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Physical and electrical properties of ZrO_2 and YSZ high-*k* gate dielectric thin films grown by RF magnetron sputtering

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Abstract

Thin films of ZrO_2 were deposited on p-Si(100) substrates using RF magnetron sputtering technique. To investigate the influence of the sputtering parameters, e.g., annealing temperature, different O_2-flux, RF power and target to substrate distance on the physical and electrical properties of the as-grown films, systematic investigation using X-ray diffraction (XRD), Fourier transform infrared (FT-IR), scanning electron microscope and energy dispersive X-ray (SEM–EDX), C–V, and I–V were carried out in this work. Deposited ZrO_2 films had polycrystalline after annealing sample at high temperature. Their silicon oxide (SiO_2) layers were formed between high-*k* film (i.e., ZrO_2 and YSZ) and Si substrate either after annealing samples at high temperature or introducing O_2-flux the sputtering process step. The high-*k* thin films have to be deposited amorphous structure without SiO_2 interlayers. We also investigated the electrical properties of both the a-ZrO_2 and a-YSZ films prepared without O_2-flux at room temperature with conditions of various RF power and target to substrate distance. The dielectric constant of amorphous YSZ was determined to be about 24 using metal–insulator–semiconductor (MIS) capacitor structure. The smallest leakage current density of the YSZ film grown at 150 W and at room temperature was obtained to be about 10^{-10} at 1 V.

Keywords: RF magnetron sputtering; ZrO_2 films; YSZ films; High-*k* gate dielectrics; Leakage current

1. Introduction

Recently, as metal oxide semiconductor field effect transistor (MOSFET) devices are scaled down to <100 nm, problems of conventional silicon oxide (SiO_2) appeared. SiO_2 layer suffered from basic problem of high tunneling leakage current and reduced drive current due to low dielectric constant (k=3.9) with thickness decreased (<2 nm) [1,2]. Hence, high-*k* gate dielectrics such as Ta_2O_5, TiO_2, HfO_2, ZrO_2, CeO_2, Y_2O_3 stabilized ZrO_2 (YSZ) [2–6] were studied to replace SiO_2. Most of these materials, however, were not thermally stable directly on Si, due to the formation of metal silicides in the course of fabrication.

ZrO_2 and YSZ are one of the most attractive andidates due to its high-*k* values (~25 and ~27, respectively), wide band gap (approximately 5.1–7.8 eV) [7,8], and good thermal stability in contact with Si [9]. Due to their excellent properties, ZrO_2 and YSZ films have been extensively studied as gate dielectric [10]. Wang et al. [11] studied the 6-nm-thick epitaxial crystalline YSZ films with electrical equivalent oxide thickness (EOT) of 1.46 nm and found that the leakage current was about 1.1×10^{-3} A/cm^2 at 1 V. In addition, Zhu and Liu [6] also studied the 6-nm-thick amorphous YSZ films with EOT=1.46 nm and obtained a leakage current to be about 7.58×10^{-5} A/cm^2 at 1 V. Moreover, amorphous films exhibited isotropic electrical properties and can easily be deposited.

In this work, the influence of the sputtering parameter such as, O_2-flux, annealing temperature, RF power and target-to-substrate distance (D_{ts}) on physical and electrical properties of amorphous ZrO_2 and YSZ films that were

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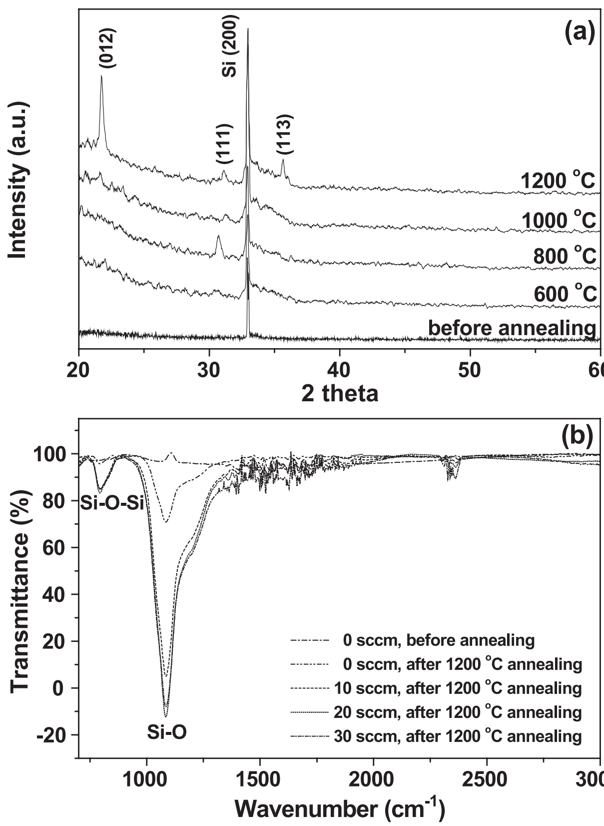

Fig. 1. (a) X-ray diffraction patterns of ZrO_2 thin films obtained with different annealing temperatures. (b) FT-IR spectra of ZrO_2 thin films obtained with different O_2 flux and annealing.

prepared at low temperature by RF magnetron sputtering method have been studied.

2. Experimental

Both ZrO_2 and YSZ films were prepared by the RF magnetron sputtering method. The purity of the ZrO_2 target was above 99.99% with a diameter of 1 in. The YSZ target were prepared with 8 wt.% Y_2O_3-stabilized ZrO_2. The sputtering gas (Ar) with a purity of 99.99% were introduced to the chamber and controlled by the standard mass-flow controllers. The sputtering pressure was 32 mTorr and p type Si(100) wafer were used as substrates without heating. The substrate–target distance was changed from 30 to 50 mm and RF power was controlled from 80 to 200 W.

The structural properties of the films were characterized by X-ray diffraction (XRD) using Cu K_α radiation (RIGAKU, D/MAX-2200 ultima). The interlayers between high-*k* film and substrate were analyzed with Fourier transform infrared (FT-IR, AVATAR 320) spectroscopy. The thickness and interlayers formation were observed using scanning electron microscope (SEM) and energy dispersive X-ray (EDX) (XL 30 ESEM-FEG). The electrical properties were measured by metal–insulator–semiconductor (MIS) capacitor structures with Al gate electrodes. The area of the capacitors was 2.4×10^{-4} cm^2. The I–V and C–V curves were measured using a HP4140B pico-A and a Bonton 7200 capacitor meter, respectively.

3. Results and discussion

Fig. 1(a) shows X-ray diffraction patterns of ZrO_2 thin films grown at room temperature without O_2-flux. The RF power was 150 W and the annealing temperature varied from 600 to 1200 °C. Below 600 °C, there were no typical diffraction peaks, indicating an amorphous structure. Between 800 and 1000 °C, the films were mainly grown in the [111] orientation, while the crystal growth direction was changed to be [012], at an annealing temperature in the range of 1000–1200 °C. The polycrystal film could thus be obtained after annealing over 800 °C. With oxygen flux, the same tendency of X-ray diffraction pattern as Fig. 1(a) was observed (not shown). However, the relative intensity was decreased substantially, suggesting the poor crystallinity in these cases.

The FT-IR spectra of ZrO_2 films are shown in Fig. 1(b). The peaks at 794.6 and 1083.9 cm^{-1} were mostly due to Si–O–Si and Si–O stretching of the silicon oxide layers. The

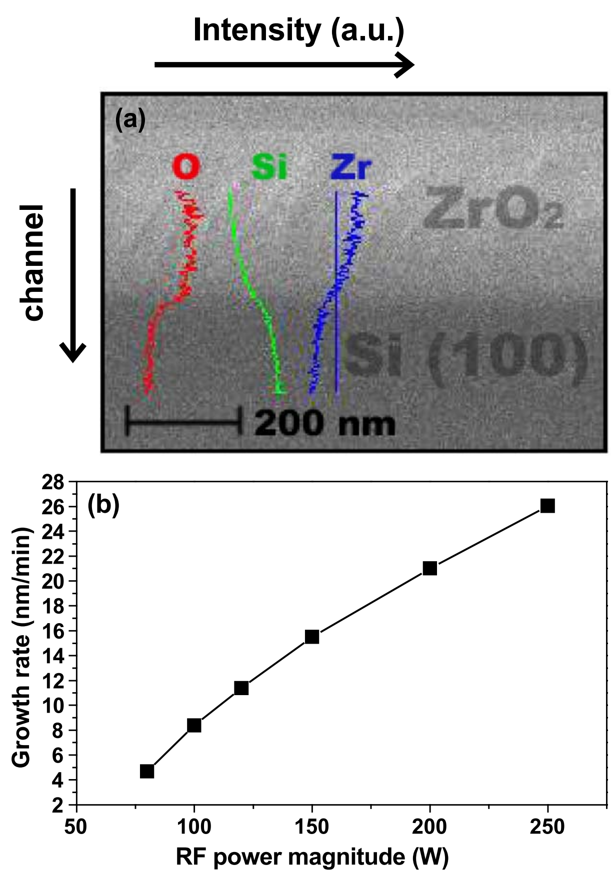

Fig. 2. (a) SEM and EDX image of a ZrO_2 thin film grown at RT and 150 W with oxygen flux of 20 sccm. (b) Variation of ZrO_2 film growth rates of with RF power magnitude (■).