Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp703-704

PS-3-04

Investigation of Ge Channel Negative Capacitance FET with Analytical Model: Impact of Ferroelectric Dielectrics

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Abstract

We characterized the Ge negative capacitance FETs (NCFETs) integrated with different ferroelectric dielectrics [$Sr_{0.8}Bi_{2.2}Ta_2O_9$(SBT), $PbZrTiO_3$(PZT), and $BaTiO_3$(BTO)] with analytical model. Our study shed light on the importance of the choosing of ferroelectric dielectric and the utilizing of high mobility channel in the NCFETs, which are the effective ways to improve the performances of NCFETs.

1. Introduction

Negative capacitance FET (NCFET) integrated with ferroelectric dielectric can overcome the Boltzmann limit of 60 mV/decade swing at room temperature [1, 2]. Recently, NCFETs have widely investigated experimentally and theoretically [3, 4]. However the existing studies of NCFETs mainly focus on the Si channel technology [5, 6]. The impacts of high mobility channel combined with various ferroelectric dielectrics on the NCFETs performances should be explored.

In this paper, we studied the boosting effects of different ferroelectric dielectrics [$Sr_{0.8}Bi_{2.2}Ta_2O_9$ (SBT), $PbZrTiO_3$ (PZT), and $BaTiO_3$ (BTO)] on Ge p-channel NCFET characteristics with analytical model. Comparison study of surface potential φ_s and inversion charge density Q_i between Ge and Si NCFET were also carried out.

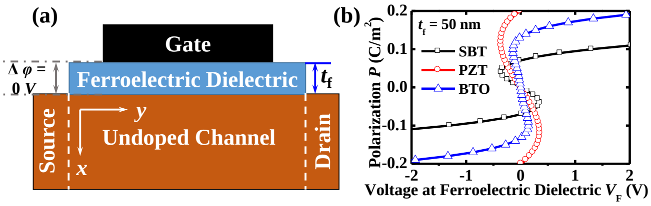

Fig. 1. (a) Schematic of Ge NCFET. (b) P versus V_F characteristics for SBT, PZT, and BTO ferroelectric dielectrics.

2. Structure and the Simulation Methodology

The schematic of the undoped Ge NCFET is shown in Fig. 1(a). As a gate voltage V_G is applied to a NCFET, we have a relation of $V_G - \Delta\varphi - \varphi_s = V_F$ [7], where $\Delta\varphi$ is the work function of the gate electrode differs from the intrinsic semiconductor, and V_F is the voltage drop across the ferroelectric insulator. V_F is given as follows according to Landau-Ginzburg-Devonshire's (LGD) theory [8]:

$$V_F = 2t_f\alpha_0 P + 4t_f\beta_0 P^3 + 6t_f\gamma_0 P^5 \quad (1)$$

Where P is the polarization charge density. In Fig. 1(b), the relations of the V_F and P for SBT, PZT, and BTO are exhibited. α_0, β_0, and γ_0 are the parameters of the ferroelectric dielectrics in the Landau theory [9, 10], which was summarized in the table I. Then, the drain current I_{DS} of NCFET is calculated using the Pao-Sah double integral [11]:

$$I_{DS} = \mu_{eff}\frac{W}{L}\int_0^{V_{DS}}[-Q_i(V)]dV \quad (3)$$

Where μ_{eff} is the effective hole mobility, Q_i is approximately equal to P, and V is quasi-Fermi potential at a point in the channel. Here, μ_{eff} of Ge is 300 cm²/Vs [12].

Table I Parameters of Ferroelectric Materials.

	α_0 (10^7m/F)	β_0 (10^8 m^{5}F/coul^2)	γ_0 (10^9 m^{9}F/coul^4)
SBT	-13	130	0
BTO	-1	-8.9	45
PZT	-4.5	5.2	5.9

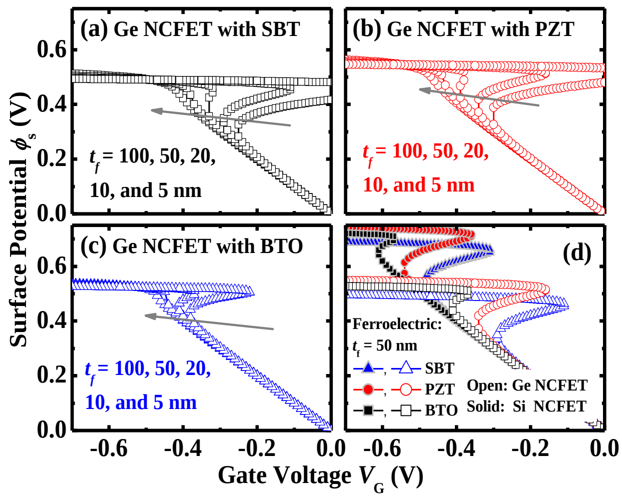

Fig. 2. φ_s versus V_G characteristics for Ge NCFETs with (a) SBT, (b) PZT, and (c) BTO. (d) Ge NCFETs have the smaller φ_s compared to Si transistors at the given ferroelectric dielectrics.

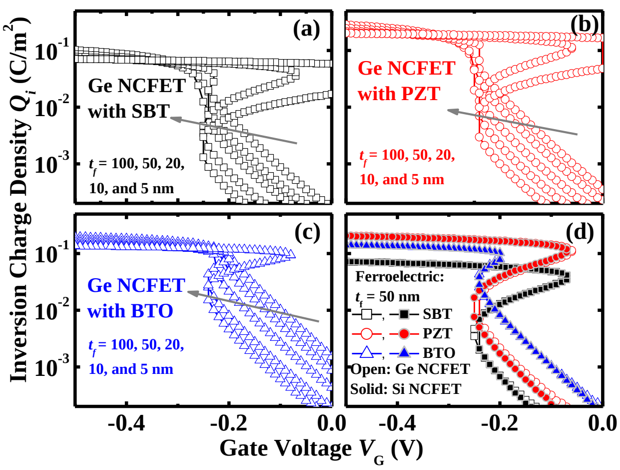

Fig. 3. Q_i versus V_G plots for Ge NCFETs with (a) SBT, (b) PZT, and (c) BTO. (d) Ge NCFETs have the same magnitude of Q_i as Si transistors with the fixed ferroelectric dielectrics and t_f.

3. Results and Discussion

Fig. 2 (a)-(c) shows the φ_s as a function of V_G for Ge NCFETs using the different thicknesses of SBT, PZT, and BTO. As the thickness of ferroelectric dielectric t_f increases, hysteresis occurs, which leads to the abrupt φ_s transition with the forward sweep of V_G. The critical thicknesses for the appearance of abrupt increasing of φ_s is arranging from 10 to 20 nm, depending on the properties of ferroelectric materials. With a given ferroelectric dielectric at the fixed t_f, Ge NCFETs exhibit the hysteresis at a smaller V_G and the significantly reduced φ_s compared to Si devices [Fig. 2 (d)]. In the practical devices, the reduction of φ_s would lead to the μ_{eff} improvement. Fig. 3 depicts the Q_i versus V_G relations of the same NCFETs devices in Fig. 2. Similarly, Q_i spikes as the ferroelectric effect appears with t_f increases. It is noted that Ge NCFETs demonstrate the same magnitude of Q_i as Si devices when hysteresis behavior occurs. This indicates that the Q_i in channel is determined by the ferroelectric dielectric, and channel independent.

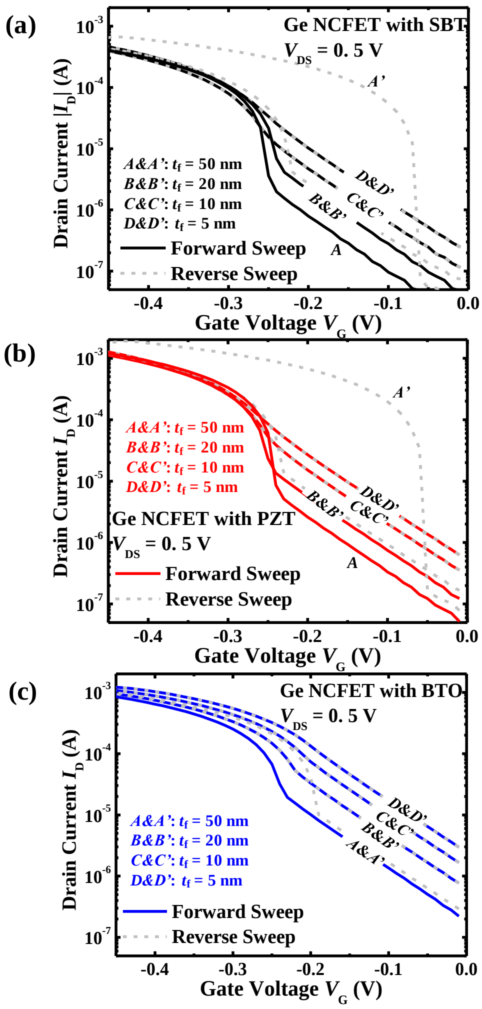

Fig. 4. I_D - V_G characteristics of Ge NCFETs integrated with (a) SBT, (b) PZT, and (c) BTO. t_f of the materials varies from 5 nm to 50 nm. Solid lines are I_D with V_G sweeping upward and dotted lines are sweeping reverse.

Fig. 4 illustrates the transfer characteristics of the Ge NCFETs with different ferroelectric materials and t_f at a $|V_{DS}|$ = 0.5 V. Above a critical thickness (20 nm for SBT, 18 nm for PZT, and 30 nm for BTO), the I_D - V_G curves exhibit

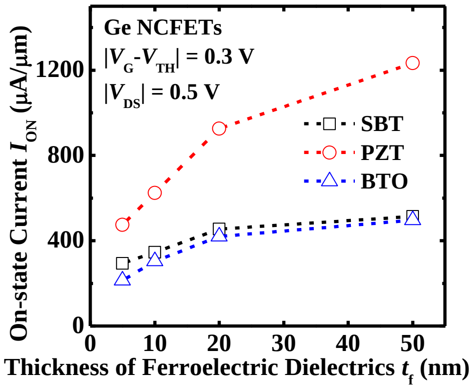

Fig. 5. Comparison of I_{ON} showing that PZT device achieves much higher I_{ON} than SBT and BTO devices. I_{ON} in Ge NCFETs is improved as t_f increases from 5 nm to 50 nm.

the hysteresis behavior. With the t_f be increased, the hysteresis phenomena as well as the I_D are enhanced significantly. The V_G is supplied in forward and reverse directions, the hysteresis loops are clearly observed when the t_f is more than the critical thickness. With an appropriate choosing of t_f, the I_D gain and hysteresis-free can be achieved simultaneously.

Fig. 5 compares the on-current I_{ON} Ge NCFETs with different ferroelectric materials at $|V_{DS}|$ = 0.5 V and $|V_{GS} - V_{TH}|$ = 0.3 V. V_{TH} is defined as V_{GS} in curves in Fig. 4 at I_{DS} of 10^{-10} A/µm. t_f is tuned for each ferroelectric. As t_f increases, I_{ON} of the NCFETs is improved, and the PZT provides a super I_{ON} to the other FE materials. At the give voltages, device with 50 nm PZT achieves an I_{ON} of 1233 µA/µm. This can be concluded from Figs. 2 and 3, which show that compared to PZT and BTO, the PZT device has a higher φ_s and Q_i when hysteresis occurs. With the increase of t_f, although the hysteresis loop is widening, the abrupt increasing of Q_i significantly boosts the I_{ON} of the devices.

4. Conclusions

Ge NCFETs with SBT, PZT, and BTO ferroelectric dielectrics are investigated analytically. We demonstrated that the magnitude of Q_i as the hysteresis occurs is mainly determined by the material properties of ferroelectric. The hysteresis of Q_i results in the abrupt increasing of I_D. With the optimized choosing of ferroelectric and the t_f, the improved and hysteresis-free I_D characteristics can be achieved in Ge NCFET. With fixed t_f, device with PZT has the higher I_{ON} compared to transistors with SBT and BTO.

Acknowledgements

This project was supported by the National Natural Science Foundation of China (Grant No. 61534004).

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