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Calibration-free temperature measurement by *p-n* junctions with varied current

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Abstract. Applying a varied current excitation to *p-n* junctions, calibration-free temperature measurement can be performed with improved accuracy, independent from manufacturing variance. For the realization of this method, an adequate modelling of the *p-n* junction I-U characteristic, taking into account semiconductor secondary effects and parameter extraction procedures, is needed. A behavioural model of this procedure is proposed. Experimental results show an improvement of accuracy relative to previous calibration-free methods. The temperature calculation procedure, which in this case is carried out within a parameter extraction procedure, converges very fast.

Key words: temperature measurement, diode temperature sensors, silicon transistor thermometers, *p-n* junction, modelling.

1. INTRODUCTION

In order to achieve a better quality, availability and reliability of measurements, several approaches can be developed for improving sensory information [1]. Multisensor systems use the redundancy and diversity of the information available in sensor signals and fuse them together for higher quality or reliability.

Sensory information can also be improved by using only one sensor element, but using varied excitations and adequate signal processing. These so-called varied input sensor systems [2] provide in general significant improvements of sensory information allowing a better consideration and separation of effects, self test, self validation, etc.

In the case of *p-n* junction thermometers, the use of several different currents allows an evaluation of the output signal not only as a function of the temperature, like in classical *p-n* junction thermometers, but also as a function of the current as a steering quantity [3].

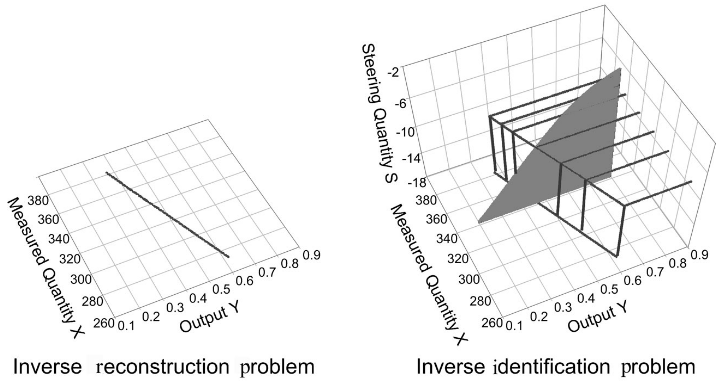

Fig. 1. Introducing the current as a steering quantity.

In fact, a p-n junction can be used for temperature measurement in different ways. For example, temperature measurement can be carried out at one suitable current value. In this case an accurate modelling of the characteristic $U(T)$ is necessary within an inverse reconstruction problem (Fig. 1).

The method we present in this paper calculates temperature from the modelling of the p-n junction I-U characteristic obtained by using the current as a steering quantity. In this case, the dependence of the output voltage on the current (steering quantity) is modelled. The temperature calculation is carried out by solving the corresponding inverse identification problem. All model parameters are calculated for every temperature measurement, so that changes of parameters due to manufacturing variances or aging don't influence accuracy of the temperature. We obtain thereby a sensor, which does not need calibration by any reference temperature.

2. CALIBRATION-FREE TEMPERATURE MEASUREMENT

If we consider scientific literature, we will find the term calibration-free used in relation to primary thermometers. Generally, only the well-known primary thermometers like gas, acoustic, noise and total radiation thermometers are regarded as calibration-free [4]. They generally have very high accuracy (Table 1) and are therefore used for the determination of the international temperature scale. These thermometers are meant for laboratories, not for industrial applications [5]. In industrial applications, a considerably lower accuracy is accepted.

The term calibration-free is itself not standardized. If we try to define a practical calibration-free method for the measurement of a certain quantity, we will come to the following definition:

Definition. Calibration-free are measurement methods, which allow to determine a certain quantity within certain accuracy limits without necessity of predetermination of any unknown parameters.

Table 1. Examples of calibration-free temperature measurement methods [5]

Measurement method	Characteristic equation	Range, K	Error, mK
Gas thermometer	Ideal gas equation	2.4–700	0.3–15
Acoustic thermometer	Ideal gas equation (speed of sound)	2.0–20	0.3–1
Noise thermometer	Nyquist-theorem (noise in an electric resistance)	3.0–1100	0.3–100
Spectral pyrometer	Planck's law of radiation	700–2500	10–2000
Total radiation pyrometer	Stefan–Boltzmann radiation law	220–420	0.5–2

Thus calibration-free temperature measurement guarantees a certain accuracy level without the necessity of a calibration process neither per batch nor per unit. This means that users can apply this method with a certain accuracy without the necessity of laboratory measurements at definite temperatures. Regarding this definition, even methods with restricted accuracy may be calibration-free. Only the quantity being measured must be calculable without the need of the pre-determination of any unknown parameters.

With respect to this definition, we conclude that temperature measurement methods based on the p-n junction I-U characteristic (Fig. 2) like the method by Verster or Goloub, satisfy the conditions of calibration-free measurements.

In the method developed by Verster [6], a simplified Shockley model is used to describe the p-n junction I-U characteristic:

$$U(I,T) = \frac{kT}{e}\ln\left(\frac{I}{I_s(T)}\right), \tag{1}$$

where k is the Boltzmann constant, e is the electron charge, T is temperature and I_s is the saturation current.

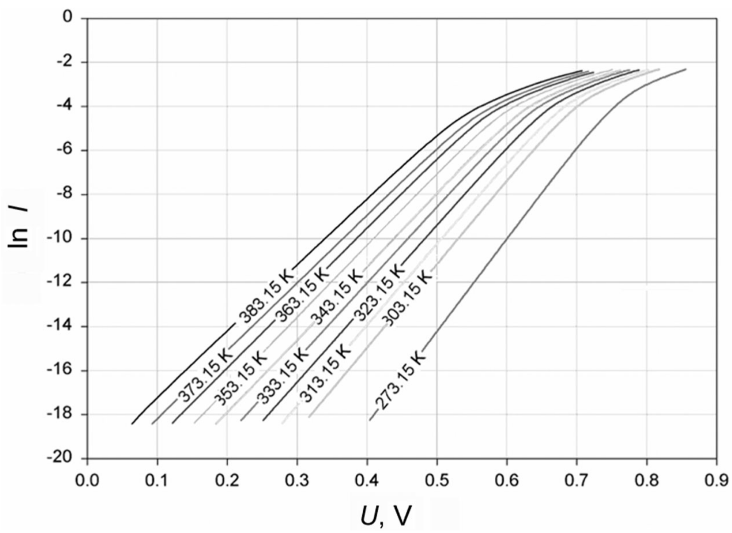

Fig. 2. I-U characteristics at different temperatures.

In this method, the temperature is calculated from the difference between two I-U points without the need to predetermine the saturation current I_s and thus the method is principally calibration-free:

$$\Delta U = U_2 - U_1 = \frac{kT}{e} \ln\left(\frac{I_2}{I_1}\right). \tag{2}$$

Goloub [7] has extended the model (1) with one term in order to describe the resistance effects:

$$U(I,T) = \frac{kT}{e} \ln\left(\frac{I}{I_s(T)}\right) + RI, \tag{3}$$

where R is resistance.

In this case, the temperature is calculated from the difference between the voltage differences at three I-U points $\{(I_0 + \Delta I_0, U_1),\ (I_0, U_2),\ (I_0 + \Delta I_0, U_3)\}$. Because temperature can be calculated without the need to predetermine the other unknown parameters I_s and R, the method by Goloub is also calibration-free.

$$\Delta(\Delta U) = (U_1 - U_2) - (U_2 - U_3) = \frac{kT}{e} \ln\left(\frac{(I_0 + \Delta I_0)(I_0 - \Delta I_0)}{I_0^2}\right). \tag{4}$$

Applying both of the methods to several transistors and diodes, we found that a typical accuracy lies between 2 and 6 K (Table 2). This limited accuracy is generally not acceptable for industrial applications.

In order to correct the remaining systematical temperature error of these methods, the model was consequently multiplied by an empirical factor m, which shall compensate the remaining differences between the measured and calculated voltages:

$$U_{corr} = mU_{model}. \tag{5}$$

The parameter m needs to be determined with at least one-point calibration. Therefore this model can not be employed in order to increase the measurement accuracy of calibration-free measurement.

Table 2. The best measurement accuracy (in K) with different devices at 343.15 K

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

3. ACCURACY ENHANCEMENT THROUGH SOLVING AN INVERSE PROBLEM

An accuracy enhancement can be reached by using a model, which takes into account secondary semiconductor effects affecting the I-U characteristic [3]. In order to realize calibration-free measurement, temperature is calculated through a process of parameter extraction in an inverse problem [8]. 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 non-linear optimization, the unknown model parameters are no longer necessarily to be eliminated from the model equation, like in the case of the method by Verster. Even the temperature must not be explicitly calculable.

All unknown parameters, including temperature, are simultaneously extracted from the used I-U characteristic model and measurement data (Fig. 3). The used I-U characteristic model has to satisfy some requirements in order to improve the stability and the accuracy of the temperature extraction procedure.

4. REQUIREMENTS TO THE MODELLING OF THE I-U CHARACTERISTIC

A measured *p-n* junction I-U characteristic at different temperatures (Fig. 2) shows mainly a voltage shift and a gradient change with rising temperature. If we especially focus on the non-linearities in the I-U characteristic,

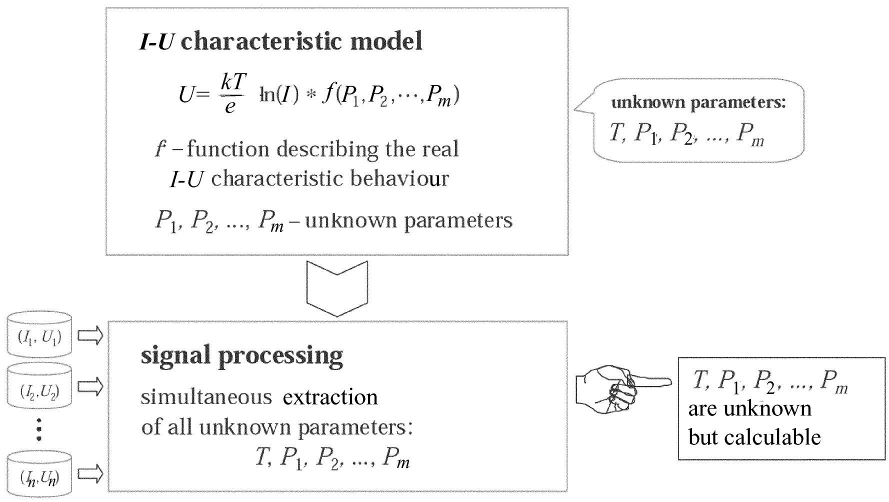

Fig. 3. Principle of the calibration-free temperature measurement.

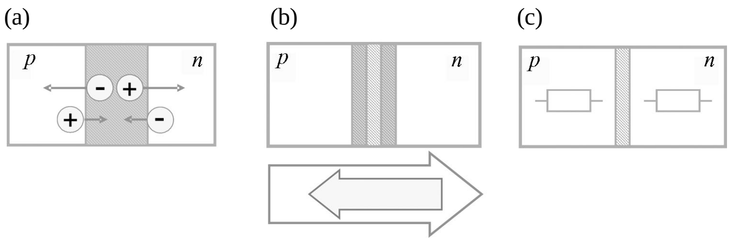

Fig. 4. Secondary semiconductor effects in the I-U characteristic: (a) generation/recombination in the depletion layer; (b) high-level injection effects; (c) resistance effects.

we find important behaviour changes at different temperatures. The first observation we make is that the non-linearities are unequally distributed and grow with rising temperature. At low temperature (e.g. 273.15 K) the non-linearities are mainly observed at high currents. At middle and high temperatures (>273.15 K) the non-linearities are observed at low and high currents. The non-linearities in the p-n junction I-U characteristic are caused by different secondary effects of the semiconductor (Fig. 4) explained below.

4.1. Secondary semiconductor effects

4.1.1. Generation/recombination effects in the depletion layer by low voltages

By low voltages, the depletion layer width is not negligible as was assumed by 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.

4.1.2. High-level injection effects by middle and high currents

By middle and high current densities, the injected minority carrier in the base becomes comparable with the majority carrier concentration and causes 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 a decrease of the current slope. At high-level injection, the total current is approximately proportional to $\exp(eU/2kT)$.

4.1.3. Resistance effects by high currents

By 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:

$$U = U_j + (R_p + R_n)I. \tag{6}$$

Consideration of the resistance effects alone is not sufficient for a considerable enhancement of the accuracy, even if a data range restriction is carried out (Table 2). This is due to the fact that high-level injection effects are dominant even by middle currents before the resistance effects come up.

The consideration of the secondary semiconductor effects in the I-U model is of great importance for the reachable measurement accuracy. All unconsidered secondary semiconductor effects cause a systematic error in the model 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 absolutely necessary parameters.

The modelling of the I-U characteristic should meet a compromise between the modelling accuracy and complexity. The temperature calculation is carried out on-line. Increasing the number of the unknown model parameters increases the number of needed measurements. A complex model structure demands more computing power and leads to slowing down of the temperature measurement procedure. Therefore, not all the characteristic sectors by low, middle and high currents are necessarily included in the used characteristic models. We can even 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 behaviour in the considered data sector.

5. MODEL OF THE I-U CHARACTERISTIC

In previous papers, we have investigated models on different physical and mathematical basis [9]. The best results so far were obtained with the reduced Gummel–Poon model (RGP).

5.1. The reduced Gummel–Poon model

The Gummel–Poon model gives a good description of the behaviour of bipolar transistors and is therefore implemented in most of the circuit simulators (e.g. PSPICE). This model was fitted to the requirements of the temperature measurement [10]. The resulting model includes six unknown parameters:

$$I = I_{\mathrm{r}}\left(\exp\left(\frac{eU_{pn}}{n_{\mathrm{e}}kT}\right)-1\right)+\frac{I_{\mathrm{s}}}{\frac{1}{2}+\sqrt{\frac{1}{4}+\frac{I_{\mathrm{s}}}{I_{\mathrm{k}}}\left(\exp\left(\frac{eU_{pn}}{kT}\right)-1\right)}}\left(\exp\left(\frac{eU_{pn}}{kT}\right)-1\right), \quad (7)$$

$$U = U_{pn} + RI. \quad (8)$$

Here I_{k} is the knee current of the high-level injection, I_{r} and n_{e} are the saturation current and emission factor of the generation/recombination effects, respectively.

The influence of these parameters on the I-U characteristic is explained in Fig. 5.

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

The parameter extraction procedure in the case of the RGP model leads to the solution of a so-called ill-posed inverse problem. It means 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 the model and a great number of unknown parameters.

Analysis of the sensitivity of I to the model parameters helps to find out the reasons of the ill-posedness of the inverse problem 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 solve the inverse problem. They should have high values [8], indicating that the measurement data provides enough information about the unknown parameters.

Figures 6 and 7 present the results of the sensitivity analysis, carried out for the RGP model. Figure 7 shows weak dependence of the normalized sensitivity coefficients on the parameters I_r and n_e. The whole data range does not provide enough information about these parameters. Figure 6 shows a linear dependence of the normalized sensitivity coefficients on the parameters I_k and I_s. This is the actual reason, why the problem is ill-posed. This demonstrates also that it will be difficult to extract the parameters even if the generation/recombination effects corresponding to the first term in Eq. (7) are not considered [11].

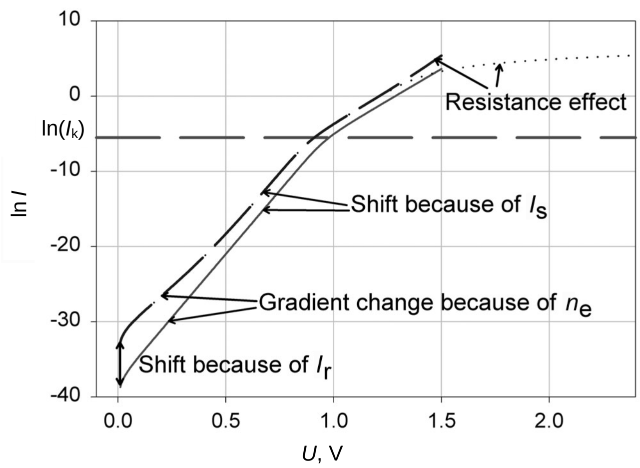

Fig. 5. Parameters of the reduced Gummel–Poon model.

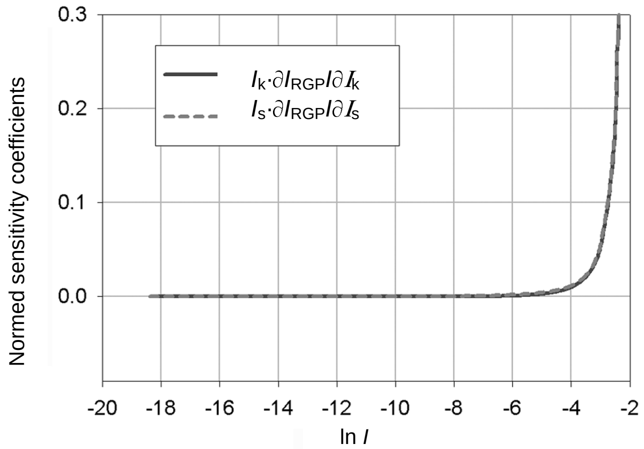

Fig. 6. Sensitivity analysis of the RGP model (Part 1).

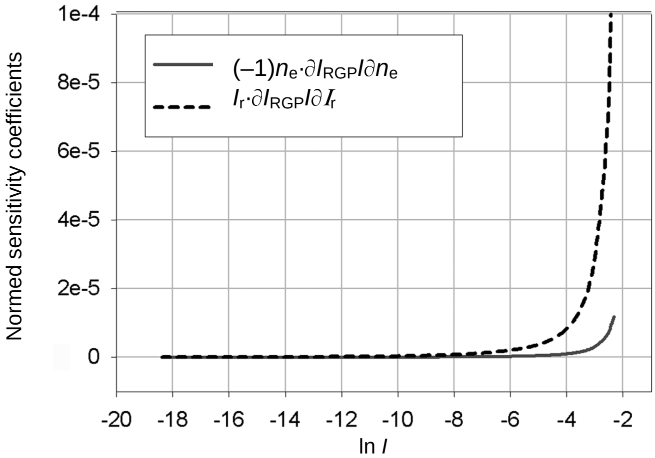

Fig. 7. Sensitivity analysis of the RGP model (Part 2).

5.2. A behavioural model

We developed a model to describe the high-level injection effects. 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 behaviour by middle and high currents:

$$U = \frac{kT}{e}\ln\left(\frac{I}{I_s(T)}\right) - a_1(T)\frac{1-\left(\frac{I}{1A}\right)}{1+\left(\frac{I}{1A}\right)^{a_2(T)}}, \tag{9}$$

where a_1 and a_2 are parameters of the high-level injection.

The model parameters depend on the temperature. Because the parameter extraction is carried out on-line, 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 is presented in Fig. 8. The parameter a_1 influences mainly the gradient of the characteristic at high currents and a_2 has an influence on the gradient in the transition zone between the middle and high current region.

The new model does not consider generation/recombination and resistance effects. It should be therefore used only by middle currents. It has a simple mathematical structure and contains only four unknown parameters. It is intended to have a better stability of the parameter extraction procedure. The results of the sensitivity analysis in Fig. 9 show no ill-posedness and confirm this hypothesis.

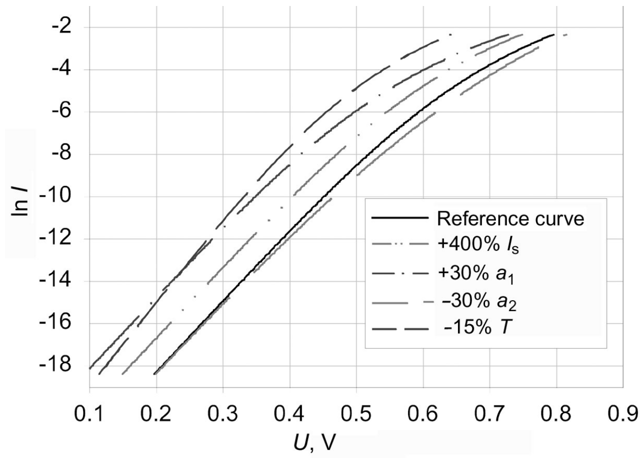

Fig. 8. Influence of the parameters of the model.

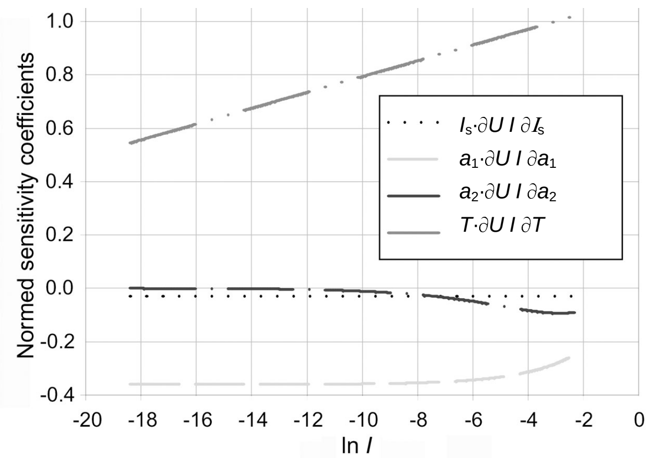

Fig. 9. Sensitivity analysis of the behavioural model.

The sensitivity coefficients for the model were compared with those of the RGP model. All normalized sensitivity coefficients are in this case uncorrelated, so that the determinability condition is fulfilled. Furthermore, the smallest sensitivity coefficient is related to R and it is 100 times higher than the sensitivity coefficient of the RGP model with regard to the parameter I_r. We notice also, that the new model has a desirable high sensitivity to temperature.

6. EXPERIMENTAL RESULTS

Figure 10 presents experimental results with different models. Because every model has its own validity sector, the results are shown together with the used optimal characteristic sector for parameter extraction. The experiments were carried out with a usual audio-frequency transistor, which is not technologically optimized for temperature measurement. At 343.15 K, all secondary effects of semiconductors are well observed.

The new model has better accuracy relative to the methods by Verster and Goloub. The reached temperature accuracy is comparable with the accuracy of the RGP model.

In Fig. 11 we show the residuals of both models in the optimal data sector for the new model. The RGP model was not able to describe accurately the I-U characteristic. It shows a high systematic error over all the current range. The results obtained with the new model are more accurate in the sector (–15, –4).

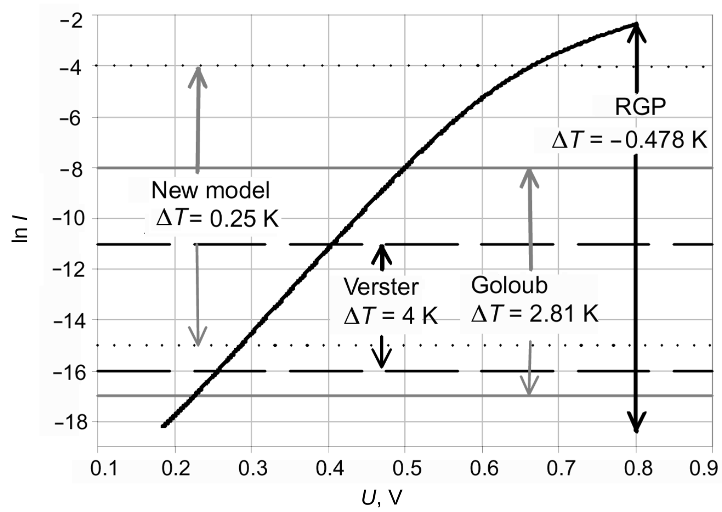

Fig. 10. Results with different models.

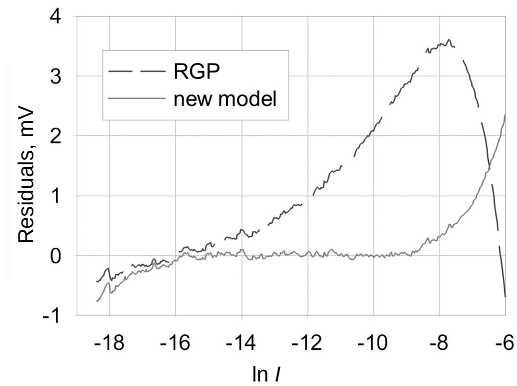

Fig. 11. Residuals for both models.

6.1. Comparison with previous models

Table 3 shows the main features of compared models. The new model was able to reach an accuracy of the same level as the RGP model by a reduced computing time and better stability of the parameter extraction procedure.

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

6.2. Model validity sector

Experimental investigation of the optimal model validity sector shows its dependence on the temperature (Fig. 12). That is due not only to the temperature dependence of the semiconductor secondary effects, but also to self-heating effects. At high temperatures, the dissipated thermal energy can not flow through the housing and the I-U characteristic shows a behaviour, which can not be described by the model. Even the resistance effects, which are not considered in the model, grow strongly with temperature and lead to a limitation of the highest allowed current.

As Fig. 12 shows, the model validity sector has a systematic dependence on the temperature and can be predicted for the optimal choice of measurement currents. The lowest limit can be predicted by determining the lower limit of the

Table 3. Main characteristics of the models

Model	Parameter	Secondary effects	Stability	Computing time, it.	Accuracy, K
Reduced Gummel–Poon model	6	Generation/recombination (2 P) Resistance effect (1 P) High-level injection effect (1 P)	–	10–1000	–0.47
New model	4	High-level injection effect (2 P)	+++	5–50	0.25

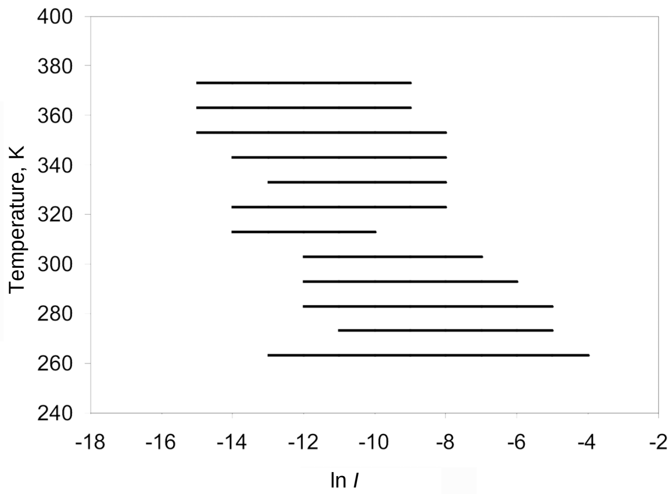

Fig. 12. Model validity sector fort he bipolar transistor BC 547 B.

characteristic linear sector of the characteristic. Different mathematical algorithms can be used thereby. Several investigations lead to following rules for the choice of the highest limit of the validity sector:

- Current limit for self-heating effects.
- A limit of the highest bend value of the I-U characteristic, which corresponds also to strong nonlinearities.
- The proportion of the highest allowed current to the lowest allowed current is approximately 10^3.

7. CONCLUSIONS

The *p-n* junction temperature measurement, using a varied current excitation, is a useful calibration-free measurement technology for industrial applications. Previously used methods reached a restricted accuracy level due to the application of simple models, not able to describe the real behaviour of the I-U characteristic. Using varied excitation and introducing the current as a steering quantity, more accurate models can be used. The models should be suitable for the parameter extraction procedure and meet a compromise between accuracy and complexity.

In this paper we presented a behavioural modelling of high-level injection effects. The improvement of the Shockley model with this behavioural mathematical model provides a simple structure and includes only four 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 by middle and high currents during the fitting procedure.

Experimental results show that the realized accuracy is better than with the method of Goloub and it is comparable with that of the RGP model. Thereby, the necessary amount of data and the computing time were reduced. The stability of the temperature calculation procedure was considerably improved.

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Temperatuuri kalibreerimisvaba mõõtmine muudetava vooluga *p-n*-siirete abil

Olfa Kanoun

Siiret läbiva voolu muutmisega saab parandada temperatuuri mõõtmise täpsust ja suurendada selle sõltumatust toote parameetrite kõikumisest. Otsustav tähtsus on adekvaatsel modelleerimisel, mis eeldab pooljuhtides toimuvate sekundaarsete protsesside mõistmist ja arvestamist. Artiklis on esitatud ja kontrollitud temperatuuri mõõtmise mudel ning selle alusel loodud parameetrite ekstraheerimise protseduur. Tulemuste rakendamine võimaldab läbi viia kalibreerimisvabu temperatuurimõõtmisi.