A SIMULATION STUDY OF SILICON-GERMANIUM HETEROSTRUCTURE DEVICES

Roberto Marani* and Anna Gina Perri**[1]

* National Research Council of Italy, Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing (STIIMA), Bari, Italy
** Electronic Devices Laboratory, Department of Electrical and Information Engineering, Polytechnic University of Bari, via E. Orabona 4, Bari, Italy
annagina.perri@poliba.it

ABSTRACT

In this paper we present a description of the physical principles relating to heterostructures and then we analyse the heterojunctions Si-Ge, simulating, in particular, the performance of a Si-Ge Photodetector.

KEYWORDS

Heterostructure, Silicon, Germanium, Technology, Photodetector, SPICE.

I. INTRODUCTION

The electronics for high frequencies was made popular in recent years by the advent of applications such as, for example, cellular telephony, with frequencies of use beyond GHz.
The growing thrust toward the high frequencies has made it necessary therefore to the study and design of new electronic devices.
Currently [1-2] silicon continues to be the semiconductor most widely used in electronics and is considered an excellent material from the technological point of view. However it does not represent the semiconductor ideal to make devices to be used in electronic circuits for high frequency. In fact in the silicon the mobility of the charge carriers, both gaps that electrons, is relatively small and the maximum speed, called the saturation speed, that these carriers can reach under high electric fields is about 107 cm/sec. Moreover, silicon, being a band gap indirect semiconductor, presents an internal quantum efficiency low, making it unsuitable for the production of optical devices active, as laser diodes.
On the other hand, many of the compounds semiconductor III - V, such as for example the Gallium Arsenide (GaAs) or Indium Phosphide (InP), have mobility and the saturation speed higher and, in virtue of their band direct gap, it is possible to realize optical devices more efficient [1-2].
Technology III - V was initially braking by practical problems related to the production of integrated circuits at low cost with high levels of integration and high production yields. Thanks to the improvement achieved in the techniques of epitaxial growth these problems have been overcome and it was therefore possible to produce devices faster and more efficient.
A further increase of the frequency performance of electronic devices is obtained through the advent of heterostructures.
In this paper, after a brief description of the physical principles relating to heterostructures, we analyse some applications of heterojunctions with particular reference to heterojunctions Si-Ge.

[1] Corresponding author.
ORCID iD https://orcid.org/0000-0003-4949-987X Scopus ID: 7004631160
e-mail roberto.marani@stiima.cnr.it **ORCID iD http://orcid.org/0000-0002-5599-903X**

As example of applications, we simulate the performance of a Si-Ge Photodetector, obtaining that the transient response is adjust, the circuit is stable and has no oscillations and overshooting.
The presentation is organized as follows. A brief review of heterojuncion characteristics is presented in Section 2, while Section 3 is devoted to the simulation of a Si-Ge Photodetector with the discussion of the obtained results. The conclusions and future developments are described in Section 4.

II. A REVIEW OF HETEROJUNCTION CHARACTERISTICS

When a contact is made between different semiconductor, i.e. having different value of the range of the forbidden band, there is talk of heterostructures [2].
The diversity of the range of the forbidden band involves, in conditions of thermal equilibrium, the formation of special profiles of the conduction band and the valence band, which can be used for the manufacture of electronic and optoelectronic devices.
Fig. 1 shows the energy band diagrams of an ideal heterojunction before and after the forming the junction [2].

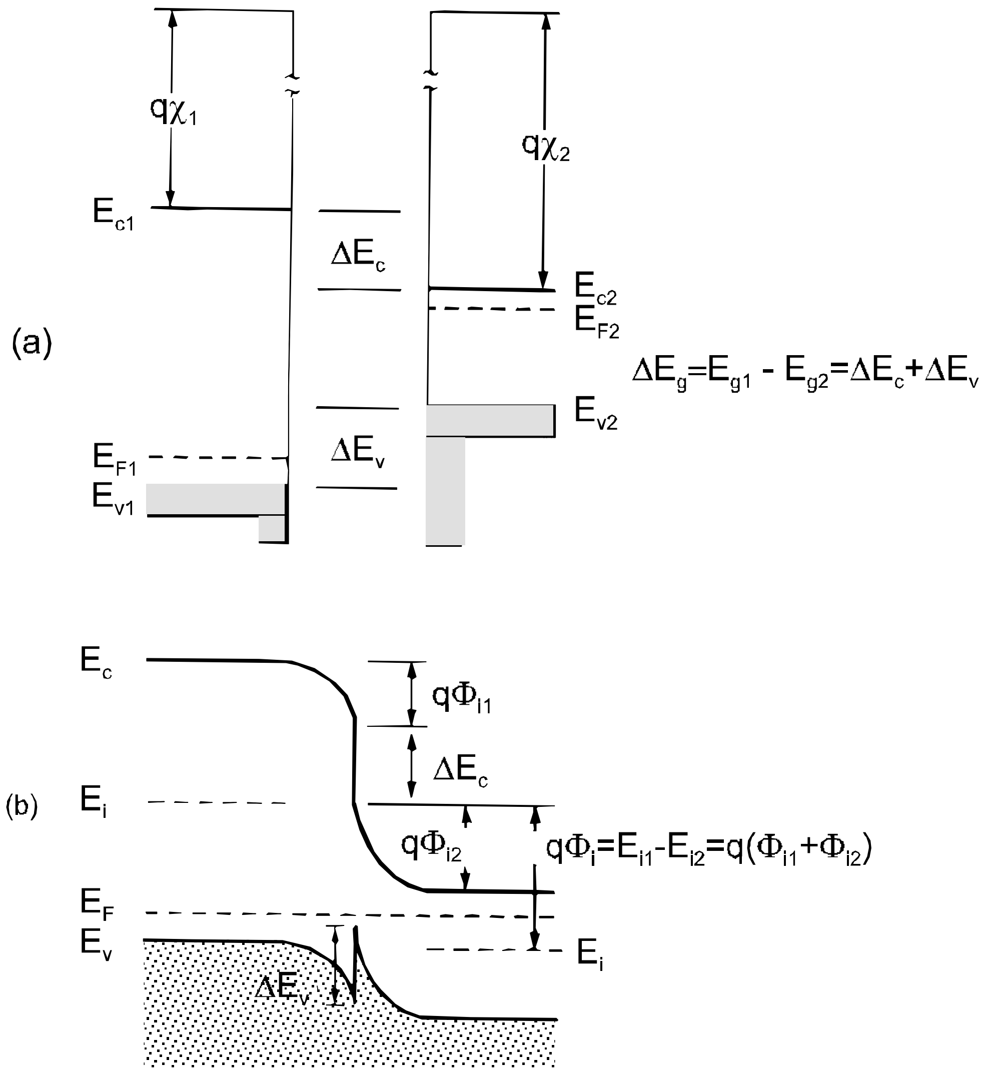

Figure 1. Energy band diagrams of an ideal heterojunction: (a) before forming the junction; (b) after.

However the hypothesis of ideality of heterojunction consists in having assumed that at the interface between the two different semiconductor there is a negligible number of traps and centers of generation-recombination. This hypothesis is in reality only checked for heterojunctios consisting of semiconductors having lattice constants of value very close together.

As can be seen from Fig. 1, the potential barrier that electrons must overcome to move from the n region to the p region is different from the one that must overcome the shortcomings to move from the p region to the n region across the junction. This is another important property of heterostructures that allows to realize different properties for injecting electrons and for the shortcomings and is used to obtain bipolar transistors to heterostructure, known with the acronym HBT (Heterojunction Bipolar Transistor).
A particularly important example of heterojunction is reported in Fig. 2, where a layer of $Al_XGa_{1-X}As$ heavily doped is grown on a layer intrinsic of GaAs.

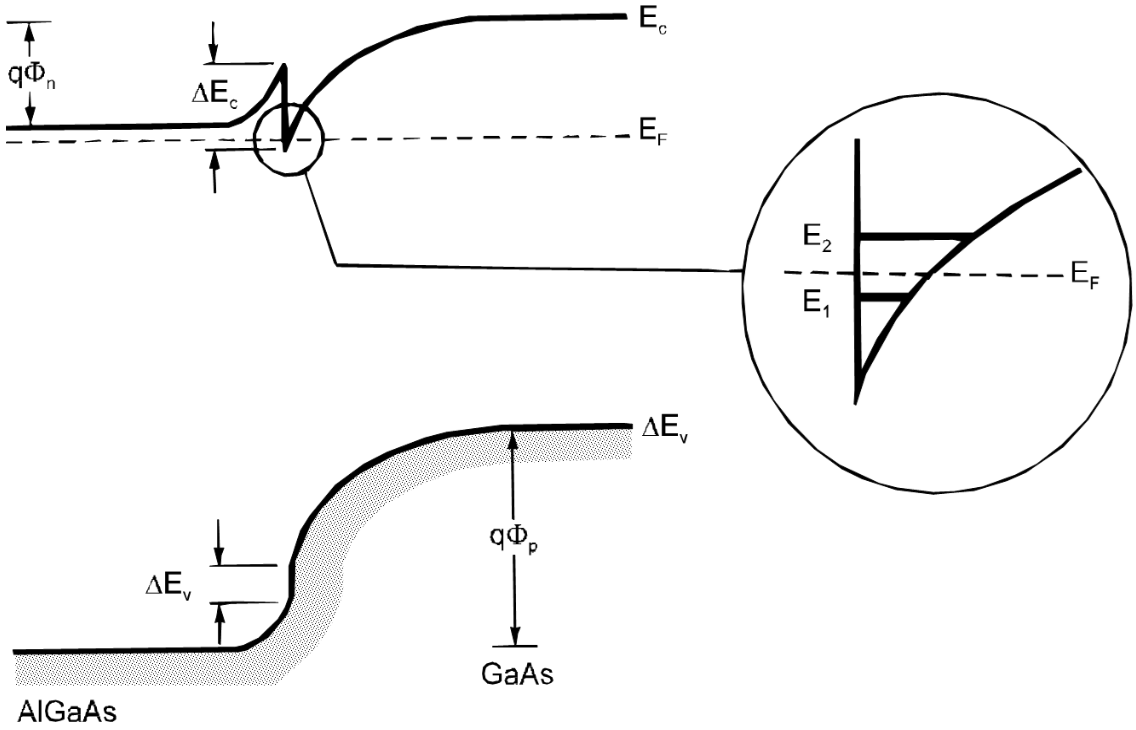

Figure 2. Energy band diagrams of an ideal heterojunction: (a) before forming the junction; (b) after.

The particular profile of the conduction and valence bands entails that the electrons spread in GaAs, where they are trapped in a pit of potential, forming a two dimensional gas of electrons available for conduction. It follows that the Fermi level at the interface of the heterostructure $Al_XGa_{1-X}As$ is above the energy level of the conduction band.
The electrons can slide parallel to the interface of the heterojunction with values of mobility which are very close to those that you have in the intrinsic GaAs. In fact, since the layer of GaAs almost inherent, mobility depends almost exclusively by the diffusion lattice. In correspondence with the low temperatures, wherein the scattering with the grating is very low, you can reach values of mobility is particularly high. This important property is used to fabricate FET with excellent performance in frequency and low noise, known as HEMT (High Electron Mobility Transistor).
A further improvement of the characteristics of the heterostructure devices is obtainable through the alloys of Si-Ge, studied since the early eighties.
The use of Ge presents a series of consequences. First, because Ge has a lattice constant greater than that of Si, the bandgap energy of Ge is smaller than that of the Si (0.72 eV for germanium, 1.12 eV for silicon) and therefore the SiGe alloy has a bandgap smaller, making it a good candidate for the so-called *bandgap engineering*, which is the process of controlling or altering the bandgap of a material. This is typically done to semiconductors by controlling the composition of alloys or constructing layered materials with alternating compositions.

Moreover the deformation by compression associated to the compounds in SiGe produces an additional variation of the bandgap which leads to a further reduction of about 75 meV for every 10% Ge introduced.

Because a film of SiGe must be very thin so that it can remain stable and therefore free of defects, is certainly a natural candidate to realize the base region of a bipolar transistor (which must be thin for high frequency operation). The resulting device is constituted by a heterojunction emitter-base (n-Si/p-SiGe) and a heterojunction the base-collector (p-SiGe/n-Si).

The SiGe HBT represents the first transistor based on bandgap engineering in silicon system.

Currently there is a strong demand for HBT SiGe in the area of monolithic integrated circuits on the basis of silicon for microwaves, essentially because of their superior performance at high frequencies and low cost compared to the products on GaAs or InP.

III. ANALYSIS AND SIMULATIONS OF Si-Ge PHOTODETECTORS

Fig. 3 shows the configuration of a photodiode of Ge on SiGe/Si.

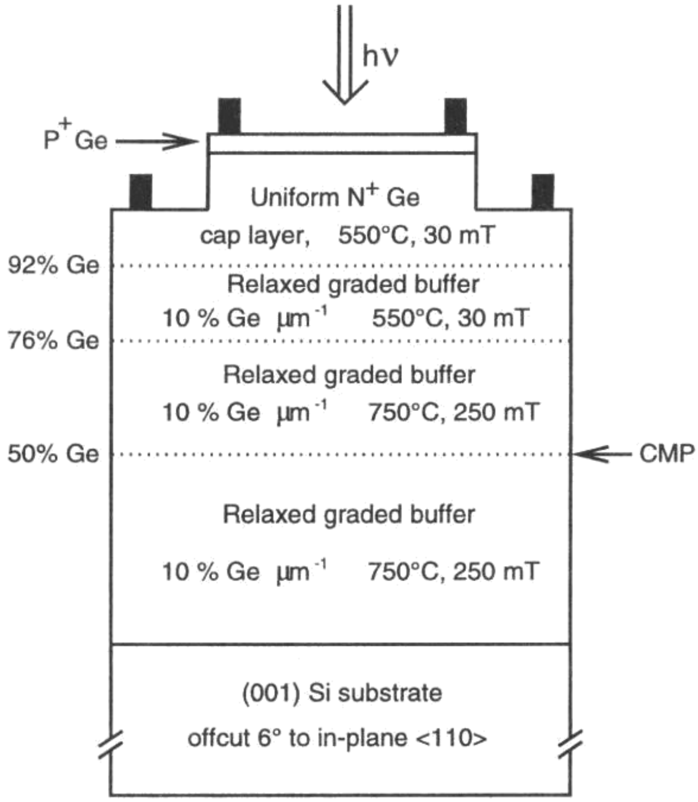

Figure 3. Photodiode of Ge on SiGe/Si.

We simulate with SPICE the performance of photodiode, using its electrical model shown in Fig. 4, where the related design data are reported.

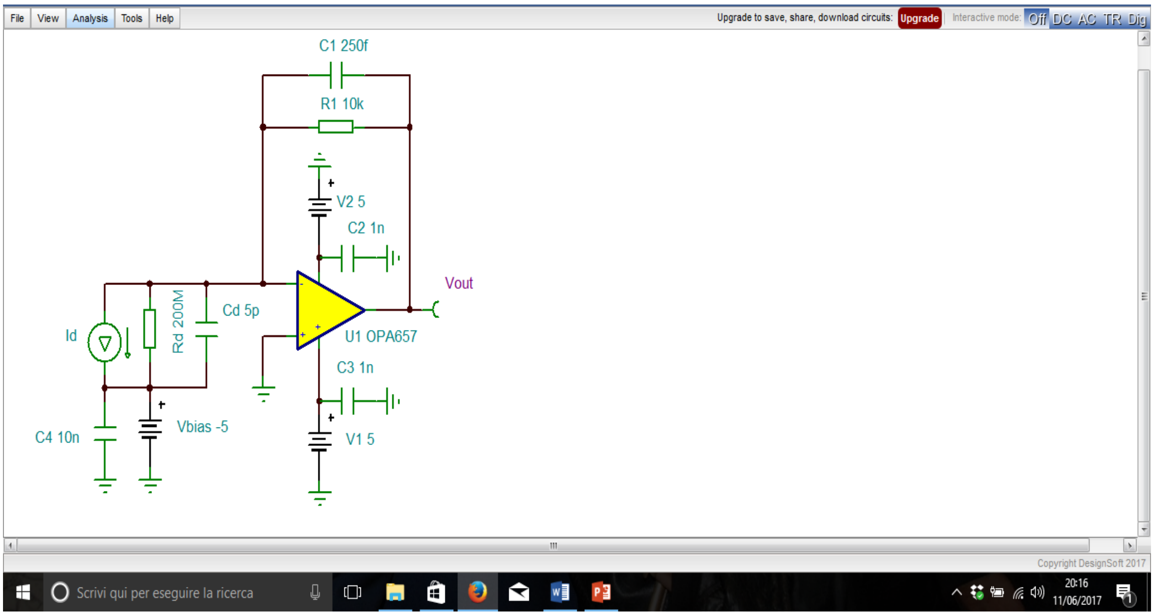

Figure 4. Electric photodiode model based on an transimpedance amplifier.

The amplifier above characterizes the detection structure of the photodiode and is based on an amplifier OPA657 JFET high speed. This amplifier is compensated for a minimum gain of closed circuit 7 V. Moreover the ability of the photodiode plus the ability to input of the amplifier and the resistance of the return R1 provide a gain of high frequency noise that allows a stable operation. The compensation capacitor C1 optimizes bandwidth gain of the amplifier.
The curves corresponding to the transient response, of the output noise and the total noise are shown in Figures 5, 6 and 7 respectively.

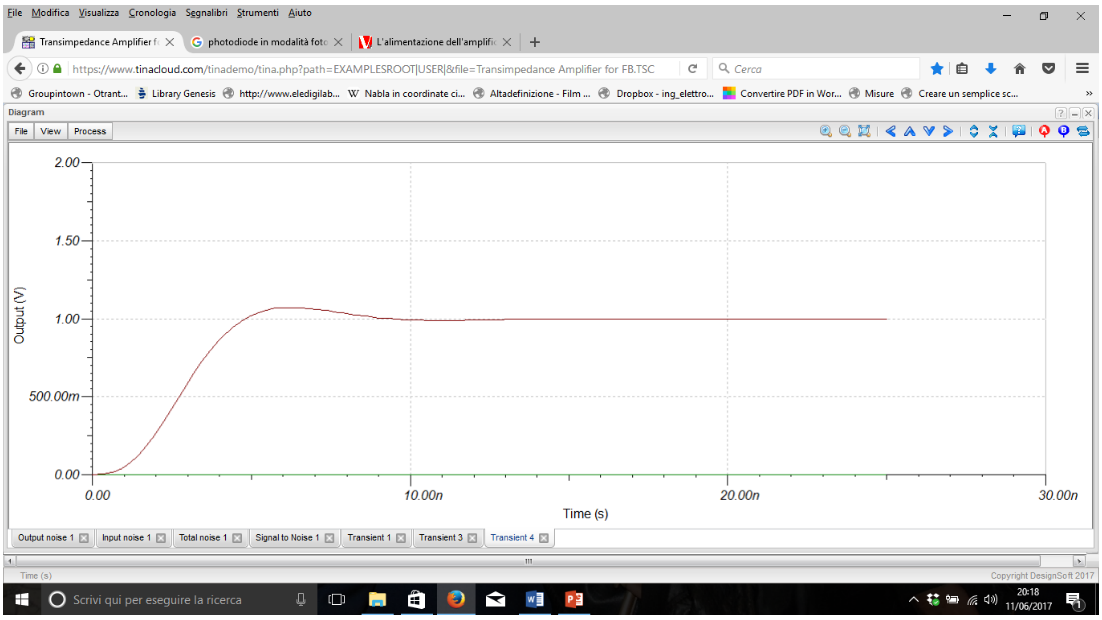

Figure 5. Transient response.

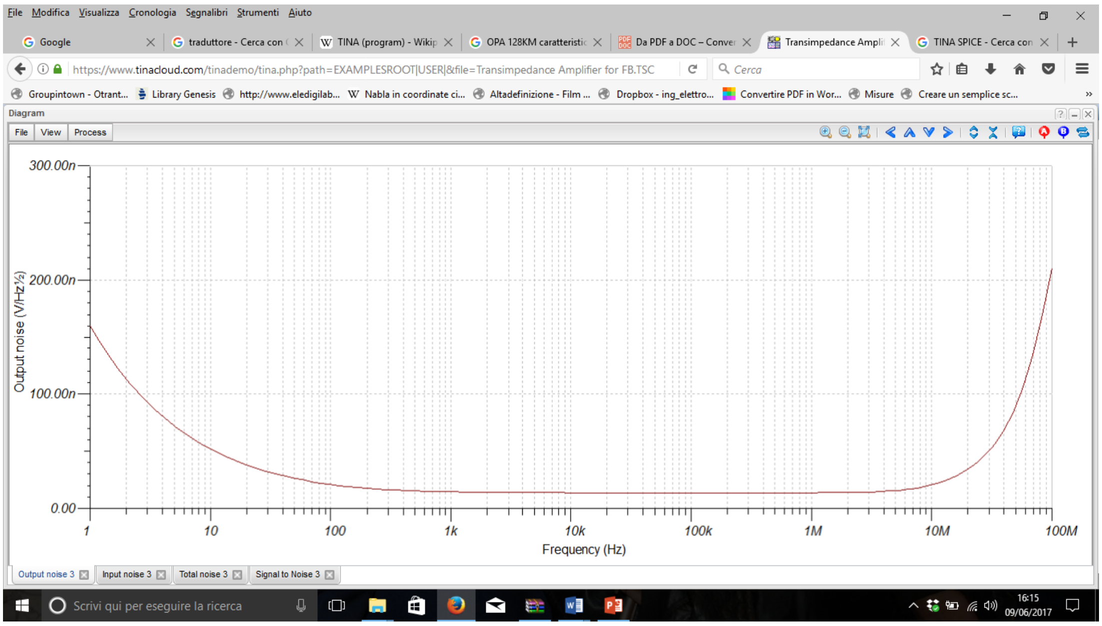

Figure 6. Output Noise.

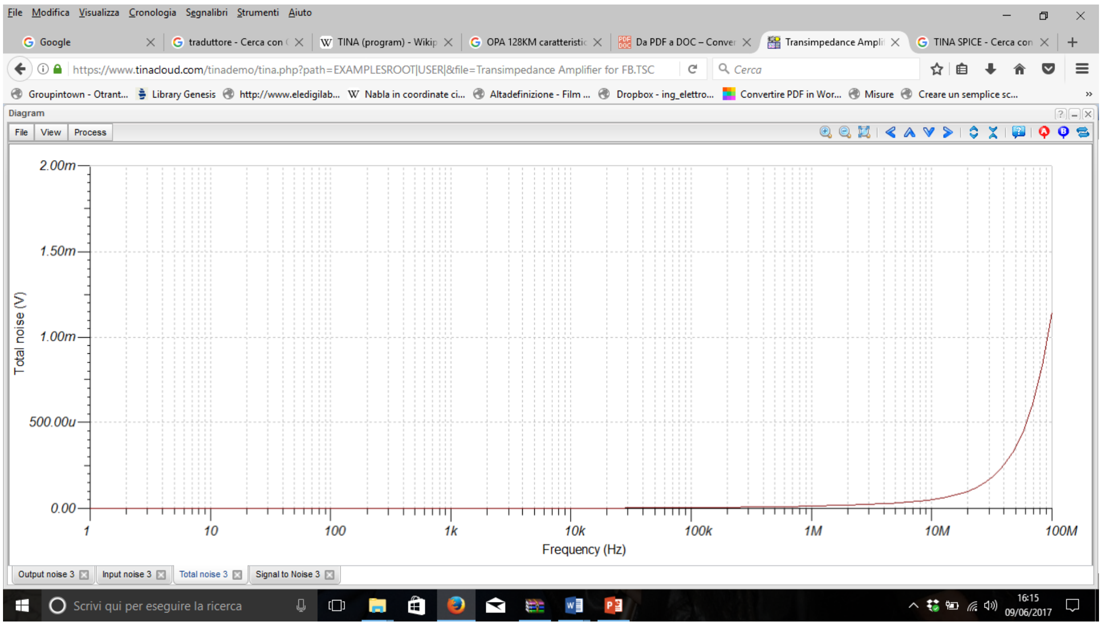

Figure 7. Total Noise.

From the analysis of previous figures we can affirm that the transient response is adjust, the circuit is stable and has no oscillations and overshooting. In the same way, the noise of the output and the total noise suffer flat responses without spikes or losses.

We have verified that with values of capacitances (see Fig. 4) lower the circuit is more subject to interference due to noise. As such, the oscillations, which are highly undesirable, are more likely.

At last, we invite the reader to examine our reference [3], in which we presented a simulation study of electro-thermal effects in HBTs based on Si/SiGe and on AlGaAs/GaAs, obtained by an analytical electro-thermal model, already proposed by us [4-6].

IV. CONCLUSION AND FUTURE DEVELOPMENTS

In this paper, after a brief description of the physical principles relating to heterostructures, we analysed some applications of heterojunctions with particular reference to heterojunctions Si-Ge.
We simulated the performance of a Si-Ge Photodetector, obtaining that the transient response is adjust, the circuit is stable and has no oscillations and overshooting. In the same way, the noise of the output and the total noise suffer flat responses without spikes or losses. Moreover, we presented a simulation study of electro-thermal effects in HBTs based on Si/SiGe and on AlGaAs/GaAs, obtaining that the breakdown voltage values in Si/SiGe HBT are relatively low. This result makes more difficult to use the Si/SiGe HBT for high-power applications, where AlGaAs/GaAs HBTs are preferred. However, this problem can be reduced by the DHBT approach.
Currently we are studying the CNTFETs, investigating about the effects of noise [7-8] in CNTFET-based A/D circuits.

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AUTHORS

Roberto Marani received the Master of Science degree *cum laude* in Electronic Engineering from Polytechnic University of Bari, where he received his Ph.D. degree in Electronic Engineering.
He worked in the Electronic Device Laboratory of Bari Polytechnic for the design, realization and testing of nanoelectronic systems. Moreover he worked in the field of design, modelling and experimental characterization of devices and systems for biomedical applications.
Currently Dr. Marani is a Reseacher of the National Research Council of Italy (CNR), at the Institute of Intelligent Industrial Technologies and Systems for Advanced Manufacturing (STIIMA), Bari, Italy, where he cooperates with the Intelligent Sensing and Perception Group.
He has published over 180 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.
Her research activities have been in the area of numerical modelling and performance simulation techniques of electronic devices for the design of GaAs Integrated Circuits, in the characterization and design of optoelectronic devices on PBG (Phothonic BandGap) and in the field of experimental characterization of electronic systems for biomedical applications.

Currently she works in the design, realization and testing of nanometrical electronic systems, quantum devices and FET on carbon nanotube.
Prof. Perri is the Head of the Electron Devices Laboratory of the Polytechnic University of Bari and is author of over 300 journal articles, conference presentations, twelve books and currently serves as a Referee and Editorial Board Member of a number of international journals. Prof. Perri is the holder of two italian patents and the Editor of three international books.