AN5584

Application note

ST25R39xx NFC reader thermal design

Introduction

With the increase electronic device integration and complexity, it is crucial to address the thermal performance of integrated circuits. The JEDEC solid state technology association is supporting the semiconductor industry by proposing test methods and product standards. All of the JEDEC standards are free on the web for downloading after a free registration.

All the STMicroelectronics datasheets state the maximum and minimum operating temperature conditions. The maximum operating temperature range defines the threshold temperature where operating beyond this point produces a high probability of permanently damaging the device. The operating temperature range also defines the perimeter where the electrical parameters are guaranteed to be within the specification.

It is common practice in the semiconductor industry to specify the operating temperature ranges based either on the ambient temperature or on the junction temperature. Semiconductor vendors use either the ambient temperature or the junction temperature as the product operating temperature range depending on the device and its power consumption.

This document describes the thermal management for ST25R39xx based applications and how to operate the device within the given operating temperature conditions. The list of products is given in Table 1.

Table 1. Applicable products

Type	Products
ST25 NFC readers	ST25R3911B, ST25R3912, ST25R3913 ST25R3914, ST25R3915, ST25R3916, ST25R3916B, ST25R3917, ST25R3917B, ST25R3918, ST25R3919B, ST25R3920, ST25R3920B.

1 Glossary

Table 2. **Acronyms and abbreviations**

Acronym	Description
DUT	Device under test / silicon package
IC	Integrated circuit
IR	Infrared
NFC	Near field communication
NMOS	N-channel metal oxide semiconductor
PCB	Printed circuit board
PMOS	P-channel metal oxide semiconductor
TA	Ambient temperature. Represented as T_A
TJ	Junction temperature. Represented as T_J

2 Thermal systems definitions and basic concepts

This section details basic definitions and concepts related to thermal systems, as applied to silicon-based integrated circuits (ICs).

2.1 Thermal system definitions

The following mentioned thermal definitions are defined in the JEDEC standard No. 51-13:

- Black body: a perfect radiator or absorber of infrared radiation.
- Emissivity: the ratio of the radiant energy emitted by a surface to that emitted by a black body at the same temperature.
- Heating current: a current supplied to a device-under-test to cause the junction temperature to rise.
- Heating power: the product of heating current and heating voltage; causing the device-under-test junction temperature to rise.
- Junction temperature: the temperature of the operating portion of a semiconductor device.
- Thermal characterization parameter: parameter characterizing the behavior of the package. The two most commonly used thermal characterization parameters; Ψ_{JT} and Ψ_{JB} are defined in JESD51-2 and JESD51-6. They measure the temperature relationship between junction-to-top and junction-to-board. While the units are °C/W, they are not resistances because the temperature difference is divided by the total power, not the power flowing between the two areas.
- Thermal equilibrium: a condition in which no heat-producing power is applied to the device under-test and the device junction temperature (TJ) is equal to the ambient temperature (TA) in the immediate vicinity of the device. (thermal steady-state at zero applied power).
- Thermal resistance: a measure of the steady-state heat flow from a point of higher temperature to a point of lower temperature, calculated by dividing the temperature difference by the heat flow between the two points.

2.2 Thermal model

The JEDEC committee JC-15 (Thermal Characterization Techniques for Semiconductor Packages) provides guidelines to model (JESD15) thermal behavior and measure, characterize and report (JESD51) its behavior. The document “JESD51-0-Metodology for Thermal Measurement of component Packages” provides a standard method to determine the junction temperature under specific conditions.

The Junction temperature is defined as:

$Tj = T_{J0} + \Delta T_J$.

In most cases, T_{J0} equals the ambient temperature.

Under carefully defined conditions for a specific environment, the change in junction temperature is defined as follows:

$\Delta T_j = P_D * R_{\theta JX} = P_D * \theta_{JX}$

Where:

- P_D is the power dissipated in the device (also referred to as heating power) stated in W.
- $R_{\theta JX}$ is the thermal resistance from the device junction to the specific environment (alternative symbol is θ_{JX}) stated in °C/W.

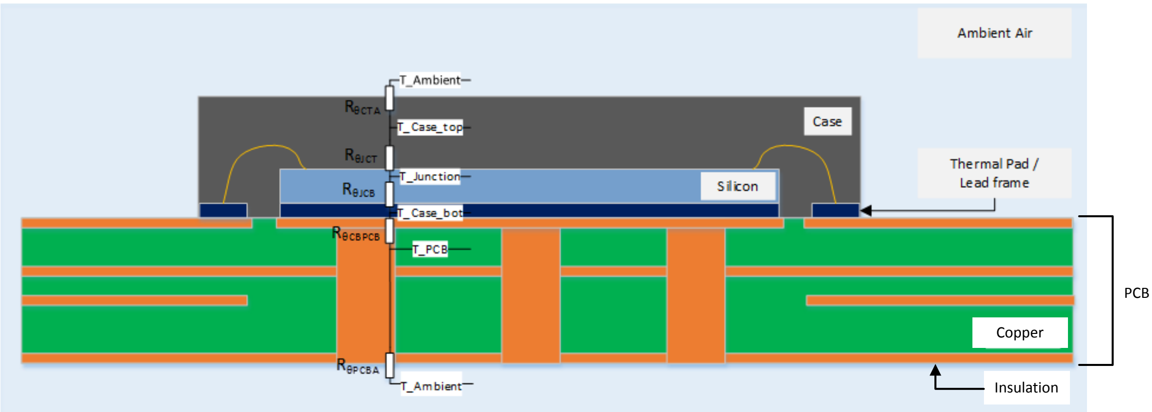
Use either ambient ($R_{\theta JA}$) or case ($R_{\theta JC}$) as a specific environment. This approach is used to set up a thermal model.

2.3 NFC reader PCB thermal model

The thermal model includes thermal resistance such as:

- $R_{\theta JCT}$ (junction to case-top)
- $R_{\theta CTA}$ (case-top to ambient)
- $R_{\theta JCB}$ (junction to case-bottom)
- $R_{\theta CBPCB}$ (case-bottom to PCB)
- $R_{\theta PCPA}$ (PCB to ambient).

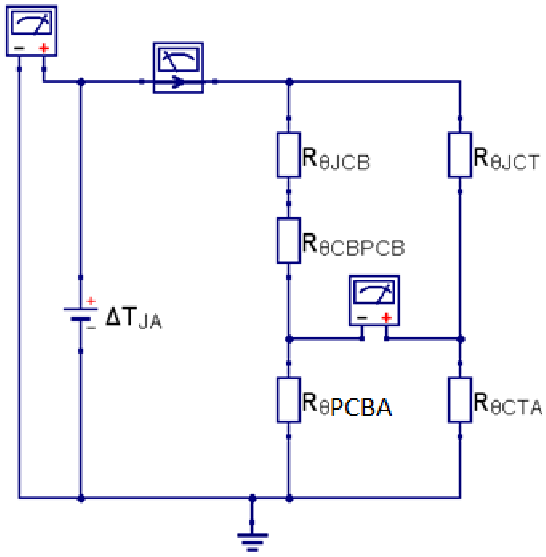
Figure 1. Thermal cross-section



The thermal resistance $R_{\theta JCT}$, $R_{\theta JCB}$, and $R_{\theta CBPCP}$ are given for a specific silicon and package combination. $R_{\theta CBPCB}$ and $R_{\theta PCBA}$ are defined for a specific PCB and a specific environment. For simplification, it is assumed that there is no temperature gradient between the top and the bottom side of the PCB. This is based on the fact that the top and bottom side of the footprint is connected via several vias. Those vias have a high thermal conductivity. Furthermore, the thermal coupling between the exposed pad of the IC and PCB copper area provides excellent heat transfer, keeping $R_{\theta CBPCB}$ very low.

The Figure 1 above represents the thermal conductivity model as an electrical model where the silicon is the heat source. The heat source is represented as a voltage source, which causes a temperature difference between the junction temperature and ambient temperature. The heating power flows through the thermal resistance of the top and bottom case. Figure 2 below represents an electrical circuit representation of the thermal model represented above.

Figure 2. Thermal model equivalent circuit



- ΔT_{JA}: Temperature difference between ambient and junction
- $R_{\theta JCB}$: Thermal resistance between exposed pad and junction
- $R_{\theta JCT}$: Thermal resistance between case top side and junction
- $R_{\theta CBPCB}$: Thermal resistance between exposed pad and PCB bottom side
- $R_{\theta PCBA}$: Thermal resistance between ambient and PCB bottom side
- $R_{\theta CTA}$: Thermal resistance between ambient and case top side.

The ST25R3916 and ST25R3911B are supplied with the VFQFPN32 package among others and have the following quoted thermal characteristics:

- $R_{\theta JCT}$: 16.95 °C/W
- R_{JCB}: 0.85 °C/W.

To solve the thermal model, the following parameters must be assessed:

- Device power dissipation
- Settled case-top temperature during continuous field on
- Settled PCB-Bottom temperature during continuous field on
- Settled junction temperature during continuous field on.

2.4 Power dissipation

The ST25R3916 and ST25R3911B have three basic blocks, which produce the largest power consumption/power dissipation inside the IC. The blocks are illustrated in Figure 3.

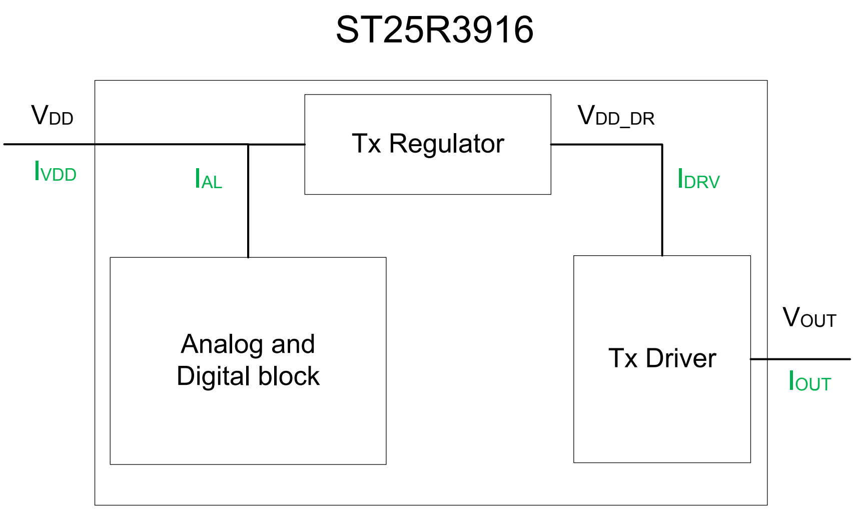
The blocks are:

- Analog and digital logic:
  - These blocks are required during operation.
  - The power consumption is calculated by:
    $P_{AL} = V_{DD} * I_{AL}$.
  - V_{DD} is the general supply voltage of the IC. I_{AL} is the "supply current all active", this parameter is defined in the *High performance NFC universal device and EMVCo reader* (DS12484).
- Internal voltage regulator:
  - Determined by the following equation:
    $P_{REG} = (V_{DD} – V_{DD\_RF}) * (I_{VDD} – I_{AL}) = V_{REG} * I_{DRV}$.
  - The voltage drop across the regulator is multiplied by the current flowing through the regulator. The current through the regulator (I_{DRV}) is calculated by measuring the overall V_{DD} current (I_{VDD}) minus the previously measured current (I_{AL}) consumed by the analog and digital logic.

- Transmitter driver stage:
  - Determined by the following equation:
    $P_{DRV} = I_{DRV}^2 * (R_{DRV\_NMOS} + R_{DRV\_PMOS})$.
  - The power dissipated in the driver is calculated by multiplying the P_{mos} and N_{mos} on-resistance of the driver stage multiplied by the square of the current flowing through the regulator.

The main power consumption blocks are illustrated in Figure 3.

Figure 3. ST25R3916 power consuming blocks

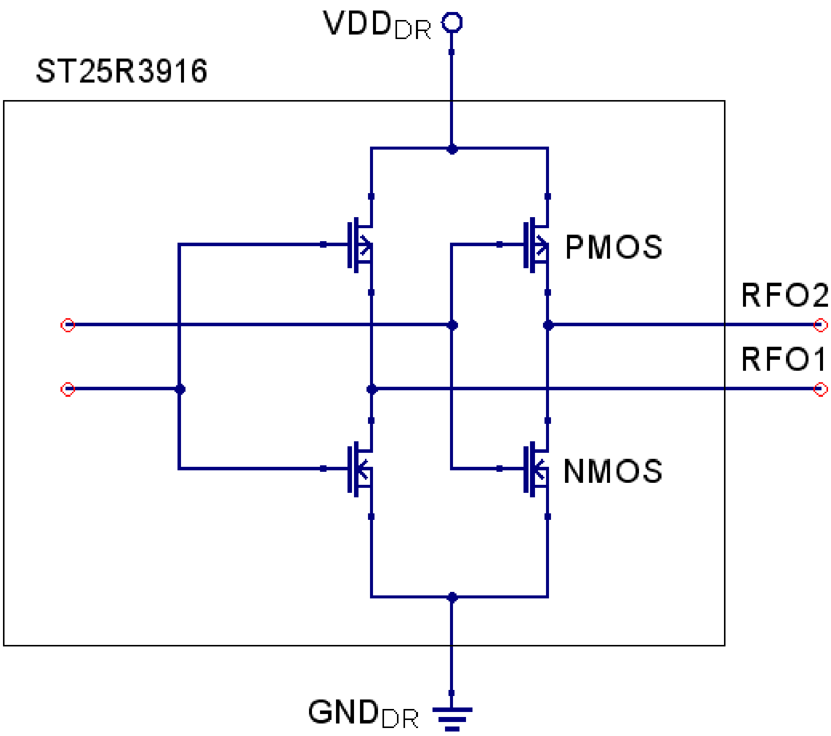


The driver consists of two push-pull drivers. To measure the resistance of each driver, the following procedure must be executed (this is specific for the ST25R3916):

1. Execute power up sequence
2. Set `tana7` = 1
3. Set `en` = 1
4. Set `tr_am` = 1
5. Set `am_mode` = 0
6. Set `d_res` = 0
7. To prevent the internal overheat protection to trigger below the junction temperature, the 3-byte frame 0xFC / 0x04 / 0x10h (register access / address / value) must be sent.

At each RFO, one transistor is now active. At RFO1, the NMOS is enabled and the RFO1 pin is connected to GND_DR. At the RFO2 the PMOS is active and the RFO2 in is connected to VDD_DR as illustrated in Figure 4.

Figure 4. ST25R3916 simplified driver stage



The NMOS driver resistance is measured by connecting an ohm-meter between RFO1 and GND_DR. The PMOS driver resistance is measured by connecting the ohm-meter between RFO2 and VDD_DR. It is recommended to use a four-wire measurement. The positive half wave seen on the load flows through PMOS of RFO1 and NMOS of RFO2, the negative half wave through NMOS of RFO1 and PMOS of RFO2. It demonstrates that the RMS current always flows through one NMOS and one PMOS. Thus the power dissipated by the driver is calculated by:

$P_{DRV} = I_{DRV}^2 * (R_{DRV\_NMOS} + R_{DRV\_PMOS})$.

Although this document is dedicated to the ST25R3916, Figure 3 and Figure 4 also apply for the ST25R3911B. For the ST25R3911B and its derivatives, the normal startup procedure stated in the datasheet must be executed.

Since the power dissipated by the three blocks is known, the heating power P_D in watts produced by the silicon flowing through the case to the ambient as indicated in Figure 1 is also known. To solve the thermal model given in Figure 4, the junction and case temperature must be measured during operation.

2.5 Case temperature measurement

There are two common methods to measure the package temperature.

- The thermocouple:
  Most thermocouples have a round sensor body which needs to be put in contact with the flat package surface. Only a very small part of the sensor body is in contact with the DUT surface. This small surface is heated by the DUT. The remaining surface is exposed to the ambient temperature and therefore cooling the sensor and DUT. Thermal compound paste is used to maximize the temperature transfer between DUT and sensor, but it increases the DUT surface and adds additional thermal boundaries. A thermocouple is very useful in closed housing environments.

- Infrared camera:
  The temperature of the PCB and IC package in this application note have been measured using a FLIR ETS320 thermal camera. The IR camera measures temperature difference very precisely, but the absolute temperature measurement has a tolerance of +/- 3 °C. There are several aspects to consider:
  – Heating sources like lamps or the sun can be reflected by the DUT and cause a wrong reading.
  – The IR camera itself is a heating source. The DUT must be placed at an angle of 45 ° to the lens.
  – To measure the +/- 3 °C temperature offset, the DUT must be stored at room temperature until it reaches ambient temperature. The difference between the measured temperature of the unpowered device and room temperature is the temperature offset of the camera.
  – The emissivity is the final critical parameter. It is described in the ETS320 user manual as outlined in Appendix A.

2.5.1 IR camera temperature offset

The previously mentioned temperature offset is easily be assessed as follows:

- Store the DUT for several hours for it to reach room temperature, also known as ambient temperature.
- Measure the temperature of your DUT using the IR camera.
- Measure the ambient temperature using a precise thermometer.

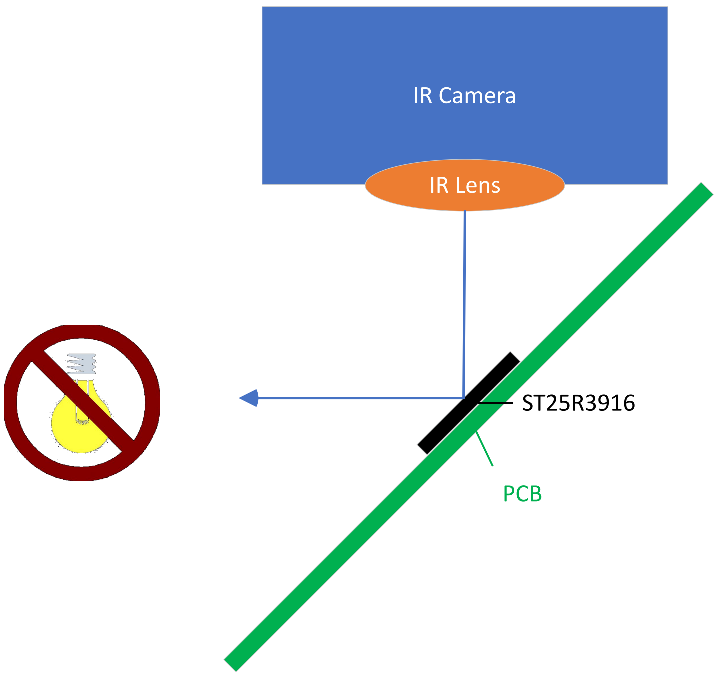
The difference between ambient temperature and measured temperature is the offset of the IR camera.

2.5.2 Temperature measurement

There are two ways to measure the silicon temperature:

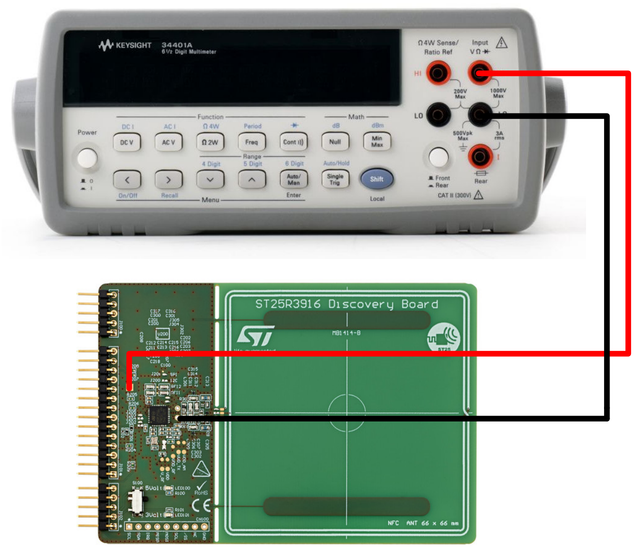
- The first is using an IR camera and an open package IC. This method is very similar to the case temperature measurement. First, the emissivity of the silicon and temperature offset of the IR camera must be found. Then the device is turned on and the actual junction temperature increase is measured. To avoid thermal reflections coming from the camera or other objects nearby place the camera measurement angle at 45 ° to the measuring plane. This is illustrated in the following figure.

Figure 5. IR camera setup



- The second method is to use the ESD protection diode of the RFO1 pin. It is very close to the heat source on the silicon. The diode measurement function of a Keysight 34401A DMM is suitable for this purpose. The DMM forces a current of 1 mA through the diode and measures the diode voltage. At room temperature (25°C) a voltage of 0.327 V is displayed. This voltage decreases as the temperature increases. Since the voltage varies from part to part, a characterization must to be done for each device. In operation, the junction temperature will increase, and the resultant diode voltage drops. To correlate the voltage, drop with the specific junction temperature, the device is heated without dissipating any power. For example, the device is placed in an environment with a higher ambient temperature and left to reach a steady state. Once the diode voltage is the same as during the self-heating process, the current ambient temperature equals the previously measured junction temperature. The positive connection of the DMM must be connected to GND_DR and the negative connection to RFO1. The measurement is done using the apparatus illustrated below.

Figure 6. RFO1 diode measurement



The output driver must be disabled during the measurement. A special sequence must be implemented in the firmware. After the output driver is turned on and the self-heating reaches a steady state, the firmware disables the driver by setting `tx_en` bit is cleared and sets the driver to high-impedance by setting the `d_resX` bit is set. In addition, the `tr_am` bit is set must be set. After a short timeout of roughly 10 µs to 50 µs, an external signal is used to trigger the measurement device to perform the diode measurement.

3 Junction temperature assessment

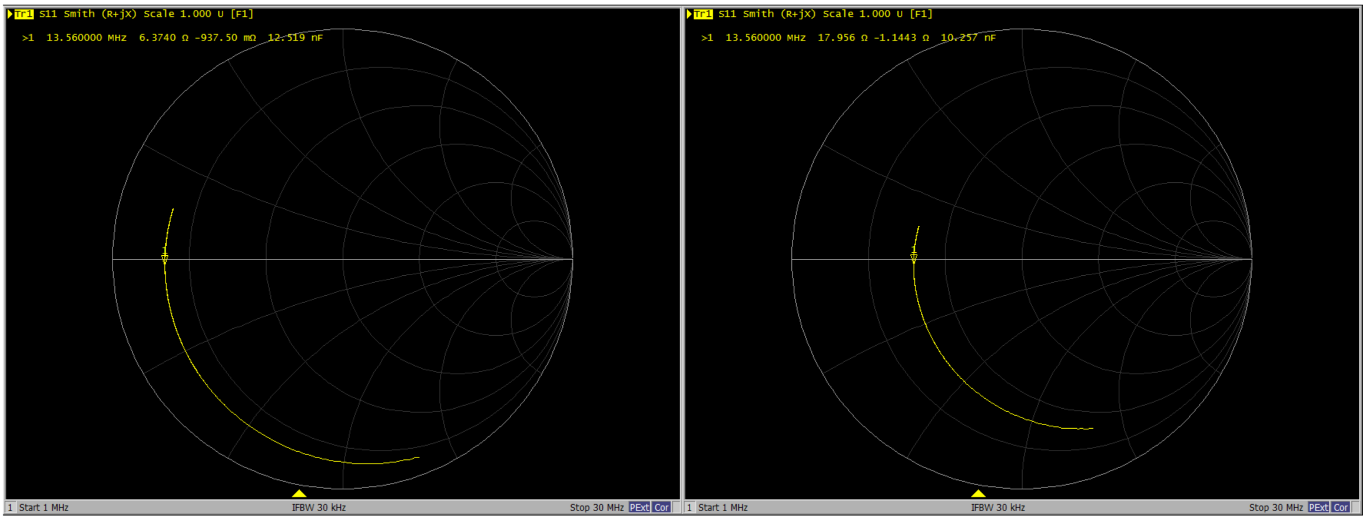
The ST25R3916-DISCO board is used as reference to measure the performance of the VFQFPN32 package. To exclude other heat sources, the antenna and matching components are replaced by a 2.2 nF capacitor and a 47 Ω potentiometer. The potentiometer, illustrated in Figure 10, allows a quick and precise loading adjustment and therefore dissipated power inside the IC. The load impedance is adjusted up to 47 Ω. The series 2.2 nF capacitor prevents a DC current from flowing between the two RFO ports.

Note: The potentiometer specification example is TE connectivity passive product: 3-1625931-8.

The possible heat sources the potentiometer is designed to replace are:

- *MCU*
- *EMC inductor*
- *Damping resistors*
- *Variable capacitors.*

Figure 7. Potentiometer impedance curve



The ST25R3916 VFQFPN32 DUT shown in Figure 8 and Figure 9 is very similar to the ST25R3916-DISCO MB1414 PCB. The PCB consists of four layers. The dimension of the NFC part is 70 x 31.5mm. The QFN32 footprint has nine thermal vias connecting the GND plane of each of the four layers together.

Figure 8. **ST25R3916 VFQFPN32 DUT–Top view**

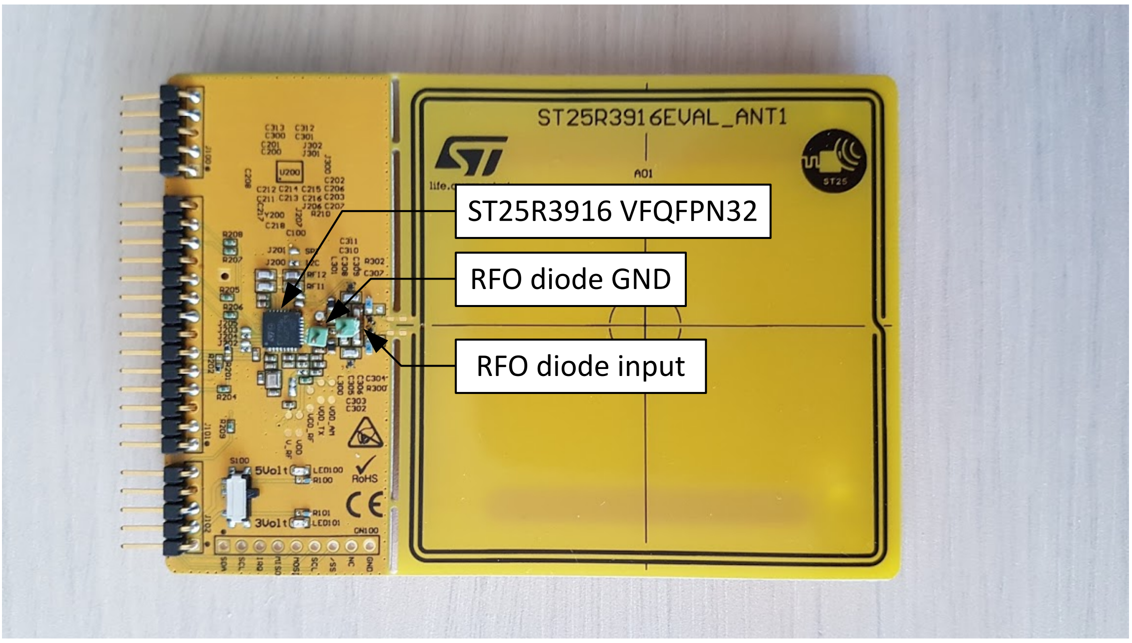


Figure 9. **ST25R3916 VFQFPN32 DUT–Bottom view**

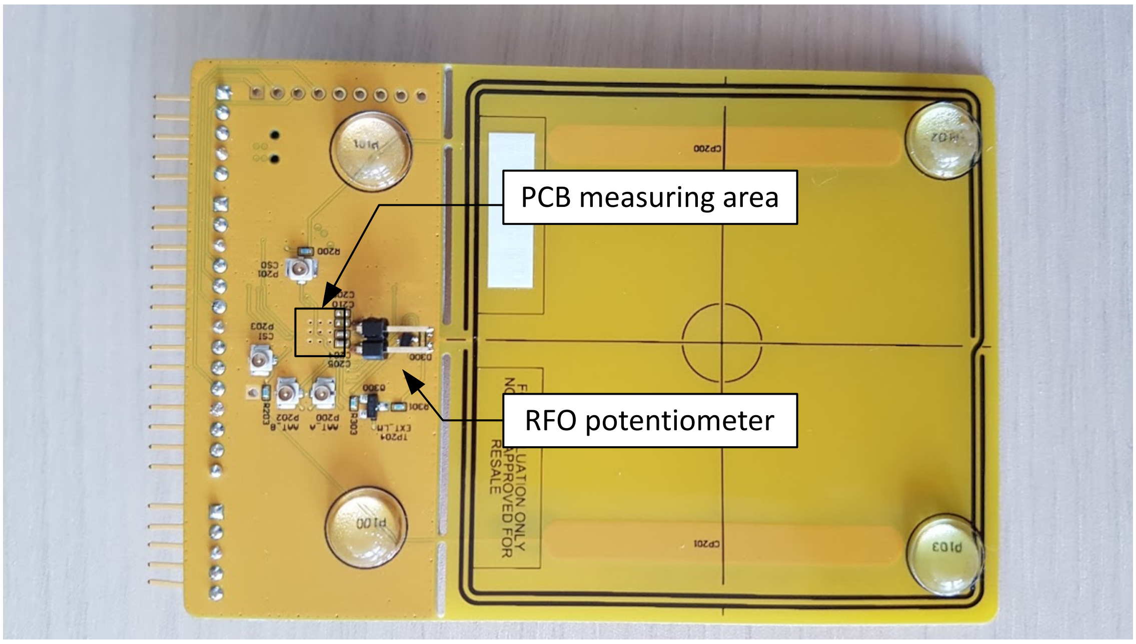
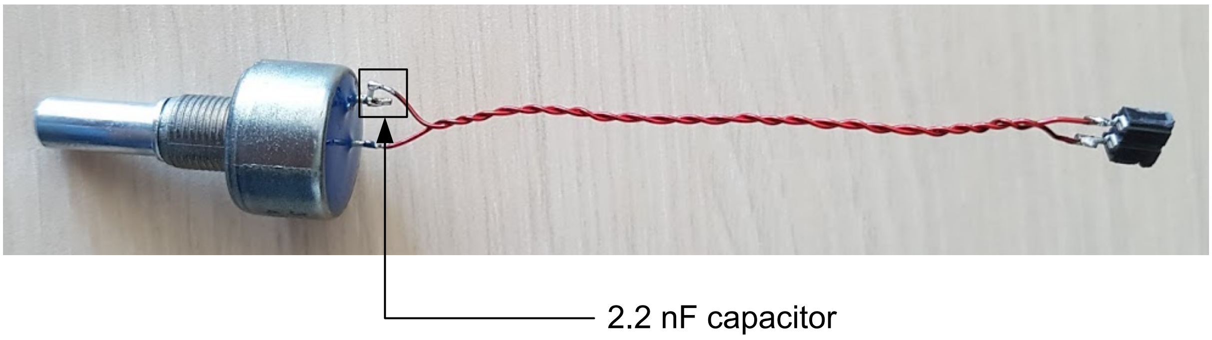


Figure 10. Potentiometer



4 Self-heating model definition at 253 mA

The potentiometer is used to setup a 253 mA driver output current. This is a typical value for NFC applications. There are six main steps required to build a thermal model of the NFC reader device. These steps are:

1. Measuring the ambient temperature and IR camera temperature offset
2. Measuring the self-heating temperature
3. Measuring the electrical parameters
4. Calculation of the dissipated power
5. Defining the thermal model
6. Calculation of the overall thermal resistance.

4.1 Temperature offset measurement

The first step to measure a components thermal dissipation is to calibrate the temperature measuring results between the IR camera and the thermocouple.

The DUT has been stored for a sufficient amount of time at ambient temperature to ensure that the DUT temperature has reached a steady state temperature. The temperature of the DUT is measured by:

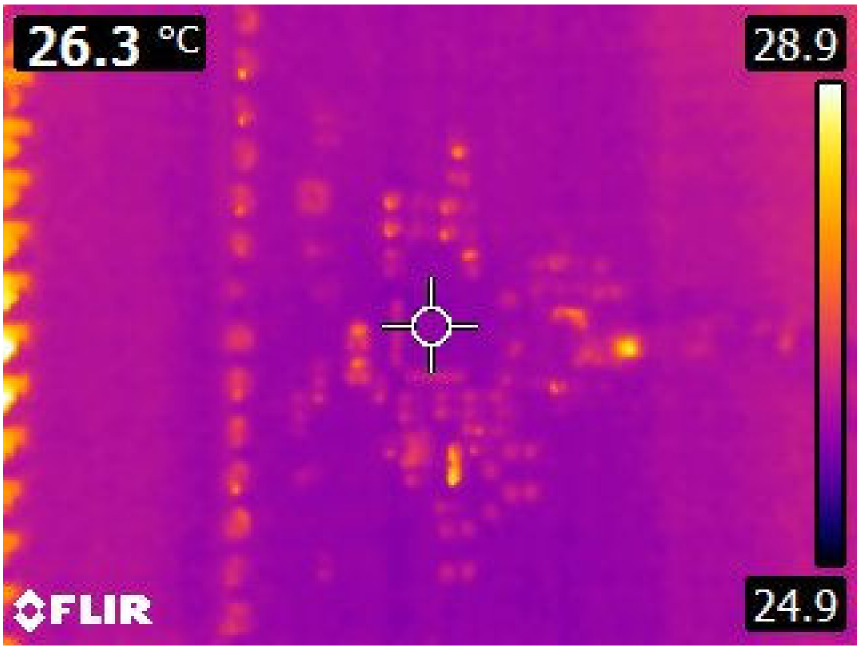
- Thermocouple as $T_{AMB\_thermocouple}$ = 23.8 °C
- IR camera as T_{AMB_IR} = 26.3 °C as illustrated in Figure 11.

The temperature offset between the IR camera and the thermocouple is calculated as:

T_{Offset} = 23.8 – 26.3 = -2.5 °C

Note: The thermocouple temperature is taken as the reference temperature.

Figure 11. **Ambient temperature measurement (ε = 0.95)**



The IR camera has been setup to use the appropriate surface emissivity which is dependent on the measurement surface. The temperature offset between the thermocouple and IR camera is -2.5 °C. This means the IR camera shows a temperature which is 2.5°C above the actual value.

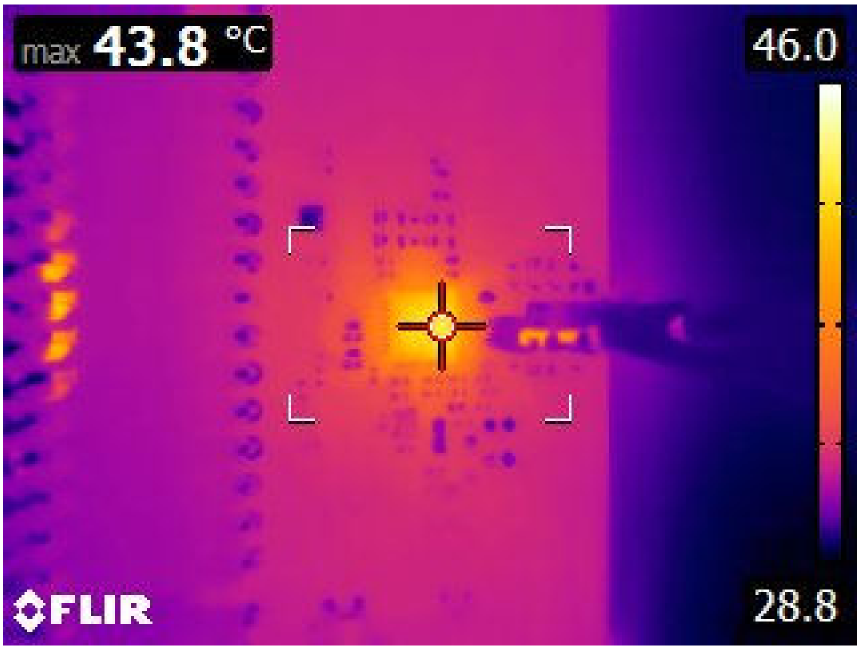
4.2 Measurement of the self-heating at 253 mA

To measure the heat dissipation, the device has to be put in a mode where it consumes the most energy. This condition occurs during continuous wave output. To configure the system in continuous wave output use the following settings:

- The DUT is configured to enable the oscillator, receiver, and transmitter by setting register 0x02 to 0xC8.
- The driver resistance is set to lowest driver resistance by setting register 0x27 to 0x70.
- The surface temperature of the IC package is being observed until it settles to its maximum temperature.

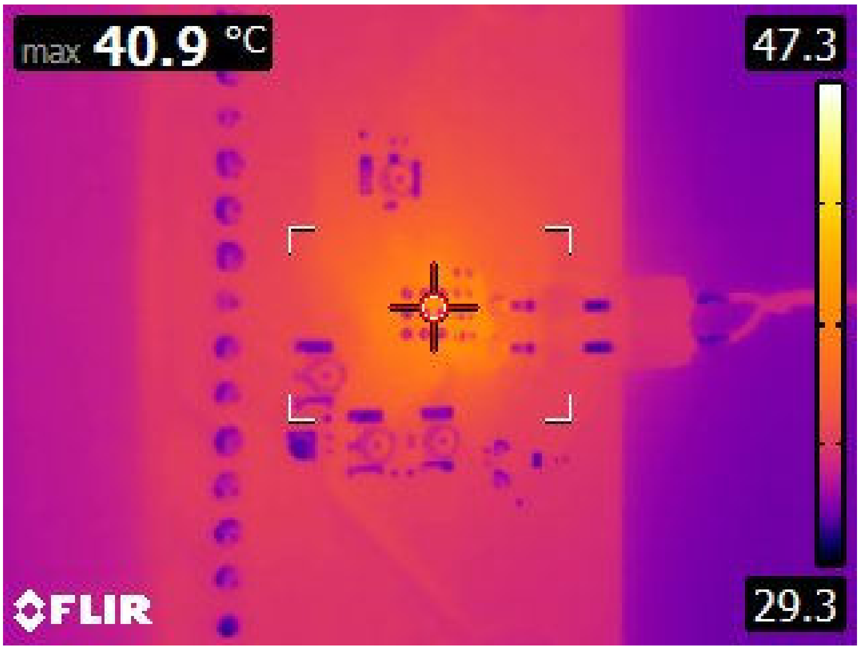
Figure 12 shows the package temperature on the top side measured with the IR camera. The IR camera shows a temperature of 43.8 °C. The real temperature of the top casing is 41.3 °C.

Figure 12. **Top case temperature (ε = 0.95)**



The bottom side of the PCB has been measured using the same procedure. The emissivity has been changed to 0.9 to take into account the surface change. The temperature on the bottom side of the PCB is 40.9 °C as illustrated in Figure 13.

Figure 13. **Bottom PCB temperature (ε = 0.90)**



After turning off the NFC field by setting register 0x02 to 0xC0, the MCU triggers the digital multimeter to measure the diode voltage. The measured diode voltage is 0.33498 V. The DUT is heated by an MPI ThermalAir TA-5000A. The temperature of the DUT is raised until the diode measurement shows the same voltage. To ensure that the device is uniformly heated, the device must be kept for several minutes at the required temperature and put in power-down mode to ensure that the device does not dissipate any power during the diode voltage calibration. For the ST25R3916 the following registers must be set:

- Register 0x00 to 0x07
- Register 0x01, bit “sup3V” set according the to supply voltage .

The calibration shows that a diode voltage of 0.33498 V corresponds to 42.9 °C. The junction temperature during self-heating rises to 42.9 °C which is a temperature increase of:

$\Delta T_{junction} = T_{Junction} - T_{AMB} = 42.9 - 23.8 = 19.1$ °C.

4.3 Measurement of the electrical parameters

The temperature measured in the previous sections is now used to complete the thermal model. The first step is to calculate the dissipated power. Some additional measurements are required:

- V_{DD} = 4.975 V
- V_{DD_RF} = 4.759 V
- I_{VDD} = 274 mA
- I_{AL} = 21 mA
- I_{DRV} = 253 mA
- R_{DRV_NMOS} = 1.95 Ω
- R_{DRV_PMOS} = 1.73 Ω.

4.4 Power dissipation calculation

The dissipated power is be calculated as described in Section 2.4. The previously measured electrical parameters are used in this section.

Dissipated power of the analog and digital logic:

$P_{AL} = V_{DD} * I_{AL} = 4.975 * 0.021 = 0.105$ W.

Dissipated power of the internal voltage regulator:

$P_{REG} = (V_{DD} - V_{DD\_RF}) * I_{DRV} = (4.975 - 4.759) * 0.253 = 0.055$ W.

Dissipated power of the transmitter driver stage:

$P_{DRV} = I_{DRV}^2 * (R_{DRV\_NMOS} + R_{DRV\_PMOS}) = 0.253^2*(1.95+1.73) = 0.236$ W.

The total dissipated power is:

$P_{TOT} = P_{AL} + P_{REG} + P_{DRV} = 0.395$ W.

The power consumed by the device is:

$P_{IN} = V_{DD} * I_{VDD} = 4.975 * 0.274 = 1.363$ W.

The output power is calculated by:

$P_{OUT} = P_{IN} - P_{TOT} = 0.968$ W.

4.5 Calculating the thermal model

The dissipated power P_{TOT} is emitted by the device. The power is radiated by the silicon, flowing through the previously mentioned thermal resistance between junction and package, and package and ambient illustrated in Figure 1. The calculation of the thermal model is optional. The thermal resistance is calculated using the known junction temperature increase and total dissipated power. Nevertheless, for evaluating and optimizing the thermal performance, it is recommended to execute the calculation of the thermal model. The two paths through bottom and top are in parallel. The dissipated power splits between them and distributes according to their thermal resistance. A lower thermal resistance results in a lower temperature increase. The previously measured temperatures is now added to the thermal model shown in Figure 14. The temperature measured on the top package is 43.8 °C. ΔT_{CTA} is therefore be calculated as:

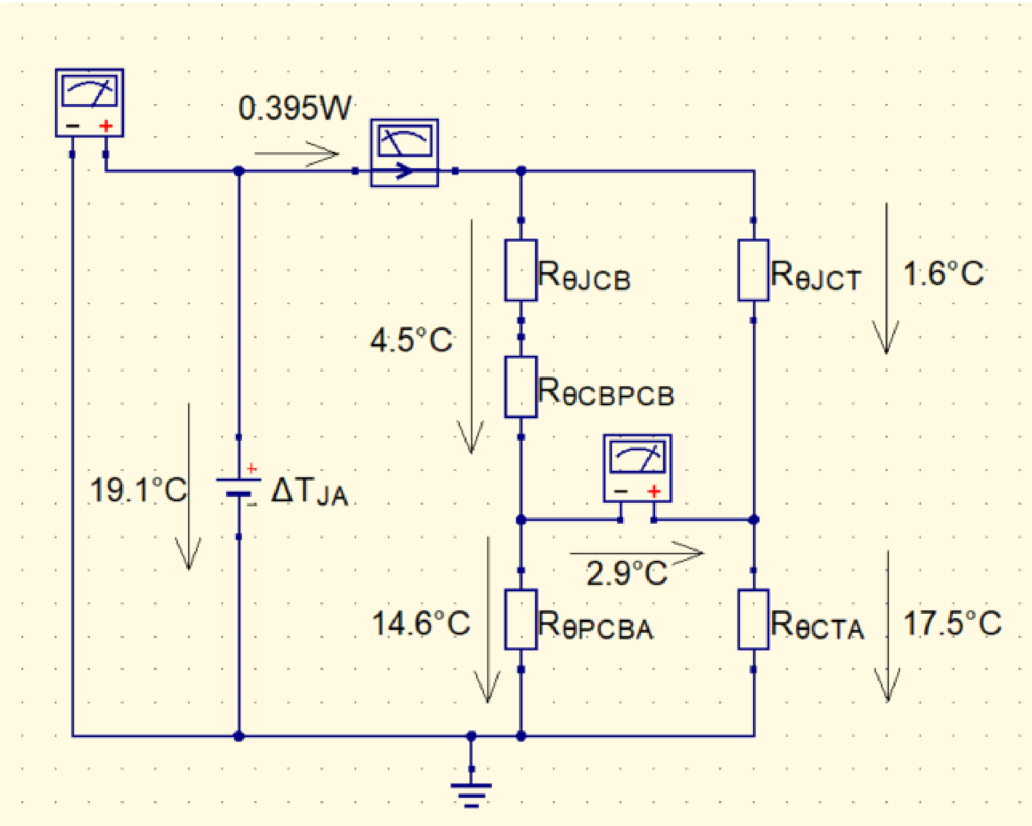
$\Delta T_{CTA} = 43.8 – 26.3 = 17.5$ °C.

ΔT_{JCT} is therefore given by:

$\Delta T_{JCT} = \Delta T_J - \Delta T_{CTA} = 19.1 – 17.5 = 1.6$ °C.

The same procedure applies for the bottom PCB temperatures.

Figure 14. Thermal model including temperatures and P_{TOT}



The first step in solving the thermal model is to calculate the power flowing through $R_{\theta JCT}$:

$P_{TOP} = \Delta T_{JCT} / R_{\theta JCT}$ = 1.6 / 16.95= 0.094 W.

Since the power dissipated through the top case is known, $R_{\theta CTA}$ is calculated using:

$R_{\theta CTA} = \Delta T_{CTA} / P_{TOP}$ = 17.5 / 0.094 = 185.38 °C/W.

The power dissipated through the bottom is calculated by:

$P_{BOT} = P_{TOT} – P_{TOP}$ = 0.395 – 0.094 = 0.300 W.

The thermal resistance between PCB bottom side and ambient is calculated by:

$R_{\theta PCBA} = \Delta T_{PCBA} / P_{BOT}$ = 14.6 / 0.300 = 48.622 °C/W.

This leads to the calculation of the thermal resistance between the exposed pad and PCB bottom side $R_{\theta CBPCB}$. Since the amount of power dissipated through the bottom case is known, CBPCB thermal resistance is calculated using:

$R_{\theta CBPCB} = \Delta T_{JCBPCB} / P_{BOT} = (\Delta T_{JPCB} - \Delta T_{JCB}) / P_{BOT}$ = (4.5 – 0.300 * 0.85) / 0.300 = 14.136 °C/W.

4.6 Calculating the overall thermal resistance

The numbers above demonstrate the split between the power dissipated through the top-case and power dissipated through the PCB bottom side depends on the PCB and how good it dissipates the heat. The overall thermal resistance is calculated by:

$R_{\theta TH} = \Delta T_{JA} / P_{TOT}$ = 19.1 / 0.395 = 48.394 °C/W.

The thermal resistance $R_{\theta TH}$ is only valid for the board shown in Figure 8 and Figure 9. Using a different package, PCB layout or ambient temperature (housing or ventilation) changes $R_{\theta BPCB}$ and $R_{\theta CTA}$ and therefore impacts $R_{\theta TH}$.

5 Self-heating model definition at 350mA

Since the thermal model is completely solved, the junction temperature for different operating conditions can now be estimated. For example, looking at the thermal performance when the driver current is increased from 253 mA to 350 mA. To do so, the following steps are required:

1. Define electrical parameters
2. Calculate the dissipated power
3. Calculate Junction temperature.

5.1 Define electrical parameters

First, the electrical parameters must be defined. Using the previously measured parameters or estimate new parameters or measure the electrical parameters from a real example. For this calculation the loading is changed from 253 mA to 350 mA and the measured electrical parameters are given below:

- V_{DD} = 4.982 V
- V_{DD_RF} = 4.585 V
- I_{VDD} = 371 mA
- I_{AL} = 21 mA
- I_{DRV} = 350 mA
- R_{DRV_NMOS} = 1.95 Ω
- R_{DRV_PMOS} = 1.73 Ω.

5.2 Calculate the dissipated power

The next step is to use these electrical parameters and calculate the dissipated power for each block.

Dissipated power of the analogue and digital logic:

$P_{AL} = V_{DD} * I_{AL} = 4.975 * 0.021 = 0.105$ W.

Dissipated power of the internal voltage regulator:

$P_{REG} = (V_{DD} – V_{DD\_RF}) * I_{DRV} = (4.982 - 4.585) * 0.350 = 0.137$ W.

Dissipated power of the transmitter driver stage:

$P_{DRV} = I_{DRV}^2 * (R_{DRV\_NMOS} + R_{DRV\_PMOS}) = 0.352^2 * (1.95+1.73) = 0.451$ W.

The total dissipated power is:

$P_{TOT} = P_{AL} + P_{REG} + P_{DRV} = 0.692$ W.

The power which is consumed by the device is:

$P_{IN} = V_{DD} * I_{VDD} = 4.975 * 0.373 = 1.846$ W.

The output power is calculated by:

$P_{OUT} = P_{IN} - P_{TOT} = 1.154$ W.

5.3 Junction temperature calculation

Since the total thermal resistance of the board is determined, the junction temperature is calculated by:

$\Delta T_{JA} = P_{TOT} * R_{\theta TH} = 0.69178 * 48.394 = 33.48$ °C.

The ΔT_{JA} states by how much the junction temperature rises, dependent on a specific ambient temperature. For example, at an ambient temperature of 25 °C the junction will rise to:

$T_J = \Delta T_{JA} + T_{AMB} = 33.48 + 25 = 58.48$ °C.

On the other side, a maximum ambient temperature is calculated based on the maximum junction temperature increase:

$T_{AMB\_max} = T_{J\_max} - \Delta T_{JA} = 125 – 33.48 = 91.52$ °C.

6 Self-heating measurement at 350 mA

The assumptions made for V_{DD}, V_{DD_RF} and I_{VDD_RF} based on real measurements of the DUT consumption set at 350 mA. Therefore, the estimated self-heating of the device vs. a real measurement is possible. The following steps are executed for this comparison:

- Measurement of the ambient temperature and IR camera temperature offset
- Calculation of the top and bottom temperature
- Measurement of the top and bottom temperature
- Measurement of the junction temperature.

6.1 Measurement of the ambient temperature and IR camera temperature offset

- $T_{AMB\_thermocouple}$ = 24.8 °C
- T_{AMB_IR} = 27.2 °C
- T_{Offset} = 24.8 – 27.2 = 2.4 °C.

6.2 Calculation of the top and bottom temperature

$R_{\theta Top} = R_{\theta JCT} + R_{\theta CTA}$ = 16.95 + 185.38 = 202.33 °C/W.

$R_{\theta Bot} = R_{\theta JCB} + R_{\theta CBPCB} + R_{\theta PCBA}$ = 0.85 + 14.136 + 48.622 = 63.608 °C/W.

The total dissipated power is calculated using:

$P_{TOT} = \Delta T_{JA}^2 / R_{\theta TOT}$.

The dissipated power through the top case is calculated using:

$P_{TOP} = \Delta T_{JA}^2 / R_{\theta Top}$.

$P_{TOP} / P_{TOT} = (\Delta T_{JA}^2 * R_{\theta TOT}) / (\Delta T_{JA}^2 * R_{Top}) = R_{\theta TOT} / R_{Top}$

Where:

- $R_{\theta TOT} = (R_{\theta Top} * R_{\theta Bot}) / (R_{\theta Top} + R_{\theta Bot})$
- $P_{TOP} = (P_{TOT} * R_{\theta Bot}) / (R_{\theta Top} + R_{\theta Bot})$ = 0.692 * 63,608 / (202.33 + 63.608) = 0.165 W
- P_{BOT} = 0.692 - 0.165 = 0.526 W.

The junction case temperature is given by:

$\Delta T_{JCT} = P_{TOP} * R_{\theta JCT}$ = 0.165 * 16.95 = 2.805 °C.

The case top side to ambient is given by:

$\Delta T_{CTA} = P_{TOP} * R_{\theta CTA}$ = 0.165 * 185.38 = 30.674 °C.

The same procedure is executed for the bottom temperature.

The junction case to bottom temperature is calculated using:

$\Delta T_{CBA} = P_{BOT} * (R_{\theta JCB} + R_{\theta CBPCB})$ = 0.526 * (0.85 + 14.136) = 7.888 °C.

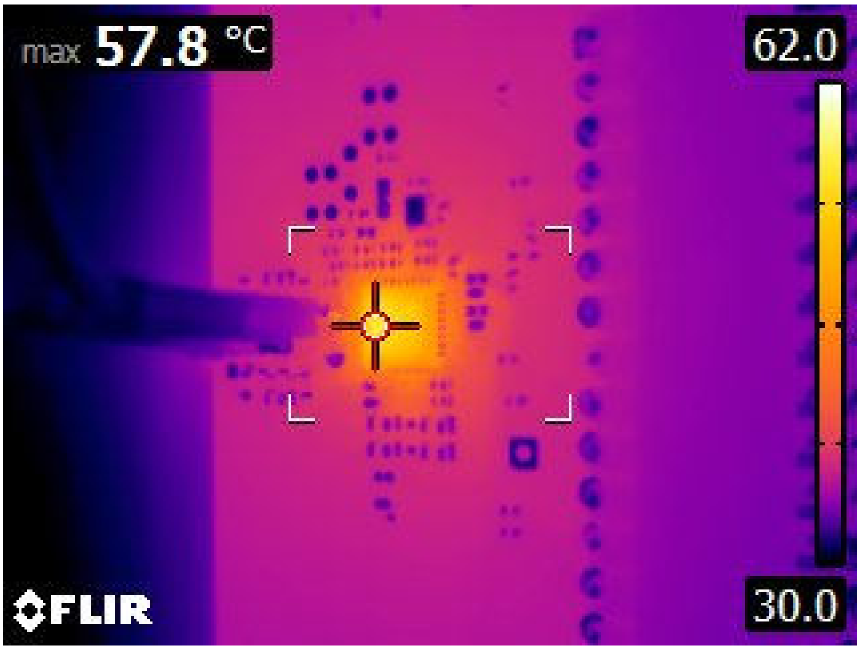
The PCB to ambient temperature is calculated using:

$\Delta T_{PCBA} = P_{BOT} * R_{\theta PCBA}$ = 0.526 * 48.622 = 25.591 °C.

6.3 Measurement of the top and bottom temperature

Measurement of case top temperature is shown in Figure 15:

Figure 15. **Top case temperature (ε = 0.95)**



The measured case top temperature is 57.8°C. After adding the IR camera offset the real temperature is:

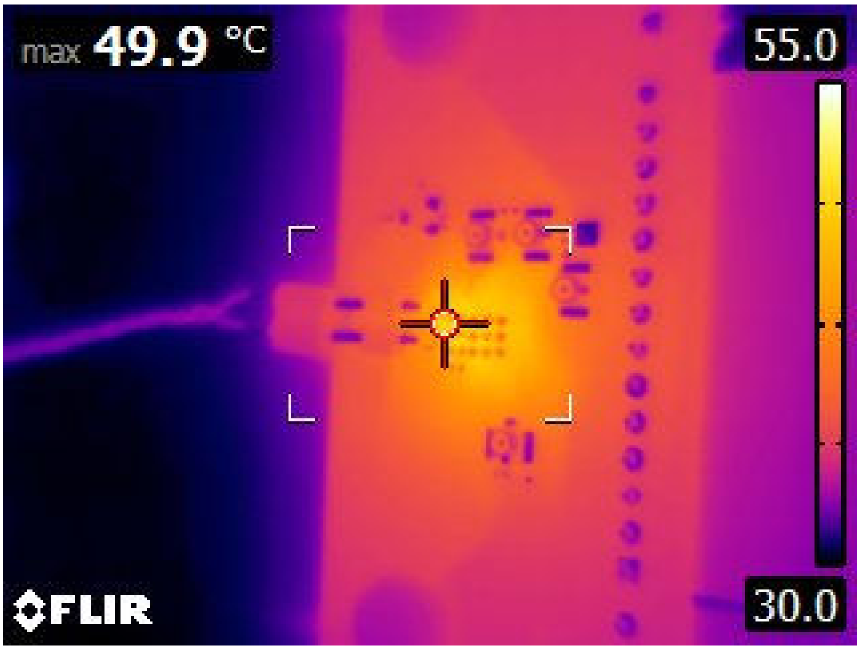
$T_{CTA\_meas} = T_{CTA\_IR} + T_{Offset}$ = 57.8 -2.4 = 55.4 °C.

The calculated case top temperature is:

$T_{CTA\_calc} = \Delta T_{JCT + TAMB}$ = 30.674 + 24.8 = 55.473 °C.

Measurement of PCB bottom temperature illustrated in Figure 16:

Figure 16. **Bottom PCB temperature (ε = 0.90)**



$T_{PCBA\_meas} = T_{PCBA\_IR} + T_{Offset}$ = 49.9 – 2.4 = 47.5 °C.

$T_{PCB\_calc} = \Delta T_{PCBA} + T_{AMB}$ = 25.591 + 24.8 = 50.391 °C.

6.4 Measurement of the junction temperature

The diode voltage during self-heating is measured at 0.318 V. This voltage correlates to a junction temperature of 58.6 °C when heating the device in power-down mode:

$T_{Junction\_measured}$ = 58.6 °C.

The calculated junction temperature is:

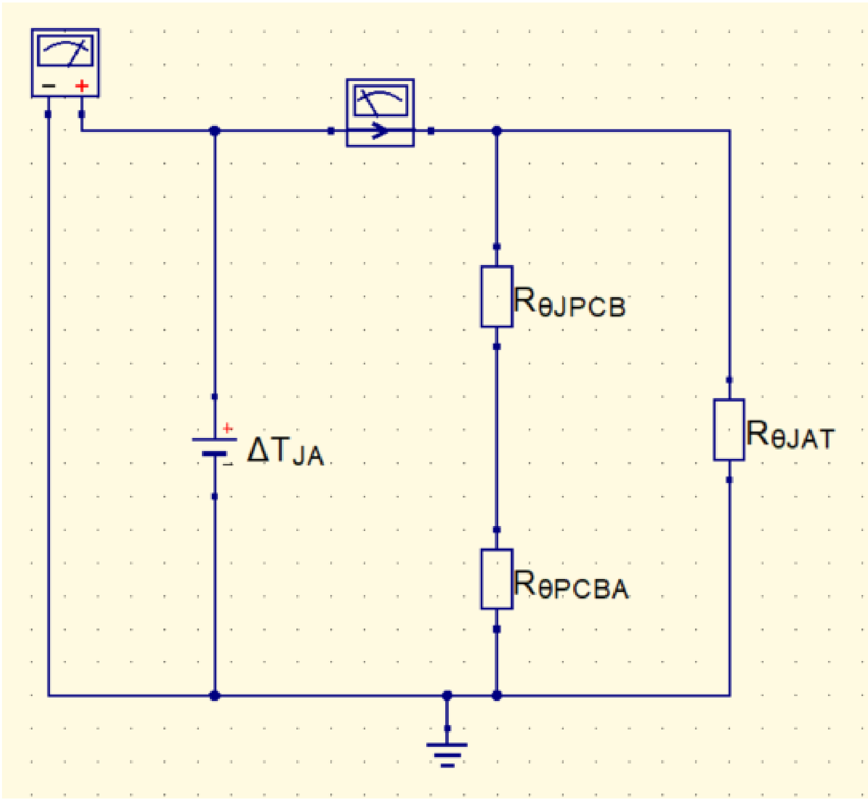
$T_{Junction\_Calculated} = \Delta T_{JA} + T_{AMB}$ = 33.48 + 24.8 = 58.28 °C.

The calculated and measured junction temperature values show very good correlation. The model derived from the 250 mA load is used to adequately calculate the junction temperature for different load scenarios and allows the adjustment of specific application parameters to target certain operating conditions like maximum ambient temperature.

7 Thermal model of a WLCSP package

The WLCSP is a special form of package. The silicon is directly exposed to the ambient. This means the junction temperature is measured directly on the silicon. The temperature gradient on the silicon is assumed to be negligeable. The thermal model is therefore simplified as illustrated in Figure 17:

Figure 17. Thermal model of a WLCSP device



There is only one thermal resistance describing the transition between junction to ambient temperature through the top surface of the silicon. On the bottom side of the silicon, the thermal resistance depends heavily on the board layout. Several parameters such as; via types, or number of layers, influence the thermal resistance to the PCB and therefore also change the ratio between dissipated power through the top and dissipated power through the bottom face. Nevertheless, the better the dissipation through the bottom of the device is, the lower its overall thermal resistance is and the cooler the device remains.

The split between dissipated power going through top case and bottom case cannot be distinguished in this configuration. Only the overall thermal resistance is calculated.

Figure 18. ST25R3916-BWLT DUT - top view

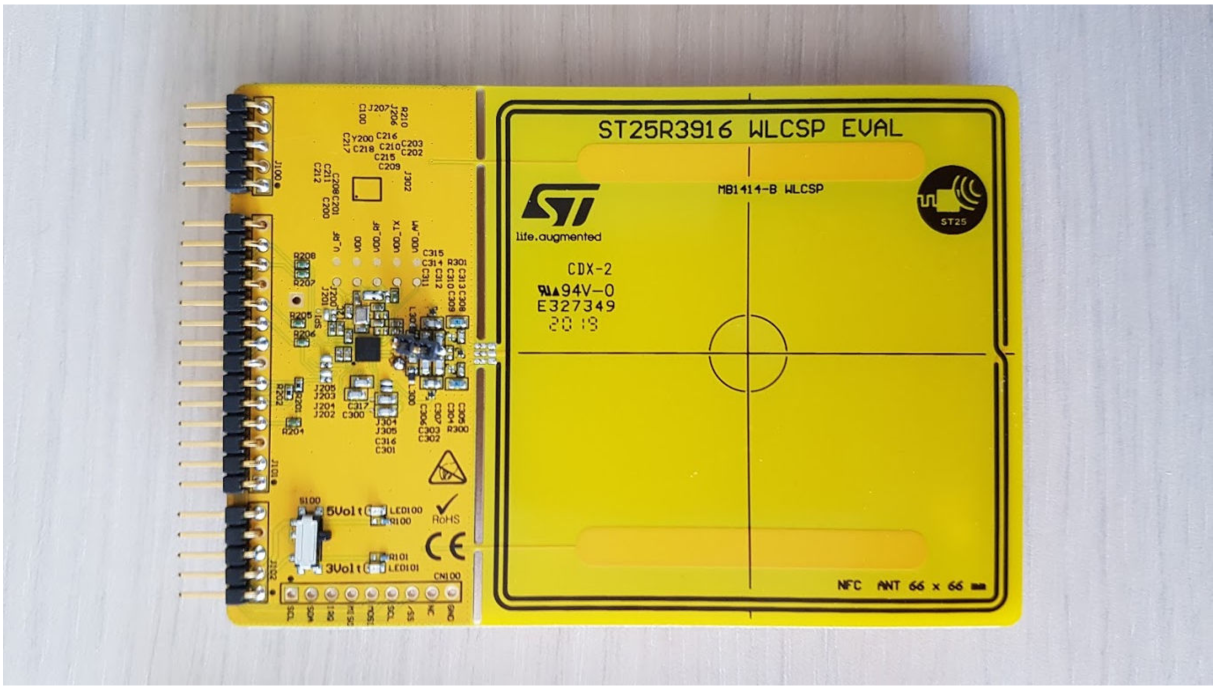


Figure 18 shows the PCB used to evaluate the ST25R3916-BWLT CSP package. It is very similar to the boards shown in Figure 8 and Figure 9.

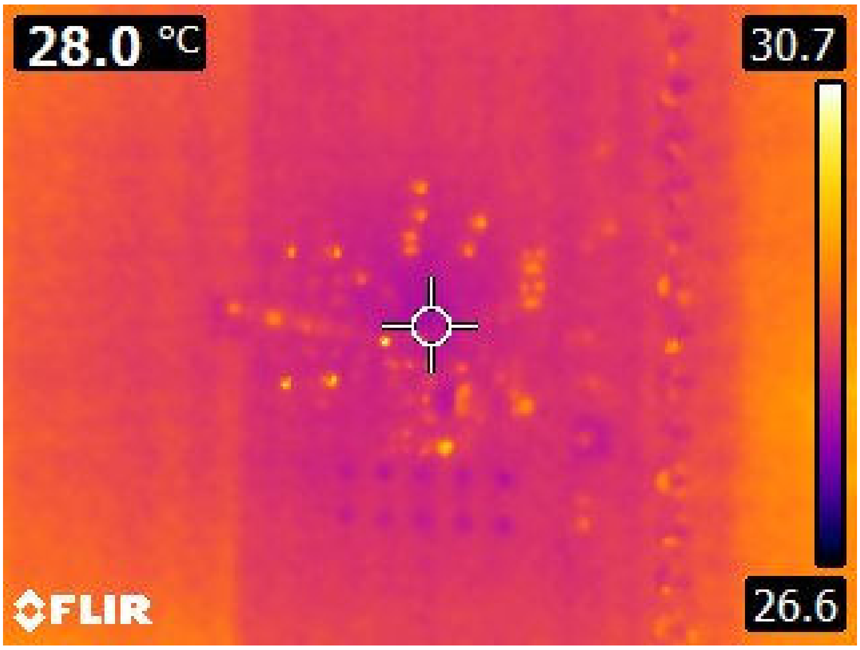
The following steps are required to calculated the thermal resistance:

1. Measurement of the ambient temperature and IR camera temperature offset
2. Measurement of the self-heating
3. Measurement of the electrical parameters
4. Calculation of the dissipated power
5. Calculation of the overall thermal resistance.

7.1 Measurement of the ambient temperature and IR camera temperature offset

For a CSP package it is very easy to measure the junction temperature using an IR camera as illustrated in Figure 19.

Figure 19. **Ambient temperature measurement (ε = 0.97)**



The first step is to assess the temperature offset between IR camera and real ambient temperature:

- $T_{AMB\_thermocouple}$ = 26.5 °C
- T_{AMB_IR} = 28.0 °C.

The temperature offset between IR camera and real ambient temperature is calculated:

T_{Offset} =28.0 – 26.5 = 1.5 °C.

7.2 Measurement of the self-heating

The junction temperature is measured directly on the top side of the package.

Figure 20. **Top case temperature (ε = 0.97)**

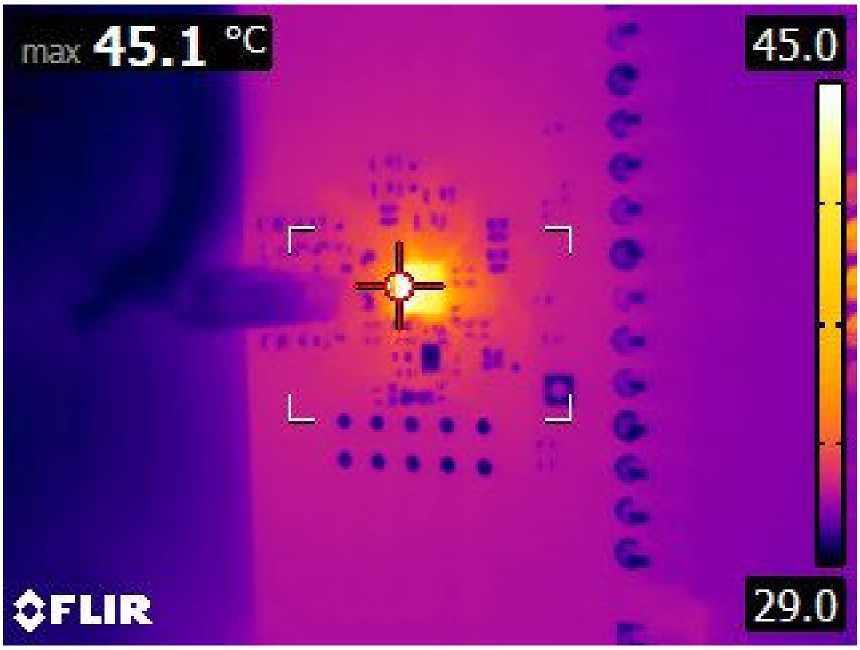
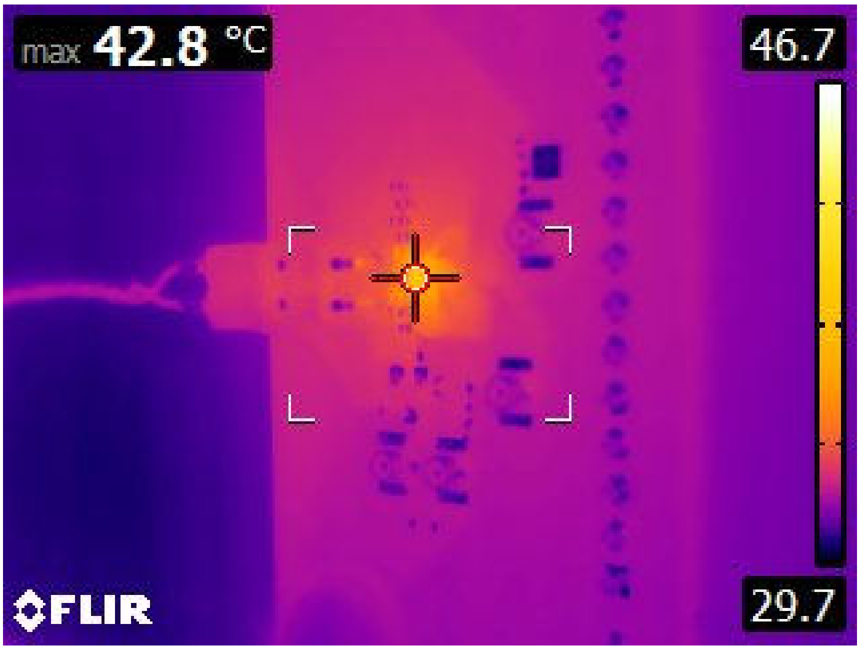


Figure 20 shows the package temperature on the top side measured with the IR camera. The IR camera shows a temperature of 45.1 °C. The real temperature of the top casing is 43.6 °C.

The bottom side, as illustrated in Figure 21, of the PCB shows a temperature of 42.8 °C. The real bottom temperature is 41.3 °C

Figure 21. **Bottom PCB temperature (ε = 0.90)**



The diode measurement shows a voltage of 0.331V which correlates to a temperature of 43 °C

The measured case top temperature is 43.6 °C, this temperature also corresponds to the junction temperature. The diode measurement shows a junction temperature of 43 °C.

7.3 Measurement of the electrical parameters

- V_{DD}=4.971 V
- V_{DD_RF} = 4.734 V
- I_{VDD} = 272 mA
- I_{AL} = 21 mA
- I_{DRV} = 251 mA
- R_{DRV_NMOS} = 1.90 Ω
- R_{DRV_PMOS} = 1.75 Ω.

7.4 Calculation of the dissipated power

Dissipated power of the analog and digital logic:

$P_{AL} = V_{DD} * I_{AL} = 4.971 * 0.021 = 0.104$ W.

Dissipated power of the internal voltage regulator:

$P_{REG} = (V_{DD} – V_{DD\_RF}) * I_{DRV} = (4.971 - 4.734) * 0.251 = 0.059$ W.

Dissipated power of the transmitter driver stage:

$P_{DRV} = I_{DRV}^2 * (R_{DRV\_NMOS} + R_{DRV\_PMOS}) = 0.251^2*(1.90+1.75) = 0.230$ W.

The total dissipated power:

$P_{TOT} = P_{AL} + P_{REG} + P_{DRV} = 0.394$ W.

The power which is consumed by the device:

$P_{IN} = V_{DD} * I_{VDD} = 4.971 * 0.272 = 1.352$ W.

The output power is calculated by:

$P_{OUT} = P_{IN} - P_{TOT} = 0.958$ W.

7.5 Calculating the thermal resistance

The thermal resistance is calculated by:

$R_{\theta TH} = \Delta T_{JA} / P_{TOT} = (43.6 – 26.5) / 0.394 = 43.420$ °C/W.

8 Conclusion

The measurement methods in this document explain how to measure the junction temperature in a specific application, and how to calculate the self-heating for different scenarios.

These methods also show that the thermal performance of an integrated circuit mainly depends on two factors.

- The thermal resistance of the package. Bigger packages with bigger thermal pads allow a better power dissipation to the PCB.
- PCB size, layout and stack-up influence the power dissipation to the ambient. If the thermal resistance from bottom to ambient is lower, then the overall thermal resistance is lower.

This means, that the thermal performance cannot be generalized. It is specific for each PCB and application. A PCB with increase copper planes have a better cooling and therefore the junction temperature remains lower during operation.

By calculating the dissipated power and solving the thermal model, the main contributors of the system are identified. The measurements in this document have been done using continuous wave output. The dissipated power is drastically reduced by introducing a duty cycle when doing the polling. The period duration of this duty cycle must be much lower than the settling of the self-heating. For example, a polling cycle with of 100 ms on-time and of 100ms off-time would reduce the dissipated power of the regulator and TX-driver by half. The junction temperature therefore would be much lower than using continuous output.

Appendix A Emissivity

The emissivity is one of the most important parameters in thermal imaging. It describes the ability of a material to emit radiation compared to a perfect black body of the same temperature. Normally the emissivity ranges from 0.1 to 0.95, where a highly polished surface falls below 0.1, while an oxidized or painted surface has a higher emissivity. Human skin exhibits an emissivity 0.97 to 0.98.

Further information about emissivity is available in the user manual of the ETS320 IR camera: (*ETS320 User manual - #T810252; r. AD/43675/43675; en-US – page 46*)

This user manual also describes a method to determine the emissivity factor of materials outlined as follows:

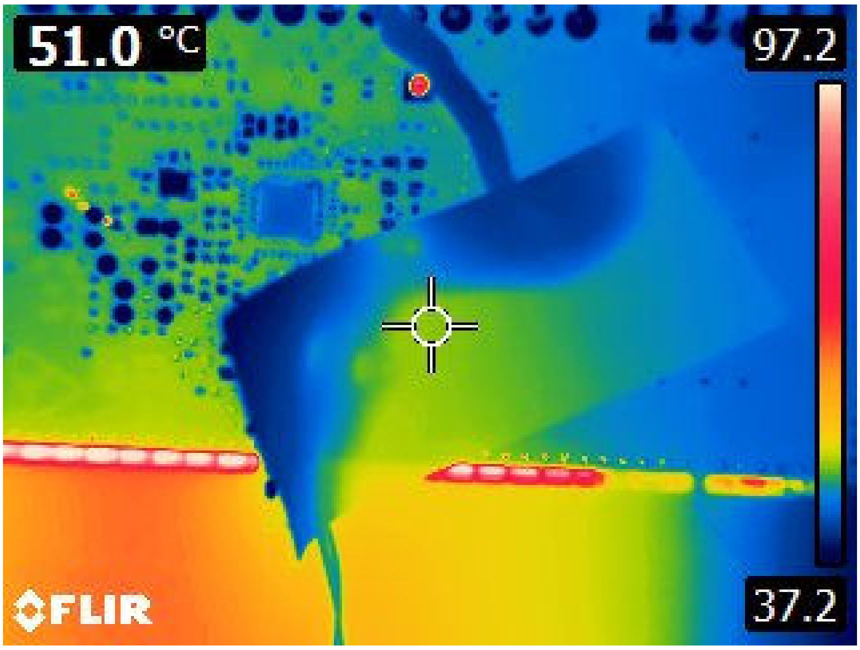
1. Select a place to put the sample.
2. Determine and set the reflected apparent temperatures according to the previous step.
3. Put a piece of electrical tape with known high emissivity on the sample.
4. Heat the sample at least 20 K above room temperature. Ensuring the heating is evenly distributed.
5. Focus and auto-adjust the camera, and freeze the image.
6. Adjust level and span for best image brightness and contrast.
7. Set emissivity to that of the tape (usually 0.97).
8. Measure the temperature of the tape using one of the following measurement functions:
   – Isotherm (helps to determine both the temperature and how evenly the sample is heated)
   – Spot (simpler)
   – Box Average (good for surfaces with varying emissivity).

   A sample measurement is illustrated in Figure 22.
9. Make a note of the temperature.
10. Move the measurement function to the sample surface.
11. Change the emissivity setting until the same temperature reading is achieved as the previous measurement.
12. Make a note of this emissivity.

To carry out this procedure, an unpowered ST25R3916-DISCO board is heated to 51°C.

The ST25R3916-DISCO board is assembled with an ST25R3916 QFN package. The top side of the package is removed to measure the actual silicon temperature.

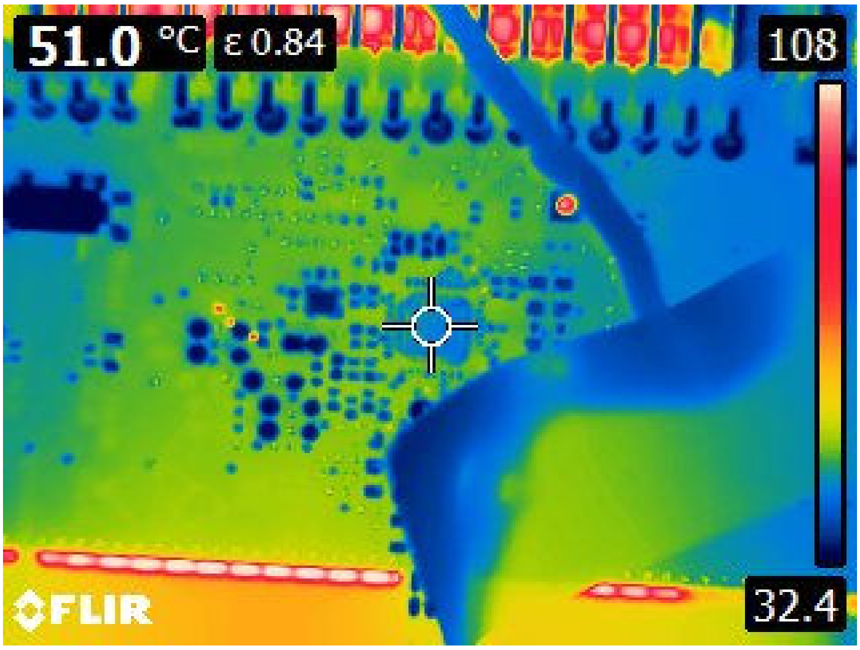
Figure 22. Measurement on plastic tape ε = 0.97



Note: The cross represents the measuring point which is on the electric tape

Then the focus spot is changed to the top side of the opened IC and the emissivity setting of the camera is altered until the same temperature is displayed as illustrated in Figure 23.

Figure 23. **Measurement on the sillicon top, adjust ε = 0.84**



This procedure must be repeated until the ε for each material is determined. The following materials have been characterized:

Table 3. **Temperature emissivity coefficients**

Material	ε
PCB surface (solder resist)	0.90
IC VFQFPN32 package	0.95
IC WLCSP package	0.97

Revision history

Table 4. **Document revision history**

Date	Version	Changes
11-Jan-2021	1	Initial release.
25-Jul-2022	2	Updated: • Introduction • Section 2.3 NFC reader PCB thermal model • Section 2.4 Power dissipation • Section 3 Junction temperature assessment • Section 4.1 Temperature offset measurement • Section 6.2 Calculation of the top and bottom temperature • Section 6.4 Measurement of the junction temperature
08-Jun-2023	3	Added ST25R3916B, ST25R3917, ST25R3917B, ST25R3918, ST25R3919B, ST25R3920, and ST25R3920B to the applicable products in the Introduction.

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