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Short Communication

Deposition of High-k Samarium Oxide Membrane on Polysilicon for the Extented-Gate Field-Effect Transistor (EGFET) Applications

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Abstract: *The paper reports samarium oxide as pH. sensing membrane on polysilicon combined with proper post deposition annealing for the extended-gate field-effect transistor (EGFET) application at the first time. It can be found that the high-k samarium oxide membrane annealed at 700 ºC could obtain high sensitivity, high linearity, low hysteresis voltage, and low drift rate due to improvements of crystalline structures. The high-k Sm_2O_3 sensing membrane shows great promise for future bio-medical device applications.*

Keywords: EGFET, Annealing, Samarium oxide, Hysteresis effects, pH. sensor

1. INTRODUCTION

The first ion-sensitive field effect transistor (ISFET) was proposed by Bergveld [1]. The basic design of the ISFET is the combination of the electrolyte and the SiO_2 as the sensing membrane replacing the traditional metal gate to form the electrolyte-insulator-semiconductor structure. The shift of the threshold voltage provides information of the ion concentration change on top of the sensing membrane. For traditional ISFET, the chemical solutions may influence the device reliability greatly due to integration of FET device and the sensing membrane because the impurities in solutions can penetrate into the FET. The disadvantage can be avoided by separating the device and the sensing membrane. The design of extended-gate field-effect transistor (EGFET) divides the original ISFET into two parts- the FET isolated from the chemical solutions and the sensing membrane [2]-[4]. The sensing membrane is connected to the signal line extended from the FET electrode. In addition to the mentioned reliability improvement, the EGFET is simple to package with high flexibility in the extended gate shape and light insensitivity.

With advancement of Si-based semiconductor technology, high–k dielectrics as the insulator of sensing membranes have attracted much attention after Matsuo et al. demonstrated Ta_2O_5 as pH. sensing membrane in 1981 [5]. Owing to low cost, rapid response, and small device size, researchers have investigated high-k dielectrics such as Al_2O_3 [6], SnO_2 [7], WO_3 [8] for hydrogen ion sensing material in Si-based ISFET sensors. Since the high-k membrane has deficiencies due to its innate defect. It is worthwhile to explore alternative material compositions, processes, and treatments to mitigate the deficiencies. Until now, intensive studies have investigated alternative material compositions, processes, and treatments for better ion sensing performance, smaller hysteresis, lower drift and higher stability for future bio-medical applications. Among the alternative materials for replacing conventional silicon dioxides, samarium oxide (Sm_2O_3), which has low interfacial state, high thermal conductivity, large band offset with Si, and good adhesion, is a potential candidate of pH. sensing membrane for future configuration. Usually, a thin SiO_2 on the bottom of the high-k insulator was deposited to lessen interfacial defect and enhance adhesion. Exempting from this additional process with the conventional Si substrate fabrication, this research deposited Sm_2O_3 directly on top of the polysilicon substrate [9], which is of potential use for future TFT applications, by RF sputtering as an alternative method. In this research, we fabricated a novel Sm_2O_3/polysilicon-based EGFET. Moreover, the device performance was improved with proper post annealing RTA treatment. The results indicate the membrane with an annealing temperature

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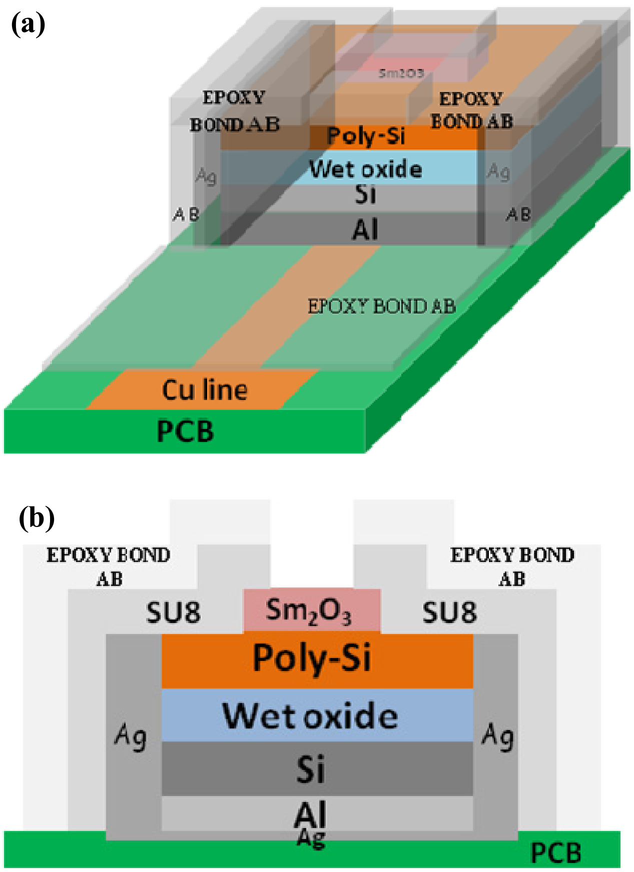

Figure 1. (a) The schematic diagram and (b) cross section of the Sm_2O_3 pH-sensing membrane deposited on polysilicon for EGFET application.

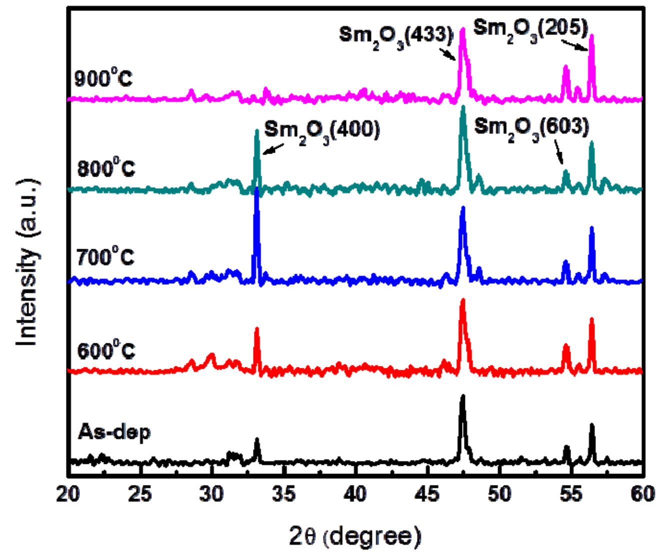

Figure 2. XRD of the Sm_2O_3 film after post-RTA annealing at various temperatures in N_2 ambient for 30 sec.

at 700 ºC could cause the EGFET to achieve a good sensing response of 48.22 mV/pH.

2. EXPERIMENTAL METHODS

The high-k samarium oxide sensing membrane was fabricated on an n^+ polysilicon/oxide/p-type silicon substrate. At first, the p-type silicon wafer was first cleaned with a regular RCA clean process, dipped in dilute HF solution to remove the native oxide, followed by thermal oxidation with an oxidized layer of 600 nm. Then, a polysilicon film of 300 nm was deposited at 625 ºC by a low pressure chemical vapor deposition (LPCVD) system. After the chip was implanted with phosphorous at a 5×10^{15} cm^{-2} dosage and 30 keV energy activated for 30 sec in an N_2 ambient at 950 ºC to obtain a sheet resistance of 70~80 Ω/sq, tapes were used to define a generally sensing area. A 25 nm high-k Sm_2O_3 sensing membrane was sputtered on the polycrystalline silicon layer in diluted O_2 ambient (Ar/O_2=20/5) at 150W power and 2×10^{-2} torr pressure by a RF Sputtering system. To reinforce the material structure and reduce the defects, post deposition rapid thermal annealing (RTA) for 30 sec in an N_2 ambient at different temperatures from 600-900 ºC was used. After the RTA treatment, the native oxide was removed by BOE solution, an aluminum layer was evaporated on top of the sensing membrane and on the backside. Finally, coating the electronic conductive from the top sensing membrane to the bottom Al, and the sensing area was defined by a photosensitive epoxy, SU8-2005 of *MicorChem Inc*. in standard photolithography. The schematic diagram and cross section of the high-k Sm_2O_3 sensing membrane deposited on poly-silicon for EGFET application are shown in Fig. 1(a) and (b). To find the optimal annealing condition and explain the improvements of the membrane performance, XRD analysis was applied since the material quality reliability were closely related to pH. detection capability. Consistent with the material analysis, pH. sensitivity, hysteresis, and drift rate were evaluated to find the most favorable annealing temperature of 700 ºC. To measure the sensing response, the I-V curves of the sensing membranes without annealing immersed in buffer solution of various pH values and the pH sensing capability extracted from the I-V curve.

3. RESULTS AND DISCUSSION

This study investigated the crystalline structure of the Sm_2O_3 with XRD spectra in the range of diffraction angle 2θ from 20° to 60° in various annealing conditions. Fig. 2 shows the XRD spectra of the high-k Sm_2O_3 film for the as-deposited and different RTA temperature samples.The crystalline Sm_2O_3 phase was observed for all samples from the peaks of XRD with four diffraction peaks (400), (433), (603), and (205) clearly presented at 33.1º, 47.4º, 54.6º and 57.4°. As the post-RTA increased to a proper temperature of 700 ºC, the intensity of peak (400) was the strongest, indicating a (400)-oriented Sm_2O_3 structure in comparison to the as-deposited sample and the sample annealed in all the other temperatures. The high-k Sm_2O_3 dielectrics with post-RTA treatment at 700 ºC featured a well-crystallized and strong Sm_2O_3 structure suitable for the sensor application.

After we examined material quality, the performance of device was investigated in terms of pH. sensitivity, pH. linearity, hysteresis and drift rate, since the sensing membranes without good stabil-

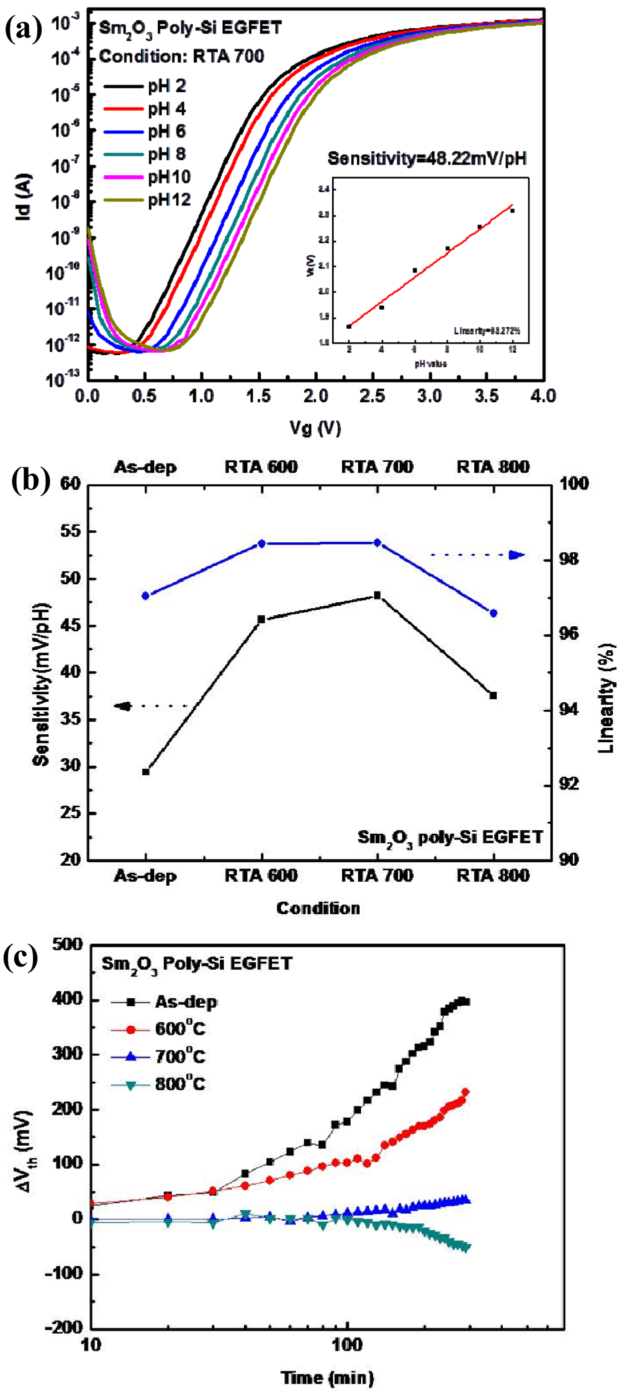

Figure 3. (a) The sensitivity and linearity of Sm_2O_3 poly-Si EGFET with post-RTA 700 ºC treatment.

(b) The sensitivity and linearity of Sm_2O_3 poly-Si EGFET with different post-RTA conditions.

(c) The drift rate of the as-deposited sample and the sample annealed at 600,700 and 800 ºC.

ity can not be used for commercial product. First, I-V curves of the sample for various pH. buffer solutions of Merck Inc. were meas-

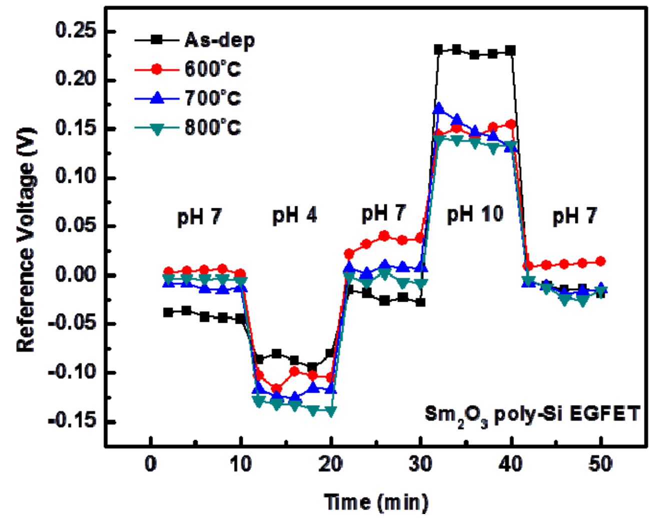

Figure 4. Hysteresis effects of Sm_2O_3 poly-Si EGFET in different post-RTA annealing conditions.

ured with a substrate bias through Ag/AgCl reference electrode (RE) by Keithley 4200 meter, and all setups were shielded in dark box. To stabilize the surface reaction, all EIS samples were immersed in the RO water for 12 hours. The reference electrode (RE) were immersed in the pH 2 buffer solution for 30 seconds, and then I-V curves were taken from the device annealed at 700 ºC immersed for 30 seconds in buffer solution with various pH. values as shown in Fig. 3 (a). The sensitivity and linearity of the Sm_2O_3 device annealed at 700 ºC extracted from the I-V curves is also shown in Fig. 3(a), indicating the sensitivity and the linearity of the device are about 48.22 mV/pH and 98.472 %. To compare with the devices annealed in all the other conditions, the sensitivity and the linearity values of all the devices are shown in Fig 3(b), revealing that the pH. sensing membrane annealed at 700 ºC with the best material and electrical properties could achieve the most preferable sensing capability among all the devices. Besides, the drift rate of the Sm_2O_3 sensing membrane for the as-deposited and RTA annealed samples at 600 ºC, 700 ºC, 800 ºC is shown in Fig. 3(c). Finally, for long-term use of the sensor device, the drift effect of Sm_2O_3-EIS was analyzed by discrete I-V measurement in pH. 7 buffer solution for 5 hours immersion. The drift rate of the as-deposited sample and the sample annealed at 600, 700 and 800 ºC were 79.22, 46.232, 7.058 and 10.32 mV/hr, respectively. In long-term measurements, the sensing membrane might react with H_2O and have weakly bonded ion on the surface of sensing membrane. Therefore, the traps and the dangling bonds on the surface of the membrane may gradually capture clusters of ions on the surface which cause the reference voltage drift of the device [10][11]. RTA annealing could remove the trap and passivate the dangling bonds.

Furthermore, to assure the availability for practical use, the hysteresis effect of the devices in different annealing conditions was evaluated. The tested samples were immersed in solutions of different pH. values in a sequence. The sequence of the solutions is pH.7, pH.4, pH.7 and pH.10 in a chronological order and the immersion time is 10 minutes for each solution. The hysteresis measurements in Fig. 4 presents that the device annealed at 700 ºC had the least hysteresis voltage among all the devices. According to the previous study [10][11], the porous structure might temporarily hold the reacting ions during the pH. value transition and cause the hysteresis effect due to the delay of the reference voltage response. The proper annealing at 700 ºC might stabilize the bond strength, fill in the holes and eliminate the porous structure. The study shows Sm_2O_3 membrane annealed at 700 ºC with good electrical reliability could attain the most favorable pH. sensitivity, linearity, hysteresis voltage and drift rate. To compare with sensing membrane made up of different other high-k materials, Table 1 shows the sensitivity and drift rate of the membrane of different materials [12][13].

4. CONCLUSION

The high-k samarium oxide/polysilicon-based EGFET was demonstrated for the first time.This research concludes the high-k Sm_2O_3 sensing membrane deposited on poly-Silicon with improved material quality with RTA treatment could achieve high sensitivity, higher linearity, low hysteresis voltage, and low drift ratio. The optimal annealing condition is 700 ºC. In this condition, material analysis and sensor performance had the most preferable properties. The reliability and the response pH sensing of this system are close to or better than the recently reported polysilicon-based pH sensor. For furture biomedical applications, the following work will focus on multianalyte sensing capability of the Sm2O3/polysilicon-based EGFET. The Sm_2O_3 sensing membrane shows promise for future commercial sensor applications.

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Table 1. Sensing performance comparison Table

Sensing membrane	pH sensitivity (mV/pH)	Drift rate (mV h^{-1})
Si_3N_4	46-56	0.8
Al_2O_3	52-58	0.3
Ta_2O_5	56-58	<2
WO_3	45-56	7.2-26
HfO_3	45-58	2.5-125
Gd_2O_3 (poly EGFET)	37-46	<3
Sm_2O_3 (poly EGFET)	30-48	<7.1