Life time prediction and design for reliability of Smart Power devices for automotive exterior lighting.

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Abstract

The concept of mission profile together with the principle of the linear accumulation of the damage related to the thermo mechanical fatigue is a powerful method to predict the lifetime of a Smart Power device operating in a given system [2]. The usage of this tool requires the full comprehension and characterization of the stresses applied to the device, which in turn requires a two-sided approach. From one side an electro thermal analysis of the interaction between power device and load in order to identify the stresses applied to the physical structure and on the other side the formulation of a reliability model of the device physical structure versus the stresses.

Both the system designer and the smart power device designers take benefits from this methodology: the system designer can safely choose the smart power actuator while the silicon designer can optimize the device protection architecture.

1 Introduction

Nowadays, Smart Power devices (figure 1) are widely used in the automotive environment to drive various actuators and lighting systems equipping modern cars (Figure 2). The main reasons to use solid state Smart Power switches are linked to the increased need of reliability, fault tolerance and diagnostic power. In general, those requirements are in contrast with the market demand for inexpensive and small Body Control Units. This challenge spurs the silicon designer to embed ever-innovative features into ever-smaller devices.

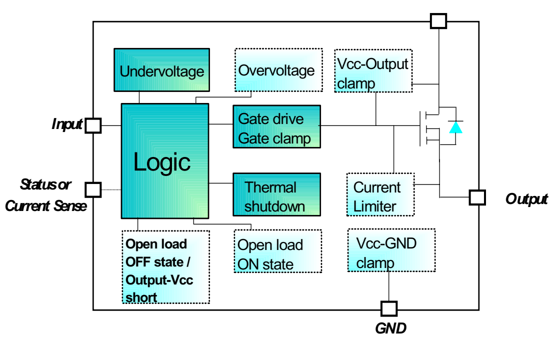


Fig. 1 Block diagram of a smart Power actuator made with M0TM technology

The harsh automotive environment requires devices able to drive huge inrush currents of automotive loads avoiding unwanted spurious fault detections.
A typical example is the dimensioning of a switch to drive incandescent lamps for automotive exterior lighting. Automotive incandescent lamps have peak currents up to about 10 times the nominal value. Consequently, the driver must be sized in order to handle

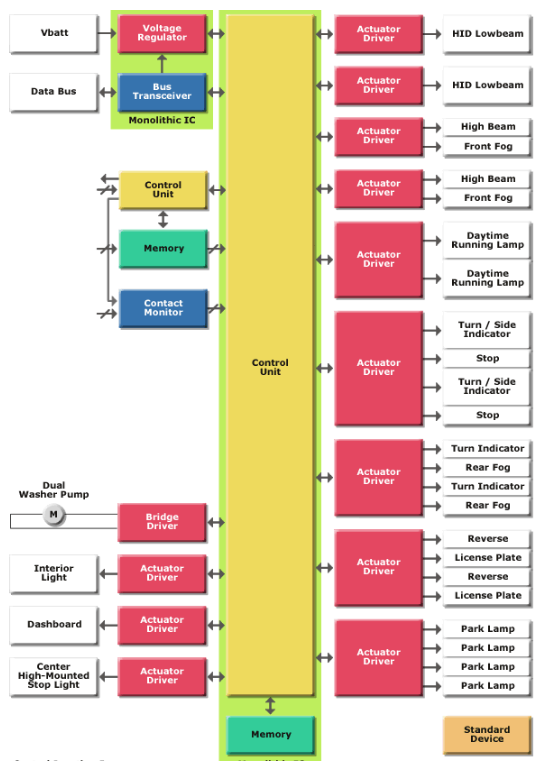


Fig. 2. Automotive Smart Junction box using Smart Power devices

the power dissipated when conducting the nominal current under steady state conditions allowing, at the same time, the few milliseconds inrush transient to safely expire with no consequences on the reliability. Additionally, the same device must be tolerant to repetitive short circuit conditions of duration ranging between 10ms and 300ms that is typically the time required by the microcontroller to recognize and validate a fault condition. In any case, for evident safety reasons, the device is generally not allowed to switch off the load on its own and suitable protections must prevent the device from destruction, minimizing the resultant stress on its own structure.

System design for reliability requires the definition of a risk assessment to take into account all potential parametric variations. In our specific case, the choice of load driver will be made on the basis of its resulting reliability in terms of number of activations versus all parameters variations (battery voltage, ambient temperature, etc.). This criterion is valid both for nominal operating condition and overload conditions. A minimum life time will be required in nominal operating conditions while a software strategy crowning a maximum number of activation will be required to prevent catastrophic failures in overload conditions and short circuit conditions.

2 Life time prediction

2.1 Definition of reliability and the life time estimation process

Reliability, R(f), is the probability that a component or system will perform its design function for a specified mission time, under given operating condition. In other words the life time prediction under given operating conditions is a way to calculate the reliability of a device. This process flow chart includes few steps intrinsic in the reliability concept:

1. Mission profile (activation time, number of activations @ given working conditions)
2. Stress mechanism that is the direct way to individuate the mission in terms of physical phenomena that create stress and damage on the device structure.
3. Stress model is the equation defining the device structure ability to sustain defined physical stress.
4. Damage, Q, is the % of the ability of the device required to perform a given mission.

2.1.1 Mission profile

The mission profile for an incandescent lamp solid state driver is defined with the maximum number of lamp activations at a given ambient temperature (fig. 3), defined battery voltage and lamp characteristics. Those data are necessary but not sufficient to evaluate the stress of the Power semiconductor as this will strongly depend on the interactions between the lamp behaviour and the driver parameters (i.e, I,T curve, current limitation, ambient temperature, battery voltage). Identification of worst case stress conditions and risk assessment can done with the help of mixed mode electro thermal simulations.

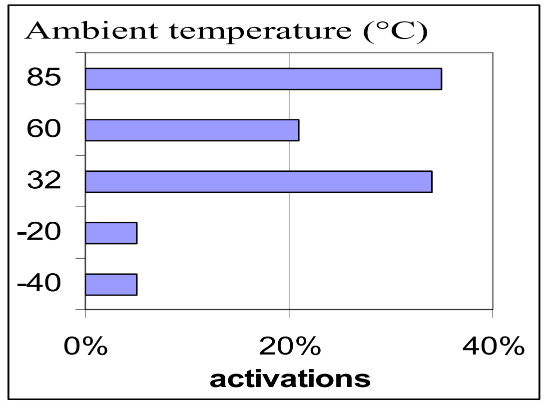


Fig. 3 Example of ambient temperature distribution required to define the mission

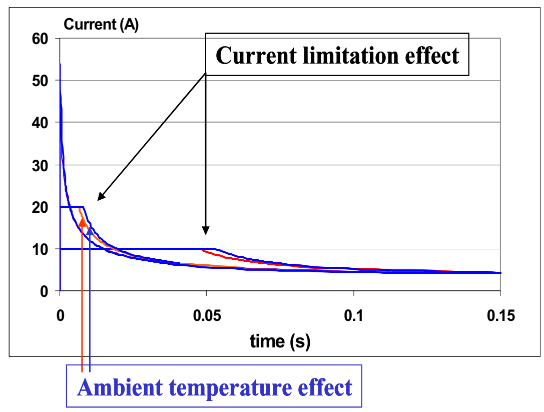


Fig. 4 Current time curve depends on smart Power current limiter influencing the incandescent lamp turn on behaviour.

2.1.2.2 Electro thermal analysis

An over current protection is normally implemented in the form of a current limiter in order to set the device working point inside a safe operating area even during short circuit operation. The choice of a Proper value for the current limitation is a matter of trade-off between short circuit reliability and load compatibility. Indeed, extreme environmental conditions, such as very low ambient temperature, and borderline system conditions, such as high battery voltages or low levels of device current limitation, may sometimes cause the inrush of the bulb to be clamped, thus letting the device work in linear mode (fig. 4) and dissipate a huge amount of power during the lamp turn on transient. This power dissipation leads to very fast temperature transients (fig. 5) responsible of thermo-mechanical stresses due to thermal cycling. The amplitude of the temperature variation can be calculated using an accurate modelling of the smart Power device and of the incandescent lamp. This method makes possible the evaluation of border line condition caused by the device parameter spread (i.e. current limit value variations) and on extreme ambient temperature (i.e. inrush current of cold lamp).

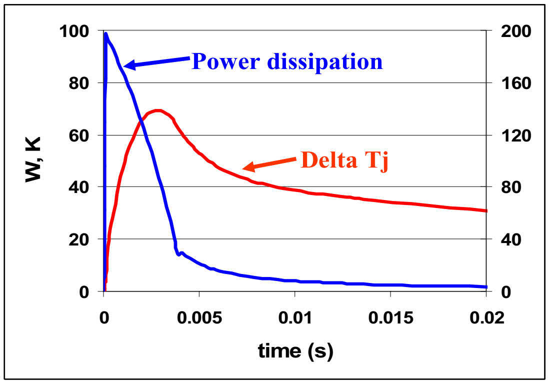


Fig. 5 Power dissipation example and resulting temperature transient on the silicon during lamp activation (Conditions: VBAT = 13.5V, TAMB = 25°C, Lamp 21+21+5+5W, Current limitation = 20A, Device is VND600SP, Simulation tool is MATLAB)

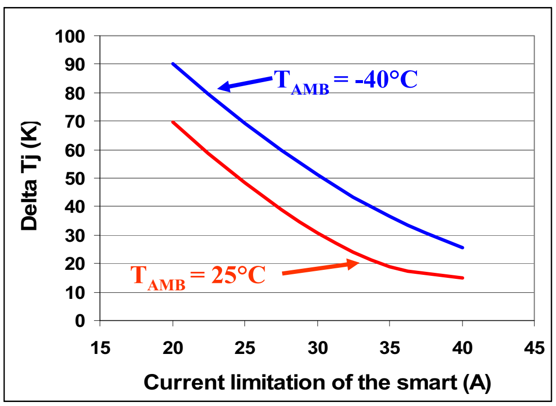


Fig. 6 Effect of the parameter variation on the thermal cycling amplitude (Conditions: VBAT = 13.5V, Lamp 21+21+5+5W, Device is VND600SP, Simulation tool is MATLAB).

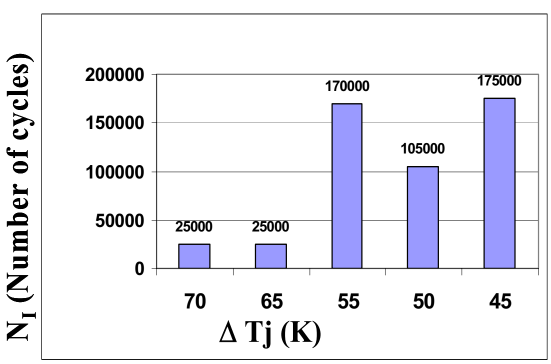


Fig. 7 Thermal mission profile @ 500 K activations, ambient temperature distribution of fig3 (Conditions: VBAT = 13.5V, Lamp 21+21+5+5W, Device is VND600SP @ current limitation = 25A, Simulation tool is MATLAB).

2.1.2.2 Mission in terms of thermal cycles

A thermal cycle is determined by an oscillation of the temperature having defined amplitude, ΔT. The temperature value starts form an initial level and comes back to the same level. The maximum temperature variation during fast thermal transient due to lamp inrush is considered as the amplitude of the thermal cycle because we approximate the steady state junction temperature of the smart power to the ambient temperature.

We can calculate the mission profile in terms of the thermal cycle by mean of a precise device and load thermo electrical simulation. Fig. 5 shows an example of calculated thermal cycle for a given condition while Fig. 6 shows the result of parameters variation. The worst case condition can be defined by the combination of current limitation process variation and Fig 6 curves. Fig. 7 shows the temperature mission profile for a worst case device having its current limitation = 25A.

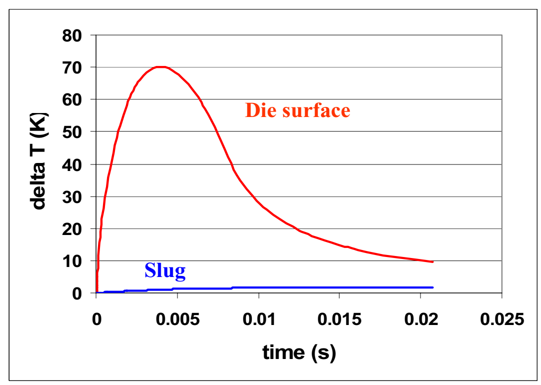


Fig. 8 Temperature variation example of the device heat slug versus the thermal cycle amplitude

2.2 Stress mechanism.

The duration of the thermal transient due to lamp inrush (<10ms) is one order of magnitude below to the thermal time constant of the package (>300ms). The heat generated inside the device junction during this very fast transient creates an adiabatic heating of the junction and the heat propagates immediately to the aluminium surface of the smart Power device, so creating a very fast thermal cycle on the aluminium source of the smart Power active area (Fig. 8).
A deeper analysis shows that the thermo mechanical stress due to the fast thermal transient [1] is the only one that can affect the life time of the device: In fact either the absolute temperature, either the low voltage applied either the relatively low current density are not able to activate the phenomena like electro migration, inter metallic growth, leakage governed by Arrhenius. Also the very low amplitude of thermal cycling of the package is not significant.

2.3 Stress model.

According to [1] the stress model is obtained with empirical method: Several tests to estimate the maximum number of cycles to failure versus fast thermal cycling amplitude were implemented. Distribution of failure is the result that statistically elaborated (Weibull) make possible to extract values of the curve NF versus ΔT (Fig. 9).
This curve fits Coffin Manson law (Equation 1) so it possible to extrapolate the NF value for intermediate or very low value of ΔT.

$NF = a\,\Delta T^m$: Simplified coffin Manson law
NF: Number of cycles to failure
ΔT: Amplitude of the thermal cycle
Where a = 1E19, m = -6.9397
Equation 1

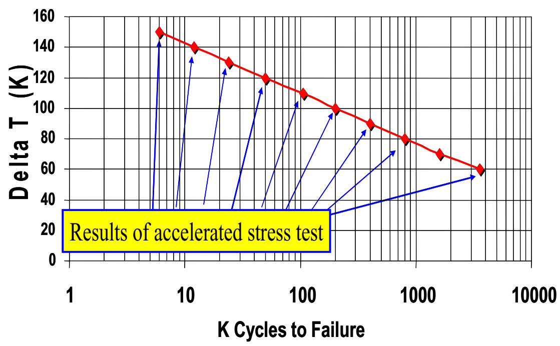


Fig. 9 Reliability Characterization of the smart Power device of M0 technology

2.4 Life time calculation

Simple life time prediction based on thermo mechanical stresses, and based on the linear accumulation of the damage related to the cyclic fatigue has been already proposed [2]. According to this method we have all the data required to predict the life time in term of maximum number of activations of a given device having the M0™ structure. The calculation will be made using equation 2.

$Q = \Sigma_{I=1 \text{ to } n} N_i/N_{Fi}$ **Equation 2**

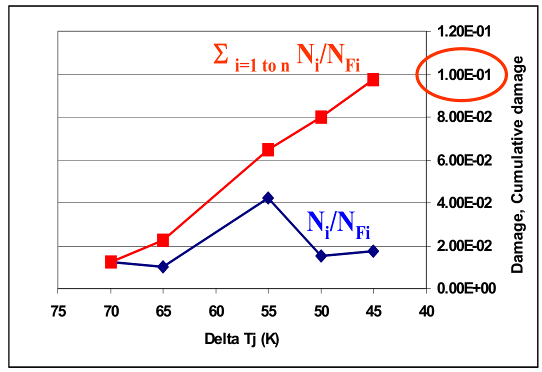
N_i: Number or frequency of activations at a given temperature T_i.
N_{Fi}: Maximum number of cycle before failure for a given thermal cycle having amplitude = ΔTi. This value can be extracted from the characterization curve or using the equation 1.
Q: Cumulative stress for the mission.

No failure is expected if Q < 1. If Q < 1, the value 1/Q is the number of missions that the device will be able to perform before failre.

2.4.1 Exampple

Fig. 10 shows an example of cumulative damage calculation. The mission defined is 500K cycles with the thermal cycling distribution of fig 7.

The blue line indicates the damage for each delta T value while the read line shows the cumulated damage Q. Since maximum Q = 0.1, the device will be able to perform 10 missions (5 millions cycles) before failure.



•Total number of activations = 500K

Fig. 10 Thermal fatigue and cumulated thermal fatigue according to the mission profile of fig. 7

3 Design for reliability

In order to optimize the device size respect to the nominal lamp current and in the same time to make the device rugged against the inrush condition, a protection against fast thermal fatigue has been integrated inside new generation of high side drivers M0-5.

3.2 Embedded protection against fast thermal fatigue.

The idea is to integrate a protection able to limit steep temperature rises as well as the usual over temperature protection typically set to an absolute temperature value of 175°C.

Fig. 11 shows that 2 thermal sensors are integrated on the chip, the first sensor is located in the hottest position [3] while the second in the coolest position. With a correct positioning of the sensors, the device shuts down when fast thermal transients reach a defined variation of temperature (fig. 12).

3.2.2 Verification of protection effectiveness

The effectiveness of the ΔT control method is consequent of the exponential function behaviour of coffin Manson model: According with fig. 9 a thermal cycling delta T = 100K, we can see that a delta T = 60K will cause a thermo mechanical stress 250 times lower and a delta T = 30K , 3000 times lower. To verify the efficiency of the protection we compare the reliability of a device protected against the thermal cycling with the reliability of the same hypothetical device without protection.

We take as an example the HSD VND5025AK (M0-5 technology 2 x 30mohm) driving 3 lamps in parallel (21W+21W+5W) at -40°C ambient temperature. For worst case evaluation we select a device having the lowest current limitation (40 A). Figure 13 shows the behaviour of the current and of the thermal cycling during lamp inrush.

According to equation 1 and fig.12 the mission profile of the device for 500K activations is:

- 500K thermal cycle $\Delta T = 60$ K
- 7*500K thermal cycles $\Delta T = 30$ K.

If by hypothesis we disable the thermal cycling protection, the mission of the device is:

- 500K thermal cycling with delta T = 110K.

By the stress model (fig. 9) we get the maximum number of cycles to failure for each delta T mission.

- $\Delta T = 60$ K → NF 60 = 4.5 E 6
- $\Delta T = 30$ K → NF 30 = 5.6 E 8
- $\Delta T = 110$ K → NF 110 = 1 E 5

The cumulated damage of the protected device is given by: Q PROTECTED =
= 500K*((1 / NF 60) + (7 / NF 30)) = 0.11 << 1

While the not protected will have cumulated damage = 500K * 1/1E5 = 5 >> 1

4 Conclusion

The life time estimation process makes easy the choice of the right device to design reliable systems. Also silicon design takes benefit from the necessary procedure because with this procedure, critical parameters affecting the device life time can be identified. In this specific case an efficient protection was carried out. This protection embedded inside the smart Power minimizes the effect of thermal fatigue.

5 Literature

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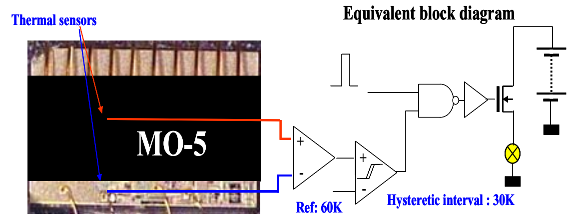

Fig. 11 Top view of the chip and principle diagram of the embedded ΔT control using 2 thermal sensors that are indicated on the smart Power chip

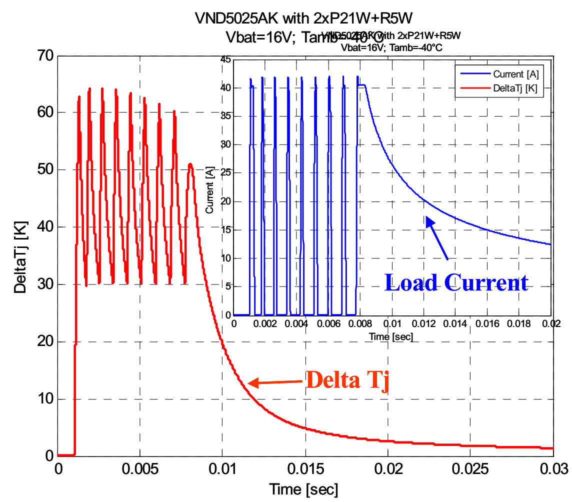

Fig. 12 Behavior of the VND5025AK show the effect of ΔT control when driving cold lamp in a worst case condition (current limitation lower than current inrush)

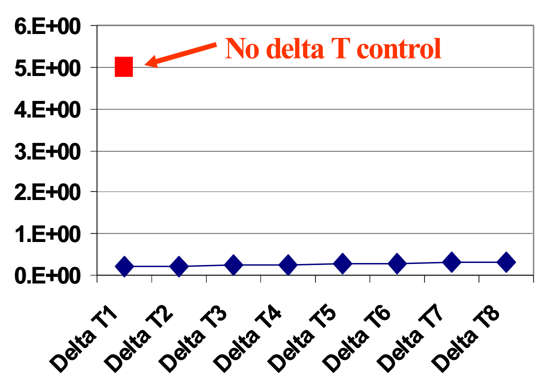

Fig. 13 Cumulated damage after 500K activations of the VND5025AK compared with the cumulated damage on hypothetical VND5025AK without ΔT control