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

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(Received 10 January 2006; accepted 24 May 2006; published online 1 August 2006)

Dy$_2$O$_3$ is a promising candidate for future metal-oxide-semiconductor (MOS) gate dielectric applications. In this work, MOS capacitors and field-effect transistors with Dy$_2$O$_3$ gate dielectric were fabricated. The maximum electron mobility was 339 cm$^2$/V s. The time dependent dielectric breakdown (TDDB) of Dy$_2$O$_3$ as a function of electric field and temperature was studied. It was observed that the Weibull slopes were independent of capacitor area and the Weibull slope increased with increasing Dy$_2$O$_3$ thickness. The TDDB of Dy$_2$O$_3$ followed the $E$ model. The activation energy $E_a$ was linearly dependent on the electric field and the field acceleration parameter $\gamma$ is independent of temperature. © 2006 American Institute of Physics. [DOI: 10.1063/1.2217708]

As the very large scale integrated (VLSI) circuit technology continues to scale down to the nanometer region, high-$k$ gate dielectric becomes a key element for suppressing the gate leakage current. Currently, rare earth oxides such as La$_2$O$_3$, Pr$_2$O$_3$, and Gd$_2$O$_3$ have emerged as promising gate dielectrics. Among the rare earth oxides, Dy$_2$O$_3$ has the potential to achieve less than 1.0 nm equivalent oxide thickness (EOT). A band gap of 4.8 eV and a relative dielectric constant of 14 were reported. In addition, Dy$_2$O$_3$ films deposited on Si (100) substrate were reported to have superior electrical characteristics including low leakage current and high thermal stability. However, no transistor result with Dy$_2$O$_3$ gate dielectric was reported and the reliability of Dy$_2$O$_3$ gate dielectric was also not investigated. In this work, metal-oxide-semiconductor field-effect transistors (MOSFETs) with Dy$_2$O$_3$ gate dielectric were fabricated and the time dependent dielectric breakdown (TDDB) characteristics using Weibull plots were studied.

$p$-type, (100) orientation, silicon wafers ($1-10 \ \Omega \ \text{cm}$) were used as the starting material. After standard Radio Corporation of America (RCA) cleaning, the source and drain areas were defined by wet etching and doped by phosphorus diffusion. The Dy$_2$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 pressure during deposition was 23 mTorr. Postdeposition rapid thermal annealing (RTA) was performed at 500 $^\circ$C for 60 s with a flow rate of 3 SCCM of nitrogen. The thickness, refractive index, and energy gap of Dy$_2$O$_3$ thin films were determined by using an N&K ellipsometer.

Aluminum was used as the top and backside electrodes. For $n$-MOSFETs, the top aluminum electrodes were evaporated and patterned using a wet etching process with H$_3$PO$_4$. All the $I$-$V$ and $I$-$t$ measurements of Al/Dy$_2$O$_3$/p-Si metal-oxide-semiconductor (MOS) capacitors and transistors were carried out using Keithley 236.

Characteristics of MOS capacitor and transistors with Dy$_2$O$_3$ gate dielectric. Figure 1(a) shows the $I_{DS}$-$V_{DS}$ characteristics and Fig. 1(b) shows the $I_{DS}$-$V_{GS}$ of $n$-MOSFETs with Dy$_2$O$_3$ gate dielectric. The channel width and length were 100 and 20 $\mu$m, respectively. The threshold voltage $V_{th}$ was 0.42 V. The subthreshold slope was 101 mV/decade measured at $V_{DS}$ of 0.05 V. The maximum electron mobility is 339 cm$^2$/V s, as shown in the inset figure of Fig. 1(b).

The $C$-$V$ measurements of separate capacitors show a dielectric constant of 15.5.

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

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

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 at various applied voltages and capacitor areas. The MOS capacitors stressed at room temperature show basically parallel distributions. The parallel slopes suggest that the Weibull slopes are independent of stress voltage and capacitor area. The Weibull slopes are 2.5 and 3.4 for capacitors of Dy$_2$O$_3$ thicknesses of 12 and 20 nm, respectively. The larger Weibull slope for thicker capacitor thickness is in agreement with the percolation model.

The TDDB models. There are two main TDDB models in widespread use, the thermochemical breakdown model ($E$ model) and the hole-induced breakdown model (1/E model). Both models have physical basis. The $E$ model can be expressed as

$$t_{50} = A \exp(-\gamma E) \exp\left( \frac{E_a}{kT} \right),$$

where $t_{50}$ is the time to 50% failure, $A$ is a constant, $\gamma$ is the field acceleration parameter, $E$ is the oxide field, $E_a$ is the thermal activation energy, $k$ is the Boltzmann constant, and $T$ is the temperature.
The thickness of Dy$_2$O$_3$ film is 12 nm. The ratio of the channel width and length (W/L) is 100 μm/20 μm. (b) The $I_{DS}$/$V_{GS}$ characteristics of n-MOSFETs with Dy$_2$O$_3$ gate dielectric are plotted at a $V_{DS}$ of 0.05 V (hollow circles). The subthreshold slope is 101 mV/decade. The inset figure shows the electron mobility as a function of electric field. Figure 3(b) shows that there is a much better fit to the linear field model. Thus, the thermochemical breakdown model is better suited for TDBD of Dy$_2$O$_3$ in the electric field of 4.1 MV/cm < $E$ < 6.6 MV/cm from 25 to 150 °C.

**Thermal activation energy and field acceleration parameter.** Figure 4 shows the Arrhenius plots of $t_{50}$ as a function of $1/T$. The activation energy $E_a$ can be expressed as

$$E_a = -0.084E + 0.796 \text{ (eV)}.$$  

This activation energy is in the same range as that of SiO$_2$ which varies from 0.4 to 1.25 eV at similar stress field (~5 MV/cm). The field acceleration parameter $\gamma$ can be obtained from the slope of the ln($t_{50}$) vs $E$ curve. The average field acceleration parameter $\gamma$ is about 2.9 cm/MV. The values of $\gamma$ have no clear dependence on temperature. This is also in agreement with the published result of SiO$_2$. At room temperature, the maximum operating gate voltage extrapolated for ten-year lifetime is $V_G$ = -2.5 V for capacitors with a Dy$_2$O$_3$ thickness of 12 nm and $V_G$ = -2.98 V for capacitors with a thickness 20 nm, respectively.

In summary, MOS capacitors and MOSFETs with Dy$_2$O$_3$ gate dielectric were fabricated. The maximum electron mobility is 339 cm$^2$/Vs and the subthreshold slope is 101 mV/decade. TDBD of Dy$_2$O$_3$ as a function of electric field (4.1 MV/cm < $E$ < 6.6 MV/cm) and temperature (25 °C ≤ $T$ ≤ 150 °C) is studied. It is shown that the Weibull slopes are independent of stress voltage and capacitor area.

is the absolute temperature. The $E_a$ model was originally used as an empirical relation but was later interpreted using thermodynamic theory. Other researchers have stated that the breakdown process is a current-driven process. $t_{50}$ should thus be dependent on $1/E$ due to the Fowler-Nordheim conduction. This model is commonly referred to as the 1/$E$ model and can be expressed as

$$t_{50} = \tau_0 \exp \left( \frac{G}{E} \right) \exp \left( \frac{E_a}{kT} \right),$$  

where $\tau_0$ and $G$ are constants, $E$ is the oxide field, and $E_a$ is the activation energy.

Figure 3(a) shows the TDBD plot of the 1/$E$ model and Fig. 3(b) the $E_a$ model. The Dy$_2$O$_3$ thickness is 12 nm. The temperature varies from 25 to 150 °C. In Fig. 3(a), the dependence deviates from the reciprocal field model at lower electric fields.

**FIG. 2.** The TDDB Weibull distributions of Dy$_2$O$_3$ MOS capacitors are plotted under different stress voltages. The data for capacitors with areas of 150×150 μm$^2$ and 200×200 μm$^2$ are represented by solid and hollow symbols, respectively. The Dy$_2$O$_3$ thickness is 12 nm and the line fitting gives a Weibull slope ($\beta$) of 2.5.

**FIG. 3.** The Dy$_2$O$_3$ thickness is 12 nm. The area of MOS capacitors is 200×200 μm$^2$. The ambient temperatures are 25, 75, 100, and 150 °C. (a) $t_{50}$ is plotted as a function of reciprocal electric field 1/$E$. (b) $t_{50}$ is plotted as a function of electric field $E$. 

In summary, MOS capacitors and MOSFETs with Dy$_2$O$_3$ gate dielectric were fabricated. The maximum electron mobility is 339 cm$^2$/Vs and the subthreshold slope is 101 mV/decade. TDBD of Dy$_2$O$_3$ as a function of electric field (4.1 MV/cm < $E$ < 6.6 MV/cm) and temperature (25 °C ≤ $T$ ≤ 150 °C) is studied. It is shown that the Weibull slopes are independent of stress voltage and capacitor area.
The Weibull slope increases with increasing film thickness and is in agreement with the percolation model. The TDDB of Dy$_2$O$_3$ follows the $E$ model. The activation energy $E_a$ is linearly dependent on the electric field and the average field acceleration parameter $\gamma$ is about 2.9 cm/MV. The values of $\gamma$ show no clear dependence on temperature.

The authors would like to thank the National Science Council of Taiwan, Republic of China for supporting this work under Contract No. NSC92-2215-E-007-020.