AN21001

RF power transistor ART2K0TFE/PE with integrated thermal sense FET

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Document information

Info	Content
Keywords	LDMOS, RF Power transistors, Thermal sense FET
Abstract	This application note describes the principle and use of the thermal sense FET integrated in the RF Power transistor ART2K0TFE/PE.

Table 1. Revision history

Revision	Date	Description
01	20250619	Initial version

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1. Introduction

In RF power applications one of the most important parameters is the temperature of the RF power transistor dies.

During (temperature) stable operation monitoring the temperature of the junction can be very useful to predict lifetime expectation of the amplifier.

During operation changing load conditions can cause temperature changes of the dies. Under extreme load variations these changes can be very rapid. For protection purposes (RF drive control or rapid shutdown of the amplifier) the temperature of the devices is usually monitored via a sensor located on the PCB board or on the cold plate, close to the transistor. This is an indirect measurement that introduces inaccuracy but also causes a delay in the temperature readout. The delay makes it difficult to use the sensor for protection against rapid changes of the die temperature. Another feature of the sensor is to monitor flange solder quality and detection of solder voids.

The new ART2K0TFE/PE is equipped with on-die temperature sensors located close to the junctions on the dies, making fast and accurate measurements and control actions possible.

The sensors are connected to the outside world by the thermal sensor leads present on the gate side of the package.

This application note describes the principles of the thermal sense FET and provides some guidelines for the use of the sensor.

2. Thermal sense FET

The thermal sense FETs for high power LDMOS transistors are introduced in the ART2K0TFE/PE transistor. ART2K0TFE/PE contains two small FET circuits positioned on the center dies in the active regions of the RF power FET's. These small FET's monitor the junction temperature very closely. The center dies are chosen because those dies run at the highest temperature during operation.

When a bias voltage is connected via a resistor to a thermal sense pin, the sense FET conducts a temperature dependent current. This current can be processed with an external circuit to monitor the junction temperature. The sense FET is electrically isolated from the RF power FETs on the die except that it shares the common ground connection with the RF power FET's. The sense FET's can be used independent from each other.

In Figure 1 the principal circuit diagram of the internal temperature sense FET is given.

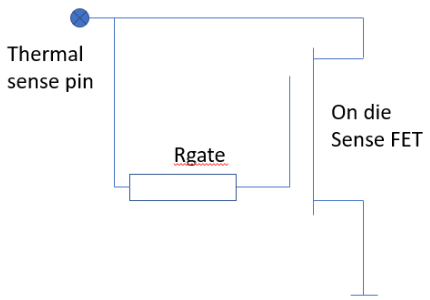
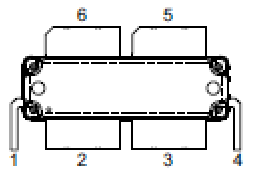
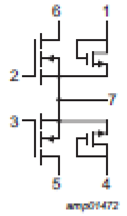


Figure 1. Diagram of thermal sense FET

Table 2 shows the pin layout and electrical circuit of the ART2K0TFE/PE.

Pins 2,3,5 and 6 are resp the gate and drain connections to the RF power MOSFET, pins 1 and 4 are the connections to the temperature sense FETs, Pin 7 is the common source grounding.

Table 1. Pinning

Pin	Description	Simplified outline	Graphic symbol
1	temperature sense FET1 [1]		
2	gate1		
3	gate2		
4	temperature sense FET2 [1]		
5	drain2		
6	drain1		
7	source [2]		

[1] The ART2K0TPE is equipped with a thermal sense FET and can be used to sense the die temperature during operation of the device. This thermal FET is electrically disconnected from the RF power FETs on the die and share only a common ground. The sensor is operated by applying a fixed voltage to its input pin and monitor the current, which is temperature depended.

[2] Connected to flange.

Table 2. Pin connections

2.1 Test setup and characterization

The characterization of the thermal sense FET is done by variation of the cooling water temperature.

In the baseplate, a water channel running alongside the transistor keeps the baseplate temperature constant with water circulating from an external water-cooling bath.

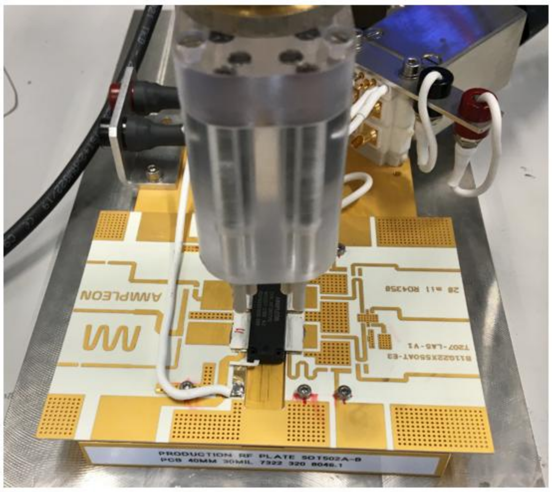


Figure 2. Ampleon test setup for characterization of the thermal FET

The thermal FET needs to be DC biased with a voltage in the range 2V – 5.5V which is supplied to the thermal sense pin through a voltage supply V_{sense} while the current through the sensor is measured.

5.5 Volts is the maximum voltage rating of the sense FET.

A high supply voltage corresponds to a higher current from the sense FET, which increases the accuracy of the reading. At the supply voltage of 2.8V the sensor becomes temperature insensitive, so this voltage level cannot be used. This is caused by the characteristics of the sensor FET.

Below and above the 2.8 Volts level, it is possible to identify two zones:

- For a V_{sense} < 2.8V the thermal FET exhibits a positive temperature coefficient behavior (PTC)

The response of the thermal sensor shows non-linear behavior and high dynamic range in this area.

- For a V_{sense} > 2.8V the sensor has a negative temperature coefficient (NTC).

The response of the thermal sense-FET shows nearly linear behavior in this area. This area will be further discussed in this report.

The sensor current response curve as a function of V_{sense}, with temperature as parameter, is plotted in Figure 3. The figure below is obtained by heating up the water that is circulating inside the baseplate. Water is heated up to 85 degrees Celsius and V_{sense} is changed from 2V to 5.5V. Therefore, neither DC nor RF power consumption exists in Figure 3.

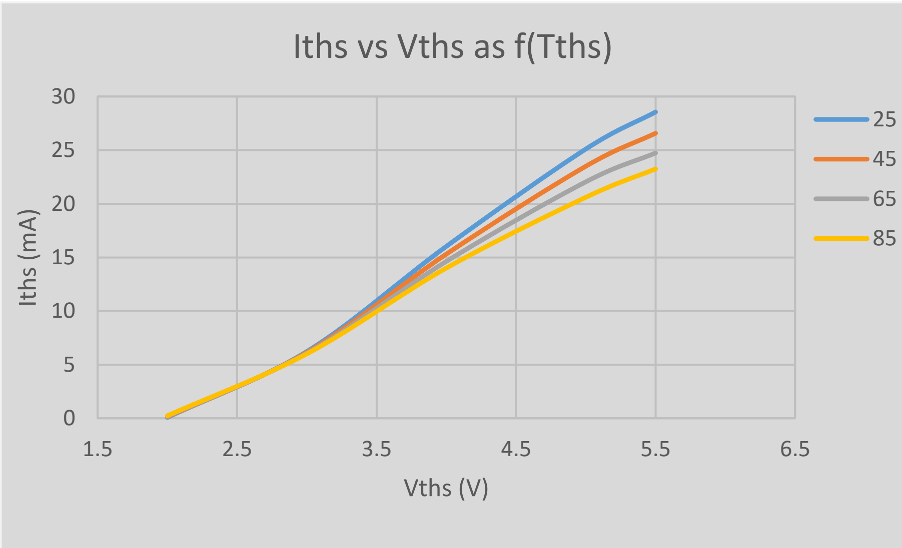
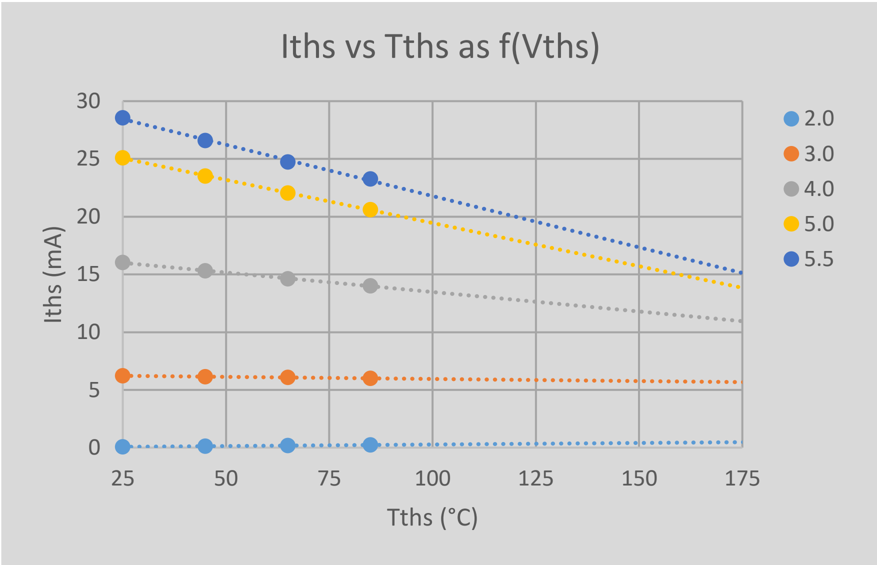


Figure 3. Thermal sense FET current vs voltage at different operating temperatures

Figure 4 shows the temperature and current characteristics between 2 and 5.5 Volts. Graphs in Figure 4 are an extraction of Figure 3 which are then fitted using a linear function and extrapolated up to 225 degrees Celcius.



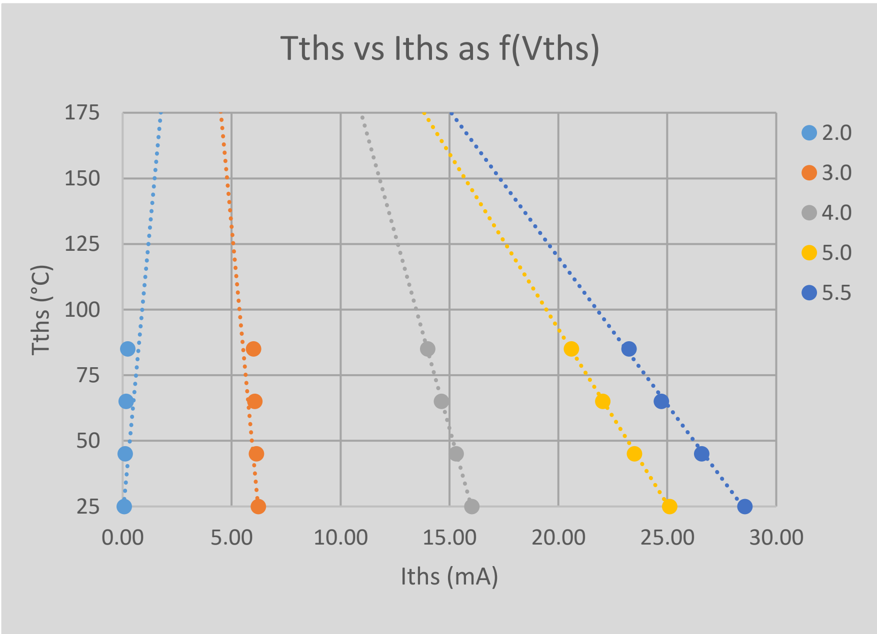


Figure 4. Temperature and current characteristics

2.2 Thermal FET usage guide

The previous paragraphs have shown the principle and thermal behaviour of the thermal sensing FET in the ART2K0TFE/PE. It was demonstrated how the integrated thermal FET can be used to monitor the device junction temperature with a linear response.

As described, operation of the thermal FET is done by applying a constant supply voltage in the range 2V – 5.5V ,and measure the temperature dependent current by use of a low value series resistor.

Self heating of the sensor, caused by the dissipation of the FET, is very low and will be neglected in this report.

The voltage over the series resistor can be amplified to a useful range and further processed to perform temperature monitoring for lifetime prediction, safety, controll and shutdown functions.

Measurements have shown that the DC voltage V_{sense} between 4V and 5.5V provides good accuracy: The lower voltage range has the highest error while the upper voltage range introducesa small error due to the self heating of the sense FET.

An example of circuit implementation using the thermal FET is shown in Figure . A supply voltage of V_{sense}= 5V is used, at 25 degrees ambient temperature the sensor draws around 25mA which flows through a 10 Ohm series resistor, giving a voltage of 250mV.

There are also integrated current monitors available on the market, which can provide an amplified voltage at their output pin. These monitors can be used to read the temperature dependent voltage over the resistor.

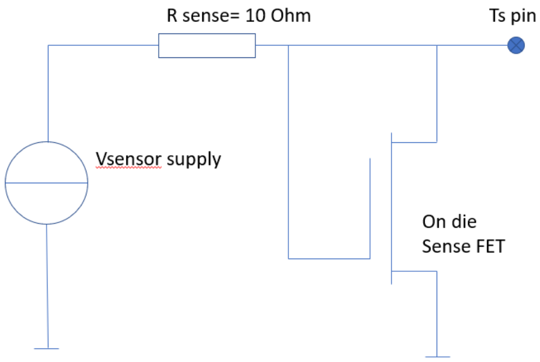


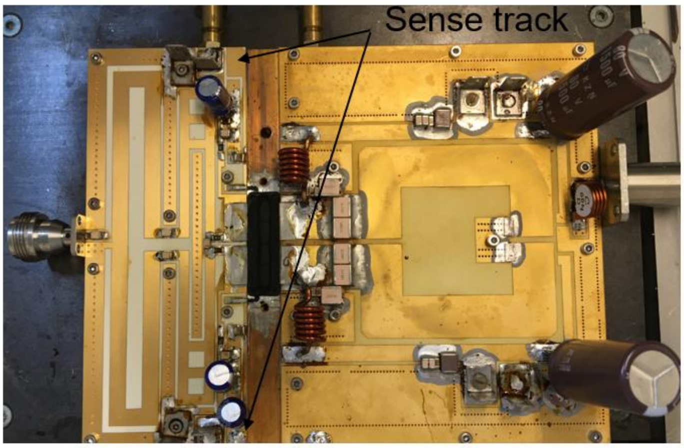
Figure 5. Schematic drawing of a circuit using the thermal sense FET

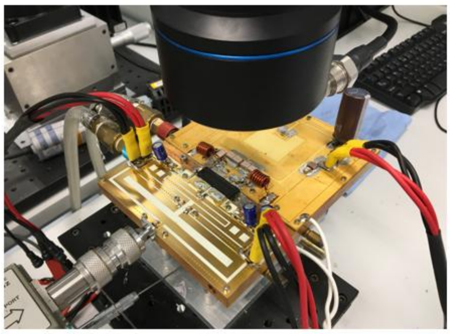
2.3 Example of a test setup with a demo circuit at 41MHz

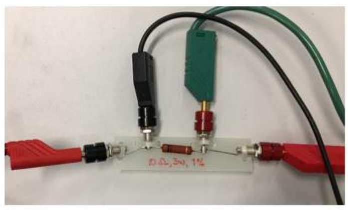
The ART2K0TFE/PE transistor has been mounted in a 41MHz demo circuit with PCB and components as recommended in the application measurement report. The transistor is soldered to the cold plate. The demo report as well as the demo will be available soon for demonstration purposes.

The input layout of the standard available 41MHz demo amplifier was slightly modified to accommodate the sense FET connections.

The measurement setup is shown below.







- Sensor is connected to external shunt resistor of 10Ohm.
- Current through sensor is calculated from the measured shunt voltage.
- Sensor voltage needs to be compensated by the shunt resistor voltage drop.
  - Vths = Vdc-Vshunt

Figure 6. 41 MHz demo setup

The table below shows the voltage level existing on the drain of the sensor FET (after 10Ohm series resistor) with respect to the temperature.

V_{DC} / Temp.	2	3	4	5
25	2,0	2,9	3,8	4,8
45	2,0	2,9	3,9	4,8
65	2,0	2,9	3,9	4,8
85	2,0	2,9	3,9	4,8
105	2,0	2,9	3,9	4,8
125	2,0	2,9	3,9	4,8
150	2,0	2,9	3,9	4,8

Table 3. V_{THS} vs. temperature for different values of V_{DC} with 10 Ohm series resistor

The power amplifier designer should be careful about the difference between feed voltage (V_{DC}) and the actual voltage that the sensor drain sees (V_{THS}). If the sensor is fed by 5V and a series 10Ohm is used, then from Figure 3, expected current between 25 and 85 degrees can be found when V_{THS}=4.8V.

In Figure 7, measurements of three different devices can be seen at 4V and 5V. The dotted lines are the average of these three measured samples. All the data below is obtained under DC power dissipation.

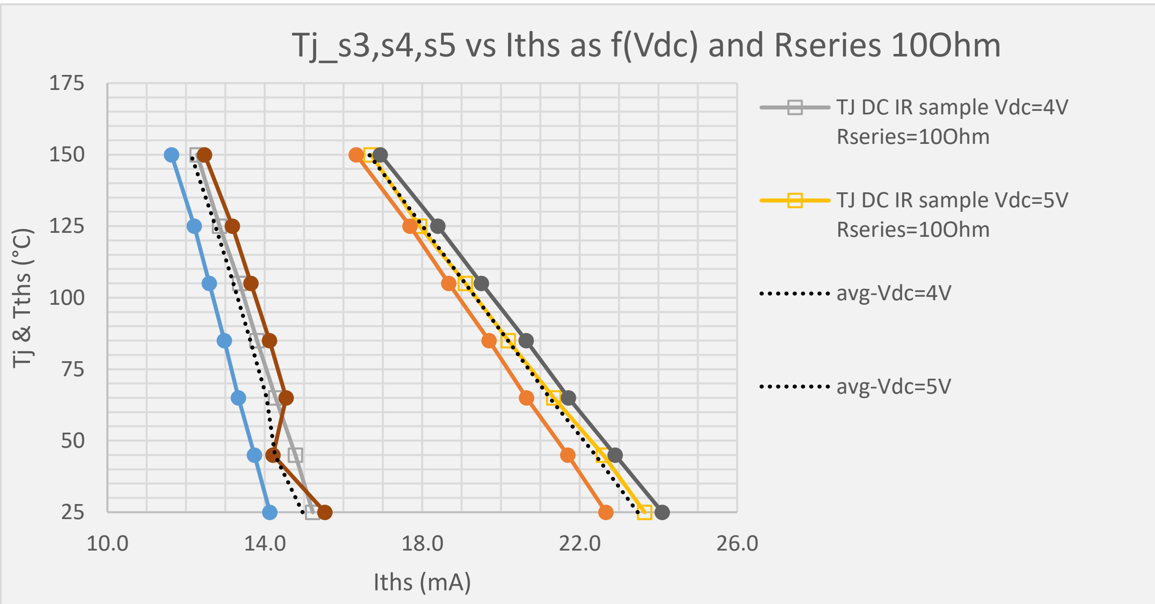


Figure 7. Measured data for 3 different samples using IR camera

The average line is approximated using a second order polynomial function. Using this function, one can estimate the temperature of the transistor using the current measured (voltage across the series 10 Ohm resistor).

Figure 8 shows the comparison of one sample to the polynomial function that is generated.

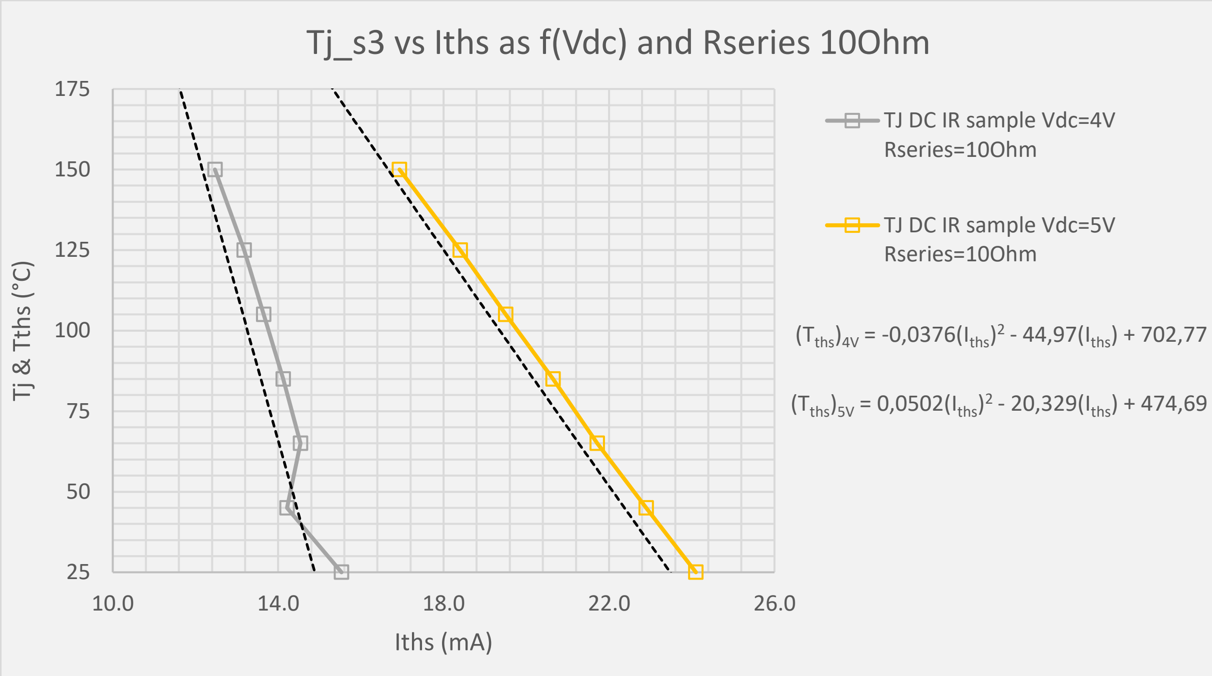


Figure 8. Comparison between the generated polynomial function and a sample

As can be seen from the figure above, there is a delta between the polynomial function and the measured data. The temperature difference between the function and the measured sample is shown in the table below.

Tj \ V_{THS}	4V	5V
25	29.7	11.1
45	-11.1	9.5
65	24.0	8.1
85	24.6	8.6
105	23.1	7.6
125	21.5	7.4
150	13.9	5.2

Table 4. Difference between the polynomial function and the measured sample

Considering the current drawn from the sensor can slightly change from one sensor to the other, a calibration can be done to fit the polynomial function more accurately. At 25 degrees Celsius, current drawn from the sensor can be measured once and inserted into the equation. By this way, the constant can be changed accordingly, and a better fitting function can be achieved. For example, at V_{DC}=5V, constant is 474.69 in Figure 8, and after calibration it is found to be 485.85.

Figure 9 illustrates the difference between the updated function and the previously measured data.

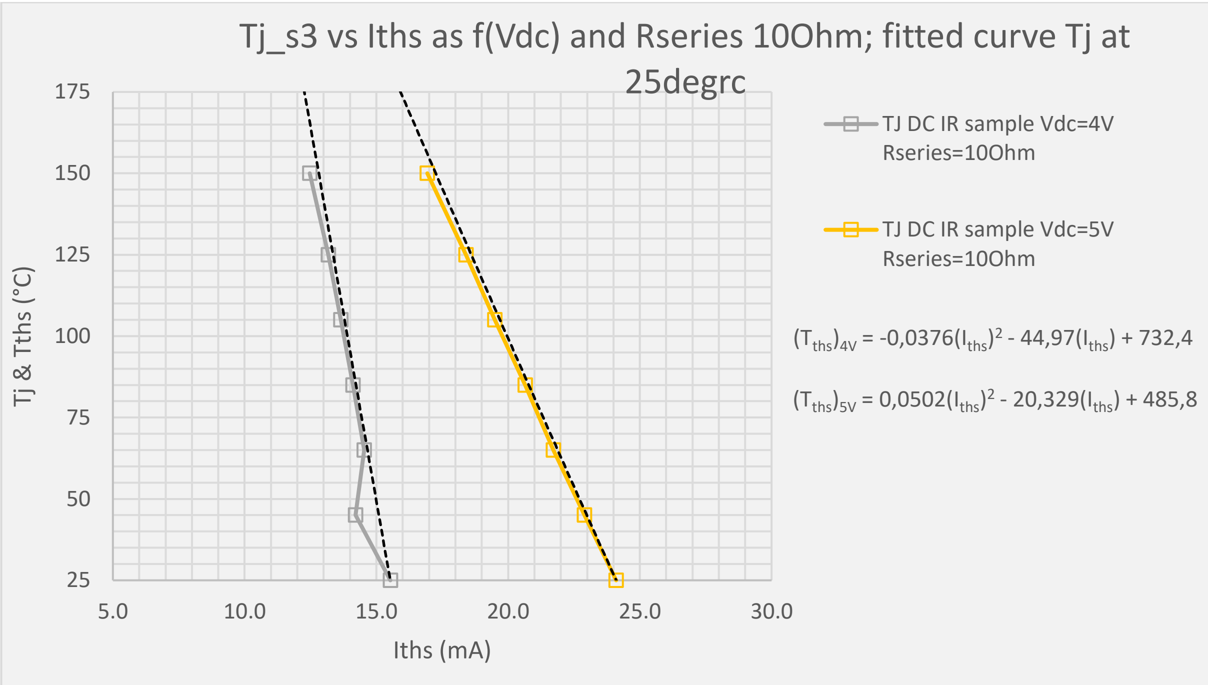


Figure 9. Comparison between the updated function and measured sample data

Table 3 shows the differences between the polynomial function and the measured sample. It can be clearly seen that after calibration, the difference between the function and the sample is lower.

Tj \ V_{THS}	4	5
25	0.0	0.0
45	-40.7	-1.6
65	-5.6	-3.0
85	-5.0	-2.5
105	-6.6	-3.5
125	-8.2	-3.7
150	-15.8	-5.9

Table 5. Difference between the updated polynomial function and the measured sample

The reason why there is a difference between the linear sensor temperature graphs (Figures 3 and 4) and non-linear junction temperature vs. sensor current graphs (Figures 7, 8 and 9) is due to the varying V_{sense} caused by the voltage drop across the series 10 Ohms resistor. Keeping V_{sense} constant would give a linear relationship.

2.4 RF decoupling of the sense FET signal

As the sense FET (inside the package, red box in Figure 10) and its surrounding circuitry are physically close to the high-power output circuit of the demo, the sense signal leads can be sensitive to pick up of RF signals.

To ensure accuracy and interference free processing of the voltage over the series resistor the signal should be RF decoupled before further processing.

To ensure a low level of RF on the sense line, the sense pin of the device is decoupled by connecting a 1uF ceramic capacitor as close as possible to the transistor body from the sense pin to the ground.

Filtering the signal further, for instance using a low pass network or a differential amplifier, can further improve the cleanliness of the signal before further processing. Care should be taken not to slow down the senser reading by adding too much capacitance.

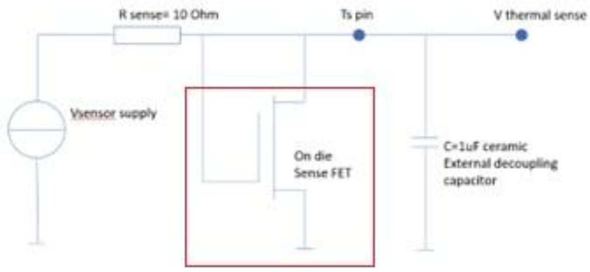


Fig 10. RF decoupling

2.4.1 Filtering the signal using a differential amplifier

A circuit which is illustrated below can be used to filter out the voltage ripple that may exist on the sensor signal due to RF coupling.

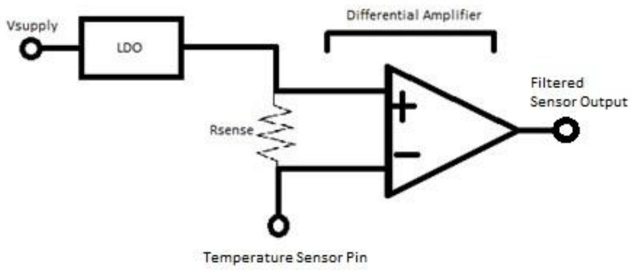


Fig 11. Reducing RF coupling using a differential amplifier

Sense resistor is connected between the inverted and non-inverted pins of the OPAMP. On the non-inverted side, supply voltage is applied via an LDO. By this way, user can choose to operate on the voltage level which is more convenient for their system. The value of the sense resistor and the gain of the differential amplifier can be chosen depending on which voltage level the user wants to observe at the output. It is good to keep in mind that too much gain can also amplify the noise or the RF coupling that may exist on the sensor signal.

2.4.2 Filtering the signal using a low pass filter

A circuit which is illustrated below can be used to filter out the voltage ripple that may exist on the sensor signal due to RF coupling.

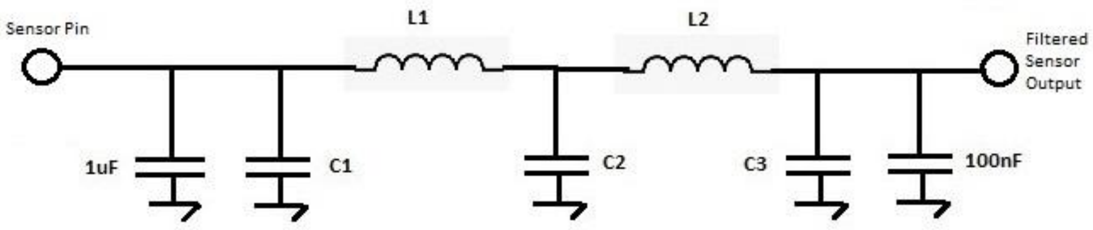


Fig 12. Reducing RF coupling using a low pass filter

A simple, 5-order low pass filter can be implemented to remove the RF coupling on the sense signal. It is important to note that a 1uF (should be as close as possible to the sensor lead of the transistor) and a 100nF (should be as close as possible to the output pad) decoupling capacitors should be added besides the filter.

The values of the capacitors (C1, C2 and C3) and the inductors (L1 and L2) can differ according to the user's needs. Their values are mostly determined by the frequency of operation. On the other hand, to design a sharper filter, the number of sections can be increased, or other filtering topologies can be used.

3. Conclusions

This short application report has described both the principle of the integrated thermal sensor, the thermal vs electrical behavior and the use of the thermal sensor.

Three different samples are measured using an IR camera and a 2nd order polynomial function is generated to fit the average of these samples. Using this function, one can find a very close estimate of the temperature after measuring the current drawn from the sensor.

Use of the thermal sensor, RF power LDMOS can be a strong asset in lifetime monitoring, RF power control, and safety shutdown functions. Furthermore, detection of solder voids and monitoring solder degradation.

Due to the integrated sensor circuit part, the application of the component is straightforward.

Since the sense FET is on top of the die, it may result in RF coupling. Two filtering topologies were discussed. Depending on the user's needs, they can be further improved.

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