Impact of thermal annealing and channel thickness on electrical characteristics and instability of ultrathin AlO_x/InO_x FETs

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1. Introduction

Oxide semiconductor (OS) materials, especially for InO_x-based channels, have gained significant attention for BEOL 3D monolithic integration [1], thanks to their low fabrication temperatures and high mobility even in thin body channels [2]. Moreover, vertical OS FET can be realized using ALD system, which offers excellent thickness controllability, uniformity and step coverage. However, a critical issue in OS FETs is the trade-off between device performance and bias instability, which can be mitigated by post-deposition process. In this work, we investigated the effect of annealing in N_2 or O_2 at different temperatures on the performance and bias stability of AlO_x-passivated InO_x (AlO_x/InO_x) FETs with different channel thicknesses. It is considered that excess oxygen [3] and hydrogen incorporation from gate dielectric [4] play a key role on performance and stability degradation.

2. Experiment

Fig. 1(a) shows the cross-sectional schematic of AlO_x/InO_x FETs. The fabrication started with a wet cleaning of SiO_2 (20-nm)/n^+-Si substrates. Then ultrathin InO_x channels and a 9-nm-thick AlO_x passivation layer were sequentially deposited by using plasma-enhanced ALD without breaking vacuum. The active area was patterned by wet etching with HF-based acid. Then, ultrathin AlO_x/InO_x channels were annealed at various temperatures (250°C~400°C) in different ambient atmospheres. The source/drain metal pads were defined by selective wet etching of AlO_x layer and lift-off of 50-nm-thick Ni with single lithography process. Finally, Al metal was deposited at the backside of samples for a better back-gate control.

3. Results and Discussion

Fig. 1(b) shows the cross-sectional STEM image of AlO_x/InO_x channel after device fabrication. The 1.8-nm InO_x channel remains amorphous even after annealing at 300°C in N_2 ambient. The flatness of ultrathin InO_x film is also confirmed thanks to the advantage of ALD process. Fig. 1(c) shows SIMS analysis on the corresponding $AlO_x/InO_x/SiO_2/Si$ structure before and after annealing. Note that the concentration of hydrogen within the InO_x film is reduced after 300°C N_2 annealing, suggesting a reduction in both interstitial hydrogen and In-OH bonding. This might be one of the important factors for improving the bias instability of ultrathin InO_x FETs.

Fig.2 (a) and (b) show the field-effect mobility and positive bias stress (PBS) instability of 1.8-nm-thick AlO_x/InO_x FETs with different annealing condition. For N_2 or air annealing, the mobility value increases as increasing annealing temperature to 300°C, but dramatically decreases when reaching 400°C. This might be due to the severe structural disorder and out-diffusion of hydrogen from InO_x channels during 400°C annealing, leading to the newly generated defect which cannot be passivated by hydrogen [5]. On the other hand, the FET annealed at 400°C outperform other devices with a lower annealing temperature in O_2 ambient. It is assumed that a similar amount of hydrogen out-diffuses from the channel as same as the N_2 annealing case. Therefore, the higher mobility value obtained in a higher annealing temperature can be attributed to the increase in the shallow-state due to the structural relaxation of InO_x channels [6]. For devices annealed in O_2 ambient at a lower temperature, structural relaxation hardly occurs and the excess oxygen at the interface of InO_x/AlO_x leads to the performance degradation as well as the severe PBS instability [3]. Fig. 2(c)-(e) show the results of the constant PBS test of 1.8-nm-, 2.2-nm- and 2.6-nm-thick AlO_x/InO_x FETs after 300°C O_2 annealing, respectively. It is observed that the extremely thin InO_x channel suffers from severe PBS instability due to a stronger impact of excess oxygen at the interface after O_2 annealing. As the channel thickness increases to 2.6 nm, the effect of excess oxygen is largely reduced attributable to the increase in the distance between the interface and channel. Thus, a thicker InO_x channel can relief the effect of excess oxygen, leading to a better bias stability.

4. Conclusions

The impact of hydrogen incorporation from the gate dielectric and the excess oxygen within InO_x channel on electric and stability characteristics of ultrathin AlO_x/InO_x FETs is studied. Importantly, the electrical and stability characteristics of ultrathin AlO_x/InO_x FETs highly depend on the concentration of remaining hydrogen and excess oxygen within channel, which is related to the channel thickness, annealing temperature and ambient atmosphere.

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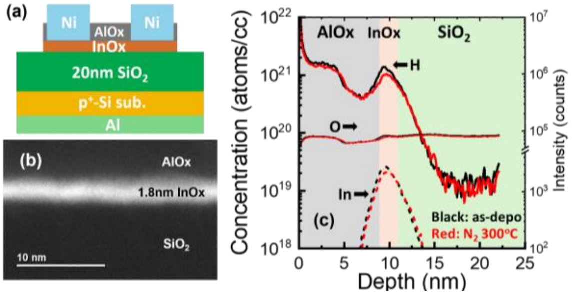

Fig.1: (a) Schematic of AlO_x-passivated InO_x FETs with back gate structure. (b) STEM images of 1.8-nm-thick InO_x channel (c) SIMS analysis on $AlO_x/InO_x/SiO_2$ film before and after 300°C annealing in N_2 ambient.

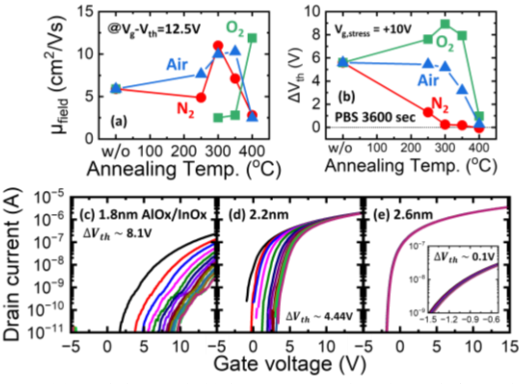

Fig.2: (a) Mobility and (b) bias-stress induced V_{th} shift results of 1.8-nm AlO_x/InO_x FETs with different annealing conditions. Evolution of I_d-V_g curves during constant PBS measurement on (c) 1.8-nm, (d) 2.2-nm, and (e) 2.6-nm AlO_x/InO_x FETs after annealing at 300°C in O_2 ambient.