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Photoresponse of Phase Separated Hafnium Silicate in Metal-Insulator-Semiconductor Structure

Chuan-Feng Shih*, Chu-Yun Hsiao, Cheng-Bo Shu, Kuang-Teng Hung, and Wei-Min Li

Department of Electrical Engineering, National Cheng Kung University, 1 University Road, Tainan, 70101, Taiwan
Phone: +886-6-2757575 ext.62398 Fax: +886-6-2080687 E-mail: cfshih@mail.ncku.edu.tw

1. Introduction

Although Si has been widely used in the integration circuit technology, optoelectronic applications are limited due to its indirect band gap. Recently, nano-scaled Si has shown great potential for photonic devices. A metal-oxide-semiconductor (MOS) structure containing nano-crystalline Si in the oxide layer has been reported to benefit the memory, electroluminescent, photovoltaic and photodetector devices. [1-8] Enhanced spectral photoresponse were found due to the Si nano-crystal embedded within the oxide layer.

As high permittivity dielectric materials, hafnium oxide and hafnium silicate are expected to replace the SiO_2 gate oxide. Extensive research focused on the electrical properties of the hafnium silicate. Particularly, phase-separated hafnium silicate shows excellent charges trapping property that could replace the conventional silicon nitride trapping layer in a memory device. [9] However, there is no report considering the optical properties of the hafnium silicate based devices. The trapped states might attribute to the photocurrent transport.

In this paper, the photoresponse of the phase separated $Hf_{0.5}Si_{0.5}O_2$ as the oxide layer in a MOS device is investigated. Effects of the annealing temperature and time on the photoresponsivity are studied. High photoresponsivity and light /dark current ratio of ~1 A/W and $\sim 7\times10^3$, respectively, are observed for samples annealed at 1100 °C for 5 min. A possible transport mechanism is also discussed.

2. Experimental details

P-type (100) Si wafers (0.01-0.09 $\Omega-cm$) were used as the substrate. Following the standard cleaning procedure, 200 nm-thick $Hf_{0.5}Si_{0.5}O_2$ was deposited by co-sputtering in Ar/O2 ambient (Ar : O2 = 20 : 5 sccm). The rf-power and dc-power for Si and Hf targets sputtering were the same (50 W). The background and working pressures during sputtering were 1×10^{-6} and 2×10^{-3} torr, respectively. The as-prepared films were annealed in furnace at elevated temperatures (500, 900, 1100°C). Thermally evaporated Al was used as the top and bottom contacts. The current-voltage (I-V) curves were acquired using Agilent semiconductor parameter analyzer (E5270B mainframe with module E5287A). A monochromatic white light source (Newport-Oriel) with (~225 μW /cm^2 at 820 nm) was used to irradiate the samples.

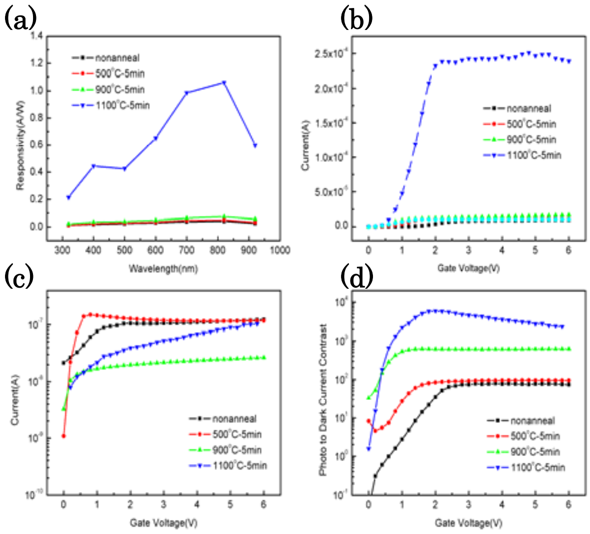

Fig. 1 Effects of annealing temperatures on (a) photoresponse of the Al/ $Hf_{0.5}Si_{0.5}O_2$/p-Si MOS detectors, (b) light current, (c) dark current, and (d) photocurrent/dark current ratio.

3. Discussions

Figure 1(a) shows the measured photoresponse in the range of 320-920 nm for the Al/ $Hf_{0.5}Si_{0.5}O_2$/p-Si MOS devices at -5 V bias. When the annealing temperature achieved 1100°C, the photocurrent markedly enhanced. An obvious photoresponse in the vicinity of ~820 nm was observed. Focusing at the most sensitive wavelength (820 nm), light current (Fig. 1(b)) increased and dark current (Fig. 1(c)) decreased with annealing temperature. The photocurrent was derived by subtracting the dark current from light current. The ratio of photocurrent to dark current was shown in Fig. 1(d). The observed high photoresponsivity (>1 A/W) and high photocurrent to dark current ratio (7×10^3) was comparable to that of the nc-Si based MOS detector. [7]

Figure 2 shows the influence of annealing time upon the photoresponse. Effect of prolonging the annealing time was similar with increasing the annealing temperature. However, reduction of photocurrent was observed when the annealing time exceeded 10 min. Optimized annealing time of ~5 min was found.

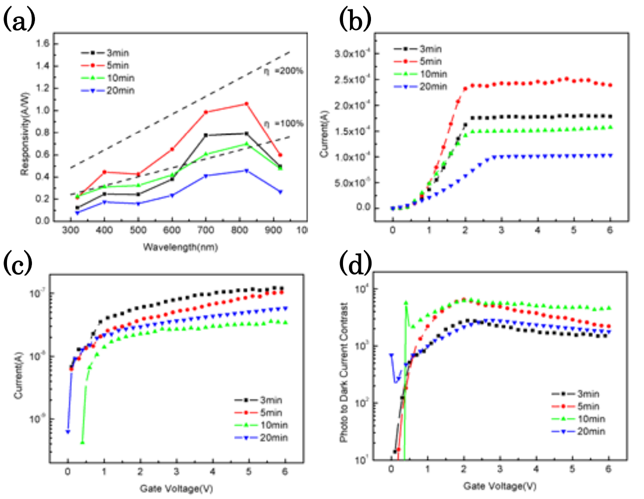

Fig. 2 Effects of annealing time (a) photoresponse of the Al/ $Hf_{0.5}Si_{0.5}O_2$/p-Si MOS detectors, (b) light current, (c) dark current, and (d) photocurrent/dark current ratio.

In order to clarify the transport behavior of photo-generated carriers within the devices, I-V curves measured under different temperature were performed. The ln(J/E) versus 1/T curves, plotted in Fig. 3, are fitted well by the Poole-Frenkel (P-F) emission model, which is given by, [10]

$$J \propto E \exp\left[\frac{-q(\phi_B - \sqrt{eE/4\pi\varepsilon_r\varepsilon_0})}{kT}\right]$$

where J is the current density, k is the Boltzmann constant, h is the Planck constant, E is the electric field, ε_r is the relative dielectric constant, and ϕ_b is the barrier height of the trap. This result indicates that the electron transport through the defect states within the oxide layer started when the electric field exceeded their activation energies. From the linear fit of P-F model, the bias-independent activation energy was estimated (~0.5-0.6 eV), indicating a shallow defect level exists within the oxide layer.

Transmission electron microscopy (TEM) image of the $Hf_{0.5}Si_{0.5}O_2$ layer annealed at 1100°C for 5 min was shown in Fig. 4. Random distributed HfO_2 nanocrystals were clearly resolved. The defects induced from annealing might be due to phase separation, attributing to the electron transport through the oxide layer.

4. Conclusion

This work demonstrated the photoresponse of the phase separated $Hf_{0.5}Si_{0.5}O_2$. Effects of the annealing temperature and time on the photoresponsivity were studied. High photoresponsivity and light /dark current ratio of ~1 A/W and $\sim 7\times10^3$, respectively, were observed for samples annealed at 1100 °C for 5 min. The observed strong photoresponse were attributed to the defects induced transport due to phase separation.

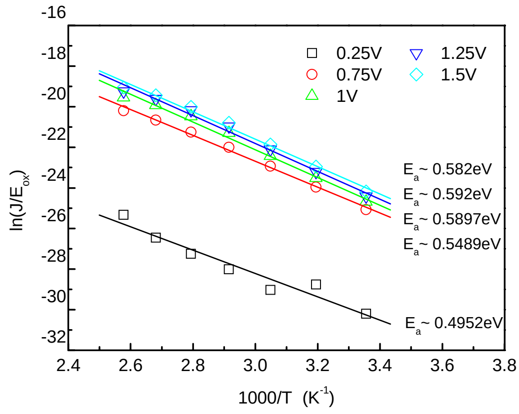

Fig. 3 Linear fitting of the ln(J/E) versus 1/T curves for Al/ $Hf_{0.5}Si_{0.5}O_2$/p-Si devices with different gate bias.

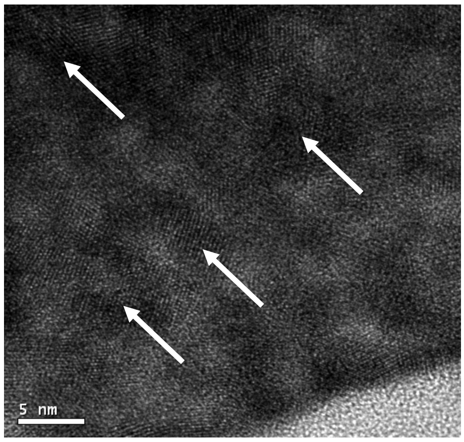

Fig. 4 TEM image of the $Hf_{0.5}Si_{0.5}O_2$ layer annealed at 1100°C for 5 min.

Acknowledgements

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