Electrical characteristics and reliability properties of metal-oxide-semiconductor field-effect transistors with La$_2$O$_3$ gate dielectric

Chih-Hsiang Hsu, Ming-Tsong Wang,a) and Joseph Ya-Min Lee

Department of Electrical Engineering and Institute of Electronics Engineering,
National Tsing-Hua University, Hsinchu, Taiwan 300, Republic of China

(Accepted 17 July 2006; accepted 18 July 2006; published online 10 October 2006)

La$_2$O$_3$ is a promising candidate for future metal-oxide-semiconductor gate dielectric applications. In this work, metal-oxide-semiconductor (MOS) capacitors and metal-oxide-semiconductor field-effect transistors with La$_2$O$_3$ gate dielectric were fabricated. The maximum electron mobility is 270 cm$^2$/V s. The time dependent dielectric breakdown (TDDB) of La$_2$O$_3$ was studied. It was observed that the Weibull slopes were independent of capacitor area. The Weibull slope increases with increasing La$_2$O$_3$ thickness. The TDDB of La$_2$O$_3$ follows the $E$ model. The percolation model and electron trapping are used to explain the TDDB of La$_2$O$_3$ dielectrics. © 2006 American Institute of Physics. [DOI: 10.1063/1.2356902]

I. INTRODUCTION

As very-large-scale-integration (VLSI) technology continues to scale down to the nanometer region, high-$k$ gate dielectric becomes a key element for suppressing the gate leakage current.\textsuperscript{1,2} Several high-$k$ materials such as Al$_2$O$_3$,\textsuperscript{3} ZrO$_2$,\textsuperscript{3,5} and HfO$_2$\textsuperscript{4–6} have been widely discussed. Recently, rare earth oxides have emerged as promising gate dielectrics for future applications.\textsuperscript{7–10} Among the rare earth oxides, La$_2$O$_3$ has the potential to achieve less than 1.0 nm equivalent oxide thickness (EOT).\textsuperscript{7,8} La$_2$O$_3$ thin film has many outstanding characteristics,\textsuperscript{5–8} including a large band gap (5–6 eV),\textsuperscript{6,8} a relatively high dielectric constant (20–30),\textsuperscript{7,10} a high breakdown electric field (>13 MV/cm),\textsuperscript{11} a low leakage current with small EOT,\textsuperscript{7,8} good oxide reliability,\textsuperscript{7} and thermodynamic stability in contact with Si.\textsuperscript{5,8} Furthermore, with a concentration of 0.0035% in earth’s crystal rocks, lanthanum is more abundant than hafnium, which has a concentration of only 0.000 28%.\textsuperscript{7,12} Although there are several reports on the electrical properties of La$_2$O$_3$ thin films,\textsuperscript{8,10} there are relatively few studies on the reliability and stress-induced leakage current mechanisms of La$_2$O$_3$.

In this work, metal-oxide-semiconductor field-effect transistors (MOSFETs) with La$_2$O$_3$ gate dielectric were fabricated and the time dependent dielectric breakdown (TDDB) characteristics were studied.

II. EXPERIMENT

$p$-type, (100) orientation, silicon wafers (1–10 $\Omega$ cm) were used as the starting material. After standard RCA cleaning, the source and drain windows were defined by wet etching and doped by phosphorous diffusion. The La$_2$O$_3$ thin films were deposited by radio frequency (rf) magnetron sputtering in argon ambience at room temperature. The flow rate of argon was 13.5 SCCM (SCCM denotes standard cubic centimeter per minute at STP). The total pressure during deposition was 23 mTorr. Postdeposition rapid thermal annealing was performed at 500 °C for 60 s in nitrogen with a flow rate of 3 SCCM. The thickness, refractive index, and energy band gap of La$_2$O$_3$ thin films were measured using an N&K ellipsometer.

Aluminum was used as the top and backside electrodes. The top aluminum electrodes were evaporated and patterned using a wet etching process with H$_3$PO$_4$. Postmetallization annealing (PMA) was performed at 400 °C in nitrogen ambience for 60 s. The channel width is 100 $\mu$m and the channel length varies from 3 to 20 $\mu$m. The sputtered La$_2$O$_3$ films were examined by x-ray diffraction (XRD), x-ray photoelectron spectroscopy (XPS), and secondary ion mass spectroscopy (SIMS).\textsuperscript{13} The thickness of La$_2$O$_3$ films varies from 8 to 35 nm and the dielectric constant is 25.5 as measured from separate metal-insulator-semiconductor (MIS) capacitors. All the $I$-$V$ and $I$-$t$ measurements of Al/La$_2$O$_3$/p-Si MOS capacitors and transistors were carried out using Keithley 236.

III. RESULTS AND DISCUSSION

A. Characteristics of MOSFETs with La$_2$O$_3$ gate dielectrics

Figure 1 shows the $I_D$-$V_D$ characteristics of $n$-channel MOSFETs. Good $I_D$-$V_D$ characteristics similar to those of conventional long-channel MOSFET with SiO$_2$ gate oxide were observed. The threshold voltage $V_T$ extracted in the linear region is 0.20 V. The maximum transconductance ($g_m$) was about 7.0 $\times$ 10$^3$ A/V. The minimum subthreshold slope was 114 mV/decade. The $I_{off}/I_{on}$ ratio was about 10$^5$ at $V_D$=0.05 V, which indicates that the transistors have good current switch capability. The average electron mobility is 270 cm$^2$/V s.

\textsuperscript{a)Electronic mail: mtwang@tsmc.com}
B. Time dependent dielectric breakdown (TDDB)

To study the reliability of the La$_2$O$_3$ thin films, constant voltage tests were performed using MOS capacitors. In these tests, the top electrode was negatively biased to ensure that all the applied voltage is applied on the gate dielectric layer. The time to breakdown is a statistically distributed quantity. The statistics of gate oxide breakdown is usually described using the Weibull distribution.14

$$F(t) = 1 - \exp \left[ - \left( \frac{t}{\alpha} \right)^\beta \right],$$  

where $F$ is the cumulative fraction of breakdown devices, $t$ is the time to breakdown, $\beta$ is the Weibull slope, and $\alpha$ is the scale factor of the distribution.

Usually, $\ln[-\ln(1-F)]$ is plotted as a function of $t$ and this will yield a straight line. Figure 2 shows the Weibull distributions with various applied voltages and capacitor areas. The basically parallel slopes suggest that the Weibull slopes are independent of stress voltage and capacitor area. The Weibull slopes are 2.6 and 6.4 for capacitors with La$_2$O$_3$ thicknesses of 8 nm (EOT=1.2 nm) and 19 nm (EOT =2.9 nm), respectively. The larger Weibull slope for thicker film thickness is in agreement with the percolation model. This is because the breakdown path for thicker oxides consists of larger number of traps and the spread on the trap density necessary to generate such a large path is smaller.14–16

C. The TDDB models

There are four main TDDB models in widespread use, the thermochemical breakdown model ($E$ model),17–21 the hole-induced breakdown model ($1/E$ model),22–24 the exponential $V_G$ model, and the power law model.25,26 The $E$ model can be expressed as

$$\ln T_F \approx \frac{\Delta H_0}{k_B T} - \gamma E,$$  

where $T_F$ is the time to failure, $\Delta H_0$ is the enthalpy of activation for oxide breakdown (usually referred to as the activation energy), $k_B$ is Boltzmann’s constant, $\gamma$ is the field acceleration parameter, and $E$ is the oxide field. The $E$ model was originally used as an empirical relation17,18 but later interpreted using thermodynamic theory and applied at electric fields close to or below 5 MV/cm.19–21 Other researchers22–24 have stated that the breakdown is due to a hole-trapping induced process. The time to failure ($T_F$) should thus be dependent on $1/E$ due to Fowler-Nordheim tunneling at relatively high field [usually $E>6$ MV/cm (Ref. 27)]. This model is referred to as the $1/E$ model and can be expressed as

$$\ln T_F \approx 1/E.$$  

As the thickness of gate oxide becomes ultrathin ($\sim 30$ Å), the exponential $V_G$ model and the power law model come to play.25,26 The exponential $V_G$ model is demonstrated that $\ln(t_f)$ should be linearly extrapolated as a function of $V_G$ based on measuring the stress-induced leakage current (SILC) at a fixed low sense voltage. The power law model suggests that $T_F$ follows a power law behavior ($T_F \sim V^{-n}$) with a thickness-independent exponent rather than the exponential law.

In this work, all four models were considered but $E$ and $1/E$ models are further studied due to the fact that the thickness of our gate oxides is in the range between 8 and 35 nm and is not ultrathin. In order to decide whether $E$ or $1/E$ models is better suited for La$_2$O$_3$, the SILC is analyzed under constant stress voltages of $-7.5$ V ($E=-3.94$ MV/cm) to $-10$ V ($E=-5.26$ MV/cm). Figure 3 shows the SILC plot of La$_2$O$_3$ MOS capacitors under a constant stress voltage of $-8.5$ V. The La$_2$O$_3$ thickness is 19 nm. The capacitor area is $2.25 \times 10^{-4}$ cm$^2$. The gate current was found to decrease with increasing stress time. This suggests electron charge trapping during the stress process, as shown in the inset of Fig. 3. Therefore, the $1/E$ model based on hole injection is not suitable and the $E$ model is used to explain the TDDB at the relatively low electric fields of $\approx 5.26$ MV/cm ($V_G \approx -10$ V) below the onset of Fowler-Nordheim tunneling.

Figure 4 shows the TDDB plot using the $E$ model. The field acceleration parameter $\gamma$ can be obtained from the slope of the $\ln(T_F)$ vs $E$ curve. The different capacitors give slightly different slopes. The average field acceleration pa-
La$_2$O$_3$ capacitors with an area of 4074.108-3. The La$_2$O$_3$ thickness is 19 nm. The capacitor areas are 2.25 × 10$^{-4}$ cm$^2$. The inset graph shows electron charge trapping during stress.

FIG. 3. The stress-induced leakage current of La$_2$O$_3$ MOS capacitors after a constant stress voltage of ∼8.5 V applied for various time periods from 0 to 30 s. The La$_2$O$_3$ thickness is 19 nm. The capacitor areas are 2.25 × 10$^{-4}$ cm$^2$. The inset graph shows electron charge trapping during stress.

FIG. 4. The mean time to failure ($T_F$) is plotted as a function of electric field $E$ for capacitors with an area of 2.25 × 10$^{-4}$ and 4 × 10$^{-4}$ cm$^2$, respectively.

IV. CONCLUSIONS

In summary, MOS capacitors and MOSFETs with La$_2$O$_3$ gate dielectric were fabricated. The maximum electron mobility is 270 cm$^2$/V·s and the subthreshold slope is 114 mV/decade. The time dependent dielectric breakdown (TDDB) of La$_2$O$_3$ at 300 K as a function of electric field was studied. It was shown that the Weibull slopes are independent of stress voltage and capacitor area. The Weibull slope increases with increasing film thickness which is in agreement with the percolation model. The TDDB of La$_2$O$_3$ follows the $E$ model. The average field acceleration parameter $\gamma$ is about 2.0 cm/MV.

ACKNOWLEDGMENT

The authors would like to thank the National Science Council, Taiwan, Republic of China for supporting this work under Contract No. NSC95-2221-E-007-243.