Lanthanide (Tb)-Doped HfO_2 for High-Density MIM Capacitors

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***Abstract*—A high-density metal-insulator-metal (MIM) capacitor with a lanthanide-doped HfO_2 dielectric prepared by physical vapor deposition (PVD) is presented for the first time. A significant improvement was shown in both the voltage coefficient of capacitance (VCC) and the leakage current density of MIM capacitor, yet the high capacitance density of HfO_2 dielectrics was maintained by achieving the doping of Tb with an optimum concentration in HfO_2. This technique allows utilizing thinner dielectric film in MIM capacitors and achieving a capacitance density as high as 13.3 fF/μm^2 with leakage current and VCC values that fully meet requirements from year 2005 for radio frequency (RF) bypass capacitors applications.**

***Index Terms*—Capacitance density, co-sputtering, HfO_2, lanthanide, metal-insulator-metal (MIM) capacitor, voltage coefficient of capacitor (VCC).**

I. INTRODUCTION

THE metal-insulator-metal (MIM) capacitor is a key passive component in radio frequency (RF)/mixed signal ICs. Most foundries provide a MIM capacitor module with a capacitance density ranging from 1 to 2 fF/μm^2 using SiO2- or Si_3N_4-based dielectrics [1]–[3]. Meanwhile, the industry will require capacitors with a capacitance density higher than 10 fF/μm^2 for RF bypass capacitor applications from year 2005, according to the latest international technology roadmap for semiconductors (ITRS) [4]. This requirement can be achieved by using insulators with a dielectric constant higher than 57, and considering the present dielectric thickness of around 50 nm. Materials such as Ba, Sr, TiO_x, and TaO_x exhibit high dielectric constant values 60 or above if crystallized by a high temperature annealing [5], [6], which is however unrealistic in the backend of the line process. Instead, amorphous dielectrics such as Al_2O_3, Ta_2O_5, and HfO_2 have recently been investigated for MIM capacitor application [7]–[10]. Considering their moderately high K values of 9 to 25, the dielectric thicknesses of these materials should be reduced to thinner than 20 nm in order to meet the requirement for high-density bypass capacitor application. Use of thin dielectrics will however cause other problems such as high leakage currents and poor voltage coefficient of capacitance (VCC) [5], [10]. In this letter, a high-density MIM capacitor using 14-nm-thick Tb-doped HfO_2 prepared by the cosputtering method is reported and the effects of Tb doping concentration on electrical properties of MIM capacitors are investigated.

II. EXPERIMENTS

TaN/Hf_xTb_yO/TaN multilayer MIM capacitor structures were fabricated on a 400-nm-thick SiO_2 layer using a pulsed dc magnetron sputtering system. After 150-nm-thick TaN bottom electrode deposition, Hf_xTb_yO films were reactively deposited at room temperature in a gas mixture of O_2 (2 sccm) and Ar (23 sccm). The pressure was maintained at 3 mTorr, a dc power of 200 W was applied to the Hf target, and four different powers, 0, 40, 50, and 60 W were applied to the Tb target in order to obtain Hf_xTb_yO films with different Tb doping concentrations. The corresponding Tb concentrations analyzed by X-ray photoelectron spectroscopy (XPS) were 0, 4, 10, and 14%, respectively. The film thickness measured by transmission electron microscopy (TEM) was 14 nm. The dielectric films were annealed at 420 °C in a forming gas ambient before forming 150-nm-thick TaN top electrodes, because our experimental experiences have shown that the forming gas annealing helps to reduce leakage current in sputter-deposited dielectric films on metal films. The top electrode was patterned by conventional optical lithography and dry etching. The area and the perimeter of the MIM capacitors used for electrical measurements are 2500 μm^2 and 2000 μm, respectively.

III. RESULTS AND DISCUSSIONS

The capacitance densities of MIM capacitors using Tb-doped HfO_2 dielectrics with four different Tb doping concentrations are shown in Fig. 1. From the capacitor with a 14-nm-thick pure HfO_2 dielectric, denoted as 0% Tb concentration, a capacitance density as high as 13.7 fF/μm^2 was achieved. A slight reduction of capacitance density to 13.3 fF/μm^2 was observed with 4% of Tb doping. Further doping of Tb has caused a substantial loss in the capacitance density, as observed in 10 and 14% Tb concentration samples. The degradation in the capacitance density for the Hf_xTb_yO samples with a high concentration of Tb is attributed to the lower dielectric constant of Tb_2O_3. While the capacitance density varies with Tb concentration, individual capacitance values remain unchanged with measurement frequency up to 1 MHz regardless of the doping conditions, im-

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Manuscript received February 19, 2003; revised March 31, 2003. The review of this letter was arranged by Editor S. Kawamura.

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Digital Object Identifier 10.1109/LED.2003.814024

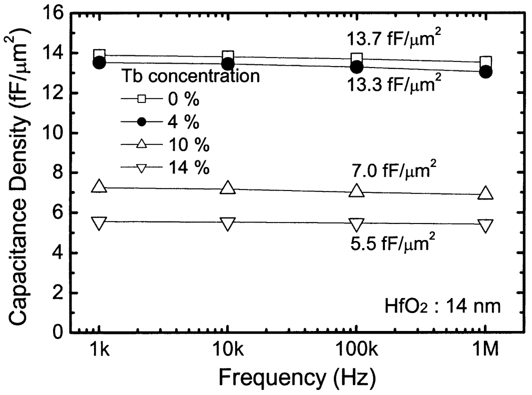

Fig. 1. Capacitance densities of MIM capacitors using Hf_xTb_yO with different Tb concentrations. High densities of 13.7 and 13.3 fF/μm^2 have been achieved for pure HfO$_2$ and 4% Tb-doped samples, respectively.

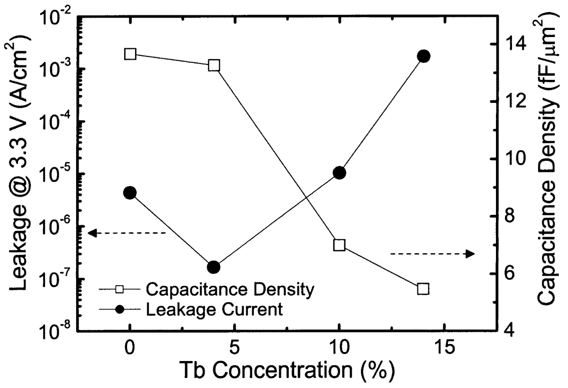

Fig. 3. Capacitance density at 100 kHz (□) and leakage current density at 3.3 V (●) against Tb doping concentration. The optimal Tb doping concentration is found at 4% in this work.

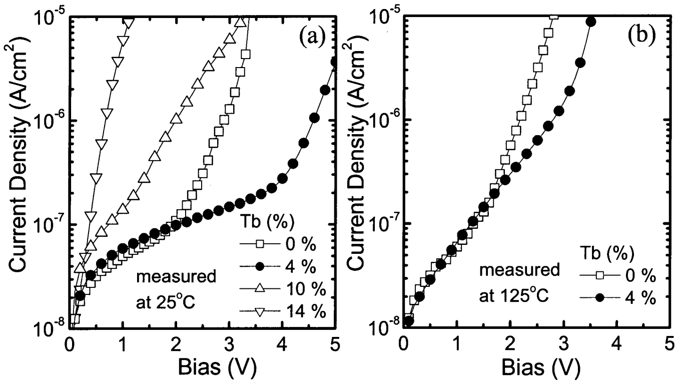

Fig. 2. (a) Leakage current densities of MIM capacitors using HfO$_2$ and Hf_xTb_yO with different Tb concentrations. The lowest leakage current is found in 4% Tb-doped sample. (b) Leakage current densities of 0 and 4% Tb-doped HfO$_2$ MIM capacitors measured at 125 °C.

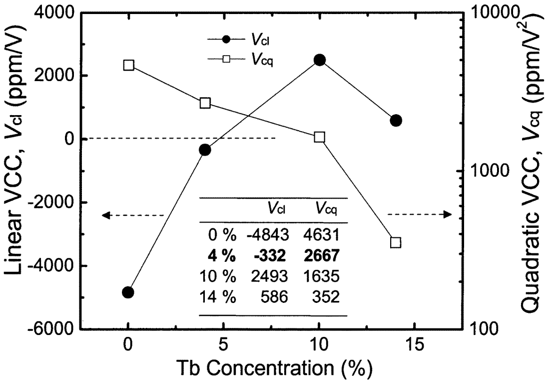

Fig. 4. Linear VCC, $V_{\rm cl}$, and quadratic VCC, $V_{\rm cq}$, against Tb doping concentration. $V_{\rm cq}$ decreases with Tb concentration while the smallest $V_{\rm cl}$ of -332 ppm/V was obtained at 4% Tb concentration. Virtually zero $V_{\rm cl}$ is obtainable with Tb doping concentration at about 5%.

plying that the addition of Tb does not deteriorate the frequency response of the capacitance.

Fig. 2(a) shows the leakage current densities of Tb-doped HfO$_2$ dielectrics with different Tb doping concentrations. The result shows that a small amount (4%) of Tb doping into HfO$_2$ significantly increases the onset voltage for the dc-type conduction, thereby the leakage current remains less than 2×10^{-7} A/cm^2 at the bias of up to 3.3 V. The lower leakage current with lanthanide-doped HfO$_2$ film is attributed to both less oxygen vacancies and to the higher packing density of lanthanide-doped HfO$_2$ that result from lower electro-negativity and larger atomic radii of lanthanide materials [11]. However, when the Tb doping concentration is increased to 10 and 14%, the leakage current property was severely deteriorated. The mechanism for the high leakage current in HfO$_2$ film with an excessive amount of Tb doping is not clear at the moment. The leakage currents at high temperature for pure HfO$_2$ and 4% Tb-doped HfO$_2$ samples are shown in Fig. 2(b). The leakage current of the 4% Tb-doped HfO$_2$ sample remains less than 2×10^{-7} A/cm^2 up to 2 V even at 125 °C.

Dependence of Tb concentration in Hf_xTb_yO film on both capacitance density and leakage current is summarized in Fig. 3. The leakage currents measured at 3.3 V and the capacitance densities obtained at 100 kHz are plotted together. From the result, we can see that a 4% Tb doping is the optimum condition as it shows the lowest leakage current while maintaining a high capacitance density similar to that of a pure HfO$_2$ dielectric.

The effect of Tb doping on voltage coefficients of a MIM capacitor is shown in Fig. 4. Linear VCC $V_{\rm cl}$ on the left y-axis in linear scale and quadratic VCC $V_{\rm cq}$ on the right y-axis in log scale are plotted against Tb doping concentration in Hf_xTb_yO film. The coefficients are extracted from the polynomial curve fitting on the capacitance–voltage (*C*–*V*) plot that is expressed as $\Delta C/C_o = V_{\rm cq} \cdot V^2 + V_{\rm cl} \cdot V$. According to the latest ITRS [4], $|V_{\rm cq}|$ less than 100 pm/V^2 is required for analog circuit applications and $|V_{\rm cl}|$ should be less than 1000 ppm/V for RF bypass capacitors. As seen in Fig. 4, an unacceptably high $V_{\rm cq}$ of 4843 ppm/V^2 and $V_{\rm cl}$ of -4631 ppm/V are obtained from the pure HfO$_2$ sample. The poor capacitance linearity of thin dielectric is expected, as VCC is known to be inversely proportional to the square of the dielectric thickness [12]. However, it was found that doping of Tb into HfO$_2$ can significantly improve VCC as well. Fig. 4 and its inset table show both $V_{\rm cl}$ and $V_{\rm cq}$ can be dramatically changed by Tb doping. The $V_{\rm cq}$ decreases monotonically with Tb doping concentration, while the $V_{\rm cl}$ swings from negative to positive values by changing the Tb concentration. The fact that $V_{\rm cl}$ curve against Tb concentration crosses the $V_{\rm cl} = 0$ line in Fig. 4 indicates that it might be possible to obtain virtually zero $V_{\rm cl}$ by optimizing the Tb doping concentration, which is about 5% of Tb doping into HfO$_2$ in the figure. In our experiment, the smallest V_{c1} of -332 ppm/V was obtained at 4% Tb concentration. This value is less than half of the best one reported from the ALD HfO_2-based MIM capacitor [10], yet having even higher capacitance density and lower leakage current.

IV. CONCLUSION

We demonstrated that lanthanide doping in HfO_2 can alleviate the two undesired properties of thin dielectric MIM capacitors, higher leakage current, and poor capacitance linearity. The 4% Tb-doped HfO_2 dielectric MIM capacitor achieved a high capacitor density of 13.3 fF/μm^2 leakage current less than 2×10^{-7} A/cm^2 at 3.3 V and the linear VCC V_{c1} as low as 332 ppm/V. Lanthanide-doped thin HfO_2 film therefore has great potential for future RF bypass MIM capacitor applications.

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