Multilayer Technology as an Integration System for Ceramic Micro Fuel Cells

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Abstract

Fuel cells are considered to be a possible alternative to battery technology for many years. But because of the too high production costs and the lack of long-term experience as well as the missing miniaturization of such systems there is no commercialisation. The aim of the Fraunhofer IKTS is the development of planar self-breathing µPEMFC system based on LTCC technology. By using this mass production technology togehter with multiple printed panels you can build highly compact and integrated micro fuel cell systems. The work presented here gives an insight into the development of µPEMFC system in various levels of integration and performance classes. They show the feasibility of miniaturization and cost reduction through integration of Balance of Plant (BoP) components and electronics in the bipolar plate of the fuel cell. Different sample systems give an outlook on possible approaches for further miniaturization.

Key words: LTCC, fuel cell, PEFC, USB charger, fuel cell charger

Motivation

In recent years the development of entertainment electronics goes to mobile computers such as tablet PC and smartphones with increasing processing power and screen resolutions. Special features for example digital camera, mp3-, video-player, mobile internet, GPS navigation leads to an increased energy consumption of these devices. In spite of increasing energy density of the Li-Ion technology the battery life of mobile devices is not extended. The desire for higher energy density and faster load times combined with a smaller volume is the first priority of the electronic industry. One possible approach for higher energy densities, especially for long time operation offer micro fuel cells (e.g. µDMFC, µPEMFC). The possibility of refilling a fuel cartridge offers an alternative to the long loading times of batteries. For many years the ceramic multilayer is used in the automotive and communication industry as a reliable and extremely robust material system. This technology offers the possibility to integrate all necessary components of a micro fuel cell system. The LTCC (Low Temperature Co-fired Ceramics) technology is a special multilayer ceramic technology which enables producing multiple printed panels similar to wafer manufacturing processes. The advantage is production of high volumes with parallel processes and lower costs.

For many years the IKTS has competence in the LTCC Technology and deals with the development of miniaturized systems in LTCC and HTCC. Because of the expertise in the development of ceramic base materials and conductive pastes the necessary operation experience for building a micro fuel cell completely available in-house. Since 2002 IKTS deals with the development of air breathing µPEMFC in LTCC and has built up various technology demonstrators. The work shown here presents an insight into the development of passive air breathing systems in LTCC and gives an outlook into possible development goals and technological challenges.

LTCC Technologie for Micro Fuel Cell Systems

The LTCC technology offers an integration platform for micro fuel cell systems. For example the electronic packaging to implement DC/DC converters, User Interfaces and actuator control is possible. Also complex channel geometries for providing reactions with fuel gases are possible to integrate. Due to the specific material properties of LTCC (hermetic, chemically stable and mechanically rigid) bipolare plates can be developed. If the micro fuel cells have to be positioned on the market they must be cost-effective and profitable. The general manufacturing process of a multilayer-based µPEMFC is shown in figure 1. At the beginning the still unsintered films are cutted into their processing dimensions (4x4, 6x6 or 8x8 inches). In the next step a punching machine punches electrical connections and stack labels in the tape (vias). In the following screen printing process metallisations are applied and the individual layers will be laminated (uniaxial or isostatic) as shown in the figure 1. By laser cutting the openings in the cathode side and the gas channels in the anode side were structured. After the sintering process and the following separation of the bipolar plates out of the multiple printed panels you get a monolithic ceramic fuel cell with the desired properties.

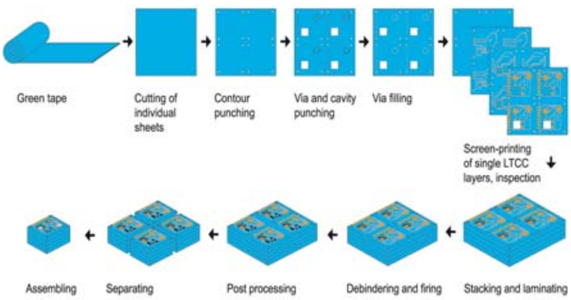

Figure 1: LTCC manufacturing process steps

High-speed 3D Structuring of Multilayer Ceramics

Because of necessary cost reduction a multilayer microstructuring equipment for large substrate sizes is needed. In cooperation with KMS Automation GmbH a new automated machine was developed which combines the ability for micro punching and laser micromachining for ablating and cutting (UV laser by Spectra-Physics, wavelength 355 nm, 20 W). The machine has an option for automated feeding of tapes or substrates. The prototype machine (figure 2) is built for Fraunhofer IKTS to test and manufacture multilayer components (LTCC, HTCC). With this prototyping machine structuring of 8x8 inch substrate in combination of ablating cavities in the range of 50 µm and punch vias in the range of 50 µm is possible [1]. Using this newly developed combination of laser and punching machine simultaneous punching and subsequent laser processing of substrates are possible.

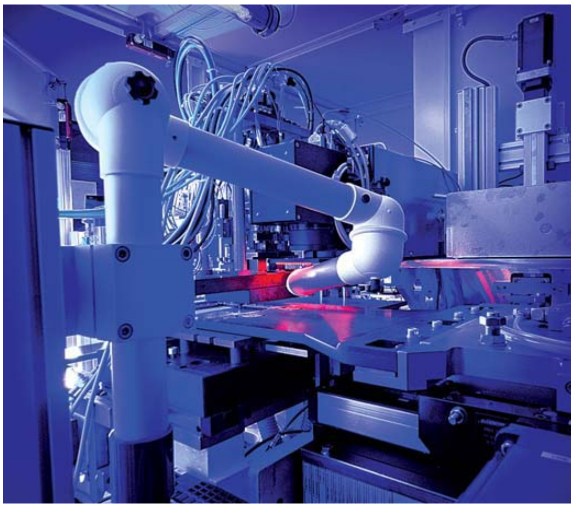

Figure 2: Prototype machine, a combination of laser and punch

The automatic feeding system allows time-efficient working. Figure 3 shows an 8x8 inch substrate of a µPEMFC cathode array produced by this new technology.

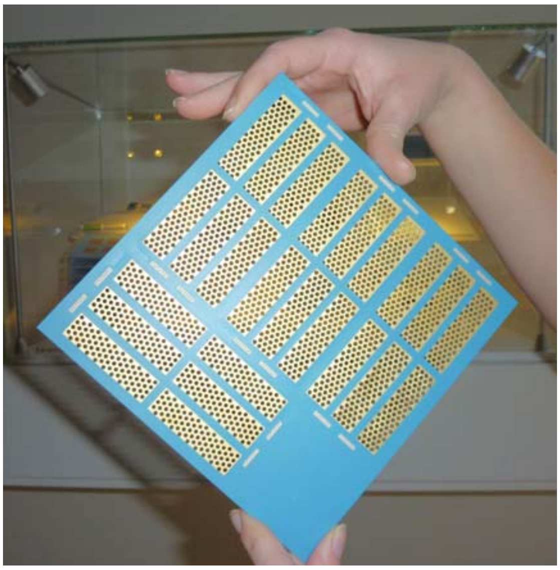

Figure 3: 8x8 inch substrate of a µPEMFC cathode array

Specifcation and Research Goals

According to the EU initiative of standardization of cell phone and smart phone charger interfaces [2] all the European cell phone manufacturers (e.g. Nokia, Apple) agreed to the micro USB standard 3.0 to be the standard charging port. This development could help the fuel cells to enter into the commercial market as universal charger systems. First prototypes of marketable system are already presented from Motorola, MYFC or Horizon.

Results of Research Aktivities for Ceramic µPEFC

Since 2002 the IKTS develops planar self breathing micro PEFCs. The goal was to develop passive, miniaturized and simply structured fuel cells in LTCC technology to build very compact and simple systems. The feasibility of PEFC production in multilayer ceramic has been shown since 2002 and was steadily improved (figure 4) [3].

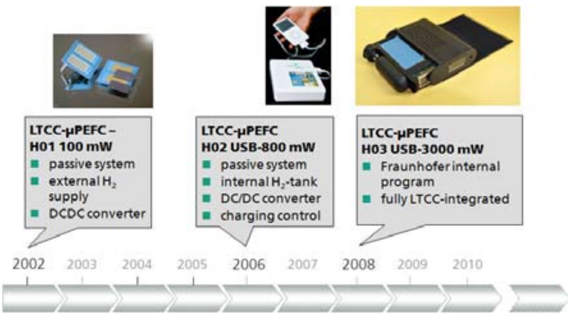

Figure 4: Timetable of micro fuel cell development at the IKTS

In early 2006, the IKTS presented a prototype of a fuel cell charger on international trade fairs and showed the feasibility of the system. The base of this unit was a 1 Watt LTCC multilayer fuel cell with a 5 volt USB 1.1 specified charge output (figure 4) [4].

In early 2008 a 3 watt USB 2.0 charging system was developed with all necessary components for the regulation and the control of the system (valves, charger interface, USB output voltage generator). In addition a user interface with a removable hydrogen cartridge system was implemented. The size of this system was 125x100x35 mm and the most space was used for the cartridge compartment and the valve implementation. The format of the planar fuel cell stack was 85x35x4 mm with a maximum power of about 3 watts a serial connection of 6 cells and a power density of 120 mW / cm^ 2. In this system metal hydride hydrogen storage was used. The system could be operated for 5 hours and had a capacity of 15 watts per hour [5].

The hydrogen cartridge was a commercially available product of the company Horizon. To extend the operating time the cartridge could be changed at any time by simple turning the cartridge out of housing. Figure 5 illustrates the buildup of the system.

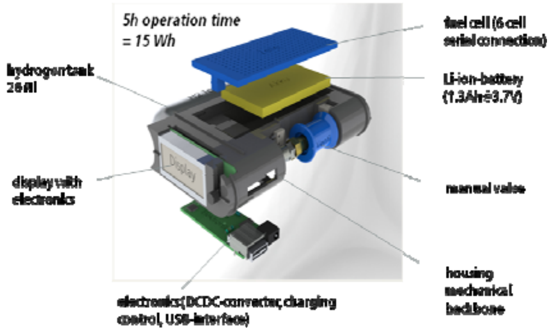

Figure 5: 3 watt USB 2.0 charging system

Since 2009, with the help of simulation tools such as Ansys and Comsol the geometry parameters were optimize. With the foundation project M3 of the Fraunhofer Gesellschaft the patent to minimize the internal resistance of an electrochemical cell was developed and with the new technological layout could be realized only by multi-layer technology [6]. A finite number of vertical through connection (vias) were introduced in the individual ceramic layers and connected to an inner current collector layer and afterwards lead to the external contacts. Advantages of this layout are the use of highly conductive internal silver layers and the parallelism of the power dissipation (uniform current distribution). This allows to minimize the use of expensive gold and additionally connects non contactable surface area to the outside. An example of the simulation results shows the figures 6a and 6b.

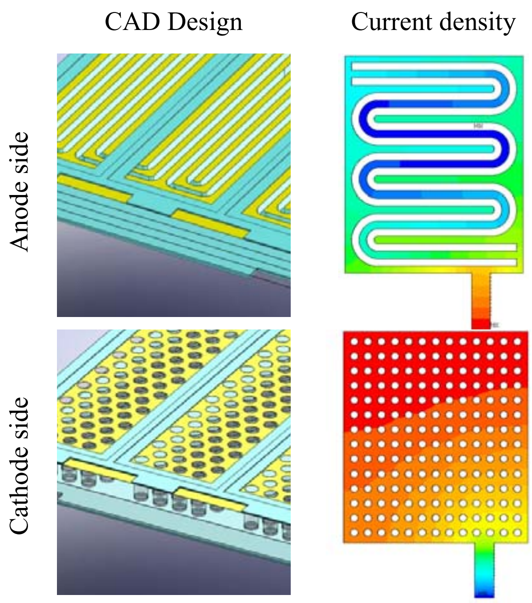

Figure 6a: Simulated top layer current collection

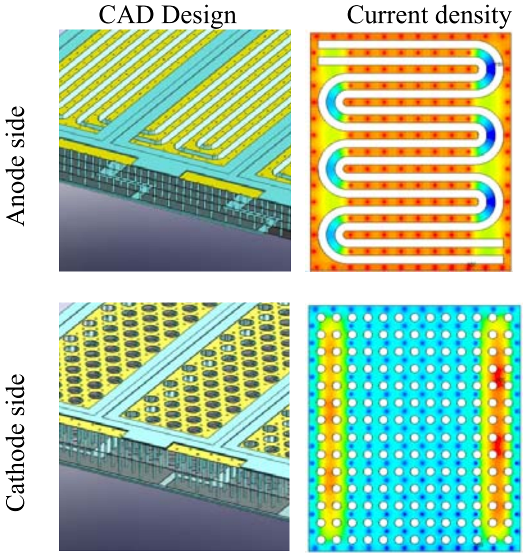

Figure 6b: Multiple layer current collection with vias

A further result of this project was a procedure to replace the gold layer on the top of cathode and anode sides [7]. By using polymer pastes after ceramic sintering a passivation with thin carbon layer was printed over the silver vias. In combination the two patents a very cost-reduced solution while minimizing the internal resistance was achieved. Therefore, the cost of a multilayer PEFC was reduced significantly whereas system integration and miniaturization was increased.

Next Step of Miniaturization and Integration LTCC µPEFC

At the moment the development of the LTCC µPEFC USB charger in the power range of 5 W with USB 3.0 specification starts. The target size of the system is 110x52x15 mm. Compared to the previous system the size is smaller by 1/3 while the energy density doubles. These properties are mainly caused by the integration of electronics directly on the anode side and the implementation of the control valves in the LTCC ceramics. An initial design for such a system be seen in figure 7. A key advantage of such packages is the close coupling between the metal hydride tank and the fuel cell. Because of the discharge of the hydrogen storage and the redox reaction inside the PEFC the stack is cooled simultaneously. Additionally overheating of the system is minimized. Using a quick-change coupling the metal hydride storage can be exchanged during operation time. In this situation the integrated battery supplies the system and the consumer load. With the special valve design (Normally Closed) and internal temperature and pressure monitoring the security of the system can be improved and the risk of failure minimized.

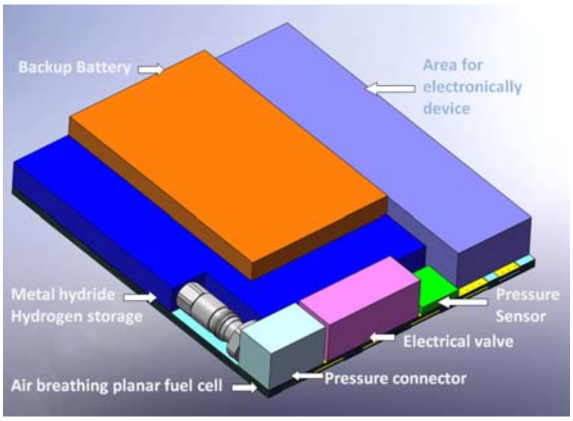

Figure 7: New schematic design of a LTCC USB charger

New µPEFC Stack Design

Current work is focused on the development of the LTCC µPEFC stack. The 6-cell stack is designed in a planar arrangement. The cathode is made completely passive and the supply of the anode with hydrogen is carried out by pressure from the hydrogen storage system. The current design (Figure 8) was designed by using the previous development with the internal power dissipation and the ability to use carbon electrodes.

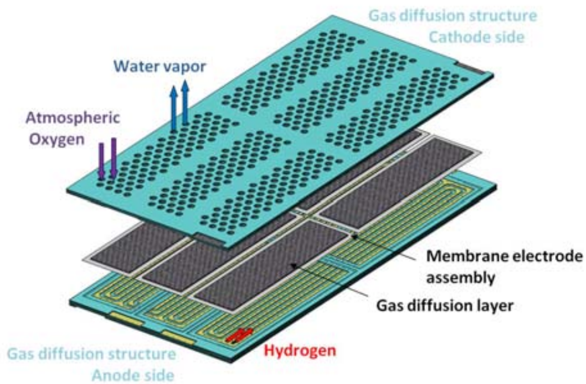

Figure 8: New µPEFC stack design

The dimensions of the stack comes to 106x51x2,5 mm. In experiment the good performance has already been proven and a maximum power density of 120 mW/cm^2 was achieved. The characteristic curve of the stack is shown in figure 9 with parameters in the following table 1.

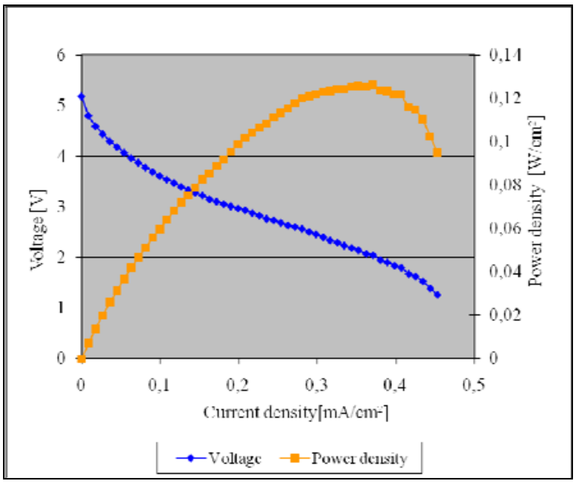

Figure 9: Characteristic of the new µPEFC stack

Table 1: Parameters of measurement

Parameter	Data / Discription
MEA	Gore 5710 (A510.1 ; K510.4) Anode: 0.1 Pt[g/cm²] ; Cathode: 0.4 Pt[g/cm²]; Thickness: 18µm
GDL	SGL Carbon Group (Anode: 35 BC / Kathode: 35 BA)
Number of fuel cell	6 cell, every 5.52 cm² (serial connection)
Gas composition	H_2 5.0 Linde
Gas pressure and flow	Anode flow mode: 100 ml/min Kathode air breathing: Atmospheric oxygen
Environment temperature	Room temperature (23°C)
Mounting force	0,8 N/mm²

The preparation was carried out in the newly evaluated 8x8 inch standard LTCC Technology (Figure 1). Every 8-inch substrate consists of four bipolar plates (Figure 3). After separation by laser the individual parts of the fuel cells were glued together with a vision controlled micro-dispenser (Asymtec Axiom X1000). The final assembly prressure was 0,8 N/mm^2. The serial interconnection of the cells was done with silver glue or soft solders at the edges. A ready manufactured fuel cell is shown in figure 10.

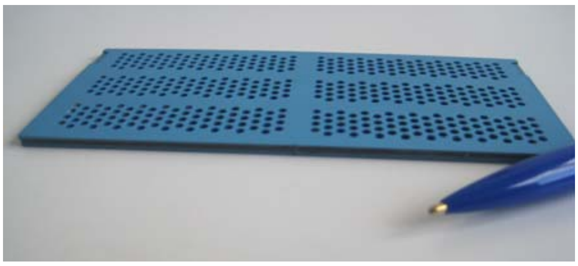

Figure 10: 6-cell µPEFC LTCC stack

Aktor integration

An important part of system miniaturization is the integration of valves on the LTCC interconnector. Gas supply, gasket seal and the positions system were integrated in the LTCC ceramic (figure 11). This special, extremely compact valve design allows the supply of hydrogen to fuel cells while providing an important safety feature. In case of an automatically power failure the valve closes and remains closed (normally closed function).

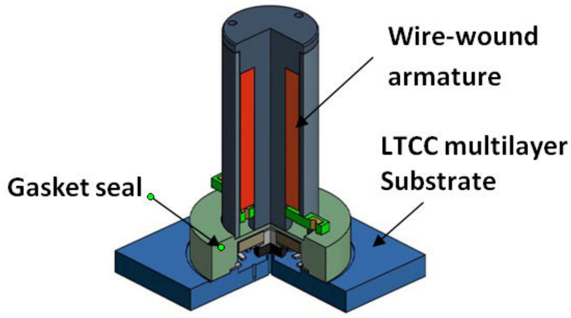

Figure 11: LTCC integrated valve

The design parameters of the fuel cell system were evaluated by FEM modelling. Already the first prototypes of the valve showed their functionality. In the next step the assembly is positioned on the LTCC substrate with subsequent characterization of properties such as leakage rate, maximum pressure, maximum flow rates of hydrogen and electric power consumption. Figure 12 shows the actuator of the valve.

Figure 12: The Actuator of the LTCC integrated valve

Electronic Integration on the Anode Side

The final step is the development of a control and evaluation unit as well as the power conversion and charging mangement for USB 3.0 devices. Efficiency is the main focus of the individual parts. Using a micro-controller all relevant systems (valves, sensors) can be controlled and displayed via a user interface. All necessary electronic components are implemented on the anode side of the fuel cell by SMD assembly. The development of electrical structure and circuit design of the controlling electronics will be the work for the next time.

Conclusion

The work on µPEFC systems and LTCC as an integration platform could make a contribution for miniaturization of fuel cells charging systems. In several prototypes the feasibility, ever-increasing functionality and power density were already demonstrated. The ongoing work shows again the increasing of the level of integration with the help of implementation of functions such as valves and electronics. Thus, the energy density per volume is increased and the overall system can be miniaturized (total volume is 86 cm$^{\wedge 3}$). In later work the following sectors of development (stack, valves and electronics) are combined and assembled as one system.

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