Power MOSFET with integrated poly-silicon diode to monitor junction temperature, with simplified external electrical shutdown circuit to prevent thermal runaway

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Abstract- This paper studies and analyzes the integrated temperature sensor of a LV power MOSFET SAFeFET™ device from STMicroelectronics (STZ150NF55T). The paper also shows a typical example of an application where this kind of device can be considered: a fan controller electrical system. For this case, the paper suggests a design example of how achieve a device shutdown event if the junction temperature reaches its maximum guaranteed value. Finally, an evaluation of the error in the junction temperature reading under different thermal conditions is performed to complete the analysis.

1. Introduction

Today, power MOSFETs can be considered as the most important power switching devices used in the modern industrial power electronics applications. In fact, they can be used to switch very high currents in a short time with lower commutation losses compared to other devices, such as power bipolar transistors and IGBTs, which work at very high switching frequencies. Switching frequency becomes a key parameter for the application designer. By increasing the operating frequency, it is possible to decrease, for instance, the transformer size and, thus, develop more compact applications. Another advantage of the MOSFET compared to the other devices is the simplicity of driving it. Power MOSFETs can be switched on or off by applying a suitable voltage source. Sometimes, in order to better adjust the dynamic performances of the power MOSFET during the commutation process, a suitable external gate resistor is placed in series with the gate pin of the device.

Recently, system design engineers have increasingly required application-specific devices for power MOSFET developers. This is to fit specific operating conditions or to have particular features required to suitably implement the device's functions, in order to increase component reliability. Unlike general-purpose components, they often require particular design and process techniques that make them more expensive devices compared to the standard transistors. The automotive segment is one of the application fields where major application-specific device requests come from. In this application field, the devices must be guarantee a higher level of reliability compared to other ones and particular attention is placed in the quality of the product. Automotive devices are subject to more restrictive rules and documents (PPAP – Production Part Approval Process), which have to be provided to the customer. In the automotive application field, one of the most important variables which affect the device reliability is the temperature. For instance, when a power MOSFET is located inside a car hood, for an ABS or fan controller system, it is subject to the external ambient conditions which, sometimes, can be considered extreme. The ambient temperature can change from more than 100 ˚C in summer when the engine is running, to less than 0 ˚C in winter just after the engine start-up. Sometimes a device's ambient conditions can change significantly in a very short time. However, power MOSFET reliability must still be guaranteed when thermal and electrical stresses affect the electrical parameters within their maximum ratings. In any case, even if the application operating conditions involve, for instance, power MOSFET overheating, the device must be saved by implementing an immediate shutdown of the transistor, to avoid either the failure of the component or, in the worst case, the whole system failure.

Already for several years, power semiconductor makers have been implementing specific devices called vertical intelligent power components, which are equipped with either a power device area or logic and control device area in the same die. These kinds of device integrate different and complex structures in the same silicon, which involve very high component costs. In order to implement a simple and cheaper power MOSFET shutdown function when the junction temperature exceeds the guaranteed value, it is possible to use standard power MOSFET devices with simple added features (SAFeFET™ components in STMicroelectronics' case). In this case, a poly-silicon diode can be used to monitor the power MOSFET's junction temperature. This paper presents a complete characterization of the poly-silicon diode to establish better operating conditions, in order to evaluate the junction temperature. The paper also shows a typical example of applications where this kind of device can be considered: a fan controller electrical system. In this kind of application, the paper suggests an example of an electrical circuit to achieve a device shutdown event when the junction temperature reaches its maximum guaranteed value (175 ˚C for automotive devices). The example of the design proposed also highlights how the junction temperature may be continuously read and displayed.

2. An example of LV power MOSFET with integrated a poly-silicon diode: STZ150NF55T from STMicroelectronics

As an example, the STZ150NF55T from STMicroelectronics was considered. The electrical characteristics of this device are summarized in Table I, while, the internal schematic diagram is shown in figure 1. The top layout view is shown in figure 2, the poly-silicon layout in figure 3 and, finally, the electrical sensing diode circuit in figure 4. As you can see in these figures, the device has five pins; three for the power MOSFET (drain, source and gate) and two for the sensing diode (anode and cathode) (PENTAWATT package). The poly-silicon sensing diode is implemented above the top dielectric layer. It is thus thermally connected to the power MOSFET system but not electrically connected. Even if the sensing diode is not directly located in the silicon area, the short distance and material characteristics allows us to suppose that the diode senses the junction temperature and that, as experimental results demonstrate, the delay time can be estimated at around a few hundred micro-seconds. Furthermore, it is possible to see that the sensing diode is composed of a series of four single poly-silicon diodes.

Table I: STZ150NF55T electrical parameters

Symbol	Parameter	Value	Unit
V_{DS}	Drain-Source Voltage (V_{GS} = 0)	55	V
V_{GS}	Gate-Source Voltage	± 18	V
I_D	Drain Current (continuous) at T_C = 25°C	40	A
I_D	Drain Current (continuous) at T_C = 100°C	40	A
I_{DM}	Drain Current (pulsed)	160	A
P_{TOT}	Total Dissipation at T_C = 25°C	250	W

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
$V_{(BR)DSS}$	Drain-Source Breakdown Voltage	I_D = 250μA, V_{GS}= 0	55			V
I_{DSS}	Zero Gate Voltage Drain Current (V_{GS} = 0)	V_{DS} = Max Rating,			10	μA
I_{GSS}	Gate Body Leakage Current (V_{DS} = 0)	V_{GS} = ±15V, V_{DS} = 0			10	μA
$V_{GS(th)}$	Gate Threshold Voltage	V_{DS}= V_{GS}, I_D = 250 μA	2		4	V
$R_{DS(on)}$	Static Drain-Source On Resistance	V_{GS}= 10 V, I_D= 20 A			9	mΩ
V_F	Temperature Sense diode forward voltage	I_f=250μA		3.5		V

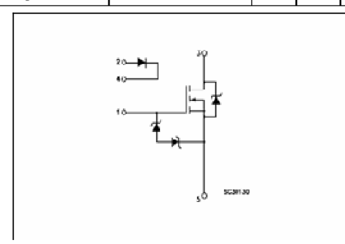

Figure 1: STZ150NF55T schematic diagram

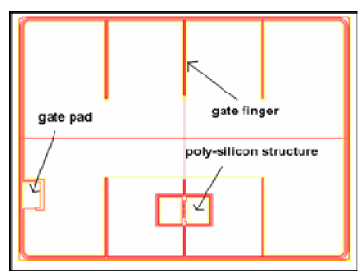

Figure 2: STZ150NF55T top layout view

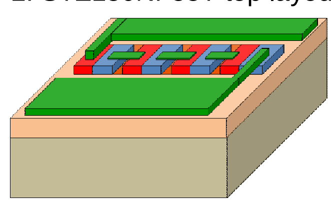

Figure 3: Poly-silicon diode design structure

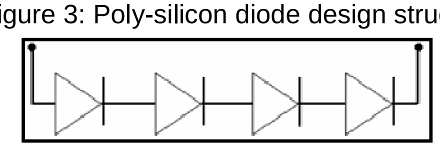

Figure 4: diode's electrical schematic

This is necessary to obtain a diode forward voltage that depends on the specific application.

3. Which procedure is selected to sense the temperature and how the working condition is chosen

To measure the junction temperature, two different theoretical approaches may be considered.

The first fixes the forward voltage and measures the diode drain current at two different temperature levels. To do this, we need an electrical circuit that imposes the diode's fixed feed voltage, and then measure the current. In this case, by increasing the temperature, the current increases too.

The second procedure fixes the drain current level and measures the voltage drop for an increased temperature. A fixed drain current must be forced in the diode and then the voltage is measured step-by-step between the anode-cathode.

Both theoretical approaches are useful to monitor the junction temperature but, from an application point of view, the second is more suitable because it has less influence on the measurement and can be easily realized. First, to implement the voltage drop method to sense the junction temperature, V_F (diode forward voltage drop) against temperature (T) must be characterized, and then the most appropriate working condition is established. Considering an n-p diode junction, the built-in voltage can be written as:

$$V_{bi} = \frac{KT}{q} \ln \frac{np}{n_i^2} \qquad (3.1)$$

where K is the Boltzmann constant (1.38e-23J/K), q is the elementary charge (1.6e-19 C), n and p are the electron and hole concentrations in the n and p doped regions respectively, and n_i is the intrinsic doping concentration. n_i depends on T as described in 3.2:

$$n_i = \vartheta T \sqrt{T} \exp\left(- E_{go} \big/ 2KT \right) \qquad (3.2)$$

where θ is a constant and E_{go} is the poly-silicon band gap energy at 0 K (around 1,21 eV). The V_{bi} variation against T can be found by:

$$\frac{\partial V_{bi}}{\partial T} = \frac{V_{bi}}{T} - 2\frac{KT}{q}\frac{1}{n_i}\frac{\partial n_i}{\partial T} \qquad (3.3)$$

The mathematical derivative of 3.2 can be written as:

$$\frac{\partial n_i}{\partial T} = \frac{1}{2}\vartheta\sqrt{T}\exp\left(- E_{go} \big/ 2KT \right)\left(3 + \frac{E_{go}}{KT}\right) \qquad (3.4)$$

Substituting 3.4 and 3.2 into 3.3, we get:

$$\frac{\partial V_{bi}}{\partial T} = \frac{V_{bi}}{T} - \frac{K}{q}\left(3 + \frac{E_{go}}{KT}\right) \qquad (3.5)$$

Replacing K, E_{go} and q with their values, considering that there are four single diodes and that, in our case, V_{bi} equals around 3 V and T about 400 K (all four diodes), the derivative of V_{bi} against T equals around -6 mV/K, exactly the value found by real measurements considering very low diode currents.

To exactly characterize the STZ150NF55T poly-silicon sensing diode, its characteristics are found for different temperatures (see figure 5). As you can see, by increasing T, the anode-cathode forward current characteristic shifts to the left direction because the built-in voltage decreases with increasing T. To study the diode's parametric variations under different operating conditions (different levels of diode current), a complete statistical approach was performed taking into account forty different devices belonged to different lots and production plants.

To implement this statistical approach, it is necessary introduce the punctual threshold forward voltage electrical diode parameter (the diode forward voltage regarding a specific current level). Considering a specific forward voltage applied and the diode, the current level equals to:

$$I_d = I_s \exp\left(\frac{qV_F}{KT} - 1\right) \qquad (3.6)$$

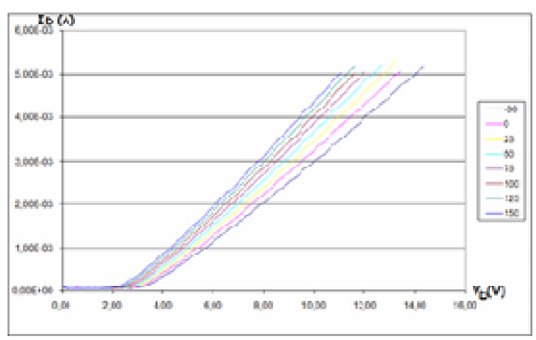

Figure 5: Poly-silicon diode input characteristics at different temperatures

where I_s is the inverse saturation current. According to 3.6, the punctual threshold forward voltage for an established diode's current level is:

$$V_F = \frac{KT}{q}\ln\left(1+\frac{I}{I_s}\right) \qquad (3.7)$$

Furthermore, note that by considering poly-silicon diodes, the differential resistance is very high compared to standard silicon devices. In particular, even if the differential resistance strongly depends on the doping of the layer, it is observed that this resistance is around 1 to 1,5 kohm Therefore, to increase the diode's current, we must apply a higher anode-cathode voltage that also takes into account the resistive voltage drop.

In figure 6, setting the temperature to 0 ˚C, the diode's characteristic statistics for several operating punctual threshold voltage levels are shown. To implement a rigorous statistical analysis required to evaluate the junction temperature error measurement, first we must establish the most suitable operating condition. Then we must understand which kinds of statistical distribution to consider (normal, uniform, exponential, ECC...) in order to apply the suitable statistical properties. Finally, we must consider a specific statistical confidence level to determine the junction temperature operating ranges for an established condition. To find the most suitable operating condition, see Table II.

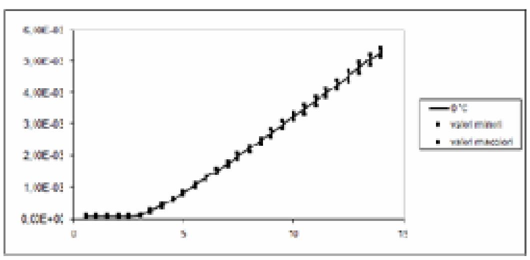

Figure 6: diode input characteristic statistic fixing the punctual threshold forward voltage

Table II: dV_F/dT statistical approach

Id (mA)	dV/dT (V/°C)	Varianza	St Dev (σ)	3Sigma (3σ)	Errore relativo σ/µ
0,25	-6,00E-03	2,62E-08	1,62E-04	4,85E-04	2,70%
0,63	-7,28E-03	2,79E-07	5,28E-04	1,59E-03	7,25%
1,05	-8,31E-03	3,77E-07	6,14E-04	1,84E-03	7,39%
1,48	-9,43E-03	8,50E-07	9,22E-04	2,77E-03	9,78%
1,93	-1,05E-02	1,48E-06	1,22E-03	3,65E-03	11,57%
2,38	-1,15E-02	3,12E-06	1,77E-03	5,30E-03	15,35%
2,85	-1,26E-02	4,15E-06	2,04E-03	6,11E-03	16,19%
3,34	-1,36E-02	5,56E-06	2,36E-03	7,08E-03	17,39%
3,83	-1,46E-02	7,21E-06	2,68E-03	8,05E-03	18,36%
4,33	-1,55E-02	9,36E-06	3,06E-03	9,18E-03	19,68%
4,84	-1,64E-02	1,11E-05	3,33E-03	1,00E-02	20,32%
5,37	-1,73E-02	1,28E-05	3,58E-03	1,07E-02	20,62%

By considering the current levels of several diodes, the dV_F/dT mean and standard deviations were measured. Then, in order to set the operating condition, the percentage errors found by dividing the dV_F/dT standard deviation against the respective mean were considered. The smaller the percentage error is the smaller the junction temperature range where the real junction temperature value is located by considering an established confidence level (95% or 97.5% typical).

In the case of the STZ150NF55T, the operating condition at 250 µA was indicated because the percentage error is lower (2.7%). Furthermore, it was observed that by increasing the diode current, the percentage error also increases up to over 20% for a current level of around 5 mA. This strange behavior was due to the high differential resistance of the diode. In fact, in this case, the variance of the resistance more strongly affects the dV_F/dT variance, enlarging the uncertainty of the measurement. In addition, the lower the current level is, the lower the influence on the same measurement.

When the diode is forward fed, it dissipates energy that could be involved in an indirect junction overheating effect. In any case, it is impossible to consider a very low current level operating condition in order to avoid the negative impact on the measurement of the device's leakage current.

Concerning the experimental results, we found that V_F@250µA at ambient temperature equals around 3.6 V and that the derivative against the temperature of the same V_F was -6 mV/K considering the average values. Table III shows the summarized V_F data at different T. To understand which kinds of distribution V_F and its derivative against T parameters observe, it is necessary to implement a series of measurement on sample devices (40 pieces).

Table III: V_F statistical data against temperature

$I_D = 250\mu A$									
T [°C]	-30	0	25	50	75	100	125	150	175
VF (avg) [mV]	3944	3783	3613	3443	3317	3158	3009	2857	2707
Std Dev.[mV]	11,71	8,47	13,18	8,90	12,52	12,14	13,23	15,97	16,13

This study was performed considering a large T range from 243.15 K to 448.13 K, and it was found that these kinds of parameters have a normal distribution. The technique used to establish the distribution types was the Cucconi-Kolmogorov statistical functional test considering a 97.5% of confidence level. Now it is possible to evaluate the junction temperature and estimate the error of the measurement (the difference between the estimated and the real junction temperature) in the preliminary phase. First, we must calculate the T against V_F transfer function. Considering that the 250 µA punctual threshold voltage can be considered equivalent to V_{bi}, $V_F(T)$ can be expressed by:

$$V_F(T) = V_F(300K) + \frac{\partial V_F}{\partial T}(T - 300K) \quad (3.8)$$

From 3.8, it is possible to find the T against $V_F(T)$ transfer function as: (3.9)

$$T(K) = \left(\frac{\partial V_F}{\partial T}\right)^{-1}\left[V_F(T) - V_F(298.15K)\right] + 298.15$$

Considering 3.9 and applying the Montecarlo statistical approach (see figure 7), we can find the estimated preliminary junction temperature against a $V_F(T)$ and $\partial V_F(T)/\partial T$. As illustrated in this figure, for a ±3σ interval variation from average value, µ, either for $V_F(T)$ or for $\partial V_F(T)/\partial T$ (corresponding to 99,7% of the both normal distributions), the ±3σ interval of junction T is around ±15 K at around 448.15 K in this example.

The standard deviation of $V_F(T)$ and $\partial V_F(T)/\partial T$, in this case, was found by the experimental data at 298.15K. It was found that these remain almost unchanged by increasing or decreasing T. Furthermore, $\partial V_F(T)/\partial T$ slightly decreases in absolute value with increasing T as in 3.5. In any case, we theoretically evaluated and experimentally found that at 423.15 K, the junction T was slightly overestimated by around 2 to 3 K compared to ambient T.

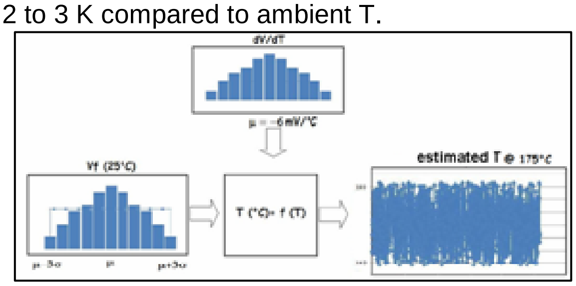

Figure 7: Estimated preliminary junction T

This is a good result. Moreover, it is necessary to consider this approximation in order to avoid considering a non linear transfer function, increasing the complexity of the study.

However, the preliminary error evaluation considered in figure 7 introduces a very high junction T interval error (±15 K) compared to the real results. This was obtained because $V_F(T)$ and $\partial V_F(T)/\partial T$ variables are considered independent of each other. Instead, it is possible theoretically and experimentally to demonstrate that these are dependent variables and, in particular, by increasing $V_F(T)$ for an established T, $\partial V_F(T)/\partial T$, in absolute value increases too.

In order to show this, it is necessary to consider 3.1 and implement the derivative of V_{bi} (V_F) under the hypothesis that it can change by changing only the np and/or n_i parameters and fixing T (3.10). It is possible to consider a n_i variation due to a small lattice differences even if T is fixed.

$$\delta V_F(T) = \frac{KT}{q}\frac{1}{np}\frac{n_i\delta np - 2np\,\delta n_i}{n_i} \quad (3.10)$$

The derivative against T of 3.10 divided by the same expression can be written as: (3.11)

$$\frac{\partial[\delta V_F(T)]}{\partial T\,\delta V_F} = \frac{n_i\delta np}{n_i\delta np - 2np\delta n_i} + \frac{-2np\delta n_i\left(1 - \frac{T}{n_i}\frac{\partial n_i}{\partial T}\right)}{T(n_i\delta np - 2np\delta n_i)}$$

By considering $n_i\delta np << 2np\delta n_i$, 3.11 can be simplified as: (3.12)

$$\frac{\partial[\delta V_F(T)]}{\partial T\,\delta V_F} = -\frac{1}{n_i}\frac{\partial n_i}{\partial T} = -\frac{1}{2T}\left(3 + \frac{E_{GO}}{KT}\right)$$

The theoretically-developed hypothesis is also verified by experimental results. In fact, considering the scatter plot between $\partial V_F(T)/\partial T$ versus $V_F(T)$, and implementing a mathematical linear regression, we find a Bravais-Person correlation coefficient, r, equal to -0.478, a linear regression coefficient, α, equals to -0.00576 taking into account that the standard deviations of $\partial V_F(T)/\partial T$ and $V_F(T)$ are 1.62e-4 [V/K] and 13.18 [mV] respectively at 298,15 K (see figure 8).

These results tell us that by increasing V_F, $\partial V_F(T)/\partial T$ also increases in absolute value slightly reducing the error of the measurement. Finally, in order to consider this last study, the Montecarlo approach was performed considering all variations in $V_F(T)$ and fixing $\partial V_F(T)/\partial T$ at

-6 mV/K as in figure 8. In this case, the junction T interval was around ±7 K, comparable with experimental results attached in Table IV.

4. Short description of a simplified external electrical shutdown circuit

In this section, a brief example of how to use the poly-silicon diode is described. First, the current generator at 250 µA was created using the LM334 device from ST in the configuration shown in figure 10 to also avoid the effect of T. This device is equipped with three pins: V+, V- and ADJ. The load must be applied between pins V+ and V-. Instead, in order to regulate the current level and avoid current derating due to a changing of T, a suitable feedback circuit is considered by connecting R1.

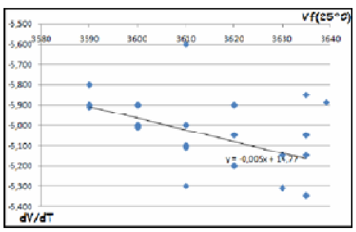

Figure 8: $\partial V_F(T)/\partial T$ vs V_F linear regression

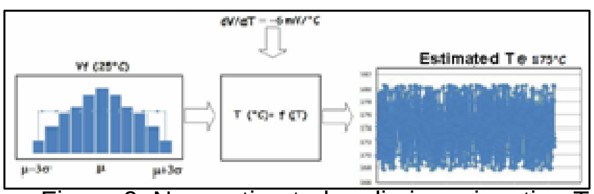

Figure 9: New estimated preliminary junction T

Table IV: T real measurements

T (°C)	T avg (°C)	T min (°C)	Temp max (°C)	Dev stand
0	0,46666667	-1,6	2,7	1,289927202
25	25,5619048	23	28,7	2,079094365
50	51,1285714	47,1	54,7	2,029813503
75	76,8761905	72,8	81,2	2,224613396
100	102,633333	98,4	107,4	2,479381643
125	128,438095	123,4	133,1	2,517235823
150	153,714286	147,6	150,2	2,605625782

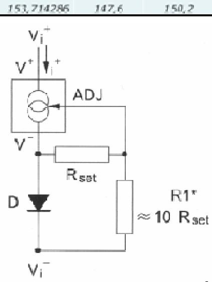

Figure 10: LM334 external schematic

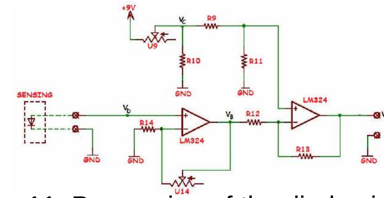

Figure 11: Processing of the diode signal

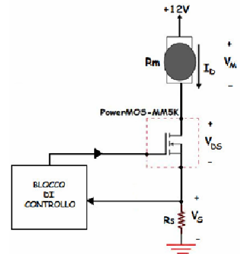

Figure 12: Example of application

Then, the diode forward voltage is read and transformed by an amplifier system shown in figure 11. In the first op-amp, the diode forward voltage was amplified to a specific value:

$$V_B = \left(1 + \frac{U_{14}}{R_{14}}\right) V_D = K V_D \quad (4.1)$$

The second op-amp allows us to have an output voltage of: $V_F(T) = V_C - KV_D(T)$ (4.2)

In this case, the forward voltage level reading is 250 mV at 298.15 K and the equivalent dV_F/dT equal to K of 10 mV/K. These conditions are useful in order to read the Celsius temperature in an array of four seven-segment displays using a suitable IC decoder. Furthermore, V_F can be simply compared to a specific voltage level (1.75 V), the voltage related to the device's maximum junction guaranteed T value, in order to implement the shutdown function and to avoid the device overheating and, thus, failing. An example of an application were this kind of system can be used is shown in figure 12 where a CC motor is driven by a power MOSFET working in linear zone. The proposed example was really implemented and its correct operation was tested.

5. Conclusions

This paper has discussed how use a poly-silicon diode, integrated in the power MOSFET package, to read the junction temperature of the MOSFET and implement a shutdown circuit to avoid the device overheating and, thus, failing. A complete diode characterization was implemented and a real application example was studied.