# SELF-HEATING COMPENSATION IN TEMPERATURE SENSOR RFID TRANSPONDERS

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**Key words:** RFID, data logger, voltage limiter, Smart Active Label.

**Abstract:** In this article we present the analysis and compensation of self-heating in a passive temperature sensor RFID transponder. The problem of heating due to the operation of the integrated voltage limiter can be observed in most RFID transponders. In temperature sensor RFID transponders this causes errors in the measured temperature, as the integrated sensor measures the IC temperature which is higher due to the operation of the voltage limiter. We propose a new algorithm of self-heating compensation with the use of an analogue to digital converter in the RF analogue front-end that measures the current level in the voltage limiter. The interrogator uses this value in the compensation equation that is presented in this paper.

# Kompenzacija lastnega segrevanja pri merjenju temperature z RFID značko

**Kjučne besede:** RFID, podatkovni sledilnik, napetostni omejevalnik.

**Izvleček:** V članku je predstavljen vpliv lastnega segrevanja na točnost merjenja temperature z RFID značkami. Predstavljen je model segrevanja integriranega vezja RFID značke zaradi vpliva energije, ki se porablja v napetostnem omejevalniku v radijsko frekvenčni enoti. Prikazan je nov način kompenzacije lastnega segrevanja, kjer se kompenzacija izvede v RFID izpraševalniku. Predstavljeno vezje RFID značke ima v analogni radijsko frekvenčni enoti integriran analogno digitalni pretvornik za pretvorbo toka napetostnega omejevalnika. Izhodna vrednost tega analogno digitalnega pretvornika se, skupaj z digitalno vrednostjo temperature, pošlje RFID izpraševalniku. Kompenzacije se izvede v izpraševalniku na osnovi izmerjene temperature, vrednosti toka v napetostnem omejevalniku in časa prisotnosti RF polja.

## 1 Introduction

RFID (Radio Frequency Identification) is no longer considered to be a pure automatic identification technology. Due to the fact that the transponder is an electronic circuit (IC), it is possible to extend the functionality to other areas /1/, /2/, /3/, /4/.

This article deals with RFID transponders with integrated temperature sensors. The application areas of such systems are spread across all kinds of industries. Just to mention few, the first is the cold-chain industry, where a RFID tag with an temperature sensor can be used as a low-budget data logger. In medicine such tags can be used as permanent human body thermometers and in the automotive industry as a tire temperature indicator.

The advantage of using RFID technology in those applications is the wireless data transfer /5/, /6/, /7/ and even more important, the fact that, in passive RFID systems, the transponder does not need its own energy source. The problem we face in passive RFID transponders is the self-heating that is caused by the operation of the voltage limiter. The amount of self heating is dependant on the distance between the interrogator and transponder antennas and is such not predictable.

Chapter 2 describes the basic principle of passive RFID transponder power supply and the problem of self-heating. The new algorithm for self-heating compensation is presented in chapter 3. The IC heating model used in our analysis is presented in chapter 4. Measurement results and comparison with the model is in chapter 5. The conclusion is in chapter 6.

## 2 Passive rfid transponder supply

Passive RFID transponders are powered from the electromagnetic field that is generated by the interrogator /8/, /9/. The electromagnetic field induces an AC voltage over the antenna (Figure 1) and can be calculated with the following equation /9/:

$$u'_2 = \frac{j\omega k \cdot \sqrt{L_1 \cdot L_2} \cdot i_1}{1 + (j\omega L_2 + R_2)\left(\frac{1}{R_L} + j\omega C_2\right)}, \qquad (1)$$

$u'_2$ - induced voltage on the IC pads,

k - coupling factor,

$L_1$ - interrogator antenna inductance,

$L_2$ - transponder antenna inductance,

$R_2$ - transponder antenna parasitic resistance,

$R_L$ - transponder load (IC current drain),

$C_2$ - transponder parallel capacitance ($C_p$+$C_L$).

The real form of equation (1) is /9/:

$$u'_2 = \frac{j\omega k \cdot \sqrt{L_1 \cdot L_2} \cdot i_1}{\left(\frac{\omega L_2}{R_L} + \omega R_2 C_2\right)^2 \cdot \left(1 - \omega^2 L_2 C_2 + \frac{R_2}{R_L}\right)^2}, \qquad (2)$$

The AC voltage is rectified by the transponder IC with a diode or transistor rectifier. The transponder antenna usually has a certain Q factor in order to boost the induced voltage and extend the reading and writing range:

$$Q=\frac{1}{R_2\cdot\sqrt{\frac{C_2}{L_2}}+\frac{1}{R_L}\sqrt{\frac{L_2}{C_2}}}=\frac{1}{\frac{R_2}{\omega L_2}+\frac{\omega L_2}{R_L}}, \qquad (3)$$

At longer distances the transponder benefits from the Q factor. At close proximity to the interrogator antenna this can cause that the induced voltage exceeds the maximum voltage defined by the technology /10/, /11/, /12/, /13/ . In modern CMOS technologies this is usually 2.5V, 3.6V or 5.5V.

For a reliable operation in a weak filed, further away from the interrogator antenna, and in a strong field, close to the interrogator antenna, the IC must have a possibility to lower its quality factor. Transponder IC manufacturers most commonly use a regulated voltage limiter that is composed of a transistor. At long distances from the interrogator antenna the induced voltage will be within the limits of the technology so the limiter transistor will be turned off completely and will drain no current. When the transponder moves closer to the interrogator, the induced voltage will rise to the point where it reaches the technology limit. At this point the limiter transistor will start to drain current from the rectifier, thus lowering the overall Q of the transponder. The current through the limiter transistor is therefore dependent on the distance between the interrogator and transponder.

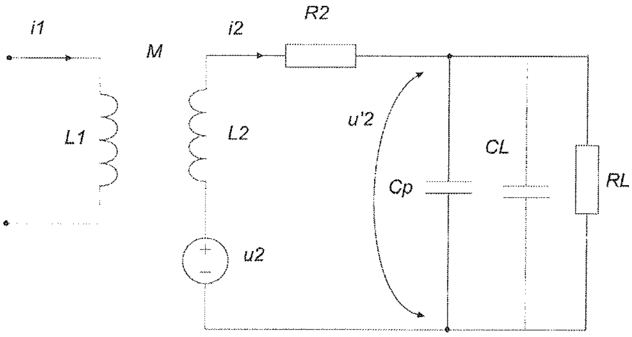

*Fig. 1: Equivalent circuit of magnetically coupled interrogator and transponder. The left part shows the interrogator and the right part shows the transponder.*

The excessive electromagnetic energy is converted to heat in the transponder voltage limiter causing a self heating effect /14/. This causes problems in transponders with an integrated temperature sensor, as the IC temperature will be higher than the environment temperature when the voltage limiter is active. This effect is not predictable as the amount of heat, that is generated by the voltage limiter, is dependent on the distance between the interrogator and transponder.

A solution to the above problem is presented in /14/. The author proposes to use a variable tuning capacitor integrated in the IC. The capacitance is regulated according to the value of the induced voltage, thus changing the resonance value of the antenna. After power-on the value of the capacitance is such, that the resonance frequency is equal to the carrier frequency. When the transponder moves closer to the interrogator and the value of the induced voltage rises, the value of the capacitance changes and de-tunes the resonant frequency. This consequently lowers the induced voltage, or rather, keeps it on a constant level, below the technology limit.

The above concept works on low and high frequency transponders (135kHz and 13.56MHz), but only to a certain level, as the value of the integrated capacitor can not be dynamically changed to any desirable level. Even more, this works only to a certain distance between interrogator and transponder, where the coupling coefficient *k* becomes too large. In this case the induced voltage can exceed the technology limit, even with a low Q value. In RFID systems in the UHF frequency range (900MHz) this approach is not feasible due to the fact that the IC capacitance has to be as low as possible to ensure the correct resonant frequency with a typical dipole antenna.

It is clear that a more robust and general approach needs to be used.

## 3 Self-heating compensation

Self heating presents a problem everywhere where temperature dependent parameters are crucial to observation or functionality of component. The easiest solution is to isolate and separate heat sources and thermal sensitive components. In our case, where we have everything integrated on a single silicon die. We can move the heat source

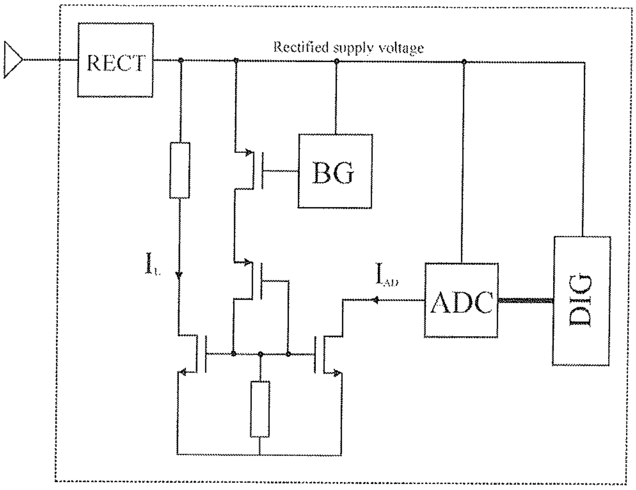

*Fig. 2: Analogue front end with current limiter AD converter. RECT - RF rectifier, BG - band gap reference, ADC - current balancing analogue to digital converter, DIG - RF digital circuit.*

far away from the temperature sensor, but this is not always possible. Sometimes components can be made invariable to temperature changes (0 TC resistors, bandgap reference voltages /15/, /16/). When temperature dependent resistors are used (Pt1000), the manufacturer usually provides data about self heating or some way of compensation to get real results.

We found ourselves in front of a unique problem, when we want to measure the temperature of surrounding air and not temperature of surrounding air plus temperature difference caused by heat source on silicon. We can ignore the self heating of temperature sensor caused by the excitation current, because the sensor is excited for brief moments (2ms) and the current passing trough the sensor is very small (a few µA). The heating of temperature sensor is caused by the current flowing into the voltage limiter. The heat source and the temperature sensor are placed far apart on the silicon die (Figure 3).

We have introduced a new method of compensation that takes part in two stages. We have to measure the duration of power dissipation and the power dissipated on heat source (voltage limiter). Time of power dissipation is measured in the RFID reader, since it has control over the RF field. When the RFID tag is powered it can measure the sink current and convert it to a digital value (Figure 2). A part of the limiter current $I_L$ is fed to the current balancing AD converter (current $I_{AD}$). The output code is then back scattered to the RFID reader, together with the temperature value, where the actual compensation is done.

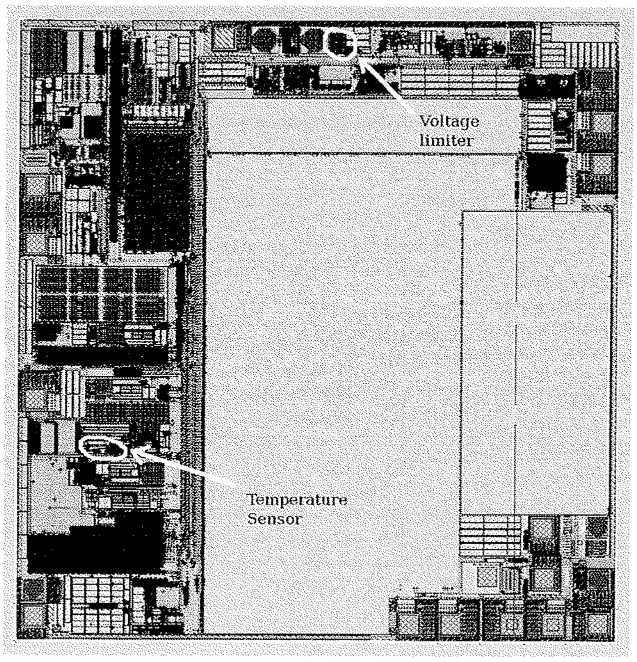

*Fig. 3: Temperature sensor RFID transponder IC layout view. The digital circuits are not shown.*

Since our heat source is a voltage limiter its voltage is constant. Therefore we can calculate how much power is dissipated with the information on the voltage limiter current level. Now that the RFID reader has all information about time and power (current), it can calculate temperature error and subtract it from the measured value. In this method of compensation we assume a time invariant power dissipation in the voltage limiter. This demands a constant distance between the reader antenna and the transponder antenna during temperature conversion. The temperature rise as the effect of self heating is calculated with the following equation:

$$\Delta T = T_s \cdot \left(1 - e^{-\frac{t}{R_T C_T}}\right), \tag{4}$$

*$T_S$ - stable state temperature,*

$\tau$ - time constant.

We can write the above equation as:

$$\Delta T = P \cdot R_T \cdot \left(1 - e^{-\frac{t}{R_T C_T}}\right), \tag{5}$$

*P - power in voltage limiter,*

$R_T$ - characteristic thermal resistance,

$C_T$ - characteristic thermal capacitance.

The $R_T$ and $C_T$ values can be determined either with measurements or analytically.

It is also possible to implement this compensation algorithm for the case where we can not assume a constant distance between the interrogator and transponder, but a more sophisticated software is required on the interrogator side.

## 4 IC heating model

Heat transfer occurs when a heat gradient is present in an object or between objects. Every object or medium with mass has a tendency to establish a thermal equilibrium with the adjacent object.

Heat transfer occurs in three different ways:

- conduction - heat transfer trough solids,
- convection - heat transfer trough liquids or. gases,
- radiation - heat transfer to distant object trough electromagnetic waves.

In describing thermodynamic events we relay on two basic laws, firs and second law of thermodynamics. The first law states that energy can be transformed (changed from one form to another), but cannot be created or destroyed. Therefore, increase in the internal energy (U) of a system is equal to the amount of energy added by heating (Q) the system minus the amount lost as a result of the work(W) done by the system on its surroundings.

$$dU = dQ - dW, \tag{6}$$

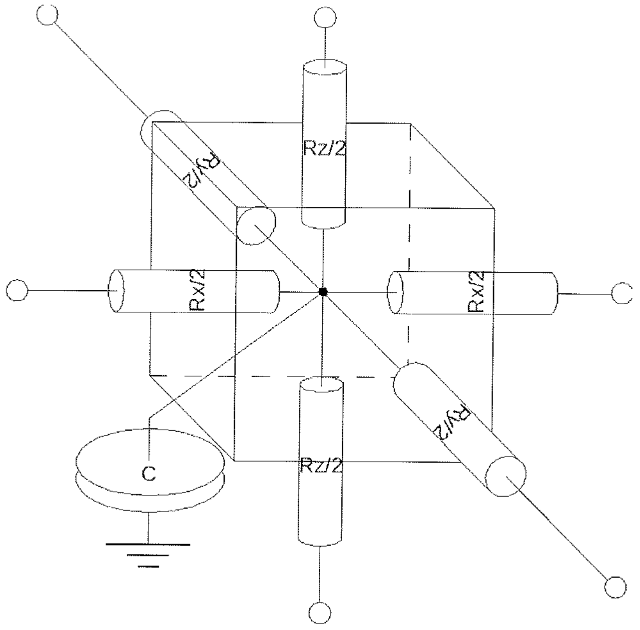

*Fig. 4: Single cell finite state multi nodal model*

The second law of thermodynamics states that the entropy of an isolated macroscopic system never decreases; that the entropy (S) of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium.

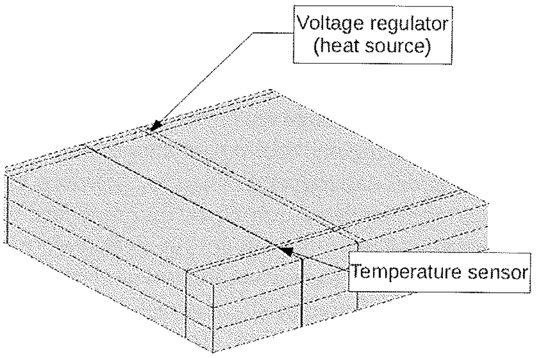

*Fig. 5: Transponder IC silicon model*

There are many methods of modeling thermal processes /17/, /18/, CFD (Computational Fluid Dynamics), ND (Nodal method), Zonal modeling. In our case we are modeling the transponder IC encapsulated in 20 pin DIL housing and the transponder IC glued directly to a PCB. Our goal is to predict heat gradient over IC on which a temperature sensor and a heat source are located. The heat source is a voltage limiter that modulates load on the rectified RF signal. Heat transfer trough solids is done with conduction so the temperature of air surrounding the housing is not in interest of observation. We can therefore simplify our model and ignore heat radiation. Natural heat convection is only present at contact surfaces of IC. The simplest method to use in this case is nodal method extended to multinodal method. Each node in model presents small piece of silicon with homogenous temperature its thermal capacity $C_T$ and thermal resistance $R_T$ in all three directions (Figure 4). This is also known as finite state model.

$$C_T = c \cdot m \left[\frac{J}{K}\right], \tag{7}$$

Where $C_T$ is thermal capacitance /J $K^{-1}$/, *c* is specific thermal capacity /J $kg^{-1}$ $K^{-1}$/ and *m* is mass /kg/.

$$R_T = \frac{l}{k \cdot S}\left[\frac{K}{W}\right], \tag{8}$$

Where $R_T$ is thermal resistance in the direction of heat transfer /K $W^{-1}$/, *l* is length in the direction of heat transfer, *k* is thermal conductivity /W $m^{-1}$ $K^{-1}$/, *S* is the area perpendicular to the direction of heat transfer /$m^2$/.

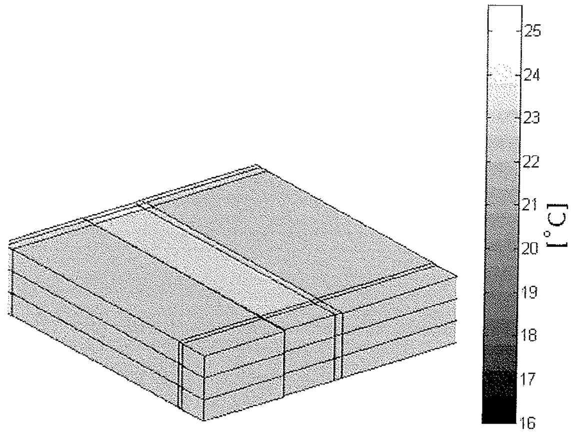

*Fig. 6: Cell temperature gradient*

The nodes that are positioned on outer edges of silicon have contact with the surrounding air. Since the heat escapes from the silicon die to air with convection, the heat transfer coefficient (*h*) of air must be taken into account. Typical values of the air heat transfer coefficient are from 10 to 100 W $m^{-2}$ $K^{-1}$. The heat transfer coefficient is greatly dependent of the direction of moving air. Planes poisoned vertically have greater heat transfer coefficient than planes positioned horizontally.

$$R_{conv} = \frac{1}{h \cdot S}, \tag{9}$$

where $R_{conv}$ is thermal resistance of air /K $W^{-1}$/, h is heat transfer coefficient /W $m^{-2}$ $K^{-1}$/ and *S* is area of contact with air /$m^2$/.

At the bottom side of the IC, where silicon is attached to the ceramic housing, thermal resistance and capacitance of the housing needs to be added to equations. Ceramic material in general has a high thermal resistance and a large thermal capacitance. We also made a model where the IC is attached directly on the PCB and covered with a plastic mass. The model of silicon die is the same as in previous case, except there is no natural heat convection directly on the surface of silicon. All heat transfer is done trough conduction. Since plastic material have a high thermal resistance (much higher than air - h ~ 0.3W $m^{-1}$ $K^{-1}$), we can neglect the thermal resistance of surrounding air.

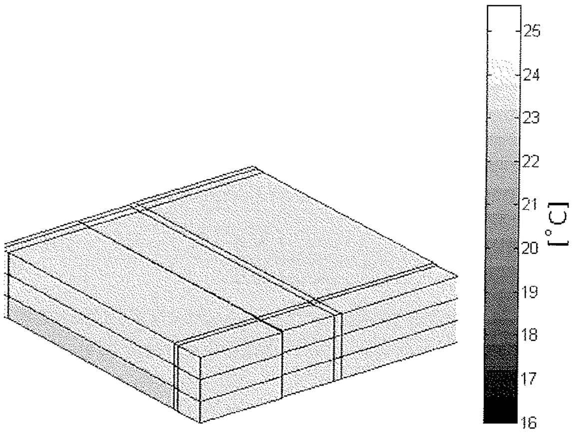

*Fig. 7: Settled cell temperature*

We expect to see that an IC in ceramic housing won't heat as fast and not as hot as an IC mounted directly on PCB, since the mass of housing and contact area with surrounding air is greater than that on IC mounted on PCB.

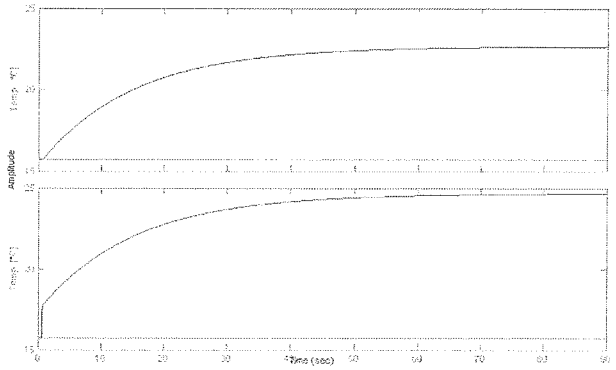

*Fig. 8: Step response plot*

Top - sensor cell response,

Bottom - heat source response (voltage limiter cell).

In the model all cells have all properties calculated, but not every property is always used. The properties are used when they are needed in relation to a position of cell. That way process for automatic calculation of cell properties is simpler. In Figure 9 properties of cell # 35 are shown. The ambient temperature for simulation was set to 15,73 °C and power dissipation from heat source was 33 mW. The heat source was turned on after 0,6 seconds. Figure 6 shows the current state of a cell's temperature after 30 seconds. The same data is shown in Figure 7 after 90 seconds. In Figure 8 the temperature of the heat source cell and temperature sensor cell are shown in relation to time.

## 5 Results

The model of an IC glued to the PCB predicts a rise of temperature for about 6°C in the area where the temperature sensor is located and with a simulated voltage limiter current drain of 10mA (Figure 10). This temperature rise is caused by the heat source located on silicon. Ambient temperature was set to 15,73 °C and the heat source to dissipate 33mW (3,3V and 10mA) of heat.

```
cell(35):
        start: [0.0014 2.9100e -004 2.5000e -004]
    dimension: [0.0012 5.2000e -005 2.5000e -004]
       center: [0.0020 3.1700e -004 3.7500e -004]
       volume: 1.5613e -011
          cap: 5.1657e -004
          res: [710.6509 1.3322 30.7929]
     resconv: [7.6923e+004 3.3306e+003
8.0061e+004 1.6012e+005]
```

*Fig. 9: The model values of cell #35.*

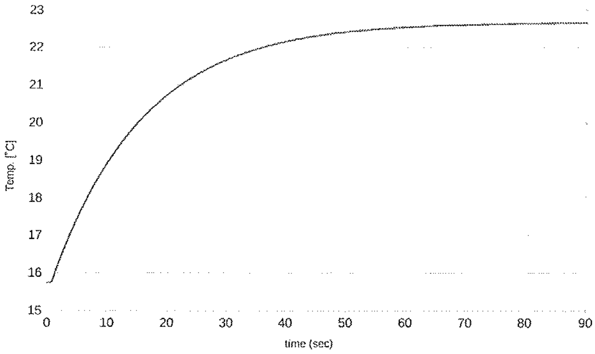

*Fig. 10: IC model step response with 33mW heat dissipation.*

From the computed results we can calculate the time constant τ, the characteristic thermal resistance and the characteristic thermal capacitance. The characteristic thermal resistance represents the combined thermal resistance of an observed cell with respect to the temperature difference to environment and the dissipated heat from the heat source (10). The characteristic thermal capacitance represents the combined thermal capacitance effect of an observed and all adjacent cells.

$$R_T = \frac{T_{observedcell} - T_{ambient}}{P_{heatsource}}, \qquad (10)$$

$$\tau = R_T \cdot C_T, \qquad (11)$$

For the model of IC glued to the PCB we can compute the characteristic values:

*R = 209,393 K/W,*

C = 0,047 J/K,

τ = 9,85 s.

We can easily measure the value of 5τ (time it takes for the temperature to rise from ambient temperature to 99.3 % of final-stable temperature) and then calculate value of τ and the characteristic thermal capacitance. The measurement can be done by forcing a known current value to the antenna pads of the transponder. The current flows to the voltage limiter thus consuming power and causing heating. As the transponder IC has an integrated temperature sensor the temperature measurements can be done by the chip itself. We used a sampling time of 200ms (Figure 11).

Measurements (*Figure 11*) gave the next results:
*R = 139,946 K/W,*
C = 0,066 J/K,
$\tau$ = 9,2 s.

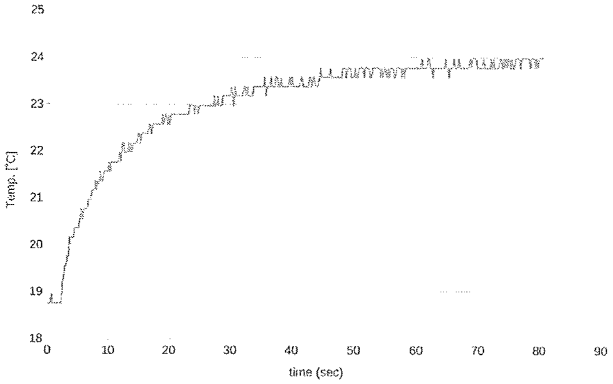

*Fig. 11: Measured step response with a constant voltage limiter current drain of 10mA (37.3mW).*

Since the model was simplified in many ways some differences between model and measurements were expected. The time constant $\tau$ has a difference of 0,65 seconds. Since the whole process of heating takes around 90 seconds, this error is minimal. A somewhat larger difference appeared in the calculation of characteristic resistance and capacitance. The modeled thermal resistance is larger than the measured and thus the temperature in an observed cell is slightly higher. A more detailed model of natural thermal convection would give a more accurate thermal resistance. The same is valid for thermal capacitance. In the model we neglected the PCB and it's mass that was not in direct contact with the IC.

The characteristic of the voltage limiter current analogue to digital converter is on Figure 12.

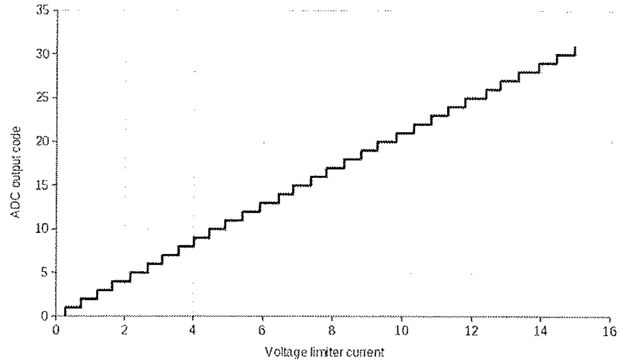

*Fig. 12: Voltage limiter current ADC measurement*

As an example we can now use the equation (5) to calculate the effect of self heating after 1 second:

$$\Delta T = P\cdot R_T \cdot \left(1-e^{-\frac{t}{R_T C_T}}\right) = \\ = 0{,}0373\cdot 139{,}946\cdot \left(1-e^{-\frac{1}{139{,}946\cdot 0{,}066}}\right) = 0{,}536K \quad (12)$$

We can see that the transponder will heat up for 0,536 °C in 1 second in a RF filed that causes a current of 10mA in the voltage limiter.

## 6 Conclusion

The algorithm for self heating compensation presented in this paper is suitable for RFID transponders with an integrated temperature sensor and also for RFID transponders with other sensors that have high temperature dependence. The characteristic temperature resistance and temperature capacitance that is required by the algorithm needs to be determined for a particular silicon die, IC package or IC mounting technology. We have presented a model for the transponder in a ceramic package and for the transponder glued directly to a PCB. We have shown that the required parameters can be determined either analytically or with measurements and that both have very similar results.

The compensation equation has an exponential dependence, therefore it is not directly suitable for the implementation in a low cost microcontroller. For such applications we propose to use a look-up table for the calculation of the amount of self heating. The equation can be simplified if the RF field is active for a predetermined amount of time before the temperature measurement is done. In this case the exponential factor becomes a constant value and the only variable remains the power (current flowing to the voltage limiter). In our case, where we have a 5-bit voltage limiter current AD converter, we require a look up table with only 31 values.

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