Effective mobility and interface-state density of La_2O_3 nMISFETs after post deposition annealing

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Abstract: In this paper, we reported the effective mobility and the interface-state density of La_2O_3 nMISFETs fabricated under different post deposition annealing (PDA) conditions; annealing temperature ($300^\circ\text{C} - 600^\circ\text{C}$) and ambient (N_2 or O_2). High effective mobility of $312\text{ cm}^2/\text{Vs}$ and low interface-state density of $6 \times 10^{10}\text{ cm}^{-2}/\text{eV}$ were obtained from La_2O_3 nMISFET with equivalent oxide thickness (EOT) of 1.7 nm after PDA at 300°C in N_2 ambient for 10 minutes. Gate leakage current density was $6.8 \times 10^{-6}\text{ A/cm}^2$. We found that peak effective mobility decreased with increasing anneal temperature, regardless of annealing ambient. We also observed a monotonous relationship between effective mobility and interface-state density. This behavior suggests that lowering the interface-state density is essential to obtain high mobility in the high- κ /Si structure.

Keywords: La_2O_3 , PDA, nMISFET, mobility, interface-state density

Classification: Electron devices

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1 Introduction

It has been well recorded in various versions of International Technology Roadmap for Semiconductor (ITRS) the importance and the need for alternative high dielectric constant materials to replace silicon dioxide (SiO_2) as the gate insulator in future MOSFETs to keep the leakage current within the acceptable level [1]. According to the ITRS 2005, high- κ gate insulator will be needed as early as 2008 for the 57 nm half-pitch generation [2]. This is because the progress in reducing silicon oxynitride thickness below 1 nm thickness (in equivalent oxide thickness) is considered to be impracticable because of high leakage current [2].

Hafnium (Hf) based family of high- κ materials has been attracted much attention and has been intensively studied during the past few years and ready to be used in production starting in year 2008. And the immediate question is which material is the candidate to replace Hf-based oxides in the future? According to the ITRS, lanthanum oxide (La_2O_3), which is a member of rare earth oxide (REO), was classified into the next group of potential

candidates to succeed Hf-based oxides [2]. Thus, La_2O_3 has attracted much attention in recent years and detailed analyses were reported [3, 4, 5, 6, 7, 8, 9].

However, effect on effective mobility and interface trapped charge at $\text{La}_2\text{O}_3/\text{Si}$ interface after low temperature post deposition annealing (PDA) remains unclear at present. In this paper, we reported the effects of annealing conditions on these properties.

2 Experiments

Ultrathin La_2O_3 films were deposited on HF-treated p-Si(100) surface with preformed source and drain regions by electron-beam evaporation in ultra-high vacuum (UHV) chamber. The pressure and temperature during the deposition were 10^{-7} Pa and 250°C , respectively. The *Ex-situ* post deposition annealing (PDA) was conducted in the rapid thermal annealing (RTA) chamber with 1.2 l/min flow rate at temperature ranging from 300°C to 600°C in either N_2 or O_2 ambient for 10 minutes prior to the Al gate electrode evaporation using bell-jar type evaporator at 10^{-5} Pa. Gate length and width of the nMISFET were 10 and $57\ \mu\text{m}$, respectively.

Effective mobility and interface-state density were evaluated through measurements of I-V, split C-V [10] and square-pulse charge pumping [11] techniques, respectively. Agilent 4284A multi-frequency LCR meter, Agilent 4156C semiconductor parameter analyzer and Agilent 41501B SMU and pulse-generator expander were used for the above mentioned electrical characteristics measurements.

3 Results and Discussions

Figure 1 shows the I_d - V_d (A) and I_d - V_g (B) characteristics of the fabricated La_2O_3 nMISFET. The annealing was done at 300°C in N_2 ambient for 10 minutes. Well behaved I_d - V_d and I_d - V_g characteristics were observed. Extracted subthreshold slope and threshold voltage by linear extrapolation method are 78 mV/decade and $-0.30\ \text{V}$, respectively. Due to the negative threshold voltage (V_{th}) shift, the transistor is ON at $V_g = 0\ \text{V}$, demonstrating a “Normally ON” characteristic. This behavior, representing generation of positive fixed-charge, maybe attributed to oxygen vacancies [10]. Flatband voltage (V_{fb}) shifted to similar direction was also found on the C-V curve [7].

Figure 2 illustrates the effective mobility (μ_{eff}) for both N_2 (A) and O_2 (B) annealed samples. From both (A) and (B) figures, we observed that the peak effective mobility decreased with increasing annealing temperature in both N_2 and O_2 ambient. Peak mobilities of $312\ \text{cm}^2/\text{Vs}$ and $244\ \text{cm}^2/\text{Vs}$ were obtained from the samples annealed at 300°C in N_2 and O_2 ambients, respectively. The peak mobility of $312\ \text{cm}^2/\text{Vs}$ that we obtained is higher than the previous reported values [7, 8]. The leakage current density is $6.8 \times 10^{-6}\ \text{A}/\text{cm}^2$ at $EOT = 1.7\ \text{nm}$ (PDA at 300°C in N_2 ambient for 10 minutes), which is $10^{-3}\ \text{A}/\text{cm}^2$ lower than the published values for HfSiON [12]. We also observed that at the same annealing temperature ($300 - 500^\circ\text{C}$), N_2

Fig. 1. I_d - V_d (A) and I_d - V_g (B) characteristics of fabricated Al gate La_2O_3 MISFET with PDA treatment at 300 °C for 10 minutes in N_2 ambient.

annealing samples gave better peak mobility as compared to O_2 annealed samples. This trend can be explained in two ways; fixed-charge or interface-state density. We found that at the same PDA temperature and duration, N_2 ambient is more effective in reducing fixed-charge than O_2 ambient [9]. We also found that the magnitude of flatband voltage (V_{fb}) of N_2 annealed samples shifted negatively lesser than O_2 annealed samples on all studied temperatures (results not shown). This suggests that N_2 annealed samples has lower amount of fixed-charge than O_2 annealed samples. Thus, reducing Coulomb scattering toward the Si channel and improves the effective mobility.

Fig. 2. Effective mobility of N_2 (A) and O_2 (B) annealed La_2O_3 MISFETs of different PDA temperatures.

The other reason is the interface-state density at $\text{La}_2\text{O}_3/\text{Si}$ interface. Figure 3A show charge pumping profiles of N_2 and O_2 annealed samples at 300 °C, measured at 100 KHz by using square-pulse with pulse amplitude of 2.2 V. We found that maximum charge pumping current (Max I_{cp}) of N_2 annealed sample is much lower than O_2 annealed sample, after PDA at 300 °C.

Similar behavior is also found on samples annealed at 400 °C and 500 °C, respectively (see Fig. 3 B). Calculated interface-state density (D_{it}) from Max I_{cp} was $6.0 \times 10^{10} \text{ cm}^{-2}/\text{eV}$ and $2.4 \times 10^{11} \text{ cm}^{-2}/\text{eV}$ for the samples annealed at 300 °C in N_2 and O_2 , respectively. The low interface-state density value is comparable to previous reported value and is extremely important for circuit to lower 1/f noise [7]. Figure 3 B shows the relationship between peak mobility and interface-state density for all PDA conditions. We found that the peak mobility increases with reducing of interface-state density. The increasing of interface-state density (or the decreasing of peak mobility) is found to be proportional to the increment of annealing temperature, regardless of annealing ambient. The formation of La-silicate at the $\text{La}_2\text{O}_3/\text{Si}$ interface at higher annealing temperature, confirmed by the XPS [3], might resulted in increment of interface-state density (as observed in Fig. 3 B), which in turn degrades the effective mobility in La_2O_3 nMISFET. Nevertheless, this monotonous relationship demonstrates the important of high quality interface in high- κ/Si interface. Same monotonous relationship was also found in Fig. 3 C, where

Fig. 3. (A) shows the charge pumping profiles of N_2 and O_2 annealed samples at 300 °C. Calculated interface-state density was $6.0 \times 10^{10} \text{ cm}^{-2}/\text{eV}$ (N_2) and $2.4 \times 10^{11} \text{ cm}^{-2}/\text{eV}$ (O_2), respectively. A monotonous relationship between effective mobility (peak mobility (B) and mobility at 0.8 MV/cm (C)) and interface-state density was observed.

effective mobility value at 0.8 MV/cm (high field region) was plotted against the interface-state density. Mobility of $281\text{ cm}^2/\text{Vs}$ at 0.8 MV/cm, which is approximately 90% of the universal curve was obtained [13], shows very promising result because practically almost all electronic devices are operating at high field region. The high mobility and low interface-state density achieved so far indicate that La_2O_3 have the potential to succeed Hf-based oxides in the future.

4 Conclusion

The effects of low temperature post deposition annealing (PDA) conditions; annealing temperatures ($300^\circ\text{C} - 600^\circ\text{C}$) and ambient (N_2 or O_2) on effective mobility and interface-state density were investigated in details. We found that peak mobility degraded when annealing temperature increased regardless of annealing ambient. The optimum temperature for both N_2 and O_2 ambient is at 300°C , where maximum peak mobility and minimum interface-state density were achieved. We also found that N_2 is more effective in improving the mobility and providing better interface property than O_2 under the studied temperatures. Peak mobility and interface-state density of $312\text{ cm}^2/\text{Vs}$ and $6.0 \times 10^{10}\text{ cm}^{-2}/\text{eV}$ were obtained after PDA at 300°C in N_2 ambient. Monotonous relationships were found when mobility (peak mobility and mobility at 0.8 MV/cm) were plotted against interface-state density. The above observed monotonous relationships demonstrated that low interface-state density is keys to achieve higher mobility for high- κ /Si structure. These promising results clearly demonstrate that La_2O_3 has the potential to be succeeded Hf-based oxides as the future gate oxide. However, further improvement is still needed, especially in improving the thermal stability in deep-sub 1 nm oxide region.

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