

# SMART SENSOR SYSTEM FOR CALIBRATION-FREE TEMPERATURE MEASUREMENT

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## Abstract

*The calibration freedom contributes to a significant reduction of the costs by production and maintenance of sensor systems. In this paper, we define the calibration-free temperature measurement and give a general survey about theoretically possible cases.*

*A novel smart sensor system for calibration-free measurement is presented, which makes use of an inverse problem approach. A new p-n junction i-u characteristic model, specially developed for the new measurement method is presented and compared to previous models. The new model is characterized by a significant improvement of the temperature measurement accuracy and a relative simple mathematical structure, which permits a faster temperature calculation making use of fewer measurement data. Achieving these essential properties, the new model fulfills all indispensable requirements towards an industrially applicable calibration-free temperature measurement.*

## 1. Introduction

The knowledge about the real behavior of a sensor contributes considerably to the definition of its optimal operation parameters and consequently to a significant improvement of the measurement accuracy. For this reason, several calibration processes are generally required all through the service lifetime of a sensor specimen. During calibration, the sensor output must be documented at definite well known input values.

Right after production, a sensor calibration process is required in order to examine the specimen scattering due to the fluctuations throughout the technological manufacturing process. During the later following sensor maintenance processes, several calibrations are carried out in order to investigate or to verify the influence of the aging processes on the sensor operation parameters.

Especially for temperature sensors, and in order to guarantee a well known and constant temperature during calibration, the sensor must remain in the calibration equipment until the thermal equilibrium is reached between the sensor itself, the liquid bath and the temperature regulation process. This process requires an expensive equipment and takes generally a long time. For several industrial applications, the additional calibration costs are supplementary costs that should be preferably avoided.

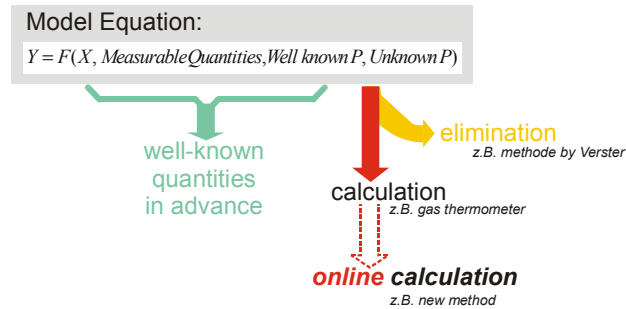
## 2. Calibration-Free Measurement

A calibration-free measurement is defined as a method that guarantees a certain accuracy level without the necessity of a calibration process. The quantity being measured must be only calculable without needing the predetermination on any unknown parameters.

The possibilities of a calibration-free temperature measurement are not widely spread. Generally, only the well known primary thermometers like gas thermometers, are regarded as calibration-free. In this case, the unknown parameters are specific for each gas, so that if they are previously calculated for the considered gas, the thermometers using this gas could be operated without any calibrations. These temperature measurement methods reach a very high accuracy level and are therefore used in the definition of the international temperature scale (ITS 90). However, these methods could not be employed for industrial applications, because of the necessary complex laboratory equipment [2]. In industrial applications, a lower accuracy is generally accepted by a reasonable experimental effort.

In fact, with respect to the definition of a calibration-free measurement, methods based on the p-n junction i-u characteristic like the method by Verster [3] or Goloub [4], satisfy the conditions of a calibration-free measurement. In this case all unknown model parameter are eliminated from the model equation, so

that temperature can be calculated without needing calibration (s. section 3).

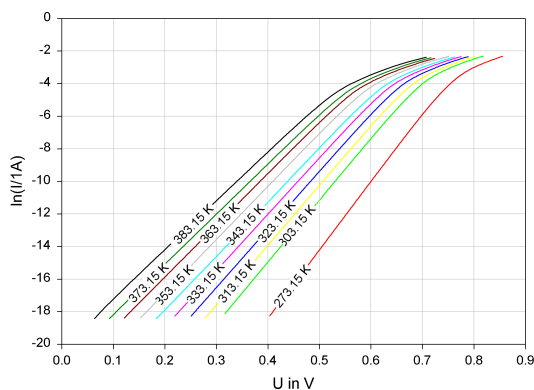


**Figure 1.** Possibilities of a calibration-free temperature measurement

In the new method we have proposed [10], the model unknown parameters are calculated *online*. In this case, no more hard model limitations for the elimination of parameters are necessary. For this kind of methods, the right choice of an i-u characteristic model should fulfill other requirements, which will be handled with details in section 5.

### 3. Calibration-Free Measurement Based on the P-N Junction I-U Characteristic

The sensitivity of p-n junction towards temperature allows it to be used as a temperature sensor. The favorable properties of transistors and diodes for this application are due to the highly predictable and time independent way in which the p-n junction voltage is related to temperature (s. figure 2).



**Figure 2.** I-U characteristic at different temperatures

In the method by Verster [3] a simplified Shockley model is used to describe the p-n junction i-u characteristic:

$$U(I, T) = \frac{kT}{e} \cdot \ln\left(\frac{I}{I_S(T)}\right)$$

with  $k$ : the Boltzmann's constant,  $e$  the electron charge,  $T$ : temperature,  $I_S$ : saturation current.

In this method, temperature is calculated from the difference between i-u values of two points without needing to predetermine the saturation current  $I_S$ . Therefore, this method is principally calibration-free.

$$\Delta U = U_2 - U_1 = \frac{kT}{e} \ln\left(\frac{I_2}{I_1}\right)$$

Goloub [4] has extended the model in (1) with one term in order to describe the resistance effects (3). In this case temperature is calculated from the difference between the voltage differences at three i-u points (4). Because temperature can be calculated without needing the predetermination of any other unknown parameters (like  $I_S$  and  $R$ ), the method by Goloub is also calibration-free.

$$U(I, T) = \frac{kT}{e} \cdot \ln\left(\frac{I}{I_S(T)}\right) + R \cdot I$$

with  $R$ : resistance

$$\Delta(\Delta U) = (U_1 - U_2) - (U_2 - U_3) = \frac{k \cdot T}{e} \cdot \ln\left(\frac{I_1 \cdot I_3}{I_2^2}\right)$$

Applying both of the methods for several transistors and diodes, we detected a typical accuracy of 2-6 K (s. Table 2). This limited accuracy level is generally not acceptable for industrial applications.

Device	Verster	Goloub
BC547	2.94 K	2.29 K
2N2905	2.22 K	2.03 K
BC237	4.73 K	4.2 K
BD437	5.53 K	3.44 K

**Table 1.** The best reached measurement accuracy with different devices at 343.15 K

In order to correct the remaining systematical temperature error [5], the model was consequently multiplied by an empirical factor  $m$  (5). This parameter shall compensate the remaining failures between the measured and the calculated voltages:

$$U_{corrected} = m \cdot U_{model}$$

The parameter  $m$  needs to be determined through at least a one-point calibration. Therefore this model extension couldn't be employed in order to increase the measurement accuracy of the calibration-free measurement.

#### 4. Accuracy Enhancement by an Inverse Problem Consideration

An accuracy enhancement can be reached through the use of a model taking into account the secondary semiconductor effects affecting the i-u characteristic [6]. In order to realize a *calibration-free* measurement, temperature will be calculated through a process of *parameter extraction* in an *inverse problem* consideration [7]. In inverse problems, measurements are used to infer values of parameters or functions on which the measurements themselves depend. In this case, the voltage through the p-n junction is measured at different current values in order to infer the temperature, which is actually calculated.

Through the deployment of nonlinear optimization, the unknown model parameters are no longer necessarily eliminated from the model equation, like e. g. in the case of the method by Verster. The temperature must not be necessarily explicitly calculable.

All unknown parameters including temperature are simultaneously extracted from the used i-u characteristic model and measurement data (s. figure 3). Therefore, no more hard model complexity limitations are requisite in this new consideration of calibration-free measurement. The used i-u characteristic model has only to satisfy some requirements in order to improve the stability and the accuracy of the temperature extraction procedure.

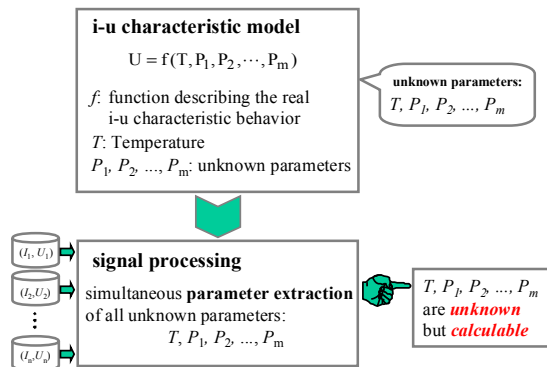


Figure 3. Principle of the new calibration-free temperature measurement

#### 5. New Requirements in the Modeling of the I-U Characteristic

A measured p-n junction i-u characteristic at different temperatures (s. figure 2) shows mainly a voltage shift and a gradient change with rising temperature. If we especially focus on the nonlinearity in the i-u characteristic (s. figure 4), we can see important

behavior changes at different temperatures. The first observation we make is that the nonlinearity is unequally distributed above the whole i-u characteristic and grow up with rising temperature. At low temperatures (273.15 K) the nonlinearity is mainly observed at high currents. At middle and high temperatures (>273.15 K) the nonlinearity is observed at low and high currents.

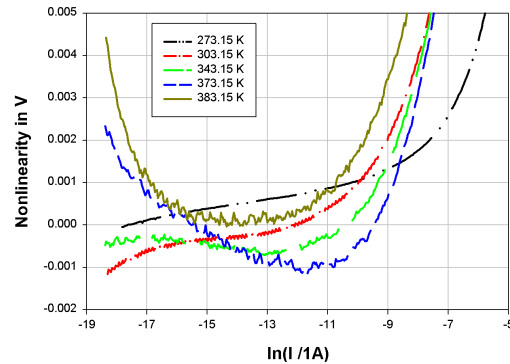


Figure 4. Nonlinearity in the p-n junction i-u characteristic

The nonlinearity in the p-n junction i-u characteristic is caused by the occurring semiconductor secondary effects explained below. The behavior changes in the nonlinearity curve (s. curve shapes in figure 4) correspond to the temperature dependence of the semiconductor secondary effect dominating in the corresponding current sector.

##### Semiconductor Secondary Effects

- *Generation/Recombination effects in the depletion layer at low voltages*

At low voltages, the depletion layer width is not negligible as was assumed in the derivation of the Shockley model. Therefore generation/recombination processes take place in the depletion layer and produce an additional current component to the Shockley model. This current is observed as an increase of the current at low voltages.

- *High-level injection effects at middle and high currents*

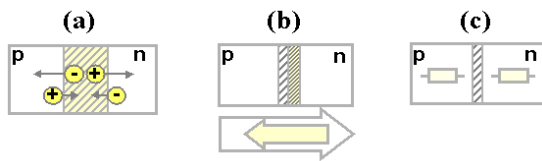
At middle and high current densities, the injected minority carrier in the base becomes comparable with the majority carrier concentration and cause a supplementary space charge in the base region. Therefore, the assumption of a negligible base drift current component in the derivation of the Shockley model is no longer admissible. The drift component of the minority carrier becomes important and leads to decrease of the current slope. At high-level injection, the total current is approximately proportional to  $\exp(eU/2kT)$ .

- Resistance effects at high currents

At high currents, the bulk resistance becomes considerable and causes a diminution of the voltage through the p-n junction. The junction voltage  $U_j$  is only one component of the total applied voltage  $U$ :

$$U = U_j + (R_p + R_n) \cdot I$$

The only consideration of the resistance effects is not sufficient for an important accuracy enhancement, even if a data range restriction is carried out (s. Table 2). This is due to the fact, that high-level injection effects are dominant even at middle currents before the resistance effects come up.



**Figure 5.** Semiconductor secondary effects in the i-u characteristic: (a) Generation/Recombination in the depletion layer, (b) High-level injection effects and (c) Resistance effects

The consideration of the semiconductor secondary effects in the i-u characteristic model is of a great importance for the reachable measurement accuracy. All unconsidered secondary semiconductor effects cause a systematical model error and represent an additional source of inaccuracy to the unavoidable measurement errors. Otherwise, in order to reduce the risk of ambiguity during the parameter extraction procedure, the characteristic model used should have a simple mathematical structure and involve only the absolute necessary number of parameter.

The i-u characteristic modeling should meet a compromise between the modeling accuracy and the modeling complexity. The temperature calculation is carried out online. Increasing the number of the unknown model parameter increases the number of measurements necessitated. A complex model structure demands more computing power and leads to a slowing down of the temperature measurement procedure. Therefore, not all the characteristic sectors at low, middle and high currents are necessarily included in the used characteristic models. We can equally consider only a restricted characteristic sector, which is suitable for a selected characteristic model. Principally, the model should give a good description of the characteristic behavior in the considered data sector.

## 6. A New I-U Characteristic Model

In previous papers, we investigated different physically and mathematically based models [8]. The best results were so far obtained with the reduced Gummel-Poon model (RGP).

### Reduced Gummel-Poon Model

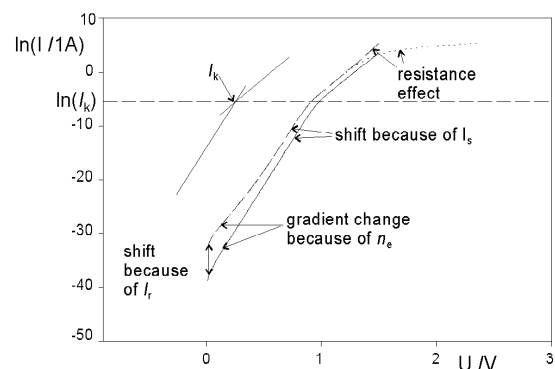
The Gummel-Poon model performs a good description of the behavior of bipolar transistors and is therefore implemented in most of the circuit simulators (PSPICE, ..). This model was reduced to the requirements of the temperature measurement [9]. The resulting model (6) includes six unknown parameters. The influence of these parameters on the i-u characteristic are explained in figure 6.

$$I = I_r \cdot \left( \exp\left(\frac{eU_{pn}}{n_e kT}\right) - 1 \right) + \frac{I_s}{\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{I_s}{I_k} \cdot \left( \exp\left(\frac{eU_{pn}}{kT}\right) - 1 \right)}} \left( \exp\left(\frac{eU_{pn}}{kT}\right) - 1 \right)$$

$$U = U_{pn} + R \cdot I$$

With:  $I_s$ : saturation current,  $I_k$ : knee current of the high-level injection,  $I_r$  and  $n_e$  saturation current and emission factor of the generation/recombination effects.

Many tests made using the RGP model show difficulties during the parameter extraction process. The obtained results are highly dependent on the chosen start values for the optimization process. The optimization process converges frequently to false or senseless results.



**Figure 6.** Parameters of the reduced Gummel-Poon model (RGP)

Using the RGP leads to a so called *ill-posed* inverse problem. The ill-posedness is explained with the fact, that several parameter combinations lead to the same value of the criterion function. This leads to an

ambiguity that prevents the convergence of the optimization procedure to the right optimum. The ill-posedness is primarily related with the mathematical structure of model and is supported by a great number of unknown model parameters.

The consideration of the sensitivity coefficients towards the model parameters helps to find out the reasons of the ill-posedness and to estimate the amount of information available in the measured data for the estimation procedure. The sensitivity coefficients of the characteristic model to changes in the parameters being estimated should be ideally uncorrelated in order to fulfill the parameter identifiability conditions. They should have also high values [7] indicating that the measurement data provides enough information about the unknown parameters.

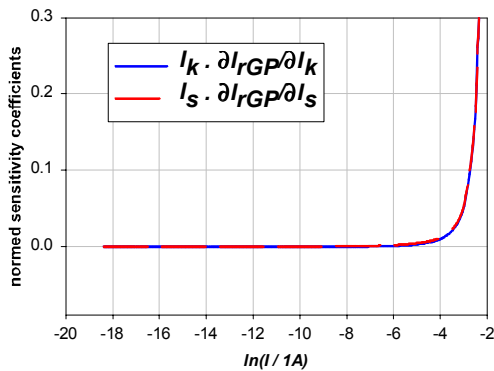


Figure 7. Sensitivity analysis: RGP (part 1)

The figures 7 and 8 present the meaningful results of the sensitivity analysis carried out for the RGP. In figure 7 we can see a linear dependence of the normalized sensitivity coefficients towards the parameters  $I_k$  and  $I_s$ . This is the reason, why the problem is ill-posed. In figure 8 we can see the small values of the normalized sensitivity coefficients towards the parameters  $I_r$  and  $n_e$ . The whole data range don't provide enough information about both parameters.

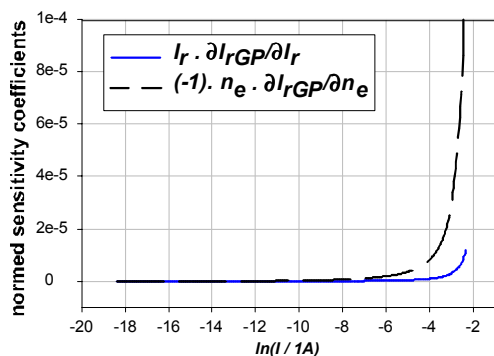


Figure 8. Sensitivity analysis: RGP(part 2)

### A New Model

In this paper we present a new model characterized by a new behavioral modeling of the high-level injection effects (7). We propose to describe the high-level injection effects with a mathematical function having two unknown parameters, which should increase the adaptability of the model to the real characteristic behavior at middle and high currents.

$$U = \frac{kT}{e} \cdot \ln\left(\frac{I}{I_S(T)}\right) + R \cdot I - a_1(T) \cdot \frac{1 - \left(\frac{I}{1A}\right)}{1 + \left(\frac{I}{1A}\right)^{a_2(T)}}$$

With  $I_s$ : saturation current,  $R$ : resistance,  $a_1$  and  $a_2$ : parameters for the characteristic nonlinearity at middle and high currents

The model parameter are just as the parameters of the RGP dependent on temperature. Because the parameter extraction is carried out online, the calculated parameters belong to the corresponding temperature during the i-u measurements. The influence of the separate model parameters on the i-u characteristic are presented in figure 9.

The new model don't consider the generation/recombination effects and should be therefore used only at middle and high currents. Ignoring the generation/effects, helps to reduce the otherwise necessary effort in order to measure very low currents/voltages with a good precision.

The model equation has a simple mathematical structure involving only five unknown parameters. It is intended to reach a better stability of the parameter extraction procedure.

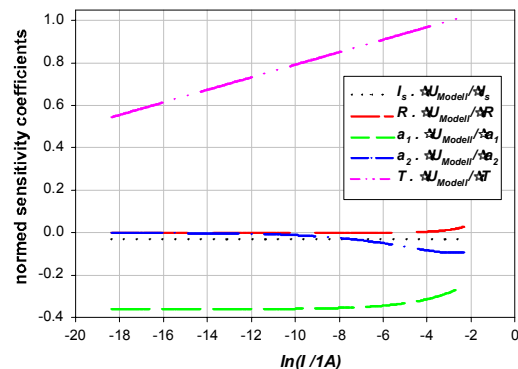


Figure 9. Sensitivity analysis: New model

The sensitivity coefficients for the new model were compared with those from the RGP. All normalized sensitivity coefficients are in this case uncorrelated, so that the identifiability condition is fulfilled. Furthermore the smallest sensitivity coefficient is towards  $R$  and is 100 times higher than the sensitivity coefficient of the RGP with regard to the parameter

$I_r$ . We notice also, that the new model has furthermore a desirable high sensitivity toward temperature.

### 7. Experimental results

Figure 10 presents the experimental results comparatively with different models together with the considered optimal data sector for each model. The experiments were carried out with a usual audio-frequency transistor at 343.15 K. At this temperature, all semiconductor secondary effects are well observed.

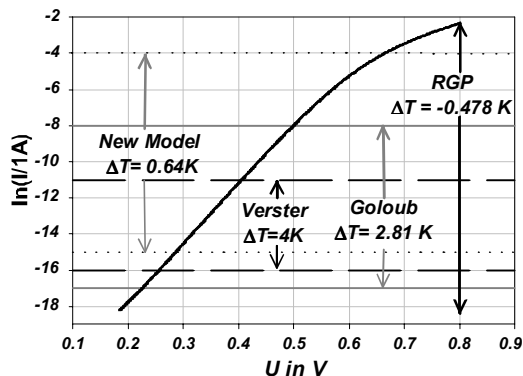


Figure 10. Results with different models

The new model permits to realize an important accuracy improvement relative to the methods by Verster and by Goloub. The reached temperature accuracy is comparable with the accuracy reached using the RGP model.

In figure 11 we can see the residuals of both models. The RGP was not able to model the i-u characteristic accurately. It shows a very high systematical error over all the current range. The results obtained with the new model were more accurate in the chosen characteristic sector in the ln(I)-Interval [-15, -4].

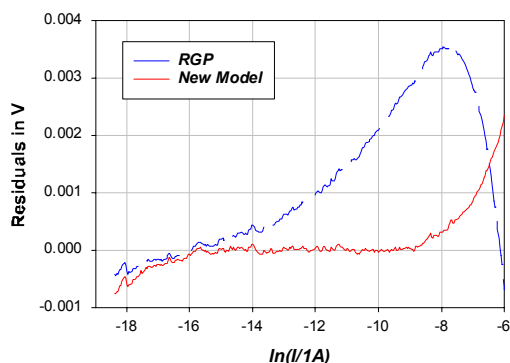


Figure 11. Residuals with both of the models

Table 3 shows the main features of compared models and the differences between them. The new model

was able to reach an accuracy of the same level as the RGP by a reduced computing time and an emphasized stability of the parameter extraction procedure.

The description of the high-level injection effects with the presented behavioral model including two unknown parameters helps to reach a better adaptability of the model to the measurement data.

Model	Parameter	Stability	Computing Time (It.)	Accuracy (K)
Reduced Gummel-Poon-Model	6	-	10-1000	- 0.47
New Model	5	+++	5-300	0.64

Table 2. The main features of the compared models

Using the new i-u characteristic model, the new calibration-free temperature measurement method reached an accuracy of about 0.5 K for several tested bipolar transistors and at different temperatures (s. figure 12). This represents an important accuracy enhancement relative to previous calibration-free methods based on p-n junctions. This accuracy level fulfills the requirements in many engineering applications.

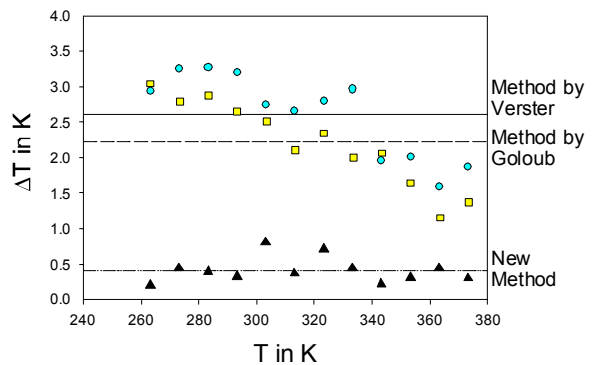
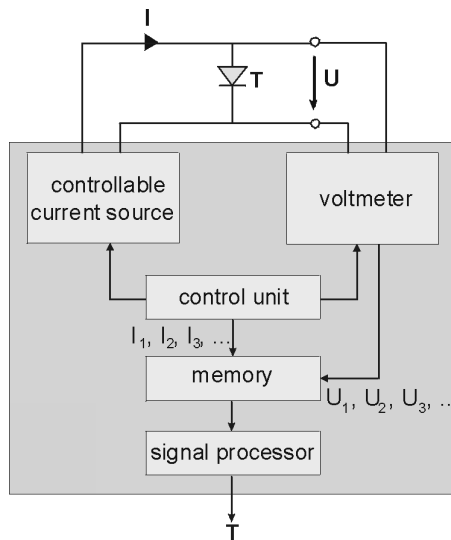


Figure 12. New calibration-free method [10]

### 8. Structure of the Smart System

Figure 13 shows the structure of the proposed smart sensor system for calibration-free temperature measurement. The p-n junction is biased at different currents. Thereby measured voltages are subjected to a parameter extraction procedure, which calculates temperature and all unknown model parameters online.



**Figure 13.** Smart sensor system for the calibration-free temperature measurement based on p-n junctions.

This concept can be adapted according to the application in which the calibration-free sensor will be used. For example, if the total measurement time is critical, the i-u-points measurement could be paralleled through use of more than one transistor of the same type. In other cases with a slow process dynamic it will be possible to carry out the i-u point measurement in a sliding time window.

## 9. Conclusions

The p-n junction temperature measurement can realize an applicable calibration-free temperature measurement for industrial applications. Previously used methods reached a reduced accuracy level due to the deployment of simple models, not able to describe the real i-u characteristic behavior.

Through the use of an inverse problem consideration, more accurate models could be used in order to realize an accuracy enhancement without affecting the calibration-free behavior. For this reason, no more hard model complexity limitations are requisite in this case. The model should be suitable for the parameter extraction procedure and meet a compromise between the modeling accuracy and the modeling complexity.

In this paper we present a new model involving a new behavioral modeling of high-level injection effects. The new model provides a simple mathematical structure and includes only five unknown parameters. Among other things, two parameters are dedicated for the high-level injection effects in order to allow a flexible adaptation of the

model to the measurement data at middle and high currents.

Because previous investigations with different models have shown, that the main improvement were so far reached by the RGP model, we compared the new model to this one.

The experimental results show, that the realized accuracy level is comparable with that of RGP model. Thereby, the necessary amount of data and the computing time were reduced. Furthermore, the stability of the temperature calculation procedure was decisively emphasized.

The presented new model provide important improvements on the field of the calibration-free temperature measurement for industrial application and helps to avoid the calibration costs which are considered as a matter of course up to now.

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