SIMULATION OF ELECTRO-THERMAL EFFECTS IN HBTS BASED ON SI/SIGE AND ALGAAS/GAAS

Roberto Marani* and Anna Gina Perri**

* Consiglio Nazionale delle Ricerche, Istituto di Studi sui Sistemi Intelligenti per l'Automazione (ISSIA), Bari, Italy
** Electronic Devices Laboratory, Department of Electrical and Information Engineering, Polytechnic University of Bari, via E. Orabona 4, Bari – Italy

ABSTRACT

The aim of this paper is to simulate electro-thermal effects in Heterojunction Bipolar Transistors (HBTs) based on Si/SiGe and on AlGaAs/GaAs, by means of an analytical electro-thermal model, already proposed by us, able to calculate the temperature and current distribution for any integrated device, whose structure can be represented as an arbitrary number of superimposed layers with a 2-D embedded thermal source.

KEYWORDS: *Heterojunction Bipolar Transistors (HBTs), Electrical and Thermal Effects, Self Heating, Electro-Thermal Modeling, SiGe, GaAs.*

I. INTRODUCTION

One of the main differences between Si based VLSI and RF electronics is the choice of semiconductor materials and transistor types. While Si is the only semiconductor used in VLSI, a wide range of alternative materials and devices are present in RF electronics. The general evolution of these electronic devices emphasizes the growing importance of the thermal problem during the design process, where analytical models for the temperature evaluation are useful tools to calculate the optimal set of geometrical parameters that minimize the device thermal phenomena.

Heterojunction bipolar transistors (HBTs) have attained enough maturity as RF power devices due to their intrinsic high-power density, linearity and efficiency [1]. Moreover HBTs are actually used in very high speed applications. They are capable of microwave performance up to 100 GHz. In order to push the frequency performance up to its limit, the operating point of the HBT lies at relatively high current density, and this current density increases with used semiconductor technologies. Therefore it is important to study the electro-thermal performance, because the self heating appears, mainly in the base-collector depletion region, where both current and field are high.

The analytical electro-thermal modelling of electronic devices is such a difficult problem to deal with that the analytical models that have been proposed until now are either over-simplified or rather inefficient from a computational point of view. The reason for that lies in the complex structure of an integrated device and in the non-linear thermal properties of the materials. However, only a physical-based analytical model can give the proper physical insight in order to understand the connections between a number of geometrical and technological parameters and the device electro-thermal performance. Unfortunately, an analytical model suffers the unavoidable simplifying hypothesis by which the numerical calculation can be carried out. In spite of that, the analytical model for the temperature evaluation is a useful tool during the design process to calculate the optimal set of geometrical parameters that minimise the thermal phenomena in an integrated device. Furthermore, in case of multifinger devices or thermal coupling between contiguous devices, the inaccuracy introduced by the ipothesis of uniform channel temperature can be relevant.

In this paper we present a simulation study of electro-thermal effects in HBTs based on Si/SiGe and on AlGaAs/GaAs in order to compare them, obtained by an analytical electro-thermal model, already proposed by us [2-5]. In particular the problem of the self-heating of transistors fabricated on GaAs substrates is investigated since GaAs has a poor thermal conductivity. The electro-thermal feedback is considered evaluating the output current as a function of the local temperature in the active region.
The calculation times for the proposed simulations are quantified in a minute for the main part of the algorithm, and in less than 0.01s for the graphic routines.
The presentation of the paper is organized as follows. In Section II we briefly review our electro-thermal model, based on the solution of the 3-D steady-state heat equation with temperature-dependent thermal conductivity for a single integrated device or a given configuration of two or more devices. Then, in Section III two application examples of Si/SiGe and AlGaAs/GaAs HBTs are given, together with the discussion of relative results. The conclusions are described in Section IV.

II. A BRIEF REVIEW OF OUR ELECTRO-THERMAL MODEL

An exhaustive description of our model is in [2-5]. In this Section we briefly describe our model, able to calculate the temperature and current distribution for any integrated device, whose structure, shown in Fig. 1, can be represented as an arbitrary number of superimposed *m* layers with a 2-D embedded thermal source, so as to include the effect of the package.

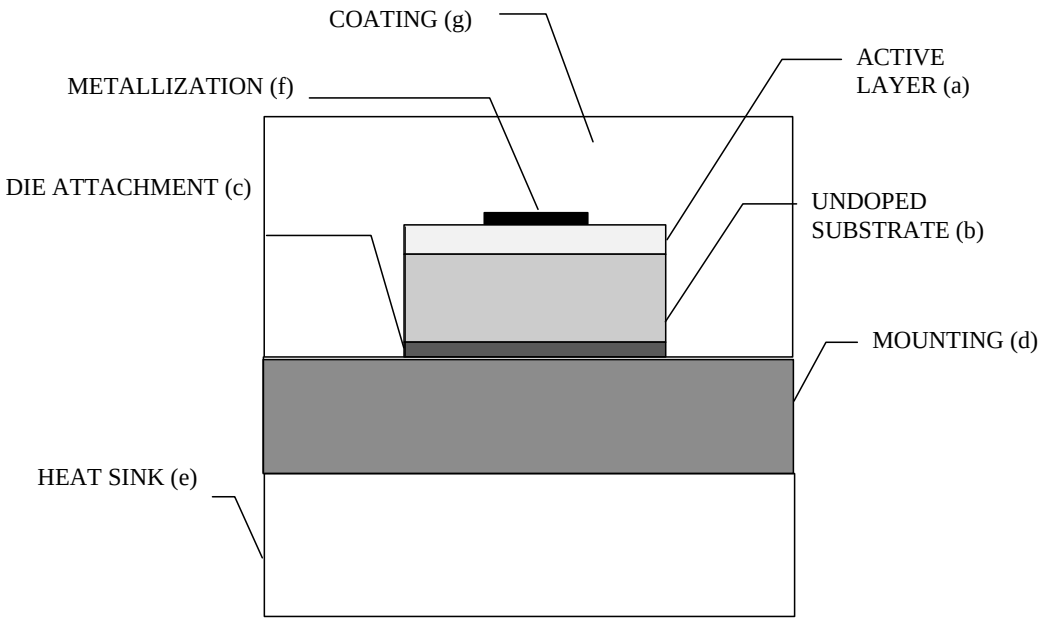

Figure 1. Typical electron device including coating, die attachment, mounting and heat sink (*from [2]*).

For a complete model, the contribution of the mounting and die-attachment layers (see layers (c) and (d) in Fig. 1 to the temperature rise and thermal resistance has been taken into account. The top path for the heat flux has also been included, e.g. mould compound (see layer (g)), where natural convection between the package top surface and the still air is the mechanism of heat loss.
The aims of our model have been:

- to solve analytically the non-linear 3-D steady-state heat equation
- to take into account the dependence on temperature of the thermal conductivity
- to take into account the interaction between two neighbouring devices
- to implement the coupling between the electrical and thermal behaviour of the device to determine the actual channel temperature
- to take into account the presence of the package
- to develop a full general model useful to simulate any multilayer electronic and optoelectronic device

- fastness and accuracy
- to implement it on a Personal Computer.

In particular, for the structure of Fig. 1, in order to determine the temperature distribution, the following non-linear steady-state heat equation has to be solved [1]:

$$\overline{\nabla}\cdot\left[k_{TH}(T)\overline{\nabla}T(x,y,z)\right]=-Q_V(x,y,z) \quad (1)$$

where $T(x,y,z)$ is the temperature field, k_{TH} is the temperature-dependent thermal conductivity and $Q_V(x,y,z)$ is the dissipated power density.

The basic assumptions of the model have been:

1. the device and package structures can be represented as a set of superimposed homogeneous layers;
2. the thickness of each layer is constant;
3. the extension of the layers in the x and y directions is infinite;
4. the contact thermal resistance is neglected;
5. the thermal source is modeled as a 2-D geometrical shape $Q_S(x,y)$, located at the interface between two contiguous layers, say the k-th and the $(k+1)$-th;
6. the device self-heating is due to the Joule heating and other contributions are neglected.

Eq. 1 can be solved considering the following expression:

$$\overline{\nabla}\cdot\left[k_{TH}(T)\overline{\nabla}T(x,y,z)\right]=0 \quad (2)$$

and accounting for the heat source in the Boundary Conditions (BCs).

We have applied the Kirchhoff transformation to each layer in the following form:

$$\Delta\theta(x,y,z)=\frac{1}{k_0}\int_{T_0}^{T(x,y,z)-T_0}k(\tau)d\tau \quad (3)$$

so as to linearise Eq. (2):

$$\nabla^2\theta(x,y,z)=\frac{-Q(x,y,z)}{k_0} \quad (4)$$

where $\Delta\theta\,(x,y,z) = \theta\,(x,y,z)-T_0$, $\theta\,(x,y,z)$ is the transformed temperature field, T_0 is the reference temperature and k_0 is the constant thermal conductivity, evaluated at a specific reference temperature T_0. In this way the solution of the transformed problem with the unknown $\Delta\theta$ is equivalent to the solution of the original non-linear problem with the unknown ΔT, when the inverse transform is carried out.

Furthermore, to simplify the mathematical steps, the 2-D Fourier transform has been applied to Eqn. (4), leading to the one-dimensional ordinary differential equation for each i-th layer.

Fig. 2 shows the flow-chart of the main mathematical steps involved in our method [2-5].

The electro-thermal feedback is considered by evaluating the output current as a function of the local temperature in the active region and iterating the solution of (4) using the actual value of $Q(\theta)$.

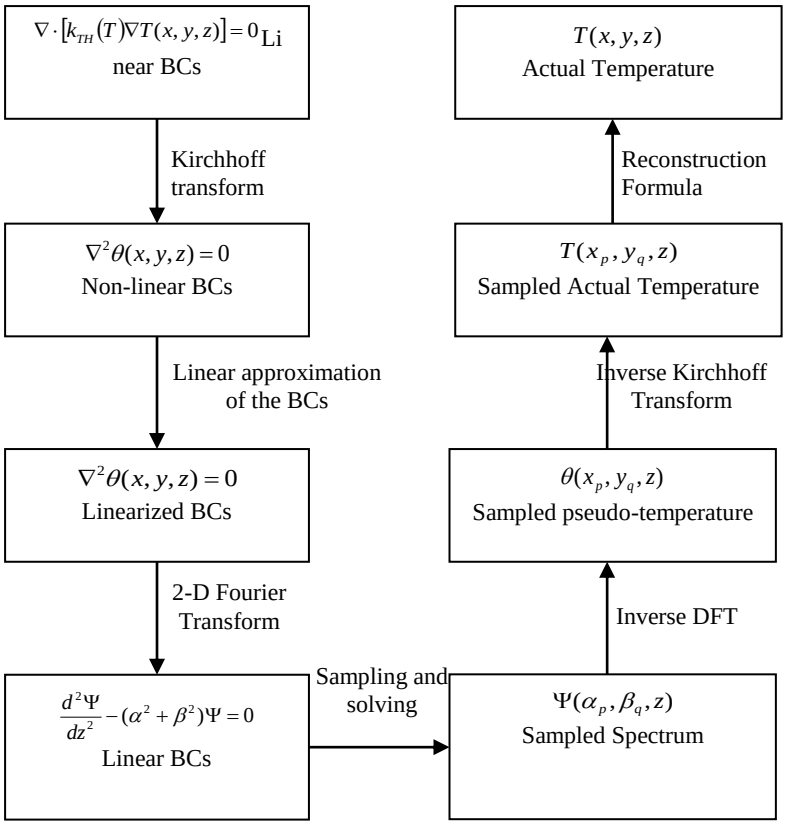

Figure 2. Flow-chart of the mathematical steps involved in the proposed method (*from [3]*).

2.a Electro-thermal model applied to HBT

In order to solve Eq. (4), we are referred to a typical HBT structure [1], in which we have used the name AlGaAs/GaAs HBT for a device with GaAs as the base material and AlGaAs as the emitter. This is also the same for SiGe based transistors.

In particular we have represented the device as a surface without any thickness, where X and Y are the dimensions of the periodic cell, in which we have divided the device.

The overall heat source, which is located in the depletion layer at the collector, has been divided into a set of elementary point sources located in the middle of each elementary X×Y periodic cell.

The first step is to solve the electro-thermal problem, assuming the heat generation and the current as mutually dependent for each single elementary device which is related to a single elementary heat source; finally the resulting thermal field of the whole structure is obtained by the superposition of all the elementary fields.

The solution of (4), for a point thermal source can be expressed as [6]:

$$\Delta\theta(x,y,z) = \frac{Q(x_{0i}, y_{0i}, z_{0i})}{2\pi\pi_0\sqrt{(x - x_{0i})^2 + (y - y_{0i})^2 + (z - z_{0i})^2}} \tag{5}$$

where x_{0i}, y_{0i} and z_{0i} are the coordinates of the *i-th* heat point source, *x,y,z* is the generic position in which the temperature increase $\Delta\theta(x,y,z)$ above the reference is evaluated and $Q(x_{0i},y_{0i},z_{0i})$ is the dissipated power of the *i-th* elementary heat source.

The electro-thermal feedback can be implemented for each *X×Y* subsection considering that *Q* can be assumed as the temperature-dependent electrical power $P(\theta_i(x_{0i},y_{0i},z_{0i}))$ of the *i-th* elementary device centred in x_{0i}, y_{0i}, z_{0i} and, thus, corresponding to the *i-th* heat source centred in the same point.

The electrical power of the *i-th* elementary device is:

$$P(x_{0i},y_{0i},z_{0i}) = P(\theta_i) = I_B(\theta_i)\, V_{BE} + I_C(\theta_i)\, V_{CE} \quad (6)$$

where V_{BE}, the voltage drop between base and emitter, is temperature-independent, I_B and I_C are the base and collector currents, respectively, of the elementary cell centred in x_{0i},y_{0i},z_{0i} having temperature θ_i, and V_{CE}, the voltage drop between collector and emitter, is temperature-independent.
The dependence of the current-voltage equation, based on physical parameters, on the temperature was widely studied in the past. The parameters that have been taken into account for their thermal dependence are the electron mobility, saturation velocity, permittivity, energy band gap, threshold voltage and built-in voltage. The reader can refer to for the empirical expression of the foregoing parameters [6].

III. ELECTRO-THERMAL MODEL IMPLEMENTATION FOR HBTS BASED ON SI/SIGE AND ALGAAS/GAAS: SIMULATION RESULTS AND DISCUSSION

We have firstly extracted, by a MATLAB code written by us only for academic non-commercial purpose, the Si/SiGe and AlGaAs/GaAs HBTs I-V curves versus bias using the Gummel-Poon model, whose parameters are those of SPICE simulator [7-8].

3.a HBT based on Si/SiGe

We have considered a HBT structure having X= 0.25 μm and Y= 30 μm for the emitter and X= 50 μm and Y= 300 μm for the collector.
In Fig. 3 we have reported the I_C-V_{CE} characteristics at room temperature T = 300 K, for a base current varying from 1 mA to 3 mA.

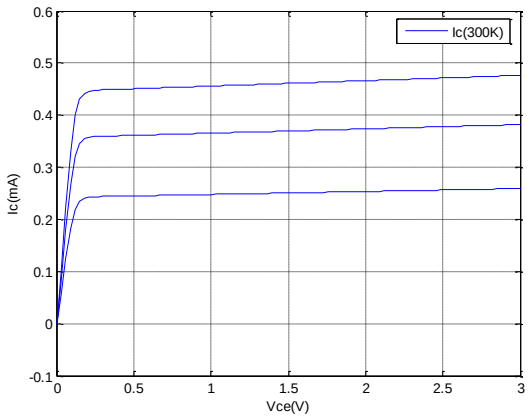

Figure 3. Simulated I_C-V_{CE} characteristics at T=300 K for a base current varying from 1 mA to 3 mA.

The obtained heat generated at the base-collector junction, by Eq. (6), has been equal to 0.0702 W.
Now it has been possible determined the temperature increase due to self heating effect.
Fig. 4 shows the simulated average temperature T_m at the BE junction versus time, in the time range $10^{-8} \div 10^{-3}$ s.

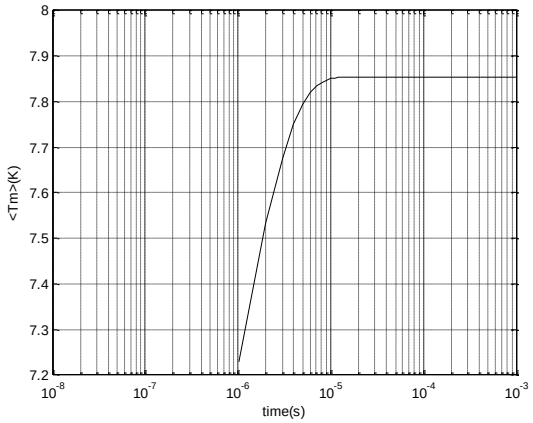

Figure 4. Simulated average temperature T_m at BE junction versus time for Si/SiGe HBT.

In the interval $10^{-6} \div 10^{-5}$ s, it clearly appears that the temperature increases more rapidly, tending to a saturation value equal to 7.85 K.
The electro-thermal feedback is shown in Fig. 5, in which we have reported the simulated output I-V characteristics both at 300 K (blue lines) and at 307.85 K (red lines). This figure shows the well-known degradation effect on I-V curves due to temperature increase.

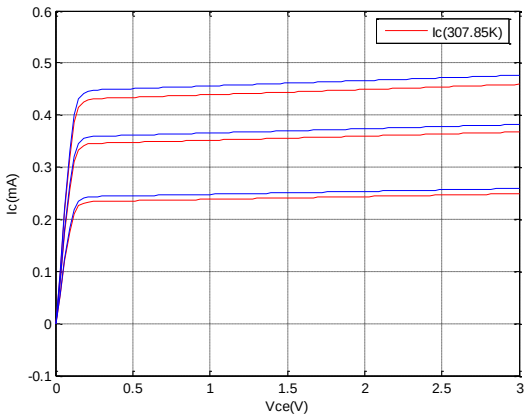

Figure 5. Simulated I-V characteristics both at 300 K (blue lines) and at 307.85 K (red lines).

We have also considered a Si/SiGe HBT, whose structure is the same of the previous one, except for the dimension X of the emitter, equal, in this case, to 2.5 μm.
Fig. 6 shows the simulated average temperature T_m at the base-emitter (BE) junction versus time. For this device the saturation value of T_m is 4.55 K and this result allows to say that the self heating is in inverse proportion to the emitter area.
Moreover, as shown in Fig. 7, in which we have reported the simulated I-V curves both at 300 K (blue lines) and at 304.55 K (red lines), the device feels more the effects of temperature increase at high base currents, with a resulting decrease of device efficiency.

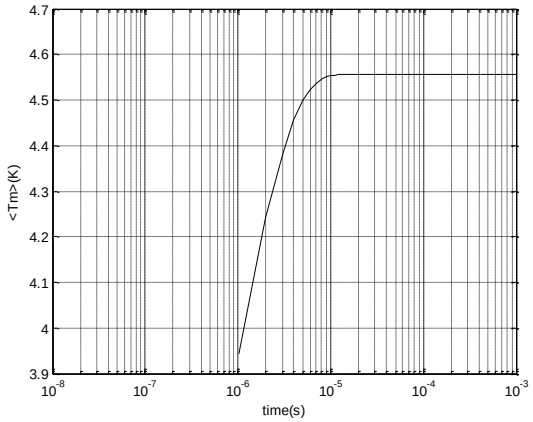

Figure 6. Simulated average temperature T_m at BE junction versus time (X = 2.5 μm for the emitter).

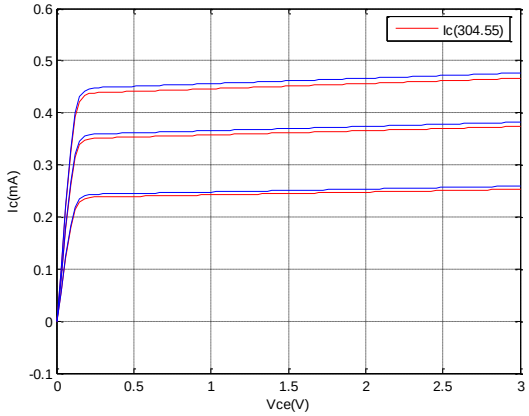

Figure 7. Simulated I-V characteristics both at 300 K (blue lines) and at 304.55 K (red lines).

3.b HBT based on AlGaAs/GaAs

We have repeated the same simulations, considering now an AlGaAs/GaAs HBT, having X= 0.25 μm and Y= 30 μm for the emitter and X= 50 μm and Y= 300 μm for the collector.
In Fig. 8 we have reported the I_C-V_{CE} characteristics at room temperature T = 300 K, for a base current varying from 1 mA to 3 mA. The obtained heat generated at the base-collector junction, calculated by Eq. (6), has been, for this device, equal to 0.0508 W.

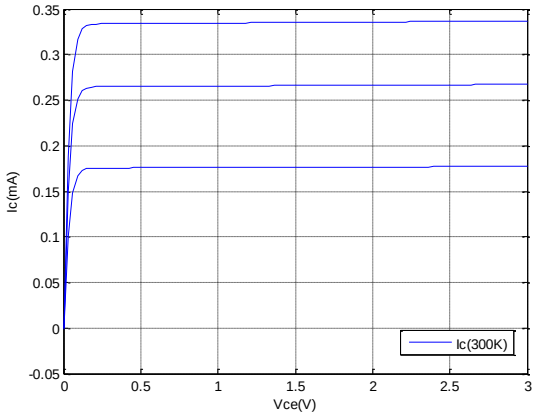

Figure 8. Simulated I_C-V_{CE} characteristics at T=300 K for a HBT based on AlGaAs/GaAs.

The temperature T_m versus time is shown in Fig. 9, in which it clearly appears that T_m tends to a saturation value equal to 8.4 K.

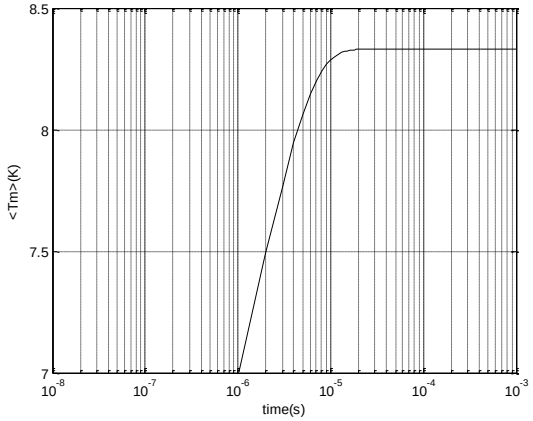

Figure 9. T_m at BE junction versus time for AlGaAs/GaAs HBT.

The electro-thermal feedback is shown in Fig. 10, in which we have reported the simulated output I-V characteristics both at 300 K (blue lines) and at 308.4 K (red lines).

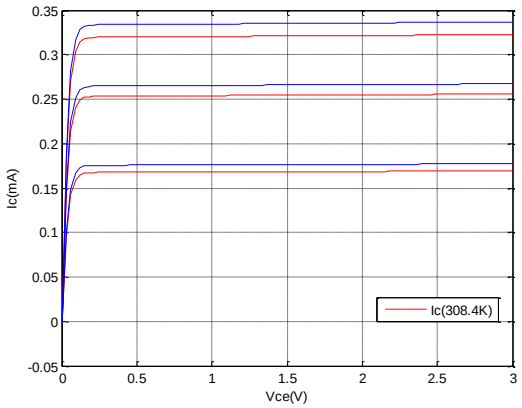

Figure 10. Simulated I-V characteristics both at 300 K (blue lines) and at 308.4 K (red lines).

Also for this device, we have modified the emitter dimension (X = 2.5 μm), obtaining that the saturation value of T_m becomes 5.4 K, as shown in Fig. 11.

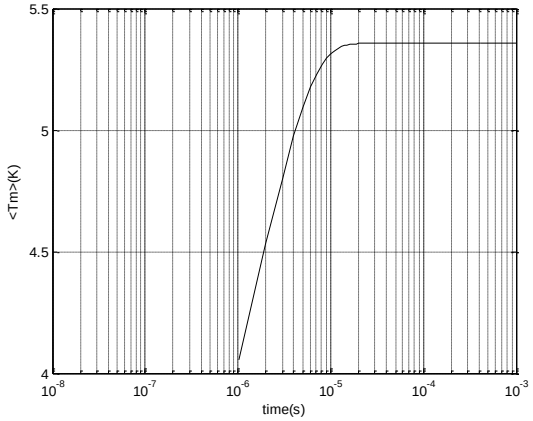

Figure 11. T_m at BE junction versus time for AlGaAs/GaAs HBT (X = 2.5 μm for the emitter).

In Fig. 12 we have reported the temperature T_m versus time for two HBTs having the same dimensions, but different substrates (Si, red line and GaAs, blue line).

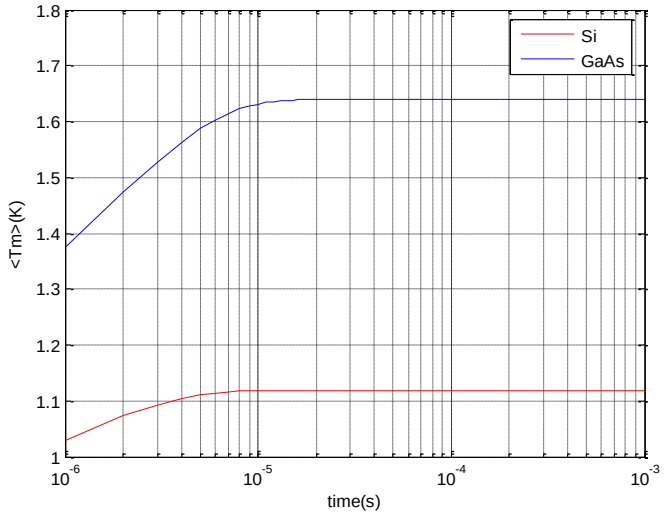

Figure 12. T_m versus time for two HBTs having different substrates (Si, red line and GaAs, blue line).

It is easy to observe that Si substrate allows to have smaller values of T_m, with a transitory time shorter.
Considering the Early effect, the breakdown voltage values in Si/SiGe HBT are relatively low due to their smaller band-gap of the collector material. This makes it more difficult to use them for high-power applications, where AlGaAs/GaAs HBTs are preferred. However, this problem can be reduced by the DHBT approach since designing the collector–base junction as a heterojunction allows to use a wide band-gap material as the collector material leading to high-breakdown values [9-11].
The calculation time for the proposed examples has been quantified in a minute for the main part of the algorithm and in less than 0.01 s for the graphic routines.
All simulations were carried out in ADS 2014 on an Asus K55VD computer which uses an Intel Core i-7 3630QM processor running at 2.4 GHz, with 4 GB of RAM.

IV. CONCLUSIONS

In this paper we have presented a simulation study of electro-thermal effect on performance of HBTs based on Si/SiGe and AlGaAs/GaAs, by means of an analytical electro-thermal model, already proposed by us, able to calculate the temperature and current distribution for any integrated device, whose structure can be represented as an arbitrary number of superimposed layers with a 2-D embedded thermal source. The electro-thermal feedback has been considered by evaluating the output current as a function of the local temperature in the active region.
Moreover it has been possible determined the temperature increase due to self heating effect, in order to evaluate the average temperature T_m at the BE junction. In this way we have demonstrated that Si substrate allows to have smaller values of T_m, with a transitory time shorter.

REFERENCES

[1] Perri A.G.; (2011) Dispositivi Elettronici Avanzati, Progedit Editor, Bari, Italy; ISBN: 978-88-6194-081-9.
[2] Marani R., Perri A.G.; (2010) Thermal and Electrical Layout Optimisation of Multilayer Structure Solid-State Devices based on the 2-D Fourier series, *Proceedings of MELECON 2010*, Valletta, Malta.
[3] Marani R., Perri A.G.; (2010) Analytical Electrothermal Modelling of Multilayer Structure Electronic Devices, *The Open Electrical & Electronic Engineering Journal*, Vol. 4, pp.32-39.
[4] Perri A.G.; (2011) Modelling and Simulations in Electronic and Optoelectronic Engineering, Research Signpost, Kerata, India, ISBN: 978-81-308-0450-7.

[5] Marani R., Perri A.G.; (2011) Electrothermal Design of Multilayer Structure Integrated Devices through the Solution to the non-linear 3-D Heat Flow Equation, in *Modelling and Simulations in Electronic and Optoelectronic Engineering*, Research Signpost, Kerata, India, ISBN 978-81-308-0450-7, pp. 1-26.
[6] Anholt R.; (1995) Electrical and thermal characterization of MESFETs, HEMTs and HBTs, Artech House Inc., ISBN:0-89006-749-X, 1995.
[7] http:\\hbt.ucsd.edu.
[8] http:www.ece.usb.edu/Faculty/rodwell/Classes/ECE594A/
[9] Esame O., Gurbuz Y., Tekin I., Bozkurt A.; (2004) Performance Comparison of State-of-the-Art Heterojunction Bipolar Devices (HBT) based on AlGaAs/GaAs, Si/SiGe and InGaAs/InP, *Microelectronics Journal*, vol. 35, pp. 901-908.
[10] Gao J.; (2015) Heterojunction Bipolar Transistors for circuit design: microwave modeling and parameter extraction, John Wiley & Sons Singapore Pte. Ltd, ISBN 978-1-118-9215.
[11] England T., Michael L., Curry M., Carr S., Carroll M., (2016) Flexible Low-power SiGe HBT Amplifier Circuits for Fast Single-shot Spin Readout, *Proceedings of American Physical Society Meeting 2016*, Baltimore, Maryland, USA.

AUTHORS

Roberto Marani received the Master of Science degree (*cum laude*) in Electronic Engineering in 2008 from Polytechnic University of Bari, where he received his Ph.D. degree in Electronic Engineering in 2012.
He worked in the Electronic Device Laboratory of Bari Polytechnic for the design, realization and testing of nanometrical electronic systems, quantum devices and FET on carbon nanotube. Moreover Dr. Marani worked in the field of design, modelling and experimental characterization of devices and systems for biomedical applications.
In December 2008 he received a research grant by Polytechnic University of Bari for his research activity. From February 2011 to October 2011 he went to Madrid, Spain, joining the Nanophotonics Group at Universidad Autónoma de Madrid.
He has been involved in the development of novel numerical models to study the physical effects that occur in the interaction of electromagnetic waves with periodic nanostructures, both metal and dielectric.
Currently he is a Research of CNR (Consiglio Nazionale delle Ricerche), Istituto di Studi sui Sistemi Intelligenti per l'Automazioni (ISSIA), Bari, Italy.
Dr. Marani has published over 150 book chapters, journal articles and conference papers and serves as referee for many international journals.

Anna Gina Perri received the Laurea degree *cum laude* in Electrical Engineering from the University of Bari in 1977. In the same year she joined the Electrical and Electronic Department, Polytechnic University of Bari, Italy, where she is Full Professor of Electronics from 2002.
From 2003 she has been associated with the National Institute of Nuclear Phisics (INFN) of Napoli (Italy), being a part of the TEGAF project: "Teorie Esotiche per Guidare ed Accelerare Fasci", dealing with the optimal design of resonance-accelerating cavities having very high potentials for cancer hadrontherapy.
In 2004 she was awarded the "Attestato di Merito" by ASSIPE (ASSociazione Italiana per la Progettazione Elettronica), Milano, BIAS'04, for her studies on electronic systems for domiciliary teleassistance.
Her current research activities are in the area of numerical modelling and performance simulation techniques of electronic devices for the design of GaAs Integrated Circuits and in the characterization and design of optoelectronic devices on PBG (Phothonic BandGap).
Moreover she works in the design, realization and testing of nanometrical electronic systems, quantum devices, FET on carbon nanotube and in the field of experimental characterization of electronic systems for biomedical applications.
Prof. Perri is the Head of the Electron Devices Laboratory of the Polytechnic University of Bari.
She is author of over 250 journal articles, conference presentations, twelve books and currently serves as a Referee of a number of international journals.
Prof. Perri is the holder of two italian patents and the Editor of two international books.
She is also responsible for research projects, sponsored by the Italian Government.
Prof. Perri is an Associate Member of National University Consortium for Telecommunications (CNIT).