Design of Al₂O₃/SiO₂ Laminated Stacks with Multiple Interface Dipole Layers to Induce Large Flatband Voltage Shifts of MOS Capacitors

Hironobu Kamata and Koji Kita

Dept. of Materials Engineering, The Univ. of Tokyo, 7-3-1 Hongo, Bunkyo-ku Tokyo113-8656, Japan Phone:+81-3-5841-6124 Email:kamata@scio.t.u-tokyo.ac.jp

Abstract

We studied the dipole induced flatband voltage (V_b) shifts of Si MOS capacitors with the Al₂O₃/SiO₂ laminated stacks designed for a large positive shift of V_b. The observed V_b shift indicates an additivity of multiple interface dipole layers in a stack. The V_b shift in expanded range (>1 V) by multiple dipoles was demonstrated.

1. Introduction

One of the strategies to manipulate the threshold voltage (V_{th}) of advanced MOSFETs is introduction of the high-k dielectric/SiO₂ interface which induces positive or negative flatband voltage (V_{fb}) shift [1]. The amount of V_{fb} shift attainable by a single dipole layer formation is limited, however, a very large V_{fb} shift can be realized if V_{fb} shifts due to the dipole layers at each interface in a multilayer stack are additive. Such expansion of the attainable range of V_{fb} shift will meet the requirement for some applications including power MOSFETs which need high V_{th}. In this study we fabricated laminated stacks with Al₂O₃ and SiO₂ films in turn, as the gate dielectric of MOS capacitors, to demonstrate a possible design of a stack with a very large positive shift of V_{fb} by using additivity of multiple dipole layer effects.

2. Experimental

The Si MOS capacitor with the structure shown in Fig. 1(a) was employed to investigate the additivity of effects of interface dipole layers on V_{fb} shift. We fabricated samples (i), (ii) and (iii) with a various thickness of top layer as Fig. 1(b) to investigate the dipole layers of **interfaces A**, **B** and **C** in Fig. 1(a) respectively. The sample (i) was the stack obtained by 2–8 nm-thick Al₂O₃ deposition by RF sputtering on a thermally grown oxide (5.3 nm-thick), followed by annealing at 800°C in 0.1% O₂ ambient. The sample (ii) was prepared by 2–7 nm-thick SiO₂ growth by the oxidation of Si deposited by electron beam evaporation method, on the same structure as sample (i) with 3nm-thick Al₂O₃ layer. This oxidation was



Fig. 1. (a) Cross section TEM image of the sample (iii). (b) The schematic images of the samples (i), (ii) and (iii).

conducted at 800°C in O₂ ambient. The sample (iii) was fabricated by the deposition of 2–6 nm-thick Al₂O₃ on the same structure as sample (ii) with 3 nm-thick second SiO₂ layer, followed by the annealing under the same condition as sample (i). This structure is shown in the TEM image of Fig. 1(a). Au was deposited on these samples as gate electrodes followed by annealing at 400°C in 1%H₂ ambient. Finally 1 MHz C-V measurements were conducted to determine V_{fb}.

To examine the impacts of the SiO_2 deposition method on the additivity of the interface dipole layer effects, another series of samples were prepared under the same conditions as described above except for employing sputtered SiO_2 instead of the oxidized EB-evaporated Si.

3. Results and discussions

The Al_2O_3 -thickness-dependence of V_{fb} of the sample (i) is shown in Fig. 2(a). The magnitude of dipole effect was determined by comparing the value extrapolated from the observed V_{fb} with 2-8 nm-thick Al₂O₃ to 0 nm, and the V_{fb} without Al₂O₃ deposition indicated as a triangle in the figure. A dipole layer inducing 0.47 V positive shift of V_{fb} was formed at interface A, which is close to the value reported previously [2]. The top SiO₂ thickness dependence of V_{fb} for $SiO_2/Al_2O_3/SiO_2$ structure of sample (ii) is shown in Fig. 2(b). Even though the net V_{fb} shift caused by the interface dipole layer at interface B is not easy to extract accurately due to fixed charges, which were corresponding to trap density to $+1.4 \times 10^{12}$ cm⁻² from the observed slope, it is approximately estimated to be 0-0.2 V to the positive direction. Because the stacking sequence of Al₂O₃ and SiO₂ is opposite to interface A, it would be natural to expect for interface B to form a "counter dipole layer", which induces V_{fb} shift with the same magnitude but the opposite direction to one of interface A, and compensates the V_{fb} shift induced by the dipole layer at interface A. Such compensation of V_{fb} shift due to the counter dipole layer formation was reported previously [3]. In oxygen density model [4], a dipole formation is considered to be triggered by an oxygen density difference at the interface. A possible reason for the lack of the dipole effect of interface B would be the reduction of the abruptness of oxygen density change at the interface due to unintentional intermixing in our processes, as shown in Fig. 3. It is also reported that intermixing of high-k and SiO2 results in a significant reduction of dipole strength [5].

Flatband voltage for sample (iii), where the second Al_2O_3 layer was deposited on the same structure of sample (ii) is shown in **Fig. 2(c)** as a function of top Al_2O_3 thickness. For the region of CET below 11 nm, a sudden increase of V_{fb} was observed corresponding to the formation process of the dipole



Fig. 2. Top layer thickness dependence of the three stacks: (a)Al2O3(various)/SiO2(5.3nm)/Si, (b)SiO2(various)/Al2O3 (3nm)/SiO₂(5.3nm)/Si, and (c)Al₂O₃(various)/SiO₂(3nm) /Al₂O₃(3nm)/SiO₂(5.3nm)/Si. The data for the stack without top layer (0nm) are also shown by triangles.



Fig. 3. Schematic of the proposed the reason why the dipole layer was not formed at interface B.

The interface with a small oxygen density difference would have a weak driving force to form a dipole.

layer. On the other hand, for the region of CET above 11 nm, V_{fb} turned to decrease gradually due to the existence of positive fixed charges, after the complete dipole layer formation. From this figure we can conclude V_{fb} shift caused by the dipole layer at interface C as approximately 0.8 V to the positive direction. The V_{fb} values of samples (i), (ii) and (iii), with 3 nm-thick top layers are summarized in Fig. 4. It should be noted that the sample (iii) achieves 1.2 V positive V_{fb} shift from the initial SiO₂/Si stack. Note that such a positive V_{fb} shift cannot be explained by the effects of fixed charges, because the net fixed charges were positive as indicated by the slope of Fig. 2(c). It is reasonable to attribute the observed



Fig. 4. Summary of observed V_{fb} of the samples (i), (ii) and (iii) with each of 3 nm-thick top layer.

large V_{fb} shift to the additivity of the shifts due to the multiple interface dipoles.

Next, to examine the impacts of SiO₂ deposition method on the additivity of the dipole layers, we fabricated another series of samples employing sputtered-SiO₂. For this experiment laminated stacks with triple Al2O3/SiO2 interfaces were fabricated to demonstrate further additivity of multiple dipoles. The top Al₂O₃-thickness-dependences of V_{fb} for the stacks with single, double, and triple Al₂O₃/SiO₂ interfaces are summarized in Fig. 5. The positive shift of V_{fb} by increasing the number of Al₂O₃/SiO₂ interfaces was clearly observed. The additivity of dipole layers was commonly observed irrespective of the film deposition techniques. The relatively less magnitude of V_{fb} shift compared with the one in Fig. 4 would be attributed to a difference of SiO₂ film quality.



Fig. 5. Top layer thickness dependence of V_{fb} of three stacks: Al2O3/SiO2/Si, Al2O3/SiO2/Al2O3/SiO2/Si, and Al2O3/SiO2/Al2O3/SiO2/Al2O3/SiO2/Si stacks using sputtered-Al₂O₃ and sputtered-SiO₂.

4. Conclusions

We have demonstrated an expanded V_{fb} shift (>1 V) in Al₂O₃/SiO₂ laminated stacks, where the effects of multiple interface dipole layers are additive and the dipole formation with unwanted direction is suppressed by the control of deposition conditions. This method is applicable for a Vth tuning in a wide range.

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Reference

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