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Simulation study on the influence of Ge concentration on the characteristics of P-type SiGe-FinFET

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Abstract: As the integrated circuit fabrication processes are developing towards higher performance and lower power consumption, the traditional silicon-based MOSFET device cannot satisfy the performance requirement of the advanced process node, as the short-channel effect and the limited carrier mobility. The p-type SiGe-FinFET combines the high hole mobility of the SiGe channel with the excellent gate control of the FinFET structure; understanding how Ge concentration affects its electrical characteristics is therefore essential for device optimization. This paper investigates how Ge concentration affects the hole mobility, drive current, and threshold voltage of p-type SiGe-FinFET devices. The two-dimensional P-type SiGe-FinFET device model is set up using the Silvaco TCAD 2020 simulation platform. With keeping the device's geometric structure, doping concentration and the bias condition the same, we do parametric scanning simulation by varying the Ge concentration in the SiGe channel; and then, the hole mobility, the drive current and the threshold voltage under different Ge concentration, which are the key performance parameters of the devices, are extracted and be analyzed. The simulation results show that as the Ge concentration increases, the hole mobility in P-type SiGe-FinFETs is remarkably enhanced, so that it can effectively increase the drive current of the device; at the same time, the variation of the Ge concentration also leads to some changed of the threshold voltage. When the Ge concentration is in appropriate range, the device can have high hole mobility, the large drive current and the reasonably optimized threshold voltage, so that the device has better overall electrical performance. This study gives us simulation based knowledge for the Ge composition of the P-type SiGe-FinFET channel to be optimized and for the device design.

Keywords: SiGe-FinFET; Ge; Silvaco TCAD; Hole mobility.

1. Introduction

1.1. Background information

With the continuous scaling of semiconductor technology, improving carrier transport capability has become one of the major challenges in the advanced transistor design. Compared with the conventional silicon-channel devices, the SiGe-channel FinFETs have attracted considerable attention, because the germanium can be incorporated to effectively improve the hole mobility while the FinFET structure can provide superior electrostatic control over the channel [1, 2].

1.2. Research questions

Previous studies have shown that strained SiGe channels can improve the hole mobility in p type MOS device [3, 4]. TCAD simulation is an effective approach for the evaluation of the electrical characteristics of the advanced FinFETs [5]. It is also reported that the optimization of Ge composition is an effective method to balance the carrier mobility and the threshold voltage in the SiGe-channel devices .

1.3. Research technique

In this study, the effect of Ge concentration on the electrical performance of p-type SiGe-FinFETs is studied. The whole analysis is made in three points, i.e. the variation of hole mobility, the change of drive current (Ion), and the change of threshold voltage (Vth) with different Ge concentration. A two dimensional device model is made by using the Silvaco TCAD 2020 simulation platform. The quantitative parameter-sweep simulations are done with the same device geometry and operating condition.

1.4. Research significance

The results of this study give a clearer picture of the relation between the Ge concentration and the electrical performance of p-type SiGe-FinFETs. The results can be used as a useful reference for the choice of the SiGe channel composition and for the improvement of the design of the coming high performance CMOS devices.

2. Device Modeling and Simulation Methodology

2.1. Device Structure and Parameter Configuration

In this work, a two-dimensional p-type SiGe-FinFET device model was set up to study the effect of Ge concentration on the transistor performance. The device structure is based on the usual FinFET structure, which includes silicon substrate, SiGe channel region, gate oxide layer, gate electrode, and heavily doped source/drain regions. Compared with the usual planar MOSFET structures, the FinFET structure with multi-gate structure give improved electrostatic control, which can suppress the short-channel effects and improve the channel modulation capability [1].

In order to see the influence of the Ge concentration correctly, the geometric parameters and the electrical parameters of the device were not changed in all the simulations [2]. The gate length was 20 nm. The fin width and fin height were 8 nm and 30 nm, respectively. A thin SiO2 layer was used as the gate dielectric. The source/drain region was heavily doped so that the carrier injection is effective. The SiGe channel was lightly doped to reduce the influence

of the impurity scattering, and to show the effect of Ge composition on the carrier transport.

The Ge concentration in the SiGe channel was chosen as the only parameter that was varied. We investigated several Ge compositions by increasing the Ge mole fraction gradually, keeping the structures of the devices and the operating conditions to be the same [7]. Such parameter-sweep strategy, allows a direct analysis of the dependence of the Ge concentration on the electrical characteristics of the p-type SiGe-FinFET devices.

2.2. TCAD Simulation Method

The device simulations were done with the Silvaco TCAD 2020 simulation platform. The ATLAS device simulator is used to solve the semiconductor transport equations and get the electrical characteristics of the SiGe-FinFET structure [5]. The procedure of the simulation is the construction of the device structure, definition of the materials, the choice of the physical model, the setting of the bias condition, and the extraction of the electrical parameters.

In order to improve the accuracy of the results of the simulation, several physical models were included . The field-dependent mobility model was applied, to consider the carrier velocity saturation under high electric field. The concentration dependent mobility model was applied to describe the carrier mobility variation caused by impurity scattering. Shockley-Rad-Hall recombination and band-gap narrowing models were considered to improve the reliability of the carrier transport calculations.

The transfer characteristics of the p-type SiGe-FinFET were obtained by sweeping the gate voltage, with the condition of fixed drain voltage. From the simulated electrical curves, the hole mobility, drive current (Ion), and threshold voltage (Vth) were extracted for different Ge concentration. By using these parameters, the effect of Ge composition on transistor performance could be also be systemically got.

3. Effect of Ge Concentration on P-Type SiGe-FinFET Characteristics

3.1. Influence of Ge Concentration on Hole Mobility

Hole mobility is one of the most important parameters determining the performance of p-type semiconductor devices [3]. In conventional silicon-based p-channel MOSFETs, the relatively low hole mobility of silicon limits the improvement of device driving capability. Introducing germanium into the silicon channel is an effective approach to overcome the limitation, because Ge possesses a smaller effective mass for holes and a different valence-band structure compared with silicon.

The simulation results show that the increasing of Ge concentration in the SiGe channel, the hole mobility is enhanced. It could be explained through the valence band structure modification and the reduction of the carrier transport restriction [4]. When the Ge content is increased, the energy band characteristic of the channel is gradually close to that of germanium. Therefore, the hole transport capability is improved.

However, hole mobility is not expected to increase indefinitely with Ge concentration. For relatively high Ge concentration, the mobility enhancement is expected to be less important since other scattering mechanisms, like the alloy disorder scattering and the effect related to the interface, can be more and more important. An appropriate concentration of Ge should be taken to be between the mobility improved and the stable material.

The dependence of hole mobility on Ge concentration shows that the SiGe channel engineering is a good way to improve the p type FinFET performance. The Ge composition is optimized to provide the higher carrier transport capability without introducing too much material-related limitation.

3.2. Influence of Ge Concentration on Drive Current (Ion)

Drive current is one of the important parameters for judging transistor switching capability. For p-type device, bigger absolute value of Ion means stronger ability of hole conduction and better circuit performance. Since drive current is related to carrier mobility [6], we expect changes of Ge concentration will affect Ion characteristically.

The enhancement of hole mobility with increasing Ge concentration also leads to the reduction of channel transport resistance. Thus, more holes can be transported through the SiGe channel for the same bias condition, which results in the increase of drive current. The improvement of Ion shows the positive influence of the Ge incorporation to the p-type FinFET performance.

The dependence of the Ge concentration on Ion also shows the point about the optimization of the channel composition. Since in general better carrier transport properties are given by higher Ge concentration, however the too much Ge incorporation may give additional material defects or make the processes more complicated. Then, the maximum of the Ge concentration does not mean the best device performance.

The variation of Ion under different Ge concentration can be used to find out the appropriate Ge composition range where the improved switching capability is obtained but at the same time the device is still operated properly.

3.3. Influence of Ge Concentration on Threshold Voltage (Vth)

Another important electrical parameter, which determines the switching behavior and power characteristics of transistor devices, is the threshold voltage. Unlike its effects on hole mobility and drive current, the influence of Ge concentration on threshold voltage is more complex, as it involves the band structure, carrier distribution, and channel potential.

With the introduction of Ge, the band-gap energy and valence-band are changed of the SiGe channel. When the Ge concentration is changed, the energy difference between the channel and source/drain regions is changed, and so the voltage needed to have a sufficient inversion charge is changed. Finally, in changing the Ge concentration there is a change in threshold voltage.

A moderate variation of Vth is beneficial because it is possible to improved carrier transport without affect much the circuit operating conditions [6]. On the other hand, if the changes in threshold voltage is very big, the leakage current may increase or the noise margin may decrease in CMOS applications. Then, the optimization of the Ge concentration should not only be done for improved mobility, but also for keep a suitable threshold voltage characteristics.

4. Comprehensive Discussion of Ge Concentration Optimization

4.1. Relationship Between Material Composition and Device Performance

As shown in the simulation analysis, the Ge concentration is an important factor for deciding the electrical performance of p-type SiGe-FinFET devices. With increasing Ge content, the hole mobility will be improved by changing the channel band structure, which will be better drive current. For the influence of Ge concentration of threshold voltage, it shows that when we consider the material composition optimization, we need to consider not one electrical parameter but many electrical parameters for the device performance.

Therefore, the design of SiGe channels should make a compromise between high carrier mobility, strong driving capability and stable threshold voltage characteristics. The Ge concentration should be chosen according to the application requirement of high performance CMOS technology.

4.2. Optimization Consideration of Ge Concentration

In conclusion, on the basis of the simulated trends, we can say that SiGe channel engineering is an effective way for improving the p-type FinFET performance. Indeed, an appropriate amount of Ge can be introduced in order to improve the hole transport capability with an acceptable electrical stability.

The results give the theoretical hint for choosing appropriate Ge compositions in the design of the future SiGe-based transistor. In this work the effect of the Ge concentration is considered. Other investigations taking into account the effect of strain engineering, interface quality and the effect of three dimensional device might give more insights in the optimization of the advanced SiGe-FinFET technologies.

5. Conclusion

In this study, we have studied the effect of Ge concentration on the electrical characteristics of p-type SiGe-FinFETs by using the Silvaco TCAD 2020 simulation. The model of the device was two dimensional and we have studied the effects of different Ge concentration mainly for keeping same device geometry, doping profile and operating condition. We have analysed three performance parameters like hole mobility, drive current (Ion), and threshold voltage (Vth), to make the systematic study of relation between Ge composition and device performance.

The results show that the Ge concentration has a great impact on the electrical characteristics of p-type SiGe-FinFETs. When the Ge concentration increases, the hole mobility is increased, because the SiGe channel has better carrier transport capability and the valence-band structure is also modified. The increase of hole mobility will result in a higher drive current, which shows that the Ge incorporation is an effective way for improving the switching capability of p-type devices. Besides, the variation of Ge concentration will also affect the threshold voltage, because the band structure and channel potential are changed. These results suggest that to improve only a single electrical parameter is not sufficient for the device optimization. In fact, an appropriate Ge concentration should be selected to improve the carrier mobility, drive current, and threshold voltage at the same time. In general, it shows that the results demonstrate that the Ge concentration engineering is an effective way for improving the performance of the p-type SiGe-FinFETs and it gives useful theoretical guidance for the design and optimization of the future SiGe-channel CMOS devices.

Nevertheless, this study is a qualitative analysis of the influence of the Ge concentration of the p-type SiGe-FinFET performance and there are some limitations. The simulations were done by using a two-dimensional TCAD model and they are mainly for three electrical parameters. The distributions of the strain, the interface defects and the process variations were not taken into account. It could be also the analysis in the three-dimensional device models and to study the effect of the Ge concentration with the strain engineering, with the high-k gate dielectrics[2] or with different channel structures for the performance of the advanced SiGe-FinFET devices in the future.

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