Innovative Balancing, Heating and Temperature Sensing Element for Automotive Batteries

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Abstract

Electrically driven vehicles are still a rarity on our streets, mainly due to the high costs of these cars compared to conventional ones. The most expensive part is the battery pack with its management electronics. By reducing these costs, electrical vehicles will gain attractiveness.

The novel concept for the integration of temperature sensing, balancing, and heating elements presented in this paper allows a significant reduction of the final battery pack costs. The proposed integration concept provides a balancing resistor, a heating element, and a printed temperature sensor together on the same flexible substrate. This foil can be easily integrated between battery cells or in existing module frames, thus reducing the development time for new modules and packs. By adding a controller and switches, the obtained smart battery cell can handle elementary functions (e.g., temperature sensing) by itself. The wiring and contacting effort is reduced to a contactless two wire communication bus.

The temperature sensor is printed directly onto a plastic substrate, featuring low thickness compared to conventional discrete temperature sensors (e.g., NTC). Furthermore, printed electronics are suitable for high-volume production at very low costs.

In the prototype presented here, two different resistors are placed on the same substrate. One resistor is used for passive balancing. The other acts as a heating element to heat up the battery cell homogeneously directly at its core (e.g., in cold start situations). There is no need for an external heating source, thus further reducing the overall costs without renouncing to functionality.

The provided concept allows a significant reduction of production and development costs of battery packs. New printed electronics technology allows a cost effective high volume manufacturing by printing the temperature sensor, the balancing resistor and even a high power heating element at a time. By easily adapting the geometry to new designs, development time is saved. In later stages also switching elements and logic circuitry can be integrated. This optimizes the functionality, minimizes the time to market and reduces the overall costs of the whole battery pack.

Kurzfassung

Der entscheidende Durchbruch der elektrisch angetriebenen Fahrzeuge steht noch aus, vor allem verursacht durch die hohen Kosten im Vergleich zu konventionell angetriebenen Fahrzeugen. Der hohe Aufpreis wird durch das Batteriepack und seine Management-Elektronik verursacht. Durch eine Senkung dieser Kosten kann der Aufpreis für ein elektrisch angetriebenes Fahrzeug gesenkt und die Attraktivität solcher Fahrzeuge für den Käufer erhöht werden.

Das hier vorgestellte Konzept integriert die Temperaturmessung, einen Widerstand für ein passives Zellen-Balancing, sowie ein Heizelement auf einem gemeinsamen Substrat. Der aufgedruckte Temperatursensor ist durch seine Herstellungsart besonders flach, im Vergleich zu herkömmlichen NTC-Sensoren. Dadurch lässt er sich frei platzieren und direkt auf den Hot-Spot der Batteriezelle ausrichten.

Dieser Temperatursensor wird auf ein flexibles Substrat aufgedruckt, das noch zwei Widerstände beinhaltet. Ein Widerstand wird für das passive Zellen-Balancing, der zweite wird als direkte Zellenheizung verwendet. Durch das Einlegen dieser Folien zwischen die einzelnen Batteriezellen können diese direkt beheizt werden (z.B. bei kalten Umgebungstemperaturen). Durch die Integration einer Schaltung mit Mikrocontroller auf diesem flexiblen Substrat, lassen sich die darauf befindlichen Funktionen einfach ansteuern. Dadurch wird die Montage vereinfacht und der Verkabelungsaufwand verringert. Durch den Einsatz von massenfertigungstauglicher gedruckter Elektronik lassen sich zudem die Herstellungskosten verringern.

1. Introduction

Nowadays batteries for electric vehicles are mostly based on lithium-ion technology. This chemistry has some advantages with respect to lead acid or nickel metal hydride chemistries. The most important advantages are the much higher energy and power densities. While this effect is not that important in stationary applications, it is very important for electric vehicles. A reduced weight of the battery pack reduces the overall mass of the car and saves energy.

But lithium-ion batteries have also some disadvantages. They are quite sensitive to high temperatures (above 60°C), over-charging, deep-discharge and in addition, their maximum current is limited in cold ambient temperature situations. These facts make sensing of the battery state very important. The implementation of the temperature and cell-voltage sensing needs intensive and costly wiring. These costs are reflected into the battery pack costs and finally into the vehicle sales price. The novel and innovative balancing, heating and temperature sensing element presented in this paper allows a significantly reduction of the battery pack costs. By using a modular design which integrates the mentioned elements on a single flexible substrate, the development and assembling time can be greatly reduced, as this foil is placed easily between the battery cells.

2. Flexible substrate

The novel temperature sensing, passive balancing and cell heating element presented here are based on a flexible substrate. This provides various advantages. The low thickness makes the integration easy, as the foil may be inserted into existing battery frames without redesigning them. Further, its flexibility improves the mechanical contact between the battery cell and the elements placed on the foil (e.g., heating element). This increases the effectiveness of the temperature sensor and the heating element, as the battery cell is heated directly at its core.

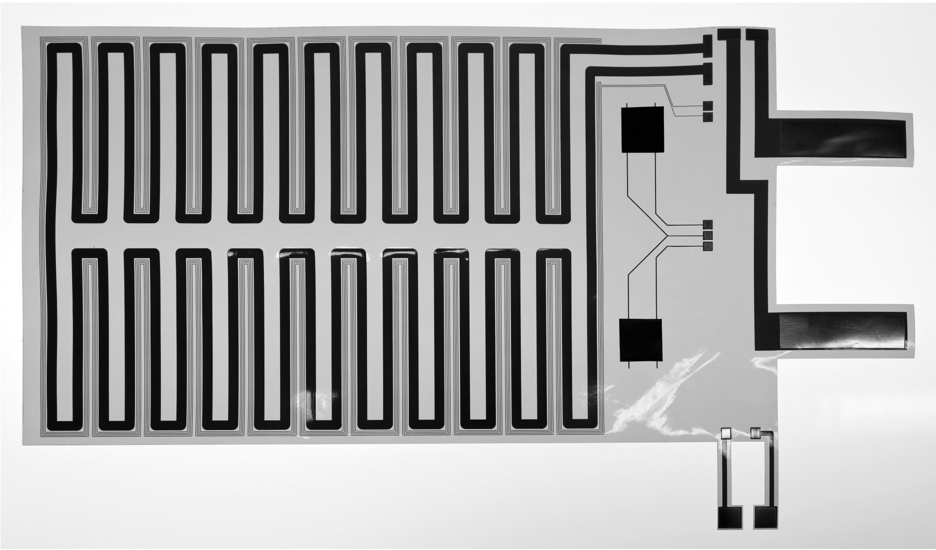


Fig. 1: Flexible foil with integrated temperature sensor, balancing resistor and heating element.

Figure 1 shows a flexible foil with all mentioned parts included on this foil. It is designed for a pouch cell battery size of 15cm width and 26cm height. Polyimide foil was used as substrate for easy soldering, but more cost effective substrates can be used (e.g., PET) instead. The copper traces are made of 35µm thick copper. The two printed temperature sensors are placed directly on the simulated and measured hot-spot of the used battery cell. Thus, an abnormal operating point or failure of the cell can be detected very fast. As the cells are mounted alternating in polarity to make the series connection easier, the hot-spot (located near the positive electrode of the cell) is also alternately on the left and right side. To simplify the flexible foil design and to be able of using only one design, two sensors are located on this foil. Dependent on the cell orientation the respective temperature sensor can be read. But also both sensors can be read to increase measurement accuracy or detect sensor failure.

2.1 Balancing resistor and heating element

Two resistors were placed on the flexible foil, one acts as a discharge resistor for passive balancing and one acts as a heating element. Both are used to extend the

overall battery pack lifetime through different methods explained in the following section.
The whole battery pack is limited by its weakest element (single cell). During usage, some cells may degrade faster than others, causing an imbalance of the state-of-charge (SOC). This degradation may be forced by the battery pack design (e.g., high temperature gradient between the cells). In addition, material or manufacturing variations between the cells are responsible for this kind of SOC imbalance within the whole battery pack. Since the performance (e.g., capacity) of the whole pack is limited by the weakest cell, the cells within the pack need to be balanced regularly or better, permanently. There are mainly two common methods of cell balancing with differing electronics complexity and functional range.

The simplest way to balance the cells is through passive balancing. The cells with higher SOC are discharged through a resistor. This enables the full charge of the cells with lower SOC without overcharging the cells with higher SOC (e.g., during the charging process). This method is very simple and cheap, since the additional component count is very low. Only an appropriate resistor and switch is needed for every single cell.

A second method for cell balancing features redistribution of energy by transferring the energy from one or more cells to a cell with a lower SOC. However, this active cell balancing method requires additional controlling and increases the component count dramatically. This makes the active balancing more expensive compared to the passive cell balancing. Since cell manufacturing tolerances are getting lower nowadays, the intervals and amount of cell balancing is reduced. Therefore, the effort and costs for an active balancing solution in mobile applications are economically more and more questionable.

The integration of a passive balancing method by using only a discharge resistor and switch was chosen for the previous mentioned reasons. Usually, a passive balancing current of approx. 150mA is used. This results in a discharge resistance of approx. 25Ω (for 3,7V cell voltage). The calculated resistance is obtained by a four string, series connected copper line. The nominal width was chosen as 0,2mm using a copper thickness of 35µm. Detail of the balancing resistor is shown in figure 2. The thin structure forms the balancing resistor, whereas the thick structure forms the heating element.

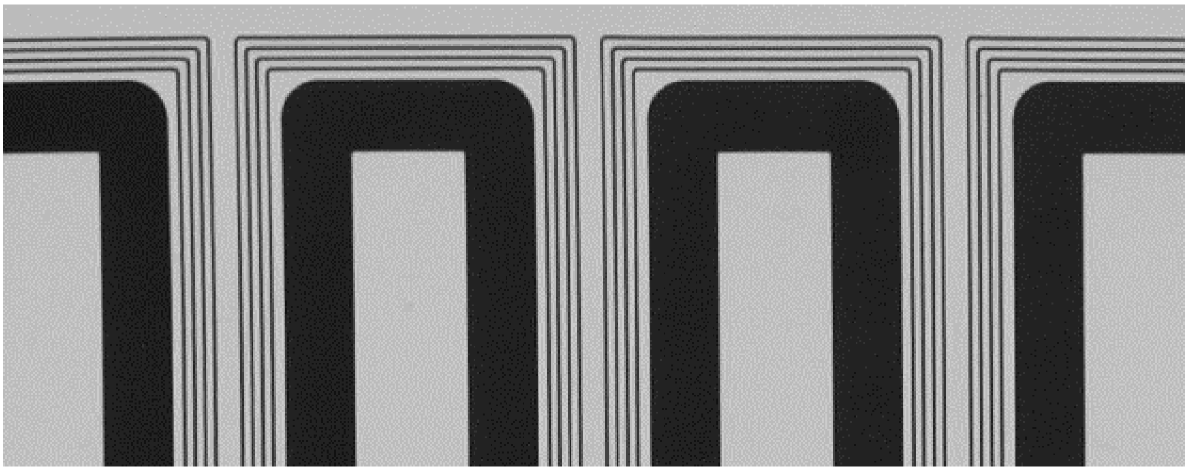


Fig. 2: Detail of the heating element and balancing resistor structure.

Apart from the balancing resistor, a second resistor was placed on the flexible foil. This resistor can be used as a heating element to heat up the battery cell at low ambient temperatures. As the maximum charging and discharging current of the battery cells is reduced by low temperatures (e.g., during the winter), the battery cells need to be heated to the nominal temperature to provide the full specified charging and discharging current. As this heating option needs complex and careful design and increases the overall battery system costs, it is often omitted in today's battery systems. In contrast, the innovative concept presented here may be integrated without extra costs. By placing a thin foil directly between the battery cells, these are heated up directly at their core. The thermal capacity is minimized, as only the battery cells are heated up by the heating element. In addition, the cells can be heated up individually, taking a temperature gradient within the battery pack into consideration. This ensures safe and energy efficient heating of the battery cells to enable their highest performance.

In order to find the optimal structure and power rating of the heating element, thermal simulations have been made with ANSYS tools. A setup including two battery cells was simulated. The heating element, rated at 18W heating power, was inserted between them. Figure 3 shows the mechanical design of the two pouch cell batteries used for thermal simulations.

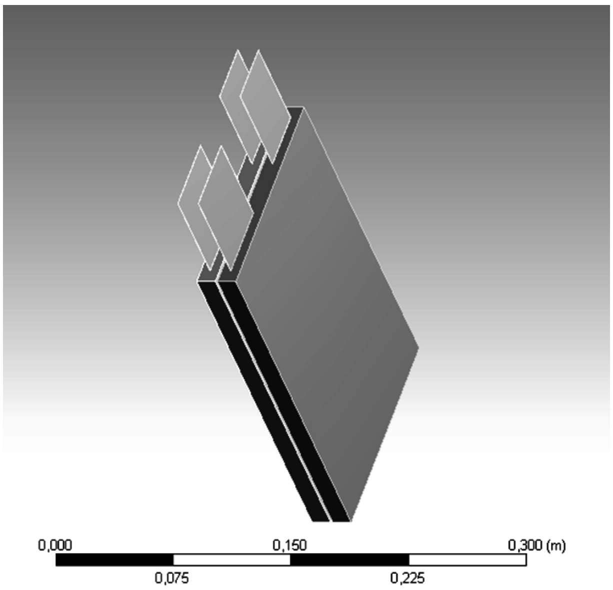
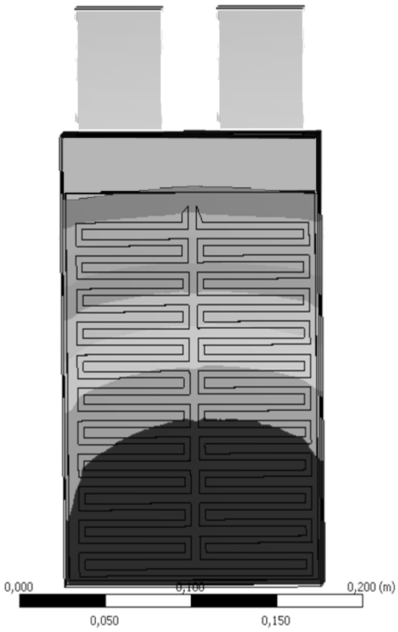


Fig. 3: Mechanical design used for detailed thermal simulations.

The simulations were used to determine the best heating element structure, the needed power rating of the heating element and the energy needed to heat up the cell for approximately 10°C. Specific material characteristics of the cell were determined by experiments. The final simulation results are shown in figure 4. The meander structure of the heating element was finally realized in the flexible foil already shown in figure 1. This specific design allows a temperature gradient of less than 2°C within the battery cell dimension.



	Simulation	
Time [s]	Min. Temp. [°C]	Max. Temp. [°C]
20	23,02	23,33
40	23,06	23,57
90	23,32	24,18
250	24,29	25,53
430	25,32	26,71
610	26,26	27,71
792	27,11	28,57
970	27,9	29,35
1150	28,61	30,06
1330	29,28	30,71
1510	29,89	31,31
1690	30,46	31,87
1800	30,79	32,19

Fig. 4: Heating element simulation results.

The achieved performance simulated by this setup was finally realized and confirmed by experimental results. It could be shown, that the proposed battery cell heating element is able to heat up the battery cell very homogenously. By easy adapting the dimension of the copper traces, this heating element may be reused in new designs.

2.3 Temperature sensor

Temperature sensors used in automotive applications, where high reliability and low costs are demanded, are commonly based on thermistors. Thermistors are thermally sensitive resistors - in these the electrical resistance of the material changes with the temperature. The advantages of thermistors are the simple, robust design and low complexity regarding the utilization and packaging of these temperature sensor types. High volume production and finally a low price per piece are guaranteed.

The benefit of the printed temperature sensor is the low device thickness compared to commercial devices. The sensor setup is more flexible due to the usage of additive printing processes. So is it possible to build the sensor on flexible substrates (figure 5) or parts of the encasement of the battery system.

Lithium-polymer batteries have a characteristic spatial extent and shrink or inflate while discharging or charging. This phenomenon, also called swelling, generates mechanical stress in the battery modules and pack. By using commercial sensors in a perl-shaped package, the single battery cells can be damaged by the sensor.

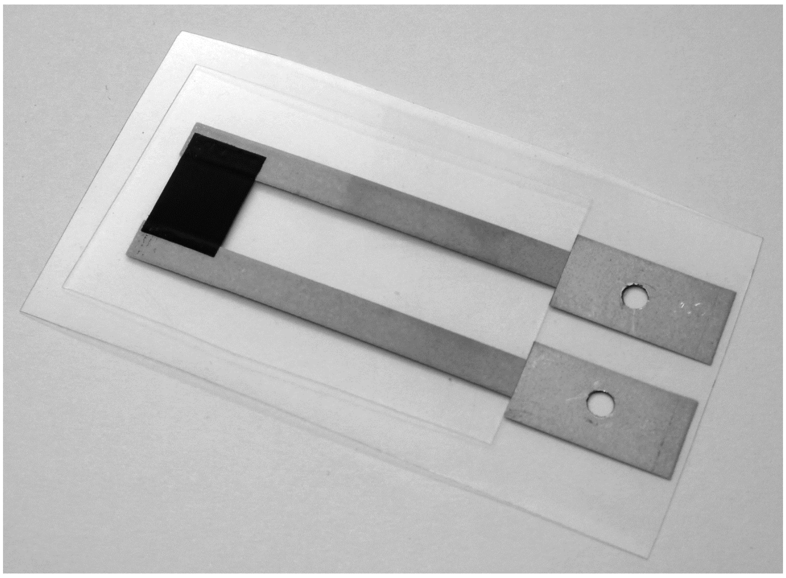


Fig. 5: Printed temperature sensor on PE substrate.

State-of-the-art temperature sensors used in automotive applications provide either a high temperature coefficient of resistance (TCR) combined with a perl-shaped package (e.g., NTCs) or a low TCR combined with a flat package (e.g. meander shaped metallic PTC materials). A high TCR results in low electronics complexity for reading the temperature sensor and a higher accuracy. The temperature sensors package directly influences the packing density battery systems and/or the complexity of its design.

The temperature sensor presented in this paper provides both advantages, namely high TCR and flat packaging. A planar design consisting of three functional layers has been chosen, which is fully realizable within the printed electronics technology for high volume production. The layers (figure 6) are each deposited in a separate printing process and stacked over each other.

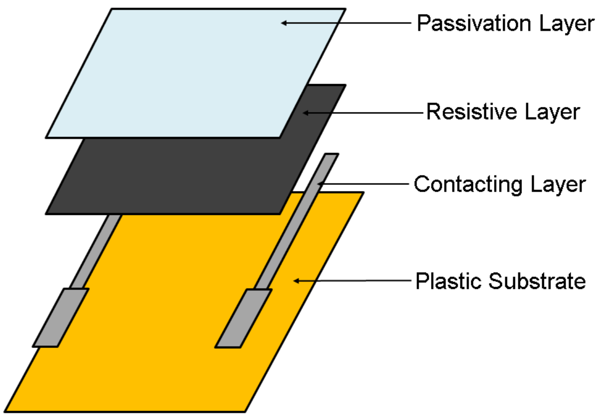


Fig. 6: Design of the temperature sensor showing the stacked functional layers

The sensor consists of a particle-filled carbon polymer-material as sensing layer, a silver layer for the electrical contact and a passivation layer to protect the sensor from environmental threads (e.g., moisture, mechanical stress). The materials are deposited successively onto a polymeric foil like polyethylene terephthalate (PET), polyethylene naphthalate (PEN) or polyimide (PI) by a screen printing process. After each layer deposition, the foil is cured on a hotplate to remove the organic solvents and the additives from the deposited material.

The pure sensing material shows several aging effects that can influence its performance. On the one hand the sensor is degrading with the number of measurements and on the other hand the sensor shows a hysteresis between the heating curve and the cooling curve. To prevent the degrading of the sensor, an artificial aging process is necessary. This is useful to remove the rests of solvent and water out of the layer. The hysteresis mainly depends on the surface of the printed layers, so a passivation of the sensor is required.

Several techniques for the passivation are available. The first is a lamination process with a laminating foil. This leads to a thicker layer but a good and tight passivation. Another way is a printed layer of polyurethane (PU). This material can also be applied onto the sensor by screen printing. This process leads to a thinner sensor compared to the laminated sensor. A third passivation material is a spray coated polymer which is also leading to a package. The applied thickness is not as homogeneous as the other two techniques.

After passivation and aging the sensors have been measured in a climate chamber. The measurement setup consists of the chamber which uses air circulation and a data logger to monitor the temperature and the relative humidity in the chamber. A 16 channel USB data logger was used for the sensor resistance measurement and logging. The chamber and the resistance logger are controlled by a LabVIEW program that is able to log the temperature within the climate chamber and the sensor resistance at a high sampling rate and display these values on a graphical user interface. The achieved data is automatically stored in a log file for further analysis. According to the sensing task, the standard temperature profile for a measurement starts at room temperature to 65°C and back.

Figure 7 shows the i-v characteristics of the proposed temperature sensors. The sensor material shows a typical PTC behaviour. The TCR of the temperature is between 1 and 3 percent per Kelvin, while the resistance is increasing with temperature. Furthermore, the hysteresis of the resistance can be seen. To enhance the performance of the temperature sensor, the device is passivated. The resulting measurements are presented by the lower picture of figure 7. It can be seen that the thermal behavior is further improved. The hysteresis is almost fully suppressed. Compared to the not passivated sample, there is a slight decrease of both TCR and resistance.

The future perspective of the sensor placement is the integration of the printed sensors directly on parts or inside of the encasement of the battery cell. By increasing the number of sensors, a sensor array could be assembled which makes it possible to get detailed information about the temperature distribution of every single battery cell. This array could also be applied for heating the battery.

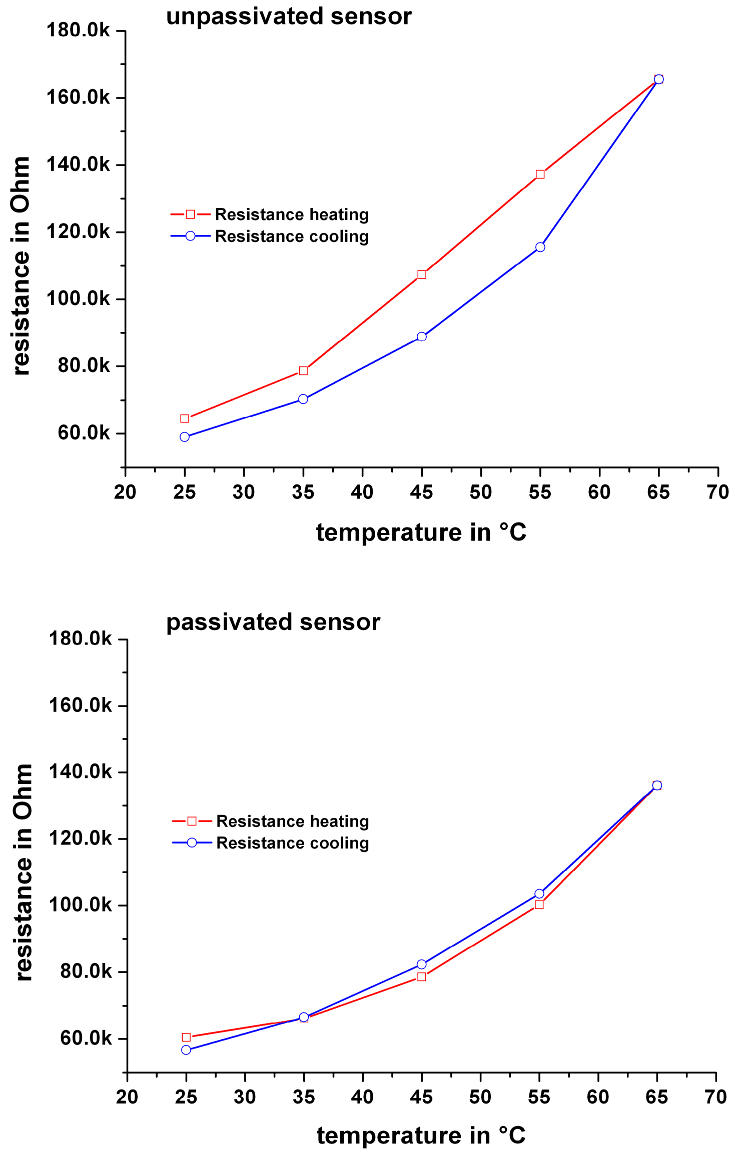


Figure 7: Thermal characterization of the carbon compound sample. The square (red) and round (blue) points show the averaged resistance values for both, heating and cooling phase. The two pictures show the hysteresis of the same temperature sensor without passivation layer (top) and with passivation layer (bottom).

3. Smart battery cell concept

Since all the previously explained elements placed on the flexible board need to be contacted and controlled, a novel smart battery concept is proposed. Every battery cell is controlled and monitored by its own microcontroller. This microcontroller is responsible for the battery cell it is placed on and communicates through a parallelized communication bus with a master unit. This concept is outlined in the following chapter.

3.1 Electronics

Since the Microcontroller is placed on each battery cell, the PCB it is placed on is powered by the single battery cell voltage. A buck-boost DC/DC converter generates a stable supply voltage from the variable cell voltage (usually between 2.7V and 4.2V). The microcontroller and the communication electronics is powered by this supply. Since this smart battery cell is connected to a parallelized capacitive coupled communication bus, a signal conditioning (for receiving data) and a line driver (for transmitting data) is needed.

As each cell is managed and monitored by its microcontroller, the wiring and mounting costs can be reduced. The microcontroller is used to read the printed temperature sensor, using its internal analog-to-digital converter (ADC). The internal ADC is also used to read the cell voltage accurately. In addition, the microcontroller is able to switch-on the passive balancing resistor and heating element placed on the flexible foil. A first prototype of this smart battery electronics is shown in figure 7. This PCB includes the microcontroller, the needed signal conditioning and line driver, as well as the switches to control the passive balancing resistor and the heating element.

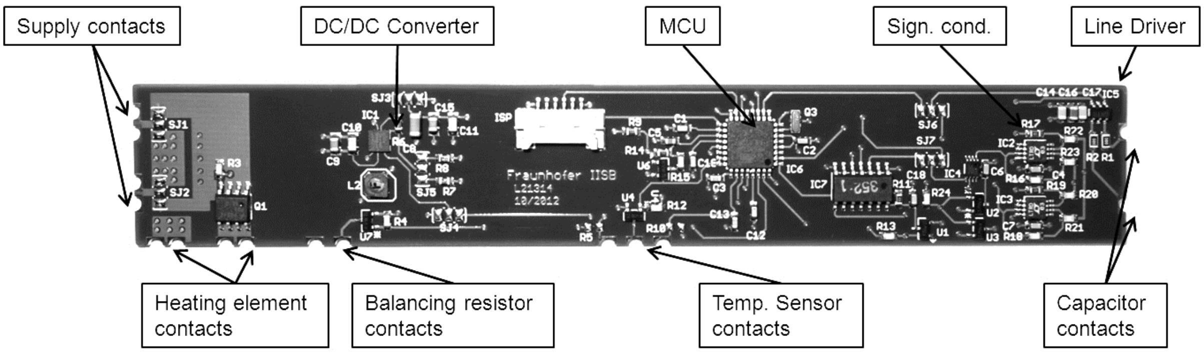


Fig. 7: Smart battery electronics with microcontroller, signal conditioning and line driver, switches for the balancing resistor and heating element

3.2 Smart battery including electronics, printed temperature sensors, passive balancing and heating element

The previously illustrated concept of a smart battery cell including printed temperature sensors, passive balancing function and an 18W heating element was finally realized in a demonstrator. This demonstrator proves the feasibility of the proposed concept by integrating the flexible foil with the electronics mounted on top into an existing battery frame. One battery frame is shown in figure 8 (without battery cell). As every cell is placed in its own battery mounting frame, these frames are stacked to the final battery module. The electronics was built from discrete components on a four layer PCB. In further development, this electronics may be integrated into an ASIC, reducing production costs and mounting space.

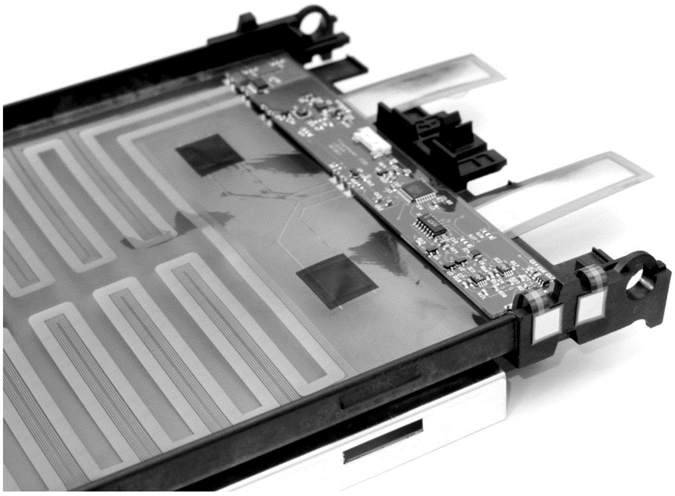


Fig. 8: Flexible foil with smart battery electronics mounted on battery frame.

Each cell can be monitored by its own electronics, through the microcontroller. The electronics and flexible foil is therefore directly connected to the battery cell tabs, thus reducing contacts and wiring efforts. The integrated ADC is used to read the cell voltage and the temperature. The communication interface was placed laterally on the battery mounting frame to simplify the contacting of the capacitive coupled communication bus. As all actions and measurements are done by the microcontrollers placed on every battery cell, the wiring of the temperature sensors, cell voltage ADC and additional elements (like the heating element) is reduced to a simple capacitive coupled communication bus. Even implementation of additional options into the smart battery cell does not affect the communication interface, since only commands and measurement data are transmitted by this communication bus. These features reduce the overall battery pack costs by simplifying the wiring and mounting effort, as all sensors and element are already placed on the smart battery cell.

4. Summary

The proposed innovative balancing, heating and temperature sensing elements integrate several new techniques onto a flexible foil element. First, the essential temperature sensing of battery cells is improved by using new printed electronics techniques. Printed electronics enables placing the temperature sensor directly at the hot spot of the battery cell. As this printed sensor is extremely flat compared to conventional pearl shaped sensors, the mechanical stress on the battery cell or the sensor is reduced. In addition, the sensor may be printed directly onto the battery enclosure or even into the battery. By doing so, the sensors can be easily adapted to the specific battery cell needs and enables much faster temperature transient measurements, speeding up failure detection and thus increasing safety of the battery system.

The second innovative component placed on the flexible foil is the heating element. By implementing a distributed heating element into the battery module, its availability and performance can be increased in low ambient temperature situations. As the maximum charge and discharge currents are limited with low battery temperatures, heating up the battery cells will speed up the charging process in these conditions. In addition, the full battery performance may be enabled in driving situations (e.g. full acceleration performance). These features increase the attractiveness of electrical driven vehicles, as no performance drop is expected in winter conditions. The feasibility of this heating element was proven by thermal simulations and experimental results.

Finally, all functions of this innovative balancing, heating and temperature sensing element were integrated into a novel smart battery concept. By incorporating a dedicated electronics including a microcontroller, all acting and sensing functions can be done by the smart battery itself. The complete wiring of sensors and additional elements is reduced to a parallelized two-wire communication bus. This reduces cost-intensive contacting and wiring during assembly. In addition, the robustness is increased. First, the amount of galvanic contacts is reduced. Second, the analog signal wires are reduced to a minimum, since all analog values are read directly be the smart battery itself.

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