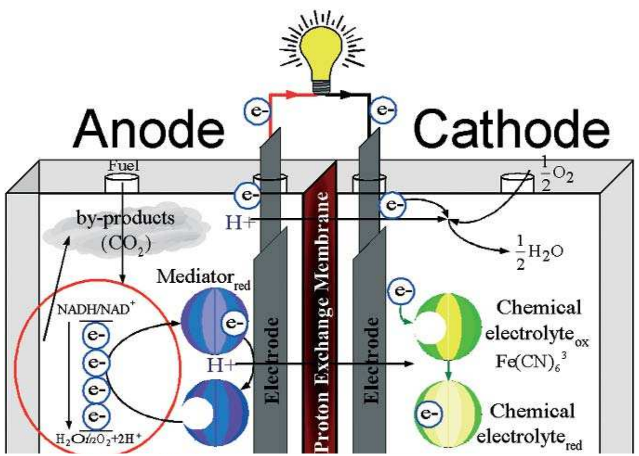
There are numerous scenarios in which autonomous robots would be extremely useful for humankind. For example, they could be employed in missions that are dangerous, undesirable or inconvenient for human beings. An autonomous agent could be used in underwater explorations feeding on plankton and sending useful information on the ecology of the ocean. On the other hand, it could be sent to monitor the sewer system of a city, and by cleaning blockages, generate energy for its maintenance. Organic waste produced at the domestic or industrial level might even be used as the fuel for such a robot that may be patrolling the premises.

One important factor for robots is, therefore, that of self-sustainability. In order to be self-sustainable, robots will be required to extract energy from the environment and in many ways they will face the same problems as animals. The aim of our work is to build self-sustainable (energetically autonomous) robots which operate on power derived by bacterial metabolism. These robots are novel in the sense that they will incorporate in their behavioural repertoire actions that involve searching for and collecting real food. They will also have to remain inactive until energy is sufficient to do the next task; lection mechanisms have been designed so far.

The EcoBot project focuses upon the creation of a smart on-board artificial 'digestion' system for an autonomous robot. The artificial 'gut' is currently designed around the novel Microbial Fuel Cell technology (MFC). Energy output from the MFC is not, at this stage, intended to sustain continuous motion activity (although computation can be continuous). The robot will therefore employ a 'pulsed' behaviour mode. The goals of this study are to (1) produce new types of MFC that in contrast to conventional MFC can operate over long periods of time, (2) produce sufficient power for autonomous robot operation, (3) utilise natural food substrates. Energy needs to be accumulated first before being accessible to the robot and we argue, is more realistic than simply managing a fixed energy budget. This issue will eventually need to be addressed by autonomous robots, but at the present moment, development of efficient on-board MFC's is the main challenge. These need to be portable, replenishable and sustainable and capable of using a wide range of natural foodstuffs. By judicious choice of different food/flora combinations, the techniques envisaged will be capable of exploiting any organic food source on land and sea, and can potentially therefore be employed by terrestrial and marine robots.

Our work is focusing upon the use of plant or insect material as a source of energy. The project is code-named EcoBot and the first stage of this investigation (EcoBot I) has been completed (see www.ias.uwe.ac.uk). The next stage, which is called EcoBot II, also performs phototaxis but at the same time senses the ambient temperature and reports the sensed data remotely. It is powered by MFCs, containing a flora of microorganisms originating from sewage sludge and fed with unrefined dead flies or rotten fruit.

Microbial Fuel Cells (MFCs)
A microbial fuel cell is a bio-electrochemical transducer that converts the bio-chemical energy produced by bacteria metabolising refined or unrefined substrates into electrical energy. There are two compartments in an MFC; the anode and the cathode and there is a proton exchange membrane (PEM) that separates the two. In the aqueous solution of the anode compartment, bacteria metabolise a given substrate and produce biochemical energy used for their maintenance. A portion of this energy, in the form of electrons, is extracted



from the bacterial metabolic cycle and diverted onto the electrode surface, also found in the anode. At the electron extraction (or reduction) stage, hydrogen ions (protons) are also released from the bacterium cell into the liquid solution. Electrons and protons flow into the cathode compartment, via different routes. Electrons flow through an external circuit, which is connected to the electrode terminals of both the anode and cathode, and protons flow through the PEM, thus 'closing' the circuit. An oxidant in the cathode takes up the electrons and protons. This is known as the oxidation stage. In general, these processes are known as redox reactions and are shown below in Figure 1.

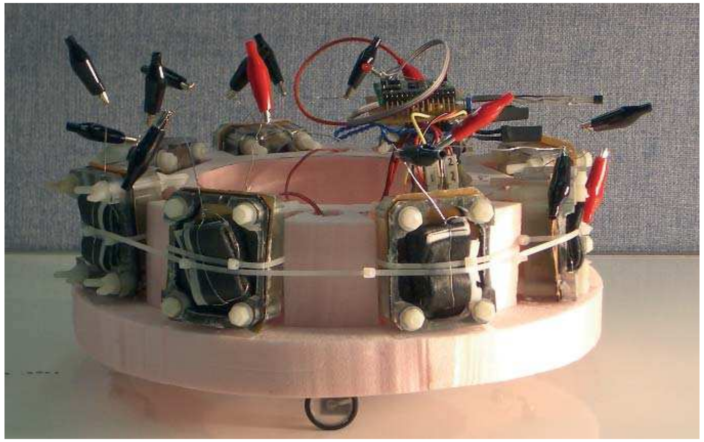


Figure 2: EcoBot II fully assembled.

There are 3 main electron transfer mechanisms from the bacterium cell to the electrode surface in an MFC that entirely depend on the bacterial species employed. These are: (a) synthetic mediator, (b) natural mediator and (c) direct contact. Synthetic mediators are manually added in the anode and degrade with operation time, thus having to be replenished. Natural mediators, on the other hand, are electro-active metabolites produced by certain microbes as part of their metabolic processes. These do not need replenishing, but can only be produced from certain nutrients that must be present in the fuel.

Some bacterial species transfer electrons to the electrode surface directly by attaching to the electrode surface, thus forming a monolayer biofilm (direct contact).

Two systems are known to be used in the cathode of MFCs; the first works with liquid ferricyanide ($K_3Fe[CN]_6$)

and the second with oxygen (O_2) gas. Ferricyanide is a good laboratory standard used in analytical studies that is highly efficient, to start with, but like the synthetic mediator in the anode, degrades with operation time. Oxygen, on the other hand, is available from free air and offers a stable and in some cases improved performance over operation time. The only condition is that the electrode must be kept moist in order for H^+ ions to flow. Since water is formed when electrons (via the circuit) combine with H^+ ions (via the PEM) and O_2 molecules (free air) at the cathode electrode surface, this system eventually becomes self-sustainable. The weight of an O_2 cathode MFC is ~ 80g.

EcoBot II
A total of 8 MFCs, employing the O_2 cathode, were used to power EcoBot II (see Fig. 2). The robot weighed 780g when fully assembled and had a diameter of 27cm. Two photodiodes in the front were used to detect the light. These were connected crosswise to the two motors (actuators), thus allowing the robot to move towards the light. A bank of 6 capacitors was used as the onboard energy accumulator.

The MFCs were connected in a series configuration and the robot moved in a discontinuous ('pulsed') mode. This means that when there was not enough energy onboard, the robot simply remained inactive. During this time, energy from the MFCs was accumulated in a bank of 6 capacitors (accumulator) until a threshold level was reached. At that point in time, EcoBot II resumed power and moved towards the light whilst wirelessly transmitting the temperature at that point in time. An electronic circuit directed power to either or both motors (depending on the reading from the photodiodes), the temperature sensor and the wireless transmitter.

Mixed bacterial cultures from sewage sludge were used in the MFCs onboard EcoBot II. This offered, amongst many other advantages, the potential of utilising a wide variety of substrates due to the diversity of the microbial community. Several substrates (pectin, chitin, sucrose) in refined form were tested in the initial experiments. Chitin, which is mainly found on the exoskeleton of insects, mollusc and crustacean organisms, proved to be one of the best.

In terms of robotic autonomy, substrates such as fruits and insects, especially the ones considered as pests, were very attractive. Hence, in the EcoBot II experiments, both dead flies and rotten fruits were employed as the 'food' for the bacteria. The experiments were split in two different categories: (a) short distance (50cm) and (b) long distance (continuous). In the first case, refined sucrose, unrefined rotten peach and unrefined whole flies were tested for comparison and the dead flies substrate proved to be better. This was the substrate used in the long distance continuous experiments, in which EcoBot II was able to run continuously, with minimum human intervention for 12 days.

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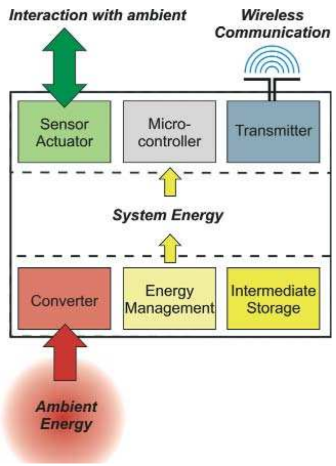
Energy Harvesting for Autonomous Microsystems

P. Woias, Y. Manoli, T. Nann and F. v. Stetten

Today, we are surrounded by a high diversity of distributed and decentralized systems. Pilot applications are easily identified with mobile phone, notebook and PDA. However, distributed systems – often based on MEMS devices – have meanwhile penetrated not only the IT sector but almost every area of our daily living. Examples are the steadily growing application of MEMS devices in cars, distributed sensor and actuator systems in buildings and industrial fabrication, distributed MEMS devices in medical care and, recently, MEMS-RFID tags in transport and logistics.
While RF communication may serve

This requires a complicated and error-prone power grid that is usually installed by hand, not easily maintained and, above all, does constitute a substantial cost factor. The use of batteries and other exhaustible energy sources is restricted to low power systems that are easily accessible for service and thus not a real alternative in many cases.

Micro Energy Harvesting, i.e. the conversion of ambient energy into a microsystem node's supply, promises a much better approach for operating a distributed system, as it would make the nodes energy-autonomous. We do this in the macro world by



varying energy supply, the need to bridge power-down phases and the environmentally friendly design of the power stations. These challenges do multiply if we tackle the field of "micro energy harvesting". A simple replacement of the battery or the supply cord by a "micro power plant" will not solve the task. In contrast, micro energy harvesting relies on a thorough design of the whole system (Figure 1). Converters have to be provided with a size and function compatible to the respective application site. The varying availability of ambient energy will require an efficient intermediate storage to bridge phases of low supply, as the back-up power grid is not available. A dedicated energy management has to transfer the electrical energy between all subsystems in an optimal way. And, finally, the energy consumption of the system node itself has to be minimized to a high extent by design and control measures.

Full compatibility with the main system functions and the ambient conditions is the prominent requirement for all energy harvesting methods. This is mostly accomplished by choosing the appropriate conversion principle. It is, for instance, not practical to employ a disturbing thermoelectric converter when the systems main task is temperature sensing. It is also impossible to use a large generator when the microsystem has to operate in a small environment, e.g. as a medical implant. This calls for conversion principles with a sufficiently high degree of miniaturization, high conversion efficiency and the capability of easy system integration. Several promising candidates for mechanical, thermal, optical and chemical energy harvesting are discussed in the following.

Piezoelectric converters

Mechanical stress in a piezoelectric material, like PZT ceramics or PVDF polymer, gener-

A dynamic mechanical load, e.g. from ambient vibration or sound, will result in an AC current. Miniaturized piezoelectric converters can deliver high electrical voltages (up to several volts) with currents in the microampere range. They do, however, require a careful mechanical design to provide a homo-geneous mechanical stress distribution in the piezoelectric material. Otherwise, the electrodes will short electrical charge from highly stressed regions with charge from low-stress regions. This internal short circuit will considerably reduce the conversion efficiency. A stress-homogenized geometric design of the converter can provide a homogeneous stress distribution and therefore maximum conversion efficiency [1].

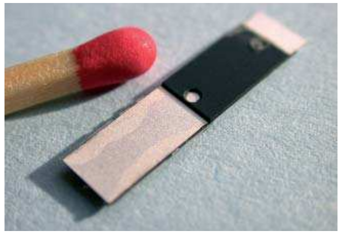


Figure 2: Piezo-polymer composite [3]

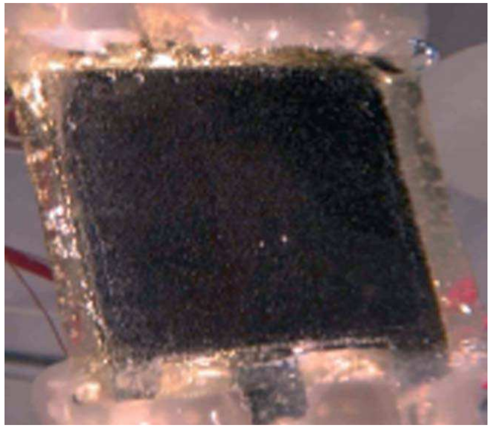


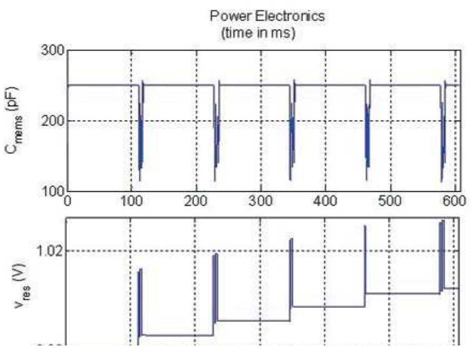
Figure 3: Polymer electrolyte glucose direct fuel cell: membrane unit with polymer coating (size approx. 30 x 30 mm²)

Today, autonomous RF power switches are available based on piezoelectric converters [2]. For these as for other applications (e.g. tire pressure sensing), a flexible and low-cost fabrication and integration concept is a premier demand. We have developed a piezo-polymer composite technology that integrates PZT ceramics into an almost deliberately shaped polymeric structure [3]. Although primarily developed for Microactuators, this concept is usable for an easy integration of piezogenerators, e.g. to make energy-delivering push buttons in polymeric electronic encasements or vibration converters in moulded IC housings.

Thermoelectric converters (TEGs) are based on the Seebeck effect, i.e. the generation of an electrical voltage in a thermocouple located in a temperature gradient. Suitable thermoelectric materials exhibit a high thermoelectric coefficient, low electrical resistivity and low thermal conductivity, such as bismuth-telluride alloys, polysilicon or silicon-germanium. If properly designed, a chip-based micro-TEG exhibits a typical power density of 0.6 µW/mm². This is sufficient for low power electronics, e.g. in wristwatches. However, the low voltage level (around 100 mV) has usually to be boosted by electronic means.

Nanocomposite Solar Cells

Photovoltaic energy conversion is among the oldest principles of energy harvesting. Especially flexible solar cells can be integrated in challenging application sites (e.g. in smart textiles) to supply energy-autonomous systems [4]. We have worked on flexible solar cells that use Cd-Te-nanocrystals embedded in a polymer semiconductor matrix [5]. These solar cells can be fabricated by spin coating technologies and are therefore much cheaper than silicon-based devices. When compared to pure polymeric concepts, their long-term stability should be higher. Also, the absorption spectrum can be tailored by applying appropriate nanocrystals.



Biofuel Cells

The sustainable power supply is a special problem for implantable microsystems. Currently such devices use secondary power cells that need surgical replacement at the end of their lifetime. Within the framework of the European "Healthy Aims" project [6] we investigate im-

body energy into electrical energy. For this, biofuel cells are superior to other technologies in terms of continuous power output, longevity, minimal invasive implantability and biocompatibility. However, not all types of fuel cells show the same advantages. Enzymatic fuel cells have a high reactant specificity, allowing a simple one-compartment design. They do, however, lack longevity and amenability to steam sterilization.

Due to their self-regenerating capability, microbial fuel cells have shown superior longevity. Until now, they have not been considered as implantable due to the infective nature of most known microorganisms. A third option, direct glucose fuel cells, is the focus of our current research due to their longevity, amenability to sterilization, and biocompatibility. A basic manufacturing protocol has already been established and tested, as shown in Figure 3. Typical energy densities of such biofuel cells are in the range of 0.1 to 100 µW/cm².

Energy and System Management

Most ambient power sources will only deliver a low level of usable energy. An energy management system will therefore have to seek ways to maximize the effectiveness of the power converter. Solar cells, for example, require an adaptive operating point in order to deliver their maximum power. This will be also true for all other sources. This adaptive control has to be intelligent enough to find the optimum set point without requiring too large amounts of energy itself. Of course, also the rest of the system needs to follow low-power concepts and must include extensive power management mechanisms.

So diverse the energy sources are, even more wide-ranging are the conversion principles that can be applied to convert the available energy to electrical power. For example, vibration energy can be converted through piezoelectrical means as described before, but also by electromagnetic or capacitive principles. And, although the energy source is one and the same, these conversion which have similar properties at their output and can be covered by similar circuit concepts. The first group includes all mechanisms that deliver high output voltages but small currents, like piezoelectric converters. The second group is constituted by converters with low output voltages but high currents, like capacitive, thermoelectric or electromagnetic generators.

In both cases the major requirement for efficient energy extraction is a proper impedance matching between transducer and conversion circuit in order to compensate for changes in the parameters of the generator or the energy source. Adaptive DC-DC converters are especially needed for piezoelectric transducers. Capacitive converters do require an even more complicated circuit structure with a synchronous switching to the energy source (figure 4). Naturally, the conversion circuit itself should be low power. It should be capable of estimating the amount of energy extractable from the ambient. It should cease conversion as soon as the energy input is below its own requirements in order not to waste power.

Many systems will not be able to rely on just one power source, either because of the amount of energy required or due to fluctuations of the ambient energies. Thus, hybrid systems will be required with different microgenerators, distinct conversion electronics and an even more demanding power management.

The development of micro energy harvesting is a challenge for science and engineering and still in its beginning. However, the vision of self-supplying networking microsystems that can be operated at remote sites and without service is an efficient commercial driver for progress in this pioneering area.

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