Reliable Smart Power System ICs for Automotive and Industrial Applications - The Infineon Smart Multichannel Switch Family

M. Glavanovics
michael.glavanovics@infineon.com

H. Estl
hannes.estl@infineon.com

A. Bachofner
andreas.bachofner@infineon.com

Abstract:

Infineon Multichannel Switches are a newly developed family of scalable, highly integrated Smart Power components for automotive and industrial applications.

In the first part of the paper, the Multichannel Switch Family is introduced together with some typical automotive applications and their performance requirements, such as reliable power switch operation under dynamic thermal stress conditions.

The second part of the paper describes a suitable method for accelerated life testing of Smart Power Devices under repetitive clamping stress. A simple thermal model is presented that allows to correlate dynamic junction temperature rise to experimentally observed mean time to failure of Multichannel Switches.

1. Introduction to Infineon Smart Multichannel Switches

Topics like comfort, safety and environmental aspects have increased the demand for highly sophisticated electronic system solutions in modern cars. Therefore the semiconductor content per car is growing much faster than the car production itself (in concrete terms: annual car production has grown around 3% p.a. over the last three years in comparison to a 10% p.a. growth rate for automotive semiconductor business.)

Penetration of the medium and low-end car market segment with advanced electronic systems like common rail injection, GDI, ESP,... will provide a continuously high growth over the next years. This trend is strengthened additionally by strong automotive industry requirements regarding reduced volume, weight and cost of electronic systems together with increasingly integrated functionality.

To cover these requirements, one has to approach the physical limits of semiconductor design and technology, while at the same time reducing the cost per unit. Therefore, Infineon has introduced a family of smart power multiple switches designed in our so-called SPT 4 technology. With this well-established process, it is possible to integrate Power DMOS, CMOS and bipolar structures in a single chip, the Smart Multichannel Switch.

1.1. Description and Functions

To cover the requirements of modern automotive applications, smart functions like full protection and diagnosis ability have to be embedded in the driver IC. Infineon Smart Multichannel Switches have powerful family features that are common for all ICs (see [3] for a detailed description). Additionally they are equipped with device specific features that are different for each single type. This creates a kind of construction set with basic device behavior, but also special features to cover the requirements of specific applications.

1.2. Basic Features:

All devices share protection circuits for the device itself and for the connected load circuit.

- Channel selective overtemperature protection with shutdown of the affected channel
- Short circuit protection.
- Active current limitation that keeps the load-current below a specified level to avoid destruction by high currents (e.g. in case of a short circuit).
- Overvoltage protection of the driver stage by active clamping (This is necessary to turn off inductive loads without freewheeling, see Figure 3).
- ESD protection >2000V (Human body model).
- This is combined with basic diagnosis functions like overload/overtemperature detection in on-state of the channel and open load detection in off-state.

Besides this all devices have a dedicated supply pin and can be driven by 5V as well as by 3.3V systems.

1.3. Specific Features:

In addition, each device has some specific features. For example SPI interface for programming and controlling the IC and to read back detailed diagnosis information and a general "Fault" pin which can be used for µC interrupt generation in case of a fault condition. A feature for applications that are permanently connected to battery is the standby mode that reduces the current consumption of the device to below 50µA. Some of these features are mandatory for special applications. For example in powertrain a "Short to GND" - detection for driving injector valves is often needed. Electronic overload shutdown or open load detection in on-state are necessary features for safety applications like ABS.

1.4. Applications

Modern Automotive Applications call for highly integrated intelligent Power Semiconductors under respect of today's and tomorrow's environmental and safety regulations. The enlarging number of loads - from a few mA up to more than 100A - must be driven in an intelligent way in combination with a real time fault monitoring. These requirements demand that protection and fault diagnostics be present in the module to keep emission levels within standard boundaries and to maintain system reliability.

The main target of Infineon Multichannel Switches are smart switching applications in Powertrain, Safety and Body with loads from 50 mA up to 5A per channel. Whenever protection of the switch and the load circuit combined with detailed diagnosis are needed, this family of smart ICs is used. On the one hand, the integration of driver, protection and diagnosis functions reduces board space and system cost, on the other hand it increases system reliability and performance.

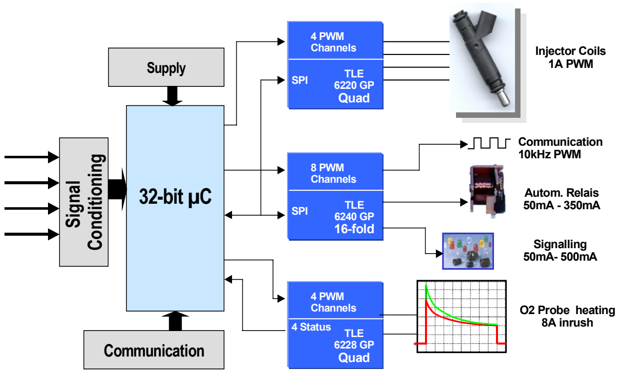

Figure 1: Engine management application with Smart Multichannel Switches

The Engine Management application example of Figure 1 shows typical loads that can be handled. On the low end of the power scale there are low current loads like signal lamps or communication lines where PWM and high switching frequencies are required combined with open load diagnosis and overload detection because of loads and wires off the ECU board. Increasing power is required by relays and other static loads and finally by dynamic loads like Oxygen probe heaters with strong inrush currents or injector valves that cause high inductive peaks at each switch off. In safety applications like ABS our devices are mostly used to switch hydraulic actuators or valves and for driving signal lines. In these application areas where life depends on electronic devices, it is important to have protection and detailed diagnosis combined with a high reliability of components and system. Also in Body applications the ICs can be found for example in door modules, keyless entry, timing and alarm modules for driving LEDs with PWM or to switch relays. In addition to the electrical functions the devices must also withstand harsh environmental conditions like up to 140°C ambient temperature (for example in transmission systems) or EMI on the battery line.

1.5. Development roadmap

The existing family of devices will grow, but not only by scaling $R_{DS(on)}$ or different numbers of channels. With the next generation of BCD technology called SPT5 new functionality and ideas will be added to our portfolio (Figure 2). An $R_{DS(on)}$ per Area improvement of 30% and up to 10 times higher logic density open new ways for smart power switches, enabling the use of integrated A/D converters, High/Low-Side configurable devices, integrated Peak&Hold functionality , DSP and state machines. Static junction temperatures will be rated up to 175°C, allowing the designer to integrate sophisticated control functions directly into sensors and actuators under extreme thermal conditions.

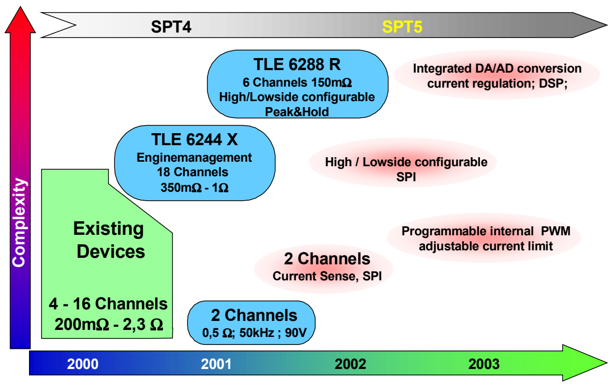

Figure 2: Infineon roadmap for Multiple Switch family

2. Reliability of Infineon Multichannel Switches

In engine management applications, Smart Power components are exposed to extraordinary thermal stress, average junction temperatures reaching 150°C in normal operation and well beyond 200°C during failure conditions. In addition, high speed periodic switching of inductive loads, such as fuel injector valves, causes additional pulse power dissipation, driving peak junction temperature up to 200°C for millisecond time intervals.

Infineon technologies have been carrying out thorough investigations on dynamic thermal stress and failure modes to ensure reliability and ruggedness of Infineon Multichannel Switch components under the aforementioned conditions.

2.1. Inductive Switching

The clamping of inductive loads during turn-off is a key feature for smart power switches. Whereas for slow switching applications the use of a freewheeling diode is acceptable, the fast and accurate current turn-off of e.g. an injector valve requires either a bridge configuration or preferably a zener clamp (Figure 3). Only in this way, a sufficiently high and well-defined negative voltage can be provided to reduce inductor current to zero in a given time with reasonable effort.

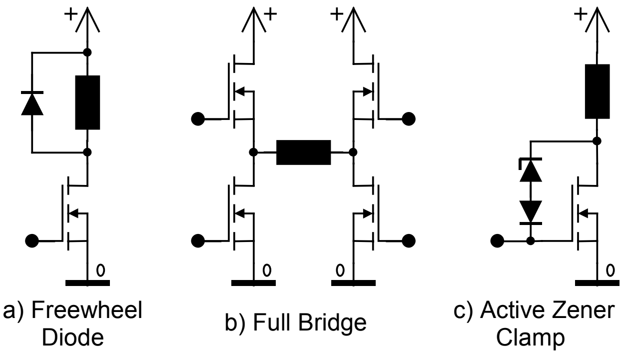

Figure 3: Inductive load turn-off circuits

The Zener Clamp is widely used in automotive designs for its reliability and cost-effectiveness. Only one switching device is needed per load, and it will be able to turn off under any circumstances, even when power supplies or external control signals fail.

The drawback of zener clamping is the high power dissipation that occurs when the inductor's energy is discharged in the DMOS power switch. Typical peak power is in the range of 100W per mm² DMOS area, compared to on-state losses of around 2W/mm².

The dramatic temperature rise associated with inductive clamping limits the corresponding pulse duration to less than a few milliseconds, allowing dissipated energies around 50mJ/mm² for a single pulse at room temperature.

More accurate predictions on permissible pulse amplitudes and energies require a dynamical thermal model of the Smart Power switch to predict peak and average junction temperatures (covered in the next chapter), and a thorough understanding of failure mechanisms under single and repetitive thermal stress.

The limiting factor to single pulse clamp energy is obviously the peak temperature that the junction may reach without destruction. The typical failure mechanism is the thermal breakdown of bipolar junctions in the Power DMOS structure (Figure 4), namely the parasitic bipolar transistor or the Drain-substrate diode, as explained in [2]. Failure temperature ranges between 300°C and 400°C, depending on technology and load conditions.

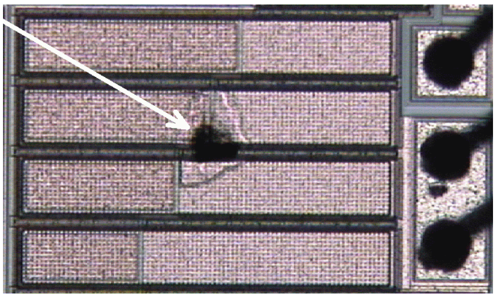

Figure 4 Catastrophic thermal failure pattern of an integrated vertical power DMOS

2.2. Repetitive Clamping Stress

Periodic switching of inductive loads like fuel injector valves (Figure 5) imposes additional stress on smart power devices. Inductive clamping is presently applied at switching frequencies up to 50Hz, which equals the injection rate of a 4-stroke engine at 6000rpm. For PWM applications at higher frequencies, the average switching losses associated with active zener clamping become unacceptable and a freewheeling diode is preferred.

However, even operation at 50Hz means $180 * 10^6$ switching cycles per 1000 hours of operating life. The repetitive thermo-mechanical stress on the power device leads to mechanical degradation of the metallization (oxide cracks, aluminium migration), which becomes the dominant failure mechanism for peak temperatures well below the aforementioned destruction temperature for single clamp pulses.

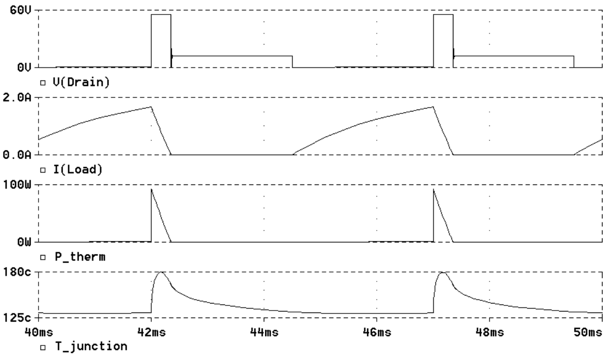

Figure 5: Repetitive clamping waveforms (simulated)

In other words, repetitive clamp energy ratings have to take into account not only the destruction limit of the power device, but also degradation of the whole smart power component through periodic thermomechanical stress. Life time experiments under repetitive clamping have to be carried out and analyzed statistically to evaluate the influence of load and environmental conditions. Dynamic junction temperature has to be measured and/or calculated in order to correlate measured life times to junction temperature stress.

2.3. Thermal Model of Short Power Pulses

The different measurement and calculation methods for determining dynamic junction temperature of power devices are well known from literature [4]. For the purpose of this reliability analysis, an analytical approximation was derived from the heat transfer equation and parameterized by indirect measurements.

It is well known, that the one-dimensional heat transfer equation

(Eq.1) $$a \cdot \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t}$$

can be analytically solved for the boundary condition of a constant heat flow injected at time t=0 into the top of a "semi-infinite" plate. This is a simple model for a silicon chip heated by power dissipation which is spread evenly over an area that is large compared to chip thickness, e.g. a Power DMOS.

The solution of (Eq.1) shall be omitted here, as it is covered in better detail in mathematical literature (e.g. [5]). For our purpose we only need to know the resulting expression for the temperature rise at the surface of the chip:

(Eq.2) $$\Delta T_{surface} = \frac{P_{therm}}{A_{DMOS}} \cdot k_{therm} \cdot \sqrt{t_{pulse}}$$

In other words, the momentary temperature rise of a plate surface exposed to a constant power pulse (e.g. junction of a silicon power chip) follows a square root law with regard to time. It has to be noted though that this approximation is accurate only for pulses that are shorter than the time that the heat flow needs to reach the chip bottom (typically 2ms for 400µm chip thickness), because the boundary condition of a cool bottom is not included in the assumptions that lead to (Eq.2).

The coefficient k_{therm} in (Eq.2) is derived from the solution of (Eq.1) and can be calculated from the material properties of silicon:

(Eq.3) $$k_{therm} = \frac{2}{\sqrt{\pi \cdot c \cdot \rho \cdot \lambda}}$$

Values for silicon at 400K:

$c \cdot \rho = 1.8 \cdot 10^6\ \mathrm{Ws/m^3K}$ .... Heat capacity / volume

$\lambda = 98\ \mathrm{W/m \cdot K}$ .... Thermal conductivity

$k_{therm} = 85\ \mathrm{mm^2K/W\sqrt{s}}$ .... Theoretical factor in (Eq.2)

Regarding the many simplifications that lead to this solution, one might prefer to measure the thermal step response of the actual Smart Power chip to gain the well-known "thermal impedance"-curve which is usually the basis of dynamic thermal calculation.

Although this approach is more complicated for integrated circuits than for discrete power devices, it has been evaluated for selected Infineon Multichannel Switches. The main experimental problem is that DMOS structures integrated on a Smart Power chip can be neither independently driven nor measured. The DMOS Gate is not even accessible from outside, so switching time and speed are internally fixed. Drain and Source are loaded with auxiliary circuits that prevent separate measurement of the DMOS reverse diode or leakage current, as required in "discrete" thermal impedance testers.

Therefore, an indirect approach was chosen. The DMOS channel under test was submitted to a constant power pulse until it was thermally destroyed. Destruction time and energy were recorded for different initial junction temperatures. Under the assumption of a constant, technology-dependent breakdown temperature [2], one can directly calculate thermal impedance from this data. (The breakdown temperature itself can also be derived from the same data set by correlation analysis.)

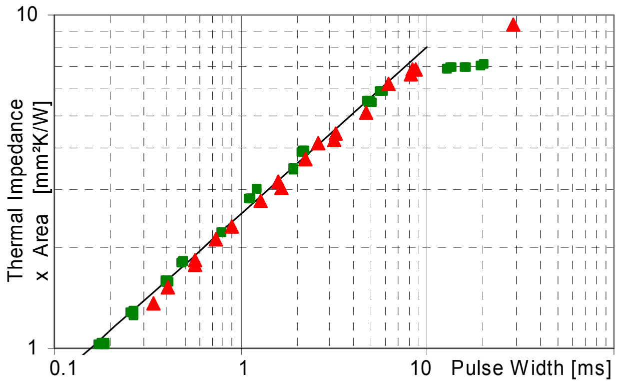

Figure 6: Thermal impedance x area of Infineon Multichannel Switches, experimental data

The result is insofar satisfying, as it fits rather well with the theoretical prediction of (Eq.2) and (Eq.3). It is obvious that the thermal impedance in Figure 6 increases about one decade for every two decades of time for short pulses ($t < 10$ms). This corresponds to the above postulated square root law (Eq.2). The empirical factor k_{therm} can thus be evaluated from the slope in the logarithmic diagram to:

(Eq.4) $$k_{therm,measured} = 80\ \mathrm{mm^2K/W\sqrt{s}}$$

Encouraged by this confirmation of the simple theoretical model, one may want to use it to calculate the junction temperature rise for other than constant power pulses. Most important is the case of a linearly decaying current and power ramp as seen in clamped inductive switching (Figure 5). The peak temperature for a given amplitude and duration of the "triangular" power pulse evaluates to:

(Eq.5) $$\Delta T_{peak,ramp} = \frac{P_{th,peak}}{A_{DMOS}} \cdot \frac{\sqrt{2}}{3} \cdot k_{therm} \cdot \sqrt{t_{Pulse}}$$

where $P_{th,peak}$ is the maximum power at the beginning of the pulse and t_{pulse} stands for the total ramp duration. As mentioned before, (Eq.5) is only valid for short pulses. The numerical factor computes to 0.471 which means that a "triangular" pulse creates approximately one half of the temperature rise compared to a constant power pulse of same amplitude and duration.

(Remark: (Eq.5) is calculated by finding the Laplace transform of (Eq.2) and replacing the step excitation by that of a decaying ramp.)

Finally, one might wish to compare the results of the approximated formulas with circuit-level thermal simulation (as described in [6]). Figure 5 shows the result of a SPICE simulation using a thermal RC-Network derived from a finite element model (FEM) of the Infineon Multichannel Switch TLE6232. The comparison yields:

(Eq.6) $$\begin{aligned} P_{th,peak} &= 92.6\,\mathrm{W} \\ t_{pulse} &= 350\,\mu\mathrm{s} \\ k_{therm} / A_{DMOS} &= 57\,\mathrm{K} / \mathrm{W}\sqrt{\mathrm{s}} \\ \Delta T_{peak,simulated} &= 48.8\,\mathrm{K} \\ \Delta T_{peak,calculated} &= 46.5\,\mathrm{K} \end{aligned}$$

Regarding the simplicity of (Eq.5), the agreement of simulated and calculated temperature seems acceptable.

2.4. Experimental Life Test Setup

To determine the operating life time of Infineon Multiple Switches under repetitive clamping conditions, a multiple component life test was designed that allows to control the main influences present in dynamic component stress.

Using true inductive loads for such a test causes several complications – large external components, high power dissipation, difficult protection of devices under test, limited choice of operating points. For these reasons a special hardware based on controlled current sources was designed to deliver constant power pulses to the devices under test (Figure 7). Amplitude, pulse duration and repetition rate can thus be freely chosen. Every channel of the driving hardware has independent short circuit protection and failure diagnosis.

Final component failure, defined by Drain-Source short circuit, was continuously monitored during the test by automated data recording on a personal computer. Some hundred Multichannel Switches of different types and power ratings were tested and evaluated this way. This allowed to determine their mean time to failure (MTTF) and correlate it to the chosen stress conditions.

The whole experiment was carried out under controlled conditions in a heated life test furnace at 85°C ambient temperature. The case temperature of the Multichannel Switches was allowed to rise to 125°C, which is the maximum rating for Epoxy resin based power packages. The limiting factor for repetition frequency and number of simultaneously operating channels was the overall power dissipation per component. 40K of self-heating was considered realistic for the case temperature, with an additional average internal temperature rise of 10..15K for the chip.

Average junction temperature therefore stayed well within the maximum ratings of 150°C during the test. However, the repetitive peak temperature stress of 50..150K at 50..200Hz repetition frequency imposed a severe additional stress, practically limiting component life to lower values than expected under static load conditions.

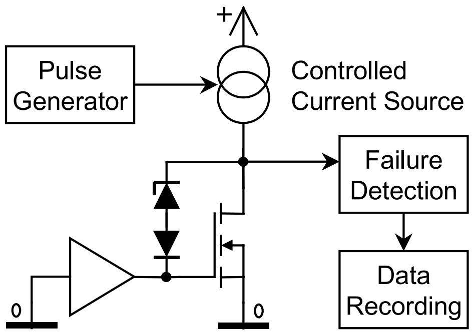

Figure 7 Test setup for repetitive clamping life test

2.5. Life Test Results

After completing up to 2500 hours of repetitive peak temperature stress, all components were electrically measured to check for parameter changes. Some representative samples were opened and inspected optically and by electron microscopy to check for degradation effects.

In general, all components that had been subjected to stress-levels below their guaranteed maximum ratings performed well within specification after the life test.

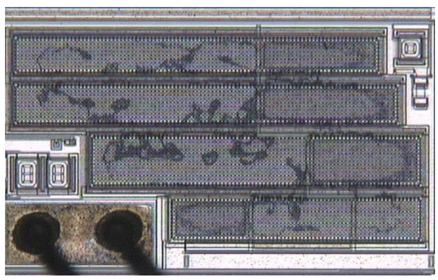

Figure 8 Typical repetitive clamp stress pattern: thermal fatigue of metallization (after 1800h @ 140°C average / 203°C peak junction temperature, 180Hz repetition rate)

However those who had been subjected to accelerated aging by overrated load conditions showed some degradation effects (also described in [1]), namely stress migration of the Aluminium metallization on the power switch. Figure 8 shows a component that is still properly operating after 1800h of accelerated stress testing. Traces of degradation were found solely in the power DMOS metallization, together with a 1.5% increase of DMOS on resistance. All other parameters (voltage levels, switching times, diagnostic functions...) of this particular component are still within specification.

The essential acceleration factors for Aluminium degradation as observed during repetitive clamping are:

Peak Junction Temperature – reliable operation requires that 200°C be not exceeded even dynamically by short thermal pulses. Static junction temperature rating for Infineon Multichannel Switches is 150°C.

Dynamic Temperature Rise – Steps of more than about 50K during the clamp power pulse cause severe thermo-mechanical stress to the chip and metallization, eventually causing early failure due to breakdown of the insulating oxide layers.

Pulse Repetition Frequency - the total number of load pulses is the key parameter for thermo-mechanical stress mechanisms rather than operating time. Therefore, life time under repetitive clamping stress is inversely proportional to pulse frequency.

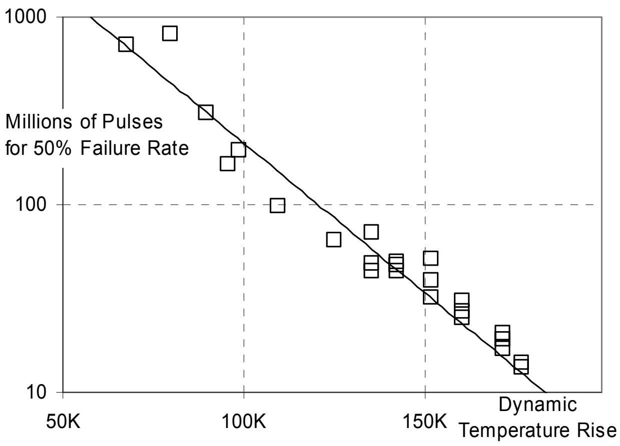

Figure 9 Measured Lifetime of Smart Power Switches under accelerated repetitive clamping stress

Figure 9 illustrates the observed empirical relationship between dynamic temperature rise and number of load pulses for a component failure rate of 50% under accelerated repetitive clamp stress test conditions.

It has to be noted though that Figure 9 covers only the range of large dynamic temperature rises and corresponding high peak junction temperatures that are well outside the above described range for reliable operation. For dynamic temperature rises below 50K, no failures were observed within the above stated life test duration. Anyhow, extrapolation of accelerated life test data to stress levels that lie within operating conditions is a well established practice in reliability analysis.

3. Conclusion and Outlook

Up to now, performance and reliability requirements for Multichannel Switches in automotive applications have been discussed together with an experimental approach to test for the corresponding reliability limits. It has been shown that under the dynamic load conditions typically present in engine management applications the number of DMOS pulse load cycles and corresponding dynamic temperature rise limit device life rather than static maximum temperature.

Future data sheet ratings for Smart Power Switches will take this into account, defining a guaranteed number of repetitive clamping cycles for given load and operating conditions. This will help automotive system designers to predict the reliability of their electronic power control systems under the influence of dynamic thermal stress.

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