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The effect of energy band gap of channel transistor region on npn transistor performance; a numerical study

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ABSTRACT

The distance between conduction and valence bands which is known as bandgap energy is an important factor for semiconductors and is different in various materials. The bandgap energy determines the electrical and optical properties of semiconductors and has a direct effect on the performance of diodes and transistors. In this article, the effect of bandgap energy of the channel region of a npn transistor has been investigated and its effects on capacitance and conductivity, threshold voltage, and the *I*on-*I*off ratio were studied. An npn transistor is designed and then the bandgap energy is changed between 0.8 eV and 2.2 eV with a step of 0.2 eV, and subthreshold slope and other electrical quantities have been obtained numerically. By comparing the results, the best performance of the transistor can be obtained. This simulation was done with Silvaco Atlas software. This study can open new windows in design of transistor devices.

1. Introduction

In solids, due to the mixing of atoms, different energy bands can be formed, so we can call the set of energy levels like energy bands [1,2]. Atoms have different energy levels and when get closer to each other, the outer shell electrons will interact with each other and bonding force between electrons known as interatomic bonding leads to performing energy levels [3,4]. Any changes in connections or atoms can change the energy levels of the electrons and shift the energy of bands [5]. Therefore, the range of electrons will not be in the same range, the range of electrons will change to a lower or higher value compared to the original level [6]. Each material contains a different amount of electron energy that exists in energy bands depending on these energy levels [7]. According to Bohr's theory of energy band, it has been believed that each shell in an atom has a separate amount of energy in different levels [8].

According to the band theory of solids, there are different energy bands [9]. The valence band in solids has different ranges of energies that can also exist at absolute zero temperature and it contains the valence electrons [10,11]. In solid materials, electrical conductivity mainly depends on the valence electrons that exited from valence band to conduction band [12-16]. The energy difference between conduction and valence bands known as the bandgap energy is the main electrical and optical parameter of the semiconductors [17].

The electrical conductivity of a solid is highly determined by the bandgap energy which is dependent on the kind of material and its dopant percent. For example, the bandgap energy of silicon, gallium arsenide, aluminum antimonite, indium phosphide, and cadmium telluride is 1.11, 1.43, 1.6, 1.35, 1.49 eV, respectively [18-22]. Classification of energy bands can be done based on the band theory of solids and by determining the valence, forbidden, and conduction bands, the type of material can be determined [23]. Certainly, the greatest achievement of

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this theory is the construction and development of diodes and transistors, which initiated a huge revolution in science and technology in the 20th century.

On the other hand, field effect transistors (FETs) have been considered as promising alternatives to metal–oxide–semiconductor field effect transistors (MOS-FETs). MOS-FETs have been widely used in the field of electronics. These devices are of particular interest due to their sub-threshold swing (SS) of less than 60 mV/dec, which is the lowest possible value for MOS-FETs [24]. In addition, in terms of short-channel effects (SCEs), FETs outperform MOS-FETs due to their low off-current (*I*off), which is required for low-power applications. However, there is still the problem of low (*I*on) current [25]. At present, MOS micro- and nano-electronic devices rely mainly on SiO_2. In the miniaturization process of these devices, the thickness of gate oxide layers has been reduced to several nanometers and sometimes to sub-nanometers. This results an increment leakage current in SiO_2 and therefore, in order to reduce the leakage current by using very thin materials, there is a need for new materials with high dielectric constants [26].

In the last decades, some researches were done on replacing SiO_2 with materials such as HfO_2, Al_2O_3, and HfON, in MOS-FETs transistors. For silicon-based complementary metal–oxide–semiconductor (CMOS) devices, there are six criteria for selecting SiO_2 replacement material: high dielectric constant, thermal stability with silicon, kinetic stability at high temperatures, high band gap greater than 1 eV, formation of good electrical interface with Si, and presence of defects [27].

The fundamental physics of MOS-FETs limits the minimum sub-threshold swing (SS) to 60 mv/dec. In addition, power dissipation has become a major concern as dimensions shrink. Consequently, reducing *I*off is essential for low leakage current and low standby power systems. To overcome these problems, new engineering solutions such as improving the device structure, considering different materials with different characteristics (Si, SiGe, Ge, etc.) in the channel area and higher dielectric constants (high -k) materials have been proposed [28,29]. It is suggested that some of them are used for better exploitation of these devices. In recent years, various devices have been studied to obtain the minimum Ioff and the maximum *I*on/*I*off ratio [30-33].

Silvaco is a simulation software for the semiconductor and electronic circuit industry used to design and analyze transistors, integrated circuits, and electronic chips. This software provides the ability to simulate and analyze various semiconductor components and asymmetric construction.

Analytical models in Silvaco software include transistor models, diode models, zener models, integrated circuit models, etc. These models make it possible to predict the behavior and performance of electronic components and allow users to analyze their designs before actual construction.

According to detailed analytical models in various fields of electronic physics and material properties, the accuracy of Silvaco software is very high.

In general, Silvaco is a powerful and widely used software for the design and analysis of semiconductor and electronic circuits by researchers.

In this paper, a new method to improve the performance of transistors is presented, which takes advantage of reverse engineering. This method seeks to find the best material for making high-speed and high-efficiency transistors based on changes in energy bands and material properties.

In this article, by examining the changes in energy bands and material properties, an attempt has been made to find a material that provides the best performance in transistors. This method not only makes it possible to make transistors with higher efficiency, but also increases the speed of electronic processes.

In other words, this article seeks to improve the performance of transistors by choosing the best materials to make them, and by applying material changes, it tries to improve the efficiency and speed of transistors.

In this article, the transistor is simulated with Silvaco-Atlas software and the effect of different energy bands of channel on the performance of the transistor is investigated and it is analyzed in order to design a perfect semiconductor material to make a favorite and high gain transistor.

2. Results and discussion

The effect of band gap energy is very important on the properties and performance of transistors. In usual, the high band gap energy in semiconductor materials leads to better control on the electric current and improve the efficiency of the transistor. On the other hand, energy bands in transistors play an important role in the absorption and transfer of electrons and can help to improve the performance and efficiency of the transistor. Therefore, in the design and optimization of transistors, the role of band gap energy is very fundamental, and their effects must be carefully investigated in order to improve the electronic properties and performance of transistors.

In this part, the band gap energy of the channel layer of a npn transistor has been changed and numerical simulation has been performed in order to find the best gain. As seen in Figure 1, the transistor is designed in a silicon on insulator (SOI) structure, the length of the transistor is considered to be 3 μm, and its is considered to be 0.62 μm. The thickness of silicon oxide deposited on the gate is 0.02 micrometers and the semiconductor diameter is considered 0.2 micrometers. A thin layer of silicon oxide with the thickness of about 0.4 microns has been used as insulator to rest of the transistor.

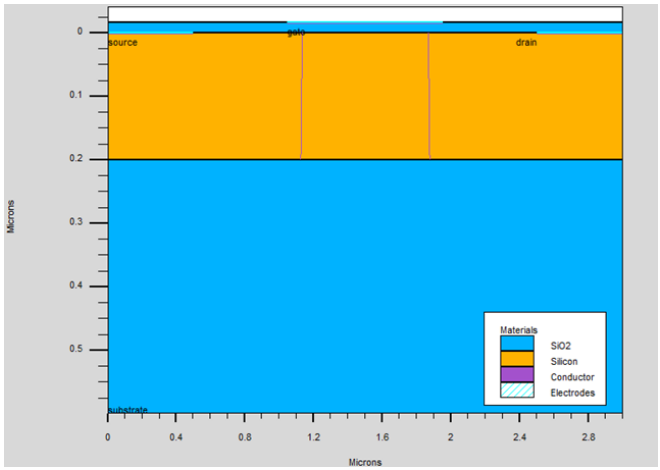

Fig. 1. Schematic of the transistor structure.

The band gap energy of the n regions (source and drain) which is Si is 1.1 eV, and the gap of the channel region is considered variable between 0.8-2.2 eV. The impurity injected into the n regions is considered 1e20 cm^{-3} and for the channel region 2e17 cm^{-3}. In this structure, the bandgap has been changed in the interval 0.8-2.2 eV to see its effect on the ratio of on-off current, sub-threshold slope, and threshold voltage of the transistor.

First, the above structure has been simulated in Silvaco-Atlas software, then the band widths have been given values of 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.2 eV and the necessary analyzes have been done on this structure. In this regard, first we consider a hypothetical horizontal cut along the length of the transistor under the top oxide layer of the gate and study and analyze this cut surface area by the software. This cut is created at a depth of 7 nm from the transistor layer.

Of course, it should be noted that for energy gaffes below 1.2 eV, it may not be appropriate to use the word semiconductor, and it is better to use quasi-metal.

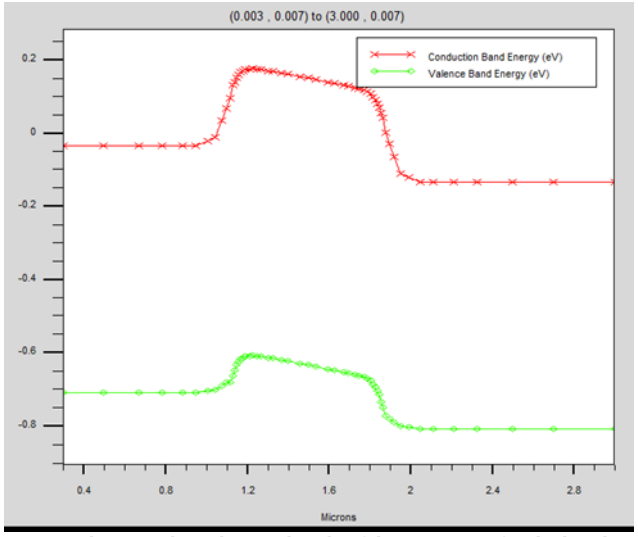

Fig. 2. Valence and conduction bands of the transistor for the bandgap energy of 0.8 eV.

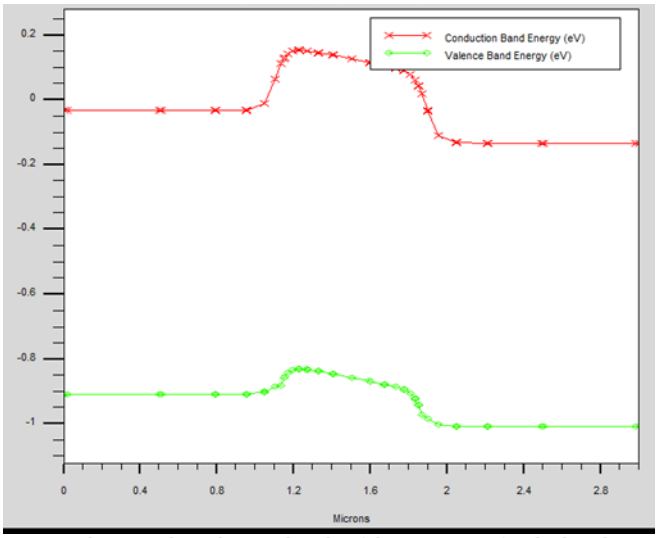

Fig. 3. Valence and conduction bands of the transistor for the bandgap energy of 1 eV.

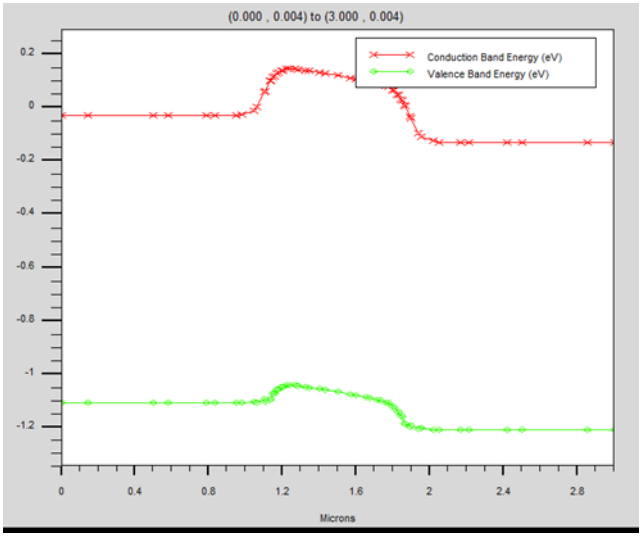

Fig. 4. Valence and conduction bands of the transistor for the bandgap energy of 1.2 eV.

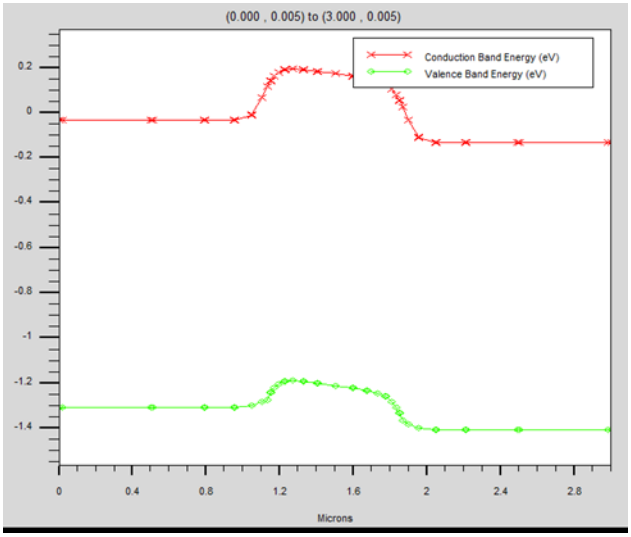

Fig. 5. Valence and conduction bands of the transistor for the bandgap energy of 1.4 eV.

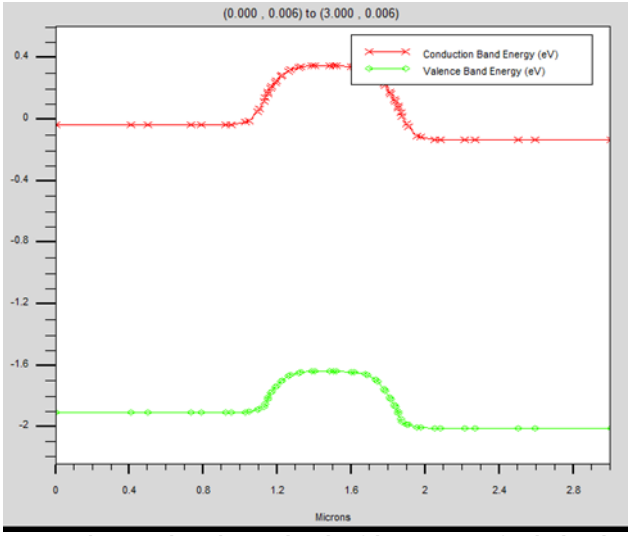

Fig. 6. Valence and conduction bands of the transistor for the bandgap energy of 2 eV.

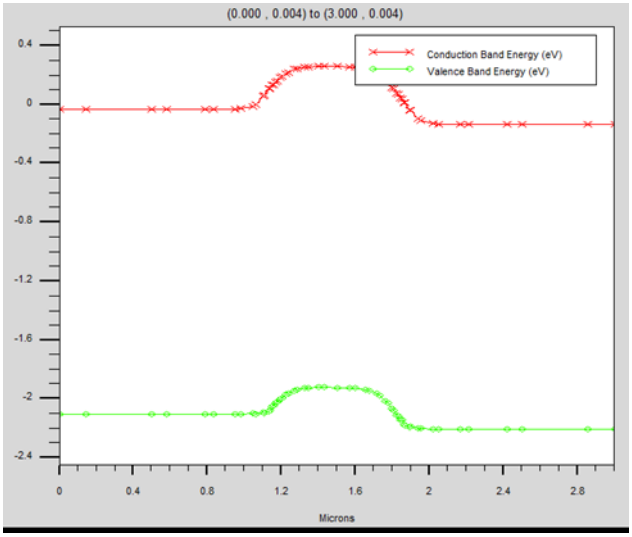

Fig. 7. Valence and conduction bands of the transistor for the bandgap energy of 2.2 eV.

In Figures 2-7, Valence and conduction bands of the transistor with different band gap energies are shown. Curves show the changes of the energy bands by various energy band gaps. The first change is the valence band shift to lower energies and away from the conduction band, while the conduction band does not change energy much. This means that the energy band gap of the transistor increases linearly with the increase of p channel band gap, which was quite expected. Also, the energy difference between n and p regions in the conduction band, which is usually named as internal voltage, has the minimum and maximum values at 1.2 eV and 2 eV, respectively.

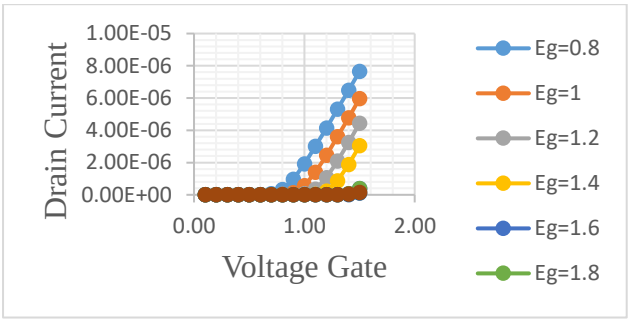

Fig. 8. diagram of the ratio of drain current to gate voltage.

The threshold voltages of the transistors have been simulated in Figure 8. For this, the drain currents were plotted versus the gate voltage which is increased from 0 V to 1.5 V with a step of 0.1 V and the drain current diagram is obtained for each band gap energies. The curves of all the cases are drawn on one graph (Figure 8). It can be seen that as the valence and conduction bands are further away from each other, the threshold voltage increases.

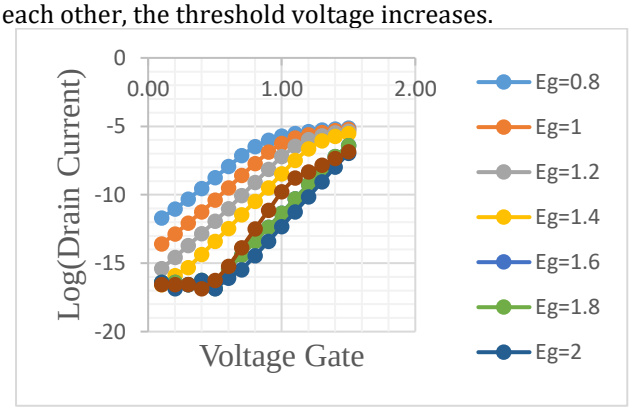

Fig. 9. Logarithm of the drain current against the gate voltage.

Fig. 9 shows the logarithm diagrams of the drain current in terms of the gate voltage, drawn for different bandgap energies, which can give the subthreshold slope, the on-off current ratio, and the on-current value. It is clear from this curves that the value of the subthreshold slope and the ratio of on-off current are maximum for the bandgap energy of 1.4 eV. In fact, we found an optimal value for the energy bandgap that can increase the gain of the transistor. In Figure 10, the ON–OFF current ratio (*I*on/*I*off) of the transistor has been plotted versus the bandgap energies that shows the bandgap energy of 1.4 eV has the maximum ratio.

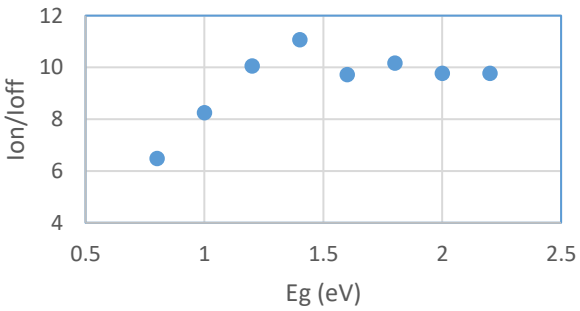

Fig. 10. Curve of the Ion-Ioff ratio against the bandgap energy.

3. Conclusion

In summary, characteristics that are considered in transistors are the threshold voltage, the slope below the threshold, and the *I*on-*I*off ratio. In this article, the structure of a npn transistor was investigated and simulated using Silvaco Atlas simulator software. In this structure, the used semiconductor band gap energy has been changed to 0.8 eV, 1 eV, 1.2 eV, 1.4 eV, 1.6 eV, 1.8 eV, 2 eV, and 2.2 eV, and the threshold voltage, sub-threshold slope, and on-off current ratio for each mode is obtained. As can be seen in the results, band gap changes do not have an effect on the slope below the threshold, but it has a direct effect on the threshold voltage and the *I*on-*I*off ratio, which according to the obtained results, the best condition can be obtained and the optimal values of the bandgap energy for the channel region are calculated. This study can open new sights in design of transistor devices.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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