Stability of planar PEMFC in Printed Circuit Board technology

A. Schmitz [a,*], S. Wagner [b], R. Hahn [b], H. Uzun [b], C. Hebling [a]

[a] *Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, 79110 Freiburg, Germany*
[b] *Fraunhofer Institute for Reliability and Micro Integration, Gustav-Meyer-Allee 25, 13355 Berlin, Germany*

Abstract

The use of planar PEMFCs in printed circuit board (PCB) technology with a thickness of less than 3.5 mm are presented. This planar design consists of an open cathode side which allows a completely passive, self-breathing operation of the fuel cell. Power densities of 100 mW/cm^2 at 500 mV with hydrogen as a fuel were achieved. A steady operation with this type of fuel cell was demonstrated over a week without any cell flooding. Since the electrical conducting elements of PCBs usually are made of copper, corrosion in the wet environment of a PEMFC is expected. Thus, a significant degradation in performance of fuel cells made of plain copper PCBs was seen in long-term operation. In order to avoid corrosion, the copper layer has to be coated. Fuel cells in PCB design with diverse coatings were tested in long-term operations up to 1000 h under load. Moreover, corrosion currents have been determined by the use of potentiodynamic scans. Promising coatings are electroplated Cr and Ni and a combination of Ni/Au.
© 2003 Elsevier B.V. All rights reserved.

Keywords: Planar PEMFC; Printed circuit board (PCB); Self-breathing; Stability of performance; Corrosion; Long-term operation; Production process; Open cathode

1. Planar PEMFC in printed circuit board (PCB) technology

Miniaturized fuel cells offer beneficial opportunities as a supplement or substitute to batteries. The recent development of miniaturized fuel cells is driven by the increasing power and energy need of electronic devices [1,2]. Among the widespread of appliances which can be powered with PEM fuel cells, promising fields of use are consumer electronics, sensors and medical devices.

For many applications, an integrated power source has to posses a flat geometry. Thus, fuel cells with a planar design are advantageous compared to the conventional stack design. Planar fuel cells can be integrated in the housing of electronic devices. In this packaging concept, the planar fuel cell can serve as part of the housing itself. Therefore, this dual use concept allows to optimize the volume of the power source.

The preferable planar design consists of an open cathode side to allow passive, full self-breathing operation of the fuel cell. Thus, a planar fuel cell could be integrated into the screen's backside of a notebook computer or into the backside of a cell phone. An important advantage of the open cathode is that an additional ventilation by fans is not needed.

The type of planar fuel cell presented in this contribution is realized in PCB technology. PCB technology is a well-established mass production process. Therefore, the main motivation to manufacture fuel cells in PCB technology is to achieve low costs. A quick upscaling and the ability to produce different cell types in the same process are other advantages of PCB technology. Furthermore, electronic circuits can be integrated on the board which might act as an electrical consumer itself or as an auxiliary unit with, e.g. dc/dc converter.

Serial connection of cells in planar design is realized by electrical connection of the anode of one cell with the adjacent cathode side. Thus, serial connection is more challenging compared to the stack design. In PCBs, several circuit layers can overlap to meet the demands of today's high density packaging electronics. In this so-called 'multilayer technology', the circuit layers are separated by insulating composite material and electrical connections from layer to layer are made standard like. The multilayer approach offers the ability for serial connection integrated on one board. Therefore, the multilayer technology is ideal to realize the serial connection of a fuel cell system consisting of several single cells in a mass production process.

* Corresponding author.
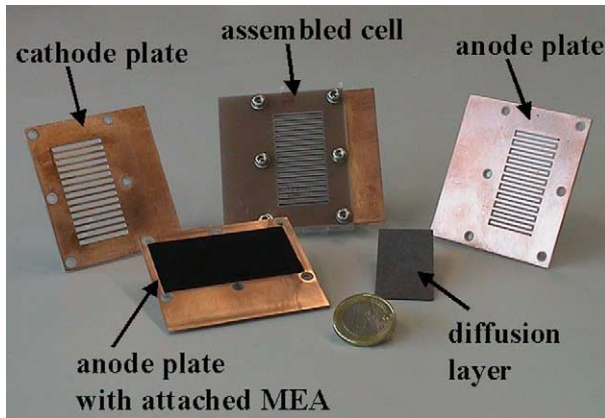*E-mail address:* astz@ise.fhg.de (A. Schmitz).

Fig. 1. Depiction of an assembled fuel cell in PCB design and components.

avoid short circuits between the copper layers plates. This assembly is pressed together by six screws (size M3) with a torque of 0.5 N m each. The assembled cell has a thickness of nearly 3.5 mm. For future applications, the contact pressure between the plates will be realized by adhesives at the edges which will be pressed together while curing.

In the experiments, the cells were supplied with a hydrogen flow of $30\,cm^3/min$. Fig. 2 shows a typical polarization curve of this open and self-breathing planar PEMFC. In the maximum power point, a power density of $110\,mW/cm^2$ is achieved corresponding to a current density of $275\,mA/cm^2$ and a cell potential of 400 mV. These characteristics are in the range of power densities reported for stacks operated at room temperature [3].

2. Construction of test cell in PCB design

The planar fuel cells used in the experimental part are made of ordinary printed circuit boards (Fig. 1). These boards consists of a thin copper layer $(35\,\mu m)$ laminated on a substrate, which is a composite material of glass fibre and epoxide. In the anode plate, a serpentine flow-field consisting of a single channel with a depth of 0.8 mm is machined. The channel and the ribs of the flow-field have a width of 1 mm. The cathode plate consists of parallel, rectangular openings $(1.5\,mm \times 20\,mm)$ having a distance of 1 mm. The electrochemical active area of this geometry has a size of $20\,mm \times 50\,mm$. In the active area, the copper layer of the PCB acts as current collector and outside as current conductor towards external electrical contacts.

The membrane electrode assembly (MEA) is attached by adhesives on the anode plate. A PRIMEA® 5510 from Gore Associates with a Pt loading of $0.3\,mg/cm^2$ and an ionomer thickness of $35\,\mu m$ is used as the MEA. Diffusion layers are located between the plates and the MEA. As diffusion layers, Toray® carbon paper with a thickness of $350\,\mu m$ was used. Additionally, a thin foil with a rectangular notch in the size of the active area is sandwiched between the plates to

3. Operation stability of fully self-breathing fuel cells

The special feature of this fuel cell type is the passive air supply of the large open cathode. In most PEMFCs, the cathode is located in a closed compartment and is supplied by an active flow. Even the openings of so-called self-breathing stacks are only in the size of the channels cross-sections. The cell described in this paper has an open area ratio of 60%. Due to this large open area, ambient conditions may effect the cell performance in such a way that the operation is unstable. Furthermore, there might be concerns that the cell performance could decrease due to a high water production and an insufficient water removal. In order to study the stability in performance, two cells have been operated and monitored for more than 100 h. As the orientation of the cell may have an effect on the performance, the cells were operated in two different positions: one cell was mounted in a horizontal position with the open cathode upside and a second was fixed in a vertical position. The cells were operated with a constant load of 1 A which corresponds to $100\,mA/cm^2$. The constant load was realized with a Wenking HP88 potentiostat in galvanostatic mode. The behaviour of the voltage under load is shown in Fig. 3. In addition, the
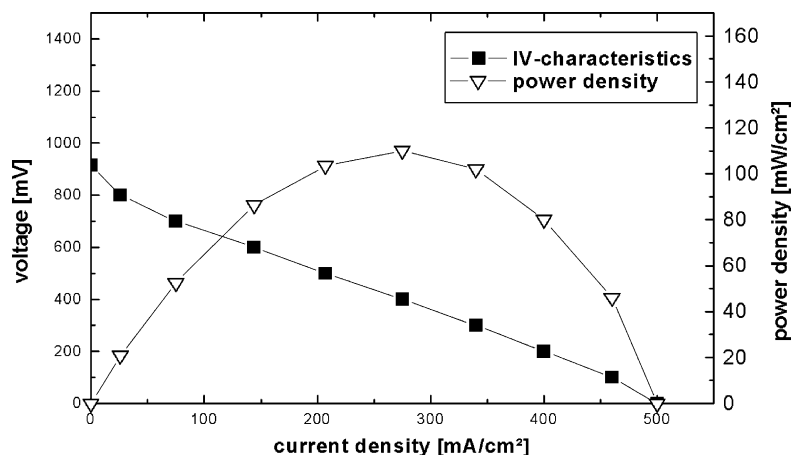

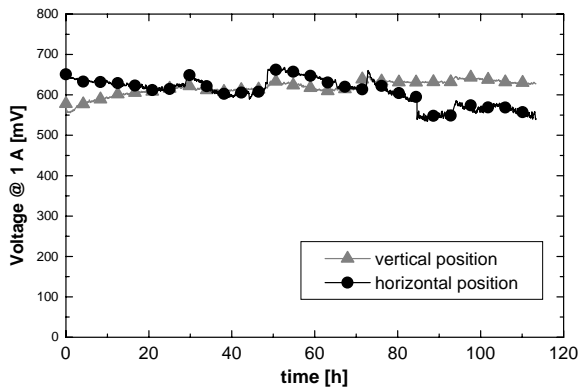Fig. 2. Typical *I–V* and power characteristics of an open, self-breathing PEMFC in PCB design operated with hydrogen.

Fig. 3. Behaviour of the voltage under a load of 1 A (100 mA/cm^2) in a long-term experiment of a PCB cell with open cathode in horizontal and vertical positions.

relative humidity and temperature were measured by sensors in a distance of 8 mm above the open cathode (Fig. 3). Furthermore, relative humidity and temperature under ambient conditions were monitored. As can be seen from Fig. 3, the fluctuations of cell potential under load of both cells were in the range of ±10% over more than 110 h operation time. Taking into account the large open cathode area this is a fairly stable result. The humidity values (Fig. 4) fluctuate in the range of 40–65% over operation time. For both cells, a higher humidity than the room humidity is measured. Further humidity of both cells is highly correlated to the humidity under ambient conditions.

The temperature near the cells and in the room is nearly identical. Therefore, in Fig. 4, only the temperature under ambient conditions is shown. The oscillations of ambient temperature were in the range of 25–31 °C. The temperature of the cells themselves were separately measured each day by hand. These cell operation temperatures were in the range of 40–44 °C.

The PCB fuel cell in the vertical position shows a more stable performance compared to the cell in the horizontal
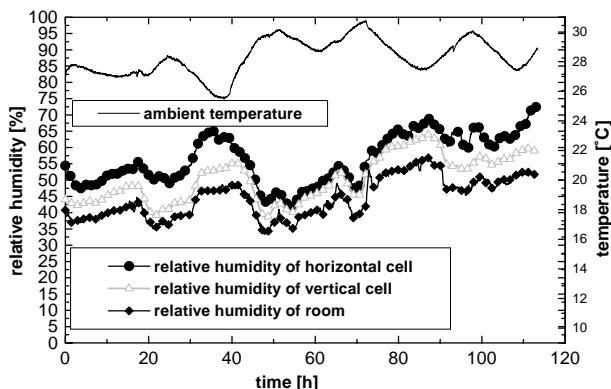

Fig. 4. Relative humidity measured during the stability test near the cathode of the cells in horizontal and vertical positions, respectively, under ambient conditions. Additionally, the temperature evolution over time near the cathode is shown.

position. Additionally, the relative humidity of the horizontal cell is slightly higher. An explanation for this behaviour might be that vertical position condensed water droplets in the diffusion layer have the ability to flow downwards. Therefore, a higher stability and lower relative humidity is measured for the cell in the vertical position.

The overall performance in both positions was fairly stable. Due to the stationary behaviour of the voltage under load, a fatal flooding with water does not occur even for the cell in the horizontal position. Furthermore, the relative humidity above the cathode of both cells is far below saturated conditions.

4. Long-term operation with pure copper layer

As the electrical conducting elements are made of copper, corrosion in the wet environment of a PEMFC is expected. Oxidation of metal components in fuel cells can have several effects [4]: as metal ions of the oxidized species are dissolved in the water produced in the fuel cell, they have the ability to migrate in the compartment of the cell. By this means metal ions come into contact with the MEA where metal which is deposited in the electrochemical active layer might lead to a poisoning effect of the catalyst. Moreover, metal ions can roam through the ionic conducting membrane and precipitate on the anode side. Thereby electrical conducting paths through the membrane can be formed. In the long run, the thin current collectors (35 μm copper) of the PCB cell will vanish as the metal is dissolved.

In order to determine the lifetime of a fuel cell using pure copper PCB current collectors, a long-term operation experiment was carried out. In this long-term test, a cell was operated in horizontal position with cathode openings upside at a constant load of 1 A according to 100 mA/cm^2.

A polarization curve with a scan rate of 1 mV/s was recorded every 24 h. Subsequently, the open circuit voltage (V_{oc}) was measured for a period of 5 min. This cell test procedure and data acquisition was performed using a MACCOR multichannel battery test facility.

In Fig. 5, the development of the I–V characteristics over a period of 800 h of operation are shown. A deterioration of cell performance can be seen in the development of I–V characteristics over time (Fig. 5). In the same period of time, the open circuit voltage (V_{oc}) of the cell decreases from 930 to 400 mV. The I–V characteristic after 10 h is only slightly below the values in the beginning but shows significant lower steepness around V_{oc}. The other I–V curves are parallel to the bottom. Moreover, they do not show any characteristic of decline near V_{oc}. The characteristic steep decrease near V_{oc} is evoked by activation losses described by Larminie and Dicks [5]. As the activation loss behaviour is not observed, the cell may be partially under load due to copper paths through the MEA. Currents flowing over these paths cannot be measured. Therefore, the observed V_{oc} is not a regular V_{oc} but a voltage under a certain internal load.
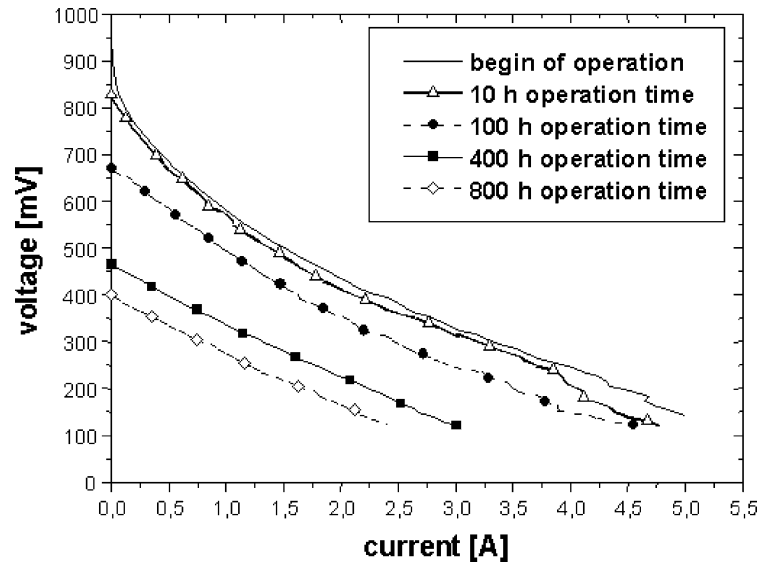
Fig. 5. Degradation of *I–V* characteristics of a fuel cell using pure copper PCB current collectors.

After degradation, the cell was operated for a few hours without an external load. During this experiment, a warming of the cell was observed, which gives an indication of internal loads. Moreover, a copper content of up to 2% has been found on both sides of the MEA by Auger spectroscopy.

As seen from other long-term tests with pure copper PCBs, a stable operation time of approximately 100 h can be achieved (see also Figs. 3 and 4). After this time degradation effects are observed. Therefore, pure copper PCB cells are not appropriate for long time operation but the testing of construction parameters such as size of openings and diffusion layer characteristics is still possible.

5. Coating of PCB plates

In order to avoid the described degradation, the copper layers can be coated with a passivating metal surface. A passivating surface can be obtained by the deposition of a noble metal or a thin metal oxide layer. Additionally, the passivating surface has to be electrically conductive with a low contact resistance. The coating has to assure an impermeable cover of the copper layer to prevent any contact of the less noble copper to the electrolyte and to prevent diffusion of the copper through the coating. Often a combination of coatings is used with a deposited metal serving as a diffusion barrier and a thin passivating layer on top. A well-known example for this is a combined coating of nickel and gold layers.

Several coatings and combinations of coatings were tested for use in PCB fuel cells. These covers have been applied on the copper surface by electroplating, chemical plating or sputtering. Single coatings examined in this paper are listed in Table 1, whereas combinations are summarized in Table 2.These coatings are state-of-the-art coatings in the PCB industry or could be easily adapted to this process.

Table 1
Single coatings of PCB plates

Notation	Description
10 μm electropl. Ni	Electroplated nickel
5 μm chem. Ni	Chemical deposited nickel
1 μm Cr	Electroplated chrome
10 μm Sn	Chemical deposited tin
TiW sputtered	Sputtered titanium–tungsten alloy (200 nm)

Table 2
Coating combinations of PCB plates

Notation	Description
10 μm Ni/2 μm Au	Electroplated nickel and electroplated gold
10 μm Ni/flash Au	Electroplated nickel and flash gold (200 nm electroplated)
10 μm chem. Ni/0.5 μm Au	Chemical deposited nickel and electroplated gold
10 μm Ni/10 μm Sn	Electroplated nickel and chemical deposited tin

The suitability of the listed coatings will be determined with the use of corrosion measurements and long-term operation tests.

6. Corrosion tests

In a corroding system, a metal specimen M is in contact with a liquid in which a species Z is in solution. When the metal sample M has no external contact the specimen assumes a potential termed the corrosion potential E_{cor} (often also referred to as open circuit voltage of the sample which has to be distinguished from the V_{oc} of the fuel cell). At the potential of E_{cor}, there are two co-existing electrochemical reactions present [6,7]: the oxidation reaction

$M \leftrightarrow M^+ + e^-$ leading to an anodic current and the reduction reaction $Z^+ + e^- \leftrightarrow Z$ leading to a cathodic current. At the corrosion potential E_{cor} anodic and cathodic currents are on the specimens surface. However, these currents are exactly equal in magnitude so there is no net current to be measured and the specimen is at equilibrium with the environment. If the specimen is polarized slightly more positive than E_{cor}, the anodic current predominates at the expense of the cathodic current.

Besides the long-term test under operating conditions, corrosion measurements were carried out to allow a pre-selection of promising coatings. The chosen corrosion test method was potentiodynamic polarization which is the characterization of a metal specimen by its current–potential relationship [6]. In a potentiodynamic experiment, a relatively large potential domain relative to the corrosion voltage E_{cor} is scanned [7]. Since the measured current can vary over several orders of magnitude usually the log current function is plotted versus potential on a semi-log chart. Fig. 6 shows an example of a potentiodynamic curve [6]. The spectra beginning at approximately -0.25 V from E_{cor} and ending at approximately $+0.25$ V from E_{cor} is referred as Tafel region. It contains the cathodic branch for negative potentials, whose negative current values are plotted as absolute numbers. The anodic branch of the potentiodynamic scan is extended up to 1.25 V versus E_{cor} and is typically non-linear and in certain situations can have S-shapes like depicted in Fig. 6.

The primary passivation potential E_{pp} is important for the interpretation. It is the potential after which current either decreases or becomes essentially constant over a finite potential range. Whereas the breakdown potential E_{bp} is the potential where current increases with increasing potential. The passive region is the portion of the curve between E_{pp} and E_{bp}. In the passive region, little or no corrosion occurs. The portion of the potentiodynamic curve where potentials are more negative than E_{pp} is referred to as the active region in which general corrosion and sometimes pitting cor-

rosion appears. The portion of the curve where potentials are greater than E_{bp} is referred to as the transpassive region of the curve, where pitting corrosion can emerge [6].

According to potential conditions in a real fuel cell which are in the range of 0–1 V, this method is suitable to simulate the corrosion behaviour in a PEMFC. Therefore, potentiodynamic scans of different coatings can be compared on a rational basis and allow a choice which coatings might be suitable for use in a PEMFC environment. The above-mentioned coatings (Tables 1 and 2) have been characterized by potentiodynamic scans.

A 5% aqueous solution of Na_2SO_4 was used as electrolyte. As working electrodes, the structured and coated PCBs were used. The counter electrode consisted of a graphite board of the same size as the board. In a sample holder working and counter electrode were parallel positioned with a distance of 8 mm. Working and counter electrode were 20 mm immersed in the electrolyte resulting in a contact surface to the solution of approximately $12 \, cm^2$ each. A saturated calomel electrode (Philips 6.0702.100) served as reference electrode, which was positioned sideways between the working and counter electrode.

The model 263 A from Princeton Applied Research was used as a potentiostat. The current–potential relationship in the experiments was recorded with a scan rate of 1 mV/s. With this technique, a pure copper PCB and the above-mentioned coatings of PCBs were characterized. The results of these potentiodynamic measurements are plotted in Fig. 7a–e.

In Fig. 7a, a potentiodynamic scan of a pure copper PCB board is compared to a board coated with a combined electroplating of 10 μm Ni and a Au flash. In the copper scan, no passivation potential E_{pp} and breakdown potential E_{bp} appears to be present and current increases continuously with potential throughout the entire anodic branch. The current increases continuously from 10^{-6} to nearly 1 A. This indicates an active corrosion behaviour where general corrosion and pitting corrosion are occurring. In the scan of the 10 μm
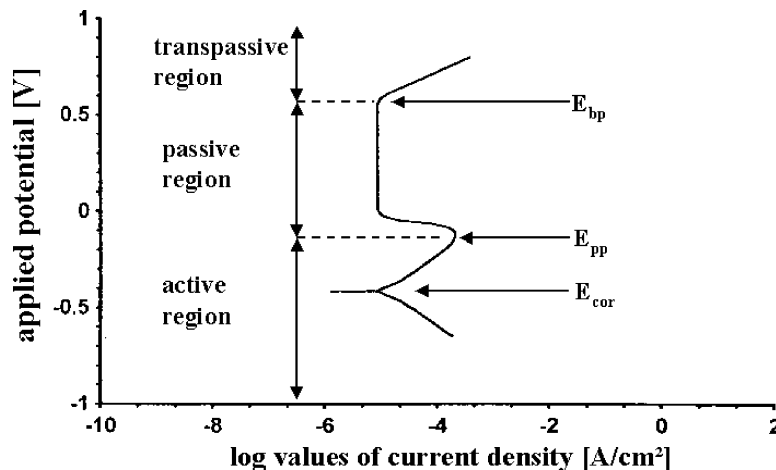
Fig. 6. Schematic example of a potentiodynamic curve showing active region, passive region and transpassive region [6].
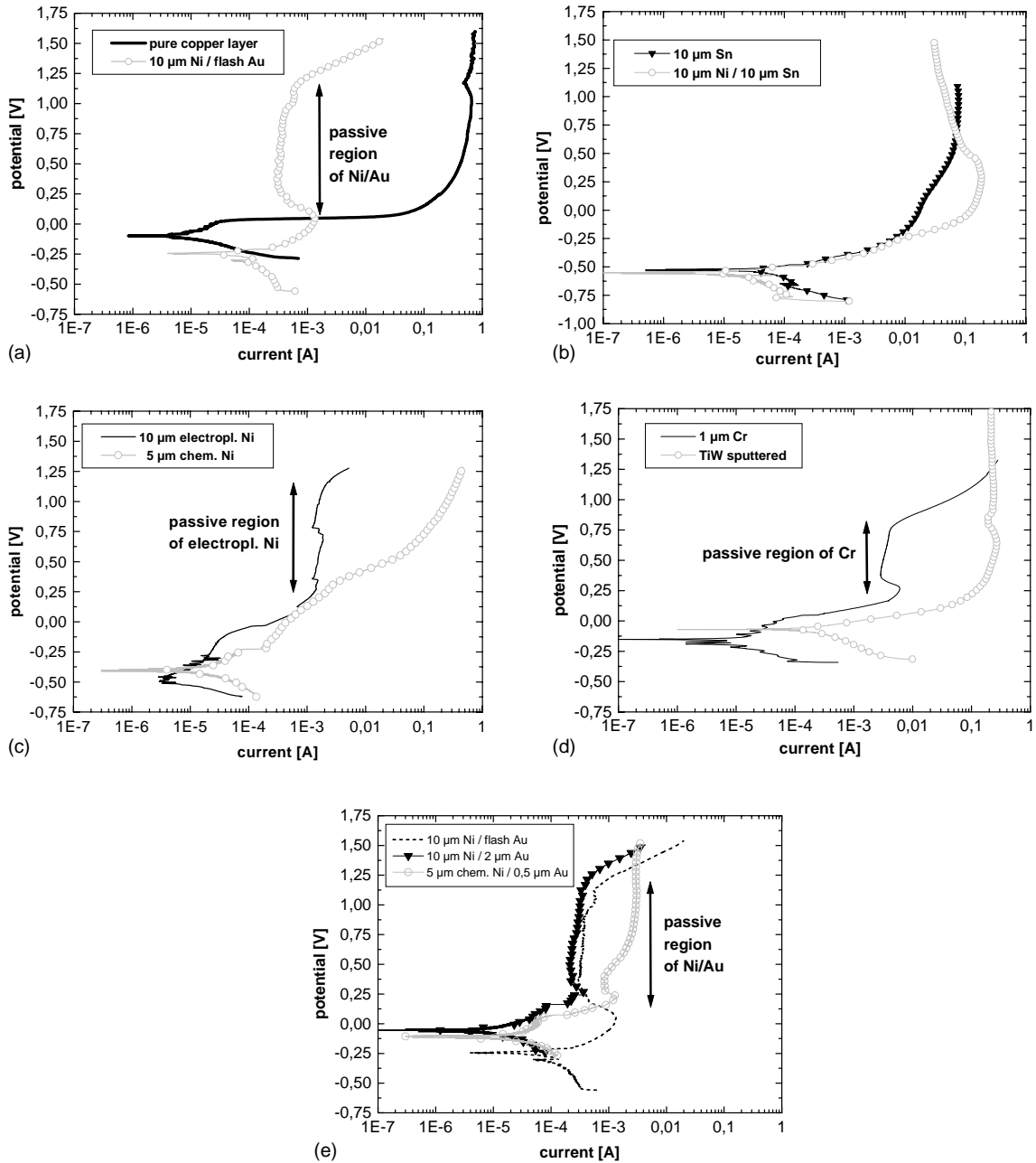
Fig. 7. Comparison of potentiodynamic scans for a plain PCB plate (pure copper layer) and different coatings of PCB plates. (a) Potentiodynamic scan for a pure copper PCB and for a combined coating of 10 μm Ni and flash Au. (b) Potentiodynamic scan for chemical deposited 10 μm Sn and a combined coating of electroplated 10 μm Ni and chemical deposited 10 μm Sn. (c) Potentiodynamic scan for electroplated 10 μm Ni and 5 μm chemical deposited Ni. (d) Potentiodynamic scan for electroplated 1 μm Cr and sputtered TiW alloy (200 nm). (e) Potentiodynamic scans for different Ni/Au combinations.

Ni/flash Au coating combination, a large passive region from 0 to 1.2 V is seen. The transpassive region with increasing currents is found in the potential range over 1.25 V. The currents in the passive region are smaller than 10^{-3} A and three decades smaller compared to the corrosion currents of the copper probe at the same potentials. The comparison in Fig. 7a displays the significantly higher passivating behaviour for a Ni/Au cover compared to a pure copper layer.

In Fig. 7b, the potentiodynamic scan of 10 μm Sn (chemical deposited) and a combination of 10 μm Ni (electro-

plated)/10 μm Sn (chemical deposited) is shown. The Sn probe shows an active corrosion behaviour over the whole anodic branch with corrosion currents a decade smaller than the plain copper board. In the scan of the Ni/Sn combination, a passive behaviour is seen above 0.25 V, but with relatively high currents in the range of 0.01–0.1 A. Both coatings do not exhibit a satisfying passivating behaviour.

Fig. 7c contains a comparison of electroplated 10 μm Ni and chemical deposited 5 mm Ni. The current in the scan of the chemical 5 μm Ni sample increases with nearly constant

slope from 10^{-6} A at -0.4 V up to 1 A at 1.25 V. In contradiction, electroplated Ni reveals a large passive region from 0.1 to 1.25 V at currents slightly above 10^{-3} A. The poor passivating behaviour of chemically deposited Ni is probably due to the porous layer structure of chemical deposited

Ni. As passivating surface, electroplated Ni is a suitable coating whereas chemical Ni is inapplicable.

In Fig. 7d, potentiodynamic scans of a sputtered TiW alloy (200 nm) coating and electroplated 1 μm Cr are shown. The scan of sputtered TiW alloy is characterized by corrosion
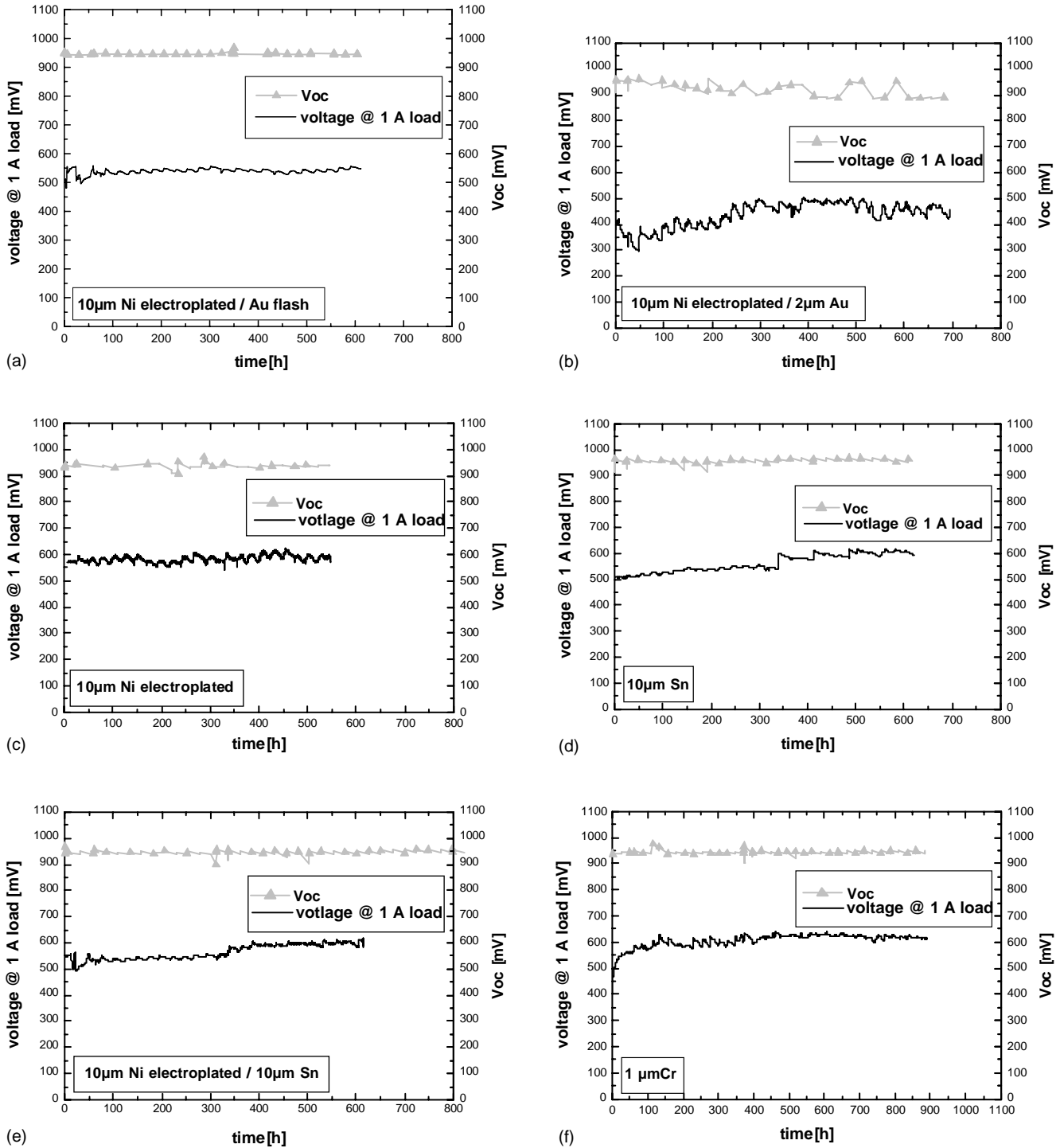

Fig. 8. Long-term behaviour PCB fuel cells with diverse coatings. Shown are the voltage under a constant load of 1 A and the open circuit voltage (V_{oc}) over operation time. (a) Combination of 10 μm electroplated Ni and flash Au. (b) Combination of electroplated 10 μm Ni and 2 μm Au. (c) Electroplated 10 μm Ni. (d) Chemical deposited 10 μm Sn. (e) Combination of electroplated Ni and chemical deposited 10 μm Sn. (f) Electroplated Cr. (g) Sputtered TiW alloy.
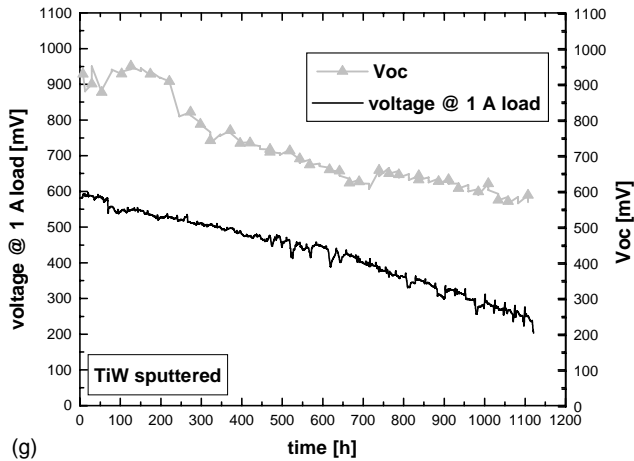
(g)

Fig. 8. (*Continued*).

currents larger than 0.1 A above 0 V. The electroplated 1 μm Cr cover reveals a passive region in the potential range between 0.25 and 0.75 V with corrosion currents significantly less than 10^{-2} A. Due to these relatively low currents in the passive region electroplated Cr might be suitable as corrosion resistant cover.

Fig. 7e contains a comparison of several combinations of nickel/gold combinations. In Fig. 7e, two potentioscans for combinations of electroplated nickel/gold (10 μm Ni/flash Au and 10 μm Ni/2 μm Au) and one potentioscan for a combination of chemical deposited 5 μm Ni and electroplated 0.5 μm Au are shown. All gold combinations have in common a large passive region from at least 0.2–1.2 V. The combination of chemical deposited 5 μm Ni and electroplated 0.5 μm Au shows corrosion currents in the passive region slightly above 10^{-3} A, whereas both combinations of electroplated Ni/Au are characterized by the lowest corrosion currents of the analyzed coating samples.

Coatings of electroplated Cr and Ni and coating combinations of Ni/Au are characterized by large passive regions in the potentiodynamic scans. Therefore, these coatings might be suitable as passivating layers for fuel cells in PCB design. However, a final recommendation for an appropriate coating can be given after evaluating the corrosion stability of these coatings in long-term operation tests in a real fuel cell environment.

7. Long-term operation tests

The previously listed coatings (Tables 1 and 2) were tested in long-term operation. Each PCB fuel cell for test consisted of an anode and a cathode plate of the same coating and was assembled following the routine described earlier. The cells were operated over several hundred hours at a constant load of 1 A (100 mA/cm^2). The continuous constant load operation was intercepted every 24 h to record an *I–V* characteristic and to determine the open circuit voltage (V_{oc}). In

Fig. 8a–g, the long-term operation of seven cells with different coatings are shown. In these graphs, the voltage at a constant load of 1 A and the open circuit voltage (V_{oc}) are plotted over time.

Since the tests did not all start at the same time, there are cells which have been monitored for more than 1100 h whereas others have been operated for just a few days. Therefore, the operation time varies from 400 to about 1100 h testing time. To the time this paper was written, the long-term experiments were still enduring. Results of long-term operation tests for seven different coatings can be presented. Only the cell with a sputtered TiW alloy layer (Fig. 8g) shows an obvious degradation during the operation time of more than 1100 h on both the voltage under load as well the open circuit voltage (V_{oc}).

For a combination of electroplated 10 μm Ni and a Au flash coating (Fig. 8a), no degradation was observed in more than 600 h of operation time. For the coating combination of 10 μm Ni/2 μm Au (Fig. 8b), an operation time of over 700 h was demonstrated.

For the electroplated 10 μm Ni (Fig. 8c), an operation time of 550 h was achieved whereas for chemical deposited 10 μm Sn (Fig. 8d) and combination of electroplated 10 μm Ni and chemical deposited Sn (Fig. 8e) over 600 h operation time was achieved. The longest stable operation time of more than 900 h (Fig. 8f) was demonstrated with an electroplated 1 μm Cr coating.

The high corrosion tendency seen in the potentiodynamic scans for plain copper boards and sputtered TiW coatings is clearly confirmed by the results of the long-term operation tests presented. Whereas for coatings with Sn and Ni/Sn, a high corrosion behaviour is seen in the potentiodynamic curves but a significant degradation in the long-term tests was not seen.

The electroplated 1 μm Cr and 10 μm Ni coatings as well as the Ni/Au combinations reveal no degradation of V_{oc} and voltage under load over operation time. This could be expected as their potentiodynamic scans (Fig. 7c–e) are characterized by relatively large passive regions. Based on corrosion measurements and long-term operations, coatings of electroplated Cr and Ni as well as combinations of electroplated Ni/Au can be regarded as promising passivating coatings for fuel cells in PCB design.

8. Conclusion

Using planar fuel cells in PCB technology for miniaturized power sources offers the following advantages:

- As the PCB technology is a well-known mass production technology, low costs in a mass production of this type of fuel cell can be expected. A serial interconnection of planar arranged cells by connecting overlapping copper layers within the board can be easily realized with the multilayer technology. In addition, electronic circuits can

be integrated onto the PCBs which might act as electrical consumer itself or as an auxiliary unit.

- Due to the flat design, this type of fuel cell can easily be integrated into the housing of a device, thus optimizing the volume of the power source. The planar design offers the opportunity of a fuel cell with an open cathode for a fully passive, self-breathing operation. Therefore, an active air feed supplied by fans or pumps is not required and a cell performance under load could be demonstrated for several days. During this operation, no cell flooding occurred. Due to the large open area and the flat geometry produced, water can evaporate and a good heat transfer to the environment is established. Therefore, no overheating occurs like that often seen for miniaturized stacks.
- As the electrical conducting elements are made of copper, corrosion in the wet fuel cell environment is expected. In order to avoid corrosion, the copper layers of PCBs have to be coated. Long-term tests of plain copper PCB cells were carried out to serve as reference for passivating coatings. A significant performance deterioration of copper PCB cells can be seen after approximately 100 h operation time. A fatal decrease of performance is seen while operating up to 800 h under load.
- Fuel cells in PCB design with 12 different coatings were tested in long-term operation. These coating processes are already used within the PCB industry and may be easily adapted to a serial production of PCB fuel cells.
- As copper layers and coatings are state-of-the-art in the PCB technology, it would be advantageous to manufacture fuel cells with these available standard technologies. But even if after long-term tests over several 10,000 h coated copper layers would reveal to be unsuitable other conducting layers can be used. Alternatively foils of stainless steel, nickel or other materials can be laminated within the PCB process on the substrate consisting of a composite material of glass fibre and epoxide. The advantage of copper layers is their good electrical conductivity which is important with regard to relative high currents in fuel cells and the lateral current flow in the planar design. Therefore, preferably copper PCBs should be employed, whereas for DMFC with much lower currents other non-corroding materials can be used as substitute.
- At the time this contribution was written, the coated cells were operated from 400 up to 1100 h under load. With most of the tested coatings, no significant decrease in performance was seen. An operation time of more than 900 h with an electroplated Cr coating was already achieved which would be adequate for a range of portable electronic applications. Further corrosion currents have been determined by the use of potentiodynamic scans. From the results of the potentiodynamic scans coatings of electroplated Ni/Au, electroplated Ni and Cr can be seen to be suitable as passivating films. So far in long-term tests, these coatings reveal steady operation behaviour. A final decision for appropriate coatings can be made after several 1000 h of operation time.
- Coatings of Cr and Ni and a combination of Ni/Au achieved excellent results in the long-term operation as well in the corrosion measurements. These coatings are promising candidates for the manufacture of planar fuel cells in PCB design.

References

[1] C.K. Dyer, J. Power Sources 106 (2002) 31–34.
[2] A. Heinzel, et al., J. Power Sources 105 (2002) 250–255.
[3] M.S. Wilson, in: Proceedings of the Fuel Cell Seminar, Washington, DC, USA, 17–20 November 1996.
[4] O. Rau, Das Korrosionsverhalten metallischer passivierbarer Werkstoffe in der PEM-Brennstoffzelle, Ph.D. thesis, Freiburg, 1999.
[5] J. Larminie, A. Dicks, Fuel Cell Systems, John Wiley & Sons, Inc., New York, 2000.
[6] W.S. Tait, An Introduction to Electrochemical Corrosion Testing for Practising Engineers and Scientists, Racine, Wisconsin, 1994.
[7] M.G. Fontana, N.D. Greene, Corrosion Engineering, Mc Graw-Hill, New York, 1986.