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Effect of Semiconductor Materials on the Current Control Voltage Source Trancitor Hall Voltage

Mourad Hebali[1,2,*], Hocine Abdelhak Azzeddine[1,3], Benaoumeur Ibari[1], Mohammed Berka[1], Abdelkader Maachou[1], Menouer Bennaoum[1] and Mohammed El Amine Beyour[1,3]

[1] *Department of Electrotechnical, University Mustapha STAMBOULI of Mascara, 29000 Mascara, Algeria.*
[2] *Laboratory: CaSiCCe, ENP Oran-MA, 31000 Oran, Algeria.*
[3] *LSTE Laboratory, University Mustapha STAMBOULI of Mascara, 29000 Mascara, Algeria.*

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Abstract

Recently, it was stipulated in a publication that a missing elementary active-device termed "trancitor" by its designer could be made and could greatly simplify electronic circuits. This elementary device has been presented as a CCVS (Current Control Voltage Source), unlike a bipolar transistor which is a CCCS (Current Control Current Source). In the present paper, the electrical behavior of the CCVS-type trancitor in Silicon (Si), Germanium (Ge), Gallium arsenide (GaAs), Silicon Carbide (3C-SiC and 6H-SiC), Indium Nitride (InN) and Indium Phosphide (InP) technologies have been studied. The input-output transfer characteristics (I_x-V_y) of the p-type and n-type CCVS trancitors have been investigated. In addition, the effect of doping concentration on the n-type CCVS trancitor in Si technology has been studied. This study is based on TCAD (Technology Computer Aided Design) simulation. The results show that the Hall voltage of the CCVS trancitor depends on the electrical properties of the semiconductor material, such as carrier mobility (μ), band gap (E_g) and hole/electron effective mass (m). Moreover, these trancitors are compatible with the model proposed for the first time. The CCVS trancitor proved its worth in semiconductor technologies as well as being a missing active device that satisfies Moore's law.

Keywords: Trancitor, Silicon, Semiconductor technologies, Hall effect, Hall voltage, Moore's law.

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1. Introduction

The Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET) is a very important device in electronic systems (ICs: Integrated Circuits) especially in micro-regime and nano-regime [1-3]. The nanotechnology study concerns the MOSFET transistor in terms of behavior and performance, as well as its various applications in the nano-scale, alongside with other electronic components such as Double-Gate MOSFET [4], Multi-gate MOSFETs [5], Fin-FETs [6, 7] and Tunneling FETs (TFETs) [8]. This is what makes electronics technology develop very significantly in the last decade. Nevertheless, the continuous shortening of the channel length of the MOSFET devices leads to various undesirable effects [4, 8, 9, 10], and the most important problem for the sustainable growth of ICs technology is the difficulty in satisfying Moore's law [11, 12].

Micro- and Nanotechnology is a field of technology and engineering used for the controlling matter of a nano-scaled device. All micro- and nano-electronic systems and their application fields are fundamentally affected by semiconductor materials [13, 14], such as silicon (Si), germanium (Ge), gallium arsenide (GaAs), Silicon Carbide (3C-SiC and 6H-SiC), Indium Nitride (InN) and Indium Phosphide (InP). This is due to their distinctive electronic properties (Table 1) [15, 16] and their extensive applications in electronic components and circuits.

To further push the limits of physical down-sizing of electronic components and satisfy Moore's law, *Sungsik* Lee [12] was the first to propose and publish in 2018, the possible structure and the operating principle of a new elementary active-device named "trancitor". As proposed by *Sungsik* Lee, this kind of active devices directly transfers an input signal into a voltage output whereas a transistor transfers its input signal into a current output. It is proven that the trancitor is able to satisfy Moore's Law better than transistor, so that the trancitor-transistor combination leads to a minimal circuit configuration as compared to the transistor-only circuit [12]. *Sungsik Lee* presented a current-controlled voltage source CCVS trancitor model for p-type semiconductor only and without examining the effect of semiconductors on its electrical behavior. Thus, in the present work, the effect of semiconductor materials (Si, Ge, GaAs, 3C-SiC, 6H-SiC, InN and InP) on the input-output transfer characteristics (I_x-V_y) of a CCVS trancitors will be investigated for both p-type and n-type semiconductors as well as the influence of the doping concentration on their I_x-V_y characteristics.

2. Sungsik Lee CCVS trancitor model

As shown in Figure 1, the possible schematic diagram of a CCVS-type trancitor structure proposed by *Sungsik Lee* is a p-type semiconductor film immersed in a magnetic field [12]. The principle of a p-type CCVS trancitor is based on the Hall effect which induces the voltage signal called the Hall voltage [12-15]. According to the trancitor structure (Figure1) and after applying the magnetic flux density (Bz) along the z-direction perpendicularly to the semiconductor

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*E-mail address: mourad.hebali@univ-mascara.dz;

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film on the x-y plane, the voltage Vy has been analytically given as:

$$V_y = \frac{I_x B_z}{q p z_0} \tag{1}$$

where V_y is the output voltage, I_x is the input current, q is the electron charge, p is the hole concentration and z_0 is the thickness of the semiconductor film [12].

Table 1. Properties of semiconductor materials

Properties	Si	Ge	GaAs	3C-SiC	6H-SiC	InN	InP
Energy Gap Eg (eV)	1.12	0.66	1.424	2.37	3.02	1.97	1.34
Mobility electrons μ_n (cm^2/V-s)	1500	3900	8500	1000	800	3200	5400
Mobility holes μ_p (cm^2/V-s)	475	1900	400	40	90	220	200
Carrier concentration n_i (cm^{-3})	1.45x10^{10}	2.4 x 10^{13}	1.79 x10^6	6.9	2.3x10^{-6}	920	1.3x10^7
Effective mass of electron m_n^*/m_0	1.1	0.55	0.067	0.68	0.20	0.11	0.08
Effective mass of hole m_p^*/m_0	0.56	0.37	0.48	0.6	1	1.63	0.6

From the expression (1), the Hall voltage of a CCVS-type trancitor depends on its thickness, the magnetic flux density and the hole concentration.

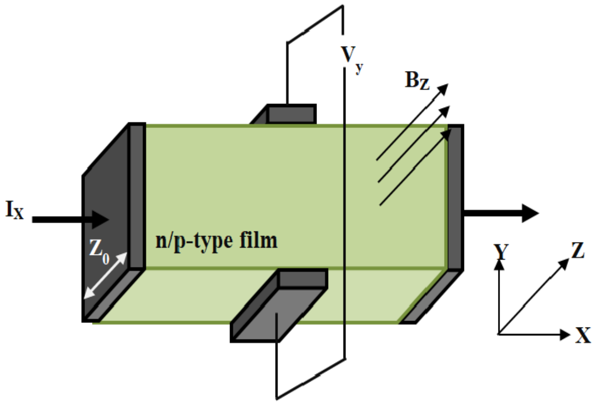


Fig. 1. Schematic diagram of CCVS-type trancitor [12]

3. Studied structure of the n-type and p-type CCVS trancitors in semiconductor technologies

Figure 2 shows the structure of the n-type and the p-type CCVS trancitors in Si, Ge and GaAs technologies used in the present study. The different dimensions and doping technologies of the *Sungsik Lee* model have been exploited to simulate both types of the CCVS trancitor (y_0=10 nm and p=n=6.2 × 10^{14} cm^{-3}). The different CCVS proposed trancitors are subject to the same magnetic field intensity, B=1μWb/cm^2.

The CCVS trancitors in various semiconductor materials were simulated using the advanced physical model of the DFT-NEGF method which combines Density Functional Theory (DFT) and Non-equilibrium Green's Function (NEGF) approach incorporated into the TCAD tool in order to obtain more accurate results. This DFT-NEGF approach is considered more effective for analyzing the electrical structure of semiconductor materials and resolving the quantum transport properties of electronic devices at the nanoscale [17-19].

The I_x-V_y characteristics show that the Silvaco TCAD simulation model of the CCVS-type trancitor correctly works according to the CCVS-type trancitor model proposed by *Sungsik Lee* since the I_x current is directly proportional to the V_y voltage variation for the different trancitors.

According to the electronic properties of the different semiconductors and the results obtained, the current I_x of the p-type and the n-type CCVS trancitors is directly proportional to the mobility of the semiconductor materials. As shown in Figure 3, if the electron/hole mobility increases, the current of the trancitors increases. For the p-type trancitor, the current Ix is inversely proportional to the gap value. However, a definitive judgment cannot be given in the case of the n-type trancitor. In addition, the current of the n-type CCVS trancitor also evolves clearly inversely with the electron effective mass. As for the p-type CCVS trancitor, the effect of the hole effective mass on the current of this trancitor is not clear. Results show that the hole effective mass has similar effect as the electron effective mass on the current of the trancitor due to the small discrepancy between the hole effective mass values of semiconductors.

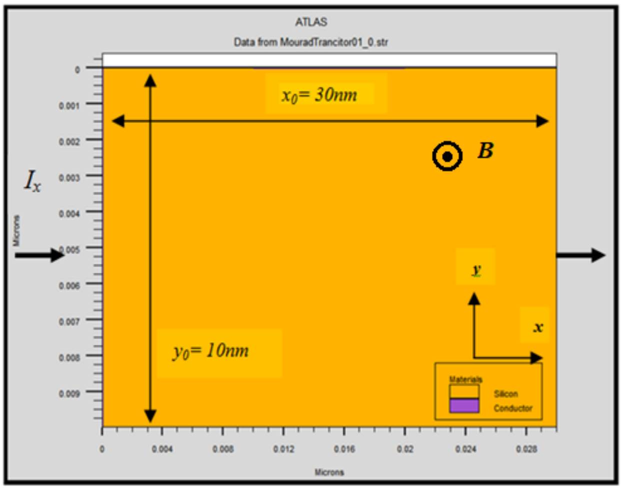
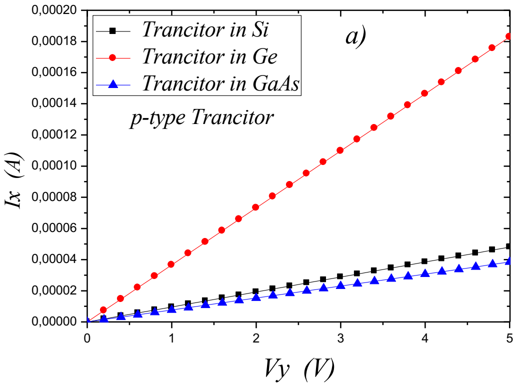


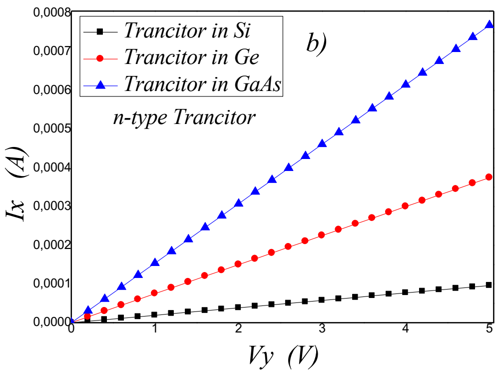
Fig. 2. CCVS-type trancitor structure used in the simulation

4. Results and discussion

Figures 3-a and 3-b show the input-output transfer characteristics (I_x-V_y) of the CCVS trancitors in Si, Ge and GaAs technologies for p- and n-type, respectively.



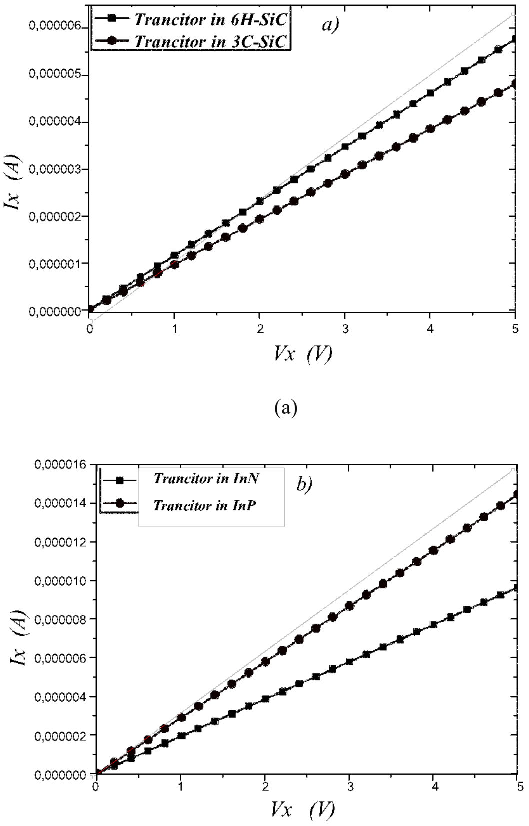
(a)



(b)

Fig. 3. I$_x$-V$_y$ characteristics of CCVS trancitor, a) p-type, b) n-type

In order to precisely study the effect of semiconductors on the electrical behavior of the n-type CCVS trancitor, the simulation framework is expanded to include more semiconductor materials (IV-IV and III-V compounds) such as 3C-SiC, 6H-SiC, InN and InP, as shown in Figures 4-a and 4-b.



(a)

(b)

Fig. 4. I$_x$-V$_y$ characteristics of n-type CCVS trancitor in, a) SiC (3C- and 6H-), b) InN and InP

The trancitor mainly depends on the Hall Effect, especially for the CCVS-type trancitor [12]. In fact, the Hall effect induces the voltage signal called the Hall voltage [15]. This statistical phenomenon results in a change in the charge density. Therefore, in the case of the p-type and the n-type trancitors, this phenomenon can be interpreted, assuming that the Lorentz force applies to a hole and an electron, respectively. Since the current of the trancitor is affected by the electronic properties of the semiconductors, the Hall voltage is also affected. Depending on the *Sungsik Lee* model and the results obtained, the Hall voltage V_y of the trancitor can be rewritten in analytical form as follows:

For p-type CCVS trancitor:

$$V_y = \frac{I_x(E_g, m_p^*)B_z}{(\mu_p)qpz_0} \tag{2}$$

For n-type CCVS trancitor:

$$V_y = \frac{I_x(E_g, m_n^*)B_z}{(\mu_n)qnz_0} \tag{3}$$

Figure 5 shows the effect of doping concentration on the I_x-V_y characteristic of the n-type CCVS trancitor in Si technology. The I_x current increases when the doping concentration increases, and this is in agreement with the expression of the Hall voltage in the CCVS trancitor model and confirms the validity of the concept proposed by *Seungsik Lee* regarding the effect of doping concentrations on the electrical behavior of the CCVS trancitor.

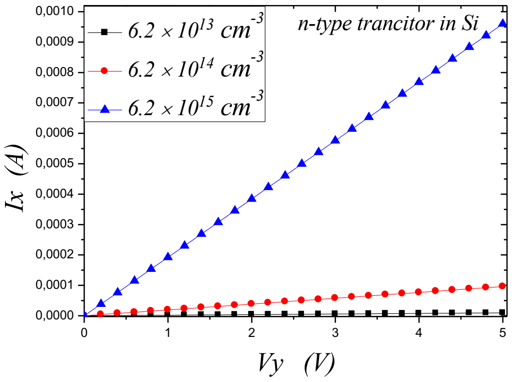


Fig. 5. I$_x$-V$_y$ as a function of doping concentration of n-type CCVS trancitor in Si

5. Conclusion

The present work discusses the relationship between the electronic properties of different semiconductors and the current of p-type and n-type CCVS trancitor proposed by Sungsik Lee. The results show that the current of the transistor is directly proportional to the mobility of the semiconductor materials. The effect of the gap value and effective mass on the current of the p-type and n-type trancitor is also discussed. The article further explains that the Hall effect plays a significant role in the CCVS trancitor characteristics. The article concludes with a discussion on the effect of doping concentration on the I_x-V_y characteristic of the n-type CCVS trancitor in Si technology. The predicted electrical behavior of the trancitor for different semiconductor materials seems to agree with the literature of active components and then reinforces the approach of the model proposed by *Sungsik* Lee. All of this necessarily leads to an increased need for this active device in nanoelectronics as well as the possibility of revolutionizing the field of semiconductor technology.

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