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High Performance Negative Capacitance Field-Effect Transistor Featuring Low Off-State Current, High On/Off Current Ratio, and Steep Sub-60 mV/dec Swing

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Abstract

In this work, we demonstrated that the 5nm-thick $HfAlO_x$ NCFET with optimized Al doping can achieve a minimum 33 mV/dec *SS*, an ultralow I_{off} of 7.44 fA/μm, and a high I_{on}/I_{off} ratio of 1.9×10^8. The experimental results reveal that well-controlled Al doping in $HfAlO_x$ not only reduces off-state leakage of transistor, but also improves ferroelectric NC effect to implement a sub-60mV/dec switching under a favorably low sub-1 voltage. The $HfAlO_x$ NCFET shows the great potential for the application of low power logic devices.

1. Introduction

Due to rigorous requirement of ultralow power consumption for modern electronic devices, it is necessary to lower switching energy of transistor. Recently, the negative capacitance transistors (NCFETs) employing ferroelectric hafnium-oxide-based films had been proposed, which can offer the sub-60 mV/dec subthreshold swing (*SS*) to further reduce V_{DD} [1]-[7]. Furthermore, the leakage issue caused by physical thickness scaling become more significant for implementing the NC effect. However, there is still lack of experimental results for reducing trap-related leakage originated from ferroelectric film and simultaneously implementing sub-60mV/dec operation. Here, we successfully achieve an excellent transistor performance in a NCFET based on a 5nm-thick $HfAlO_x$ film with 8% Al doping. Furthermore, a steep sub-35 mV/dec *SS* and a sub-10 fA/μm leakage can be simultaneously reached under a favorably low overdrive voltage (V_{GS}-V_T) of <1V.

2. Device Fabrication

First, a 1-nm chemical oxide was grown on *p*-type silicon substrates as a buffer oxide. Then, a 5-nm-thick $HfAlO_x$ films with an Al/Hf ratio of 3% and 8% were deposited by atomic layer deposition (ALD). In order to improve the film quality of gate stack, a remote fluorine plasma treatment was performed. After that, a TaN stressed metal was then deposited on $HfAlO_x$ film [3], [4]. Finally, the S/D region were implanted and activated by rapid thermal annealing (RTA). The HRTEM cross-section image of 5nm-thick $HfAlO_x$ NCFETs gate stack is shown in Fig. 1.

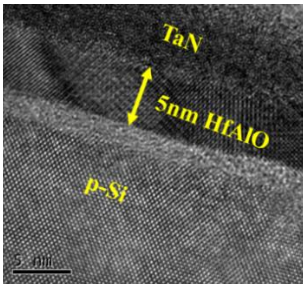
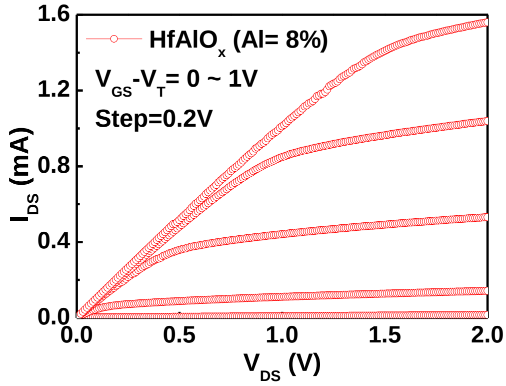


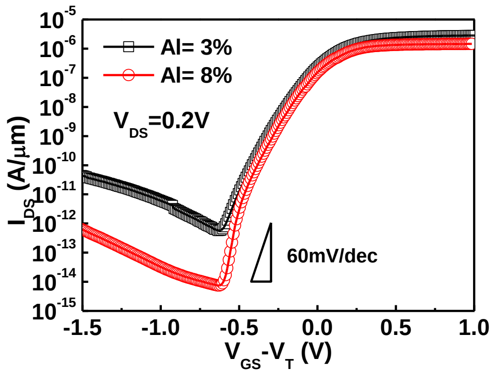
Fig. 1 HRTEM cross-section image of 5nm-thick $HfAlO_x$ NCFET.

3. Results and Discussion

Fig. 2(a) and Fig. 2(b) show the output drain current versus drain voltage (I_{DS}-V_{DS}) and transfer drain current versus gate voltage (I_{DS}-V_{GS}) characteristics of 5nm-thick $HfAlO_x$ NCFET with Al doping of 3% and 8%, respectively. Compared to sample using 3% Al doping, the transfer characteristic of $HfAlO_x$ NCFET using 8% Al doping shows a much lower off-state current (I_{off}) of 7.44 fA/μm, significantly improved by ~2 order of magnitude. Furthermore, a large I_{on}/I_{off} ratio of 1.9×10^8 also can be obtained in $HfAlO_x$ NCFET with 8% Al doping. This is because the phase transition from monoclinic to orthorhombic phase would be enhanced through an increase of Al content. The appropriate Al doping can effectively reduce the shallow traps of $HfAlO_x$ dielectric [3] and also boosts the formation of ferroelectric crystalline phase.



(a)



(b)

Fig. 2 (a) Output I_{DS}-V_{DS}, and (b) transfer I_{DS}-V_{GS} characteristics of 5nm-thick $HfAlO_x$ NCFET with 3% and 8% Al doping.

Fig. 3 shows the SS-V_{OV} and the SS-I_{DS} characteristics extracted from Fig. 2(b). Compared to SS value of 71 mV/dec measured in control sample with 3% Al doping, the 5nm-thick $HfAlO_x$ NCFET with proper 8% Al doping exhibits a steep SS_{min} of 33 mV/dec and a sub-60 mV/dec-SS range spanning over 2 decade of I_{DS}. The excellent SS property is mainly ascribed to ferroelectric NC effect. Besides, the observed ultralow leakage is mainly originated from proper Al doping and fluorine remote plasma passivation.

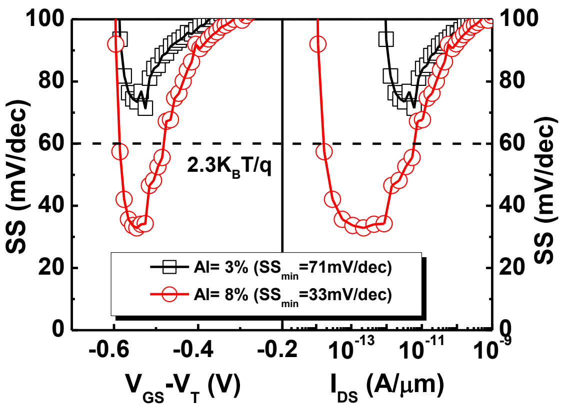
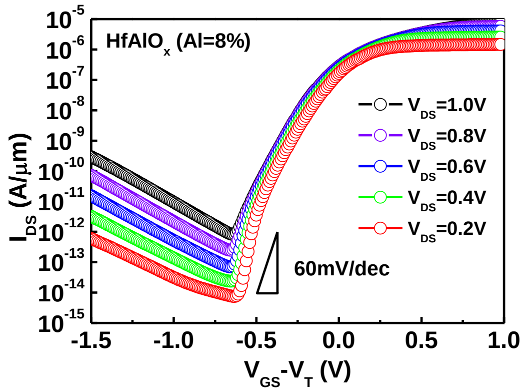
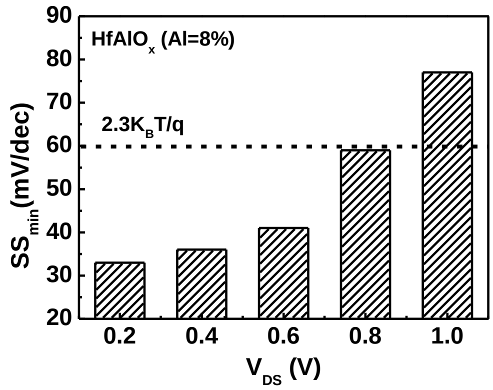


Fig. 3 SS as the function of gate overdrive voltage (V_{OV}) and I_{DS} of 5nm-thick $HfAlO_x$ NCFET with 3% and 8% Al doping.

Fig. 4(a) and Fig. 4(b) show I_{DS}-V_{GS} and SS characteristics (measured by various V_{DS}) of 5nm-thick $HfAlO_x$ NCFET with 8% Al doping. As shown in Fig. 4(b), the NC switching with sub-60mV/dec SS can be maintained from V_{DS}=0.2V to 0.8V due to an ultralow I_{off}. The experimental results reveal that an appropriate Al doping into HfO_2 not only significantly reduces leakage current but also enhances the ferroelectric negative capacitance effect. Table 1 summarizes the important features of state-of-the-art $HfAlO_x$ NCFETs. Our NCFET employing a thinner 5-nm-thick $HfAlO_x$ and 1-nm-thick ultrathin oxide exhibits the excellent transistor characteristics even comparable to recently published NCFET with a 10-nm-thick $HfAlO_x$ [4].



(a)



(b)

Fig. 4 (a) I_{DS}-V_{GS} and (b) SS_{min}-V_{DS} characteristics of 5nm-thick $HfAlO_x$ NCFET with 8%-Al doping.

Table I Comparison for state-of-the-art $HfAlO_x$ NCFETs

NCFETs	$HfAlO_x$ NCFET [4]	**$HfAlO_x$ NCFET (This work)**
FE Thickness	10 nm	**5nm**
IL Thickness	3nm	**1nm**
SS_{min} (mV/dec)	24	**33**
I_{off} (fA/μm)	4	**7.44**
I_{on}/I_{off}	2×10^8	**1.9×10^8**

4. Conclusions

We can understand that the well-controlled Al doping and additional remote-plasma defect passivation significantly affects transistor characteristics of $HfAlO_x$ NCFET, especially in a scaled thickness. An ultralow I_{off} of 7.44 fA/μm, a steep SS_{min} of 33mV/dec and a >10^8 I_{on}/I_{off} ratio can be achieved in our scaled $HfAlO_x$ NCFET under optimization.

References

[1] M. H. Lee *et al*, *IEEE IEDM Tech. Dig.* (2015) 616.
[2] M. H. Lee *et al*, *IEEE IEDM Tech. Dig.* (2016) 306.
[3] C. C. Fan *et al*, *Symp. on VLSI Technology* (2018) 139.
[4] C. C. Fan *et al*, *IEEE IEDM Tech. Dig.* (2017) 561.
[5] Y. C. Chiu *et al*, *IEEE Trans. Electron Dev.* **64** (2017) 3498
[6] C. H. Cheng *et al*, *Phys. Status Solidi-RRL* **11** (2017) 1700098
[7] Y. C. Chiu *et al*, *Phys. Status Solidi-RRL* **11** (2017) 1600368