# Power Antifuse Device to Bypass or Turn-off Battery Cells in Safety-Critical and Fail-Operational Systems

V.R.H. Lorentz, R. Waller, S. Waldhör, M. Wenger, M. Gepp,
R. Schwarz, S. Koffel, S. Wacker, M. Akdere, M. Giegerich, M. März
Fraunhofer IISB ; Schottkystrasse 10 ; D-91058 Erlangen ; Germany
vincent.lorentz@iisb.fraunhofer.de

***Abstract*—This paper presents a new power electronic device, named power antifuse, providing an irreversible bypassing function for the current after having been ignited by an external electrical signal. The antifuse is a scalable power electronic device of 1 cm$^2$ of active area. A pristine antifuse device provides an electric resistance of more than 100 mega-ohms between the terminals. After having been activated, the same antifuse device becomes a bidirectional bypass element offering less than 20 micro-ohms of resistance to the electric current. The activation time corresponding to the delay between the reception of the electrical trigger signal and the full conduction of the antifuse is less than 10 ms even at environment temperatures below -40°C. This paper shows how the integration of antifuse devices in battery cells can be used to bypass and turn-off lithium-ion battery cells thus improving the safety and availability of battery systems used in transport applications like aircraft, railways, ship and road vehicles. The characteristics of the proposed antifuse device make it also an ideal power electronic device for bypassing faulty series connected sub-systems used in high-availability applications or fail-operational redundant systems.**

***Keywords—Antifuse Device; Power Electronics; Lithium-Ion Battery; Fail-Operational; Safety; Redundant Architecture; Smart Battery Cells; Shutdown Battery Cells; Bypass Battery Cells; Aircraft, Railways, Ship and Road Vehicles***

## I. Introduction

Nowadays, battery systems based on series connections of lithium-ion battery cells are widely used in a vast variety of mobile and stationary applications [1] [2]. Since lithium based batteries provide a high energy density, they are potentially dangerous when they release their energy in an uncontrolled way. The hazards can be of several types, for example chemical, mechanical, electrical or thermal. A faulty battery cell principally generates two main threats:

- the threat coming from the faulty battery cell (e.g., thermal runaway, electrolyte or gas leakage, explosion, fire)
- the threat of making the system unusable or worse, destroying it and hurting persons

Safety critical high-power and high-energy applications require preventive safety measures during the conception phase and during the definition of their architecture [3]. A fail-safe device is defined as a device that will cause no harm to the persons using the system in which the device is integrated, and limit this caused harm for the other components of the system. A fail-safe system will in general show a clear change in behavior (e.g., being shut down) or a dramatic decrease in performance. For instance, the failure of a motor in an electric vehicle will lead to the immobilization of the vehicle.

The next level of safety-demanding systems is defined by the term fail-operational. This level of safety is mandatory when the function of the system must be maintained at a certain level even in the case of a single device failure. In general, fail-operational systems provide a certain amount of redundancy. This level of safety is required for example in aircrafts, where shutting down is never an option. A very similar strategy is used in high-availability systems, requiring a non-stop service, for example in uninterruptible power systems (UPS) supplying hospitals or data centers.

This paper describes a new power electronic antifuse device that can be used as current bypass in applications requiring a high level of availability. First, the antifuse device is described in its context and the design of the antifuse is exposed. Further, the integration of an antifuse in a battery cell is considered and the triggering explained. Finally, thermal simulations and direct measurements on high-power lithium-ion cells are presented.

## II. Power Antifuse Device

### A. Motivation for Bypass Devices in Battery Systems

High-power and high-energy battery systems are using series connections of lithium-ion battery cells, in general between several dozens and several hundreds of cells, to reach the required power levels for the considered mobile or stationary application. A battery system illustrating such current bypass elements is shown in Fig. 1. Without the bypass elements, the battery system would no more be able to operate, because the current path would be irreversibly opened.

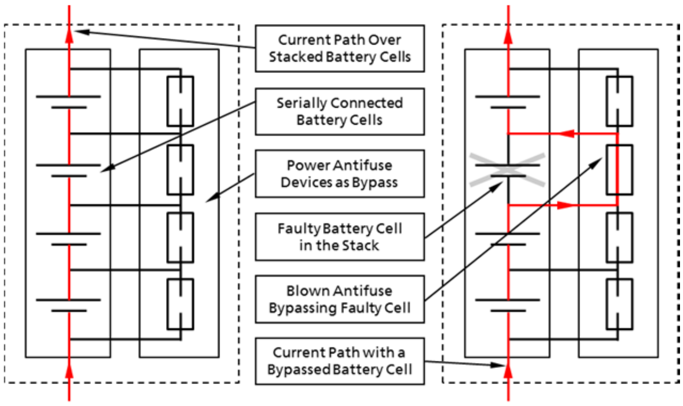


Fig. 1. Battery system consisting of battery cells connected in series and having integrated antifuses. The current path is shown during normal operation on the left side and in case a battery cell has failed and the current must be bypassed by one of the antifuses on the right side.

## B. *State-of-the-Art in Bypass Devices in Battery Cells*

State-of-the art electric road vehicles are using lithium-ion battery systems based on cylindrical, pouch or prismatic hard-case automotive battery cells. These battery cells are made smarter from generation to generation, thus integrating communication functions [4] [5], temperature estimation functions [6] [7], and protection functions, like current interrupt devices (CID) or overcharge protection device, as shown in Fig. 2. The battery cell is a state-of-the-art automotive grade 60 Ah prismatic lithium-ion battery cell (14) providing an integrated safety device (28) that is pressure sensitive [8] [9]. The negative battery cell terminal (24) is galvanically isolated from the cell case (12), whereas the positive battery cell terminal (26) is electrically connected to the cell case (12). In case of an overpressure event in the cell compartment (14), the electrical conductive membrane (30) in the safety device (28) flips out of the battery cell (14) and enters into contact with the prolongation (22) of the negative terminal (24), thus providing a direct current path between the negative terminal (24) and the positive terminal (26), further disconnecting the electrode stack (16) by blowing the fuse (18).

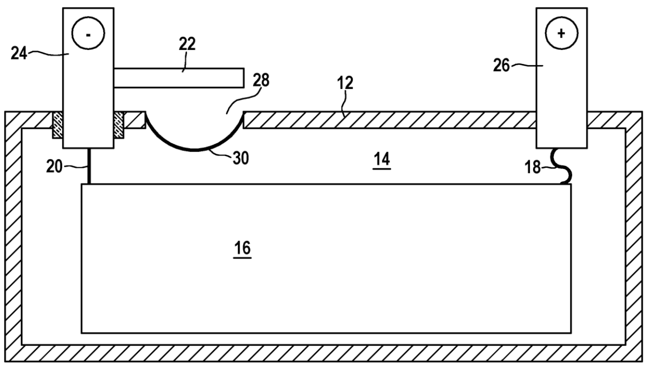


Fig. 2. State-of-the-art 60 Ah prismatic lithium-ion battery cell (14) providing an integrated pressure sensitive safety device (28) [8] [9]. In contrary to the antifuse, the device (28) cannot be triggered by an external signal and is therefore not able to provide a controlled irreversible shutdown of the battery cells in case of a vehicle crash.

The concept proposed and realized in [8][9] provides a very efficient solution to bypass the battery cell in case of an internal cell failure producing enough gas to increase the internal cell pressure to a level pressing the membrane (30) to the contact (22), as depicted in Fig. 2. This is for example the case when the battery cell is being overcharged, but it does not cover all possible failure modes [10]. It cannot disable or shutdown all cells in the battery system in case of a severe vehicle crash. This paper proposes to integrate in each battery cell a power antifuse that can be activated electrically anytime to ensure a much wider coverage of the possible failure modes in safety-critical, high-availability and fail-operational systems.

## C. *Design of the Power Antifuse Bypass Device*

The proposed power antifuse device was designed based on strict requirements defined for battery systems designed for modern transportation applications, more specifically coming from the automotive and aviation domains. These requirements are summarized in TABLE I.

TABLE I. OVERVIEW OF THE REQUIREMENTS OF THE PROPOSED HIGH-CURRENT LOW-VOLTAGE ANTIFUSE POWER DEVICE

| **Parameter Name** | **Required Value** | **Reached Value** |
|---|---:|---:|
| Isolation Voltage | >10 V | >30 V |
| Open Circuit Resistance | >10 MΩ | >100 MΩ |
| Closed Circuit Resistance | <200 μΩ | <20 μΩ |
| Ignition Delay Time | <30 ms | <20 ms |
| Total Activation Time | <50 ms | <25 ms |
| Lifetime at 60°C | >10 years | >15 years |
| Costs [11] | <1.00 €/cell | 0.15 - 0.45 €/cell |

The proposed power antifuse device consists of two major functions: an ignitor function triggered by an electric current, heating a reactive material generating an exothermal reaction; and the antifuse function, in which tin is molten to shorten two high-current electrodes. Both functions have been brought together in a single electrically triggered power antifuse device. An electrical symbol for the antifuse device is proposed in Fig. 3 and the corresponding mechanical assembly shown in Fig. 4.

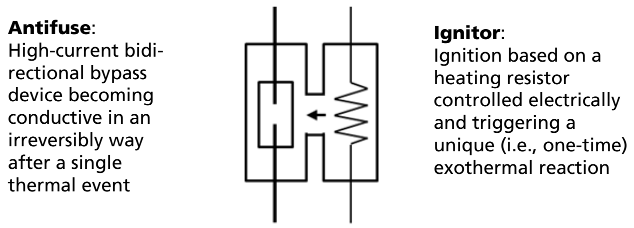


Fig. 3. Proposed electrical symbol for the new controlled power antifuse device in which the antifuse device symbol is shown directly accolated to the electro-thermal ignitor device symbol.

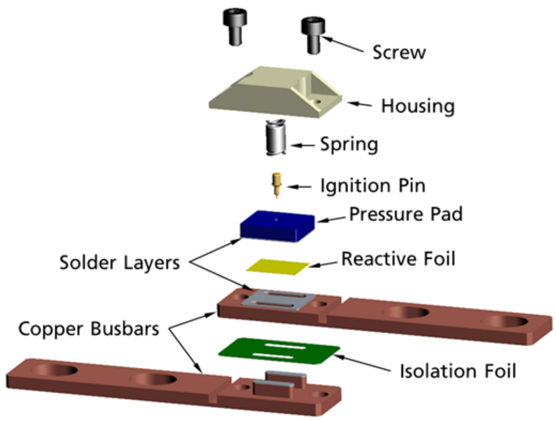


Fig. 4. Exploded view of the assembly of a high-current low-voltage power antifuse bypass device prototype.

As shown in Fig. 4, the power antifuse bypass device consists of two electrodes, which can actually be copper or aluminum busbars. In case aluminum is used, it must be treated, for example with a nickel layer, to be able to be soldered with tin. An electrically isolating foil, for example polyethylene (PE) is used to galvanically isolate both busbars from each other. The thickness of the polyethylene isolation foil can be adapted to the electrical isolation required by the final application. Two holes in the upper busbar allow both pins from the lower busbar to enter in these holes, but without exceeding the thickness of the upper busbar, as illustrated in Fig. 5. A reactive multilayer foil consisting of stacked very thin aluminum and nickel bi-layers (i.e., <50 nm) alternating up to a total thickness of around 80 µm is used as electrically triggered heat source. To ignite the reactive foil, a temperature increasing rate of at least 200°C.min$^{-1}$ when passing at least the 200°C threshold is necessary. A slower heating rate will only anneal the reactive foil, without bringing it to ignition. When ignited, the reaction front propagation velocity is between 2-10 m.s$^{-1}$, depending on the age of the reactive foil. A pristine reactive foil provides an energy of 1 kJ.g$^{-1}$ with a density of 6 g.cm$^{-3}$, thus corresponding to 6 kJ.cm$^{-3}$. An 80 µm thick 10×12 mm$^{2}$ reactive foil generates around 57.6 J (i.e., 48 J.cm$^{-2}$) of heat to melt the solder layers of both busbars and establishes an electrical short between them. A pressure pad is applied over the reactive foil to ensure a good thermal and electrical contact between the reactive foil and the solder layers on the busbars. The pressure pad can be an electrically conductive or isolating material.

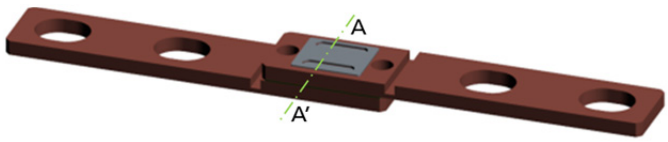


Fig. 5. Assembly of a high-current low-voltage antifuse device showing the difference in height ensuring the electrical isolation in the pristine state. The cross-section AA' is shown in Fig. 7.

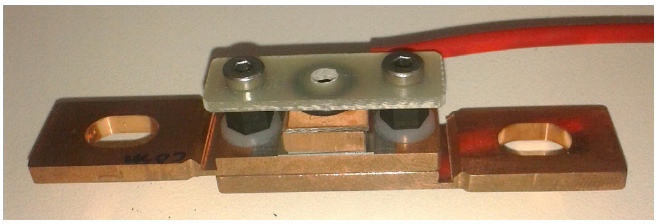

Fig. 6. Photography of a power antifuse device with its trigger contact.

A cross section view of the antifuse assembly in Fig. 5 is depicted in Fig. 7. The isolating air gap plays an essential role for the electrical isolation. This air gap is sufficient to block battery cell voltages up to more than 5 V. The geometry of the holes was chosen to apply the ignition pin between both holes, so that a strong counter pressure can be provided by the upper busbar. This is important to ensure that the ignition pin will not perforate the reactive foil or press it against the lower busbar.

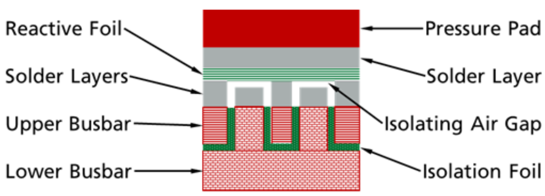


Fig. 7. Cross-section AA' of the assembly of a high-current low-voltage antifuse device as shown in Fig. 5.

## III. Cell Integration and System Architecture

### A. Battery Cell with an Integrated Antifuse

Adding functions to battery cells increases their complexity and costs, therefore a cost-efficient integration of the power antifuse is essential to ensure the development of cost-efficient battery systems. An integration concept showing a battery cell with a power antifuse device is proposed in Fig. 8.

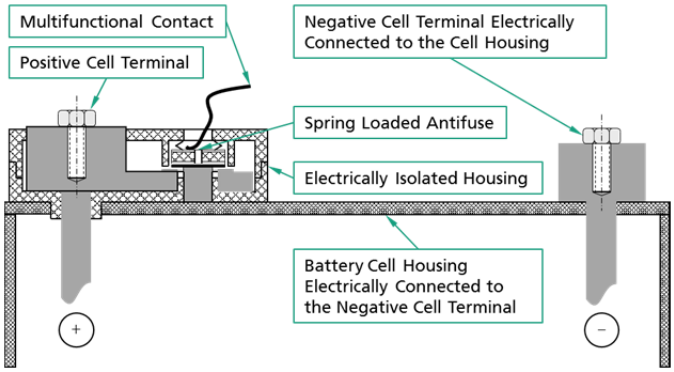


Fig. 8. Prismatic hard-case battery cell drawing showing the integrated power antifuse and its multifunctional electrical contact for cell voltage sensing, cell balancing and antifuse triggering.

### B. Battery Cell with a Multifunctional Contact

In Fig. 8, the housing of the battery cell is electrically connected to the negative terminal of the battery cell. The spring loaded antifuse is held in place by a solder layer that melts away, when the exothermal reaction of the reactive foil was ignited, thus pushing the pressure pad to the bottom and shorting the positive terminal with the negative terminal of the battery cell. The reactive foil of the antifuse is also electrically connected to the negative pole of the battery cell, and further to a so called multifunctional contact. The antifuse is designed in such a way that, as shown in Fig. 9, a multifunctional battery cell contact can be used to measure the battery cell voltage, to perform the passive charge balancing process (i.e., battery cell charge equalization), and to ignite the antifuse to irreversibly bypass and shutdown the battery cell (i.e., disable the battery cell by forcing its voltage externally to zero volts).

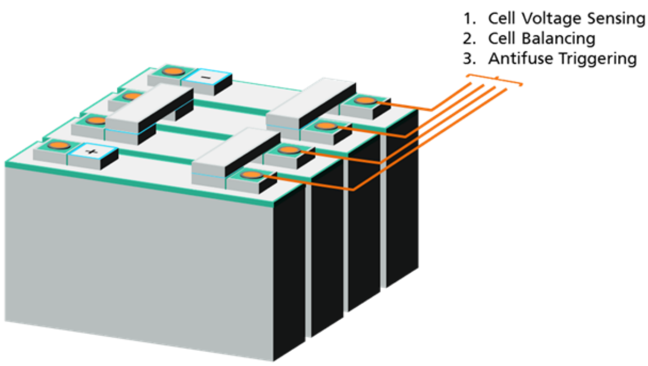


Fig. 9. Assembly of battery cells in a battery module showing the connection to a multifunctional battery cell contact allowing all three functions over a single electrical cable connection: cell voltage sensing, cell balancing (i.e., charge equalization), and antifuse triggering.

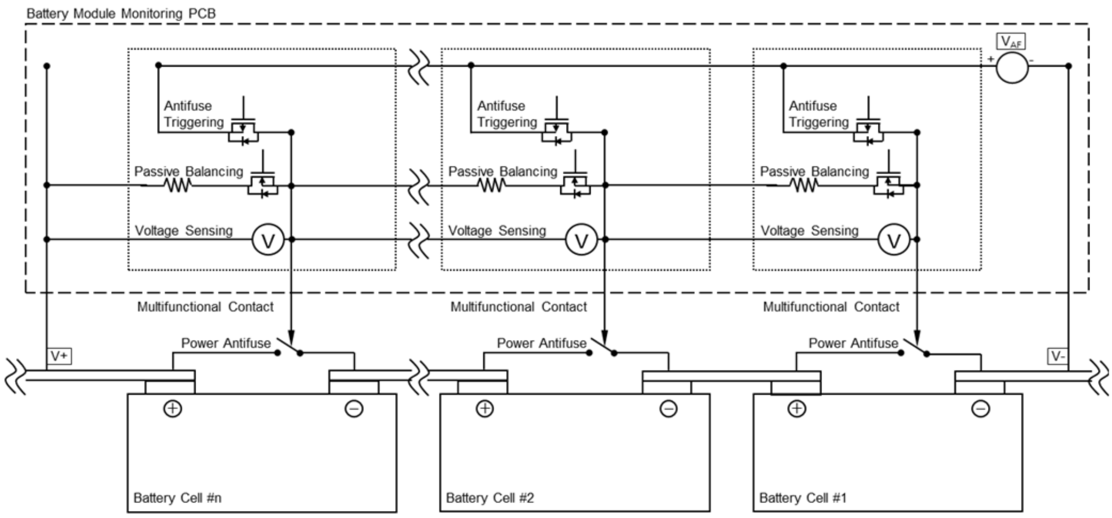


Fig. 10. Schematic of a battery module showing the general principle of series connected battery cells having an integrated antifuse and a multifunctional contact allowing the three following functions over a single wire: cell voltage sensing, passive balancing (i.e., charge equalization), and antifuse ignition.

### *C. Battery System Architecture with Integrated Antifuse*

The schematic of a battery system using power antifuse bypass devices in every battery cell as depicted in Fig. 10 shows how the three functions (i.e., cell voltage sensing, passive cell balancing, and antifuse triggering) can be realized over one single multifunctional contact. With this battery system architecture, there is actually no need for additional wires between the smart battery cells and the battery module monitoring printed circuit board (PCB). The current flowing through the multifunctional contact flows also over the reactive foil. The battery cell monitoring function requires less than 100 µA of current, while the passive battery cell balancing consumes 50-200 mA of current.

The ignition of the reactive foil of the antifuse requires a current pulse of 50-100 A during 1-2 ms (i.e., approximately 100 mJ). The extreme ignition velocity of the antifuse makes it an ideal device to fulfill a further function: if integrated in every battery cell, it is able to be used to shut the cell down (i.e., turn it electrically off) in the case of a vehicle crash. When the antifuse device is integrated in each battery cell, it does not only allow a bypassing in case of a faulty cell, but it also further provides the ability to shut down (i.e. reduce the external cell voltage to zero) every cell, with a trigger velocity of less than 30 ms. The typical airbag activation and deployment time is around 30-80 ms. This means that the antifuse technology proposed in this work is able to shut down every cell of a battery system in a very short amount of time, in the case of a vehicle crash, thus guaranty the safety of the work that will be performed by the rescue services. The detailed driver circuit for triggering all the antifuses sequentially or simultaneously is not part of this paper. It is simply represented in Fig. 10 by the voltage source $V_{AF}$ and the PMOS antifuse triggering transistor.

Currents below 500 mA are not able to ignite the reactive foil or to accelerate significantly its ageing. The reason is that the terminals of the battery cells in high current applications are submitted to higher temperatures than the passive balancing electronics on the battery module monitoring PCB, thus the power losses occurring in the busbars connecting the positive pole of one battery cell to the negative pole of the next battery cell in series have a higher impact on the temperature of the reactive foil in the antifuse, like it is represented in Fig. 8, than the temperature increase generated by the battery cell balancing current. In conclusion, the ageing of the reactive foil in the antifuse is not firstly determined by the current flowing during the passive balancing process, but by the temperature elevation generated by the main current flowing over the busbars connecting one cell to the next in the series.

Models developed by using differential scanning calorimetry (DSC) thermal analyses have confirmed that after a period of 10 years at a constant temperature of 60°C, the reactive foil can still be ignited and that the generated exothermal energy is more than 2/3 of the initial energy, thus being sufficient to melt the solder layer, even at ambient temperatures of -40°C. This is further investigated in the next section, which will explain the thermal modelling and simulation methods, and present the corresponding simulation results.

## IV. Modelling and Simulation of the Antifuse

### *A. Modelling Configuration of the Antifuse*

To design the antifuse capable of fulfilling the requirements shown in Table I, a thermal simulation model based on the drawing shown in Fig. 7 was developed and analyzed in ANSYS. The phase change of the solder layers is modelled via a temperature dependent enthalpy curve. Due to the temperature dependent material properties, the analysis is nonlinear, requiring an iterative solver. To obtain a converging solution, time step control and mesh properties were set accordingly. Because of the short times considered, the heat generated by the reactive foil does not affect the outer parts of the busbars. As a consequence, these outer parts were not taken into account for the simulation. Other elements like the packaging were also discarded for the simulations. With a $10{\times}12\ mm^2$ reactive foil, the minimum and maximum reaction period was calculated to be respectively 1.3 ms with 10 m.s$^{-1}$ and 6.5 ms with 2 m.s$^{-1}$ reaction front velocity.

### *B. Thermal Simulation of the Antifuse*

The criterion defining a successful activation of the antifuse was defined to be a melting depth of the solder layers of at least the equivalent height difference shown in Fig. 7 by the isolating air gap. The evolution of the melted solder depth was investigated when the energy stored in the reactive foil diminishes for example due to ageing. The thermal simulation results for an ambient temperature of 22°C are shown in Fig. 11. The total simulated time is 10 ms to include the cool down phase, with heat being generated by the reaction in the reactive foil only during the first 6.5 ms. The temperature distribution after 6.5 ms is plotted for different energies from the reactive foil (i.e., new reactive foil with 100% of reaction energy, aged reactive foil with 75% and 50%).

The thermal simulation results presented in Fig. 11 show that a successful melting of the solder layers occurs only when the reactive foil releases 100% of its initially stored energy. During the reaction period, the heat front propagates through both solder layer sides (i.e., both busbars and the pressure pad), thus indicating that the insertion of a thermal barrier on the side of the pressure pad shown in Fig. 4 would allow a deeper melting of the solder layers on the busbars, especially when less energy is released by the reactive foil. The simulation has shown that with the insertion of such a thermal barrier (e.g., a thermal insulation foil), at an ambient temperature of 22°C, the antifuse device can be successfully activated even when only 50% of the initial energy remains in the reactive foil. At -40°C, the device can be successfully activated when at least 75% of the energy remains in the reactive foil.

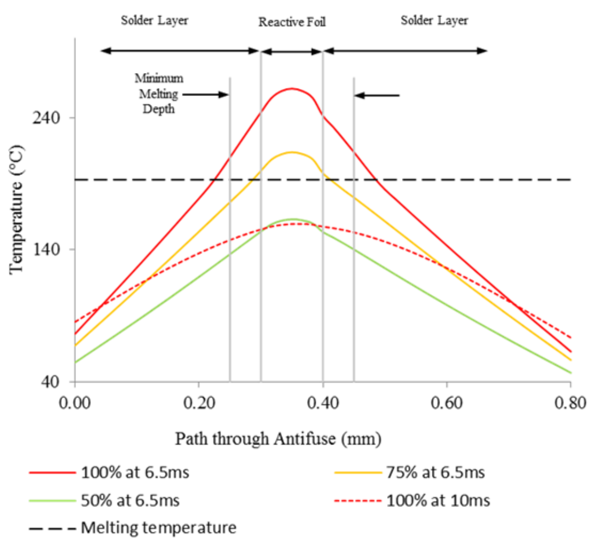


Fig. 11. Thermal simulation results obtained with an ambient temperature of 22°C and a reaction period of 6.5 ms. The temperature profile for various remaining energies in the reactive foil is plotted. The minimum melting depth for activation corresponds to the equivalent height difference shown in Fig. 7 by the isolating air gap. No thermal barrier was considered between the pressure pad and the busbars.

## V. Experimental Results

### *A. Ageing Considerations of the Reactive Foil*

The thermal simulations shown that the reaction time has an impact on the melting depth of the solder layers, therefore the reaction period of aged reactive foils was analyzed. Along with these measurements, the ignition delay was also studied. To investigate the long term ignition capability of the antifuse, artificially aged reactive foils were examined relating to their ignition capability, ignition delay and reaction period. These investigations were realized by means of a high-speed camera recording 10,000 frames per second (i.e., a frame every 100 µs) with a resolution of 512×256 pixels.

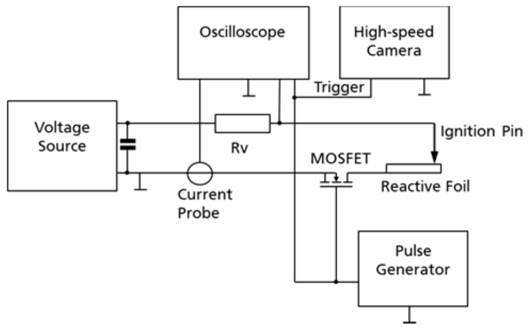


Fig. 12. Schematic of the measurement setup used to ignite the antifuses and measure the ignition delay and the reaction period.

Fig. 12 shows the schematic of the measurement setup. To start the measurement process, a 5 V pulse generator provides a 40 ms pulse that triggers the oscilloscope, the high-speed camera and the switching MOSFET simultaneously. To achieve a fast slope of the ignition current, a constant voltage source and a series resistor were used. The ignition delay (respectively the reaction period) of the reactive foil was derived by counting the frames from the trigger pulse to its ignition (respectively to the reaction end frame). An example of an oscillogram of the ignition sequence is shown in Fig. 13. The measured 10-90% current rise time of the reactive foil ignition sequence is approximately 48 µs.

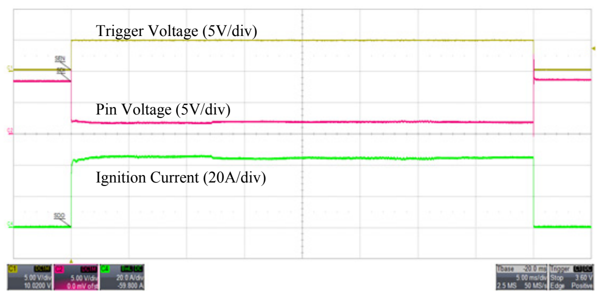


Fig. 13. Oscillogram of the reactive foil ignition sequence.

The artificially aged reactive foils could all be ignited successfully, as shown in Fig. 14. It was measured that the ignition delay varies in the 0.2-1.2 ms range, but without any recognizable dependency on the amount of artificial ageing. The reaction period however shows a significant dependency on the amount of artificial ageing: the reaction time increases with increasing ageing time and ageing temperature. The reaction period was measured to be in the 1.5-8.0 ms range.

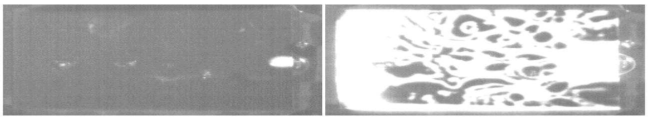

Fig. 14. Reactive foil with visible ignition point (left) and end frame (right) showing the propagation of the reaction front, with a duration of 1.5-8.0 ms. The sequence was made with a 10,000 fps camera.

### *B. Battery Cell Bypassing Tests*

The antifuse was connected to a 30 Ah $LiFePO_4$ cell with a graphite anode. The cell was fully charged by CC – CV. The current was measured noninvasively with a Hall-effect sensor at a sampling rate of 500 kS/s.

The antifuse was triggered by a current of 48 A with a pulse duration of 40 ms generated by a voltage source providing a fast rise time. Fig. 15 shows the trigger signal, the trigger current and short circuit current. The delay after which the antifuse carries the full short circuit current was less than 20 ms. The peak short circuit current flowing over the antifuse was about 955 A and occurred 5 ms after the antifuse created the short circuit over the cell. The complete discharge of the cell took about 200 s (not shown in Fig. 15). The antifuse carried the current over the complete time with no damage or other functional fault.

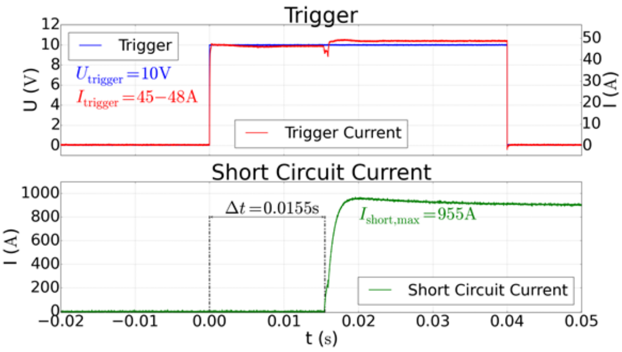


Fig. 15. Short circuit current when shorting a 30 Ah prismatic high-power lithium-ion LFP/Graphite battery cell charged at 100% SOC.

## VI. Conclusion

Due to application demands, the requirements for safety and availability in battery powered applications are increasing dramatically. State-of-the-art automotive grade battery cells with integrated pressure safety devices are no more sufficient to fulfill these requirements. A novel power electronic device called power antifuse was proposed with its associated electric circuit symbol to solve these new safety requirements. Thermal modelling was done to obtain the design margins, especially after ageing. Investigations of the ignition delay and reaction period with a high-speed camera have shown that the performance level reached for shutting down high capacity battery packs in crash cases is given. Further, to obtain the highest cost-efficiency, the antifuse should be integrated in each battery cell and the cell should provide a multifunctional contact allowing cell voltage measurement, passive balancing and antifuse ignition. The newly proposed power antifuse device offers both battery cell bypass function in single cell failure case, and shutdown function in battery system crash case, thus dramatically enhancing the offered safety and availability levels in the transportation and energy domains.

## Acknowledgment

Parts of the research leading to these results have received funding from the Energie Campus Nürnberg (“EnCN”) financed by the State of Bavaria (Germany) as part of the program “Bavaria on the Move”, and the SEEDs project funded by the Bavarian State Ministry of Economic Affairs, Infrastructure, Transport and Technology. Further funding was received from the European Union Seventh Framework Program (FP7/2007-2013) under grant agreement n°285739 (“ESTRELIA”); and from the ECSEL Joint Undertaking under grant agreement n°662192 (3Ccar) and grant agreement n°737469 (AutoDrive). This Joint Undertaking receives support from the European Union’s Horizon 2020 research and innovation program and the ECSEL member states (i.e., BMBF for Germany). Some further funding was received from the Federal Ministry of Education and Research of Germany under grant agreement n°03XP0027 (“MiBZ”).

## References

[1] P. Notten, H. Bergveld, and W. Kruijt, “Battery Management Systems: Design by modeling,” *Kluwer Academic Publisher*, 2002.

[2] F. Baronti, G. Fantechi, R. Roncella, R. Saletti, G. Pede, and F. Vellucci., “Design of the battery management system of $LiFePO_4$ batteries for electric off-road vehicles,” in 22st IEEE International Symposium on Industrial Electronics, pp. 1–6, May 28–31, 2013.

[3] M. Gepp, R. Filimon, S. Koffel, V. Lorentz, and M. März, “Advanced Thermal Management for Temperature Homogenization in High-Power Lithium-Ion Battery Systems Based on Prismatic Cells,” in 24st IEEE International Symposium on Industrial Electronics, Jun. 3–5, 2015.

[4] V. Lorentz, M. Wenger, J. Grosch, M. Giegerich, M. Jank, M. März, and L. Frey, “Novel Cost-Efficient Contactless Distributed Monitoring Concept for Smart Battery Cells,” in 21st IEEE International Symposium on Industrial Electronics, pp. 1342–1347, May 28–31, 2012.

[5] N. Martiny, T. Mühlbauer, S. Steinhorst, M. Lukasiewycz, and A. Jossen, “Digital data transmission system with capacitive coupling for in-situ temperature sensing in lithium ion cells,” *Journal of Energy Storage*, vol. 4, pp. 128–134, Oct. 31, 2015.

[6] J. Schmidt, S. Arnold, A. Loges, D. Werner, T. Wetzel, E. Ivers-Tiffée, “Measurement of the internal cell temperature via impedance: Evaluation and application of a new method,” *Journal of Energy Storage*, vol. 243, pp. 110–117, Jun. 12, 2013.

[7] R. Schwarz, K. Semmler, M. Wenger, V. Lorentz, and M. März, “Sensorless Battery Cell Temperature Estimation Circuit for Enhanced Safety in Battery Systems,” in 41th Annual Conference of the IEEE Industrial Electronics Society, Nov. 9–12, 2015.

[8] S.W. Byun, Y.S. Kim, D.W. Han, B.K. Ahn, and S.B. Kim, inventor; Samsung Sdi Co., Ltd. and Robert Bosch GmbH, assignee “Rechargeable battery comprising short circuit unit responsive to pressure and module thereof,” U.S. Patent 8,557,418, Oct. 15, 2013.

[9] U. Lange, and F. Eberle, Robert Bosch GmbH, “Safety device for a galvanic cell,” U.S. Patent 20140272492 A1, Sept. 18, 2014.

[10] J. Langheim, inventor; Stmicroelectronics Sa, “Method and device for extending the lifetime of a battery in particular of a vehicle,” U.S. Patent 9,123,978, Sep. 1, 2015.

[11] M. Grießer, “Cost Optimization of an Integrated Bypass Device for Lithium-Ion Battery Cells Used in Electrified Vehicles,” Master Thesis, Mar. 3, 2017.