The characteristics of Organic Thin Film Transistors with high-k dielectrics

Chang Su Kim, Woo Jin Kim, Sung Jin Jo and Hong Koo Baik

Department of Metallurgical Engineering, Yonsei University, Seoul 120-749, Korea,

Phone : +82-2-2123-2838, E-mail : thinfilm@yonsei.ac.kr

Abstract

We report on the structural and electrical properties of amorphous Yttria-stabilized zirconia (YSZ) thin films which are the potential high-k gate dielectric material of organic thin film transistor (OTFT). To investigate the influence of the oxygen flow rate on the structural and electrical properties of the YSZ films, XRD, XPS, J-E, I-V were carried out in this work. Oxygen vacancies are expected to be the most predominant type of defect in metal-oxide dielectrics. The leakage current density decreased mainly because of the reduction of oxygen vacancies with increasing oxygen flow rate.

1. Introduction

Organic thin film transistors (OTFT) have attracted a great deal of attention. Recently, a tremendous amount of research has been focused on OTFT as they are one of the most important components in the fabrication of low cost, large area flexible displays and low end electronics [1,2]. A major problem that hinders the development of practical OTFT devices is that current devices require rather high voltages to operate, while in a typical low-end application, the available voltage will be very low. The key to low-voltage operation is reduction of the threshold voltage and the inverse subthreshold slope. These transistor parameters are largely controlled by the gate insulator rather than the semiconductor. The reason for that was shown to be the mobility dependence on the accumulated charge in the OTFT channel. Since this charge is proportional with both the dielectric constant and the gate voltage, it has been suggested that the use of high dielectric constant (k) materials will allow the necessary charge to accumulate at much lower voltages [3-6]. However, high-k gate dielectric generally caused a high leakage current. De Boer et al. reported that leakage current from the gate electrode causes irreversible degradation of OTFT, even when it is orders of magnitude smaller than the source-drain current. How to reduce the leakage current has become an important subject in the study of OTFT [7,8].

Yttria-stabilized zirconia (YSZ) may be good candidates for the high-k gate dielectric films of the OTFT due to its high-k values of about 30 at room temperature and wide band gap of 5.1-7.8 eV, good chemical stability, high resistivity [9,10]. Due to their excellent properties, YSZ films have been extensively studied as gate dielectric [11,12]. In this work, the e-beam evaporation technique was used for the low-temperature growth of high-quality YSZ films on a ITO substrate in vacuum. Usually YSZ films are characterized by stoichiometry deviations due to the deficiency of oxygen, and they can be changed by the variation in the conditions of film preparation. The value of this deflection essentially influences the electric properties of YSZ. It is important to address the problems of the defects both at the interface and within the oxide layer since they will critically limit the efficiency and reliability of the OTFT devices. These issues will require more detailed analysis to identify the atomic nature of the defects and their role in device degradation to develop a quantitative model for device breakdown and reliability prediction.

It is known that the processing conditions have an important effect on the properties of high-k thin films [13,14]. During the e-beam evaporation process, processing parameters, such as substrate temperature, deposition rate and oxygen flow rate, have a significant influence on the microstructure and hence the dielectric and electrical properties of the deposited films. Compared to other parameters, the effect of oxygen flow rate is the most pronounced. High oxygen flow rate is usually required to produce oxide films with stoichiometric composition, leading to a good leakage characteristic. Generally, films produced at low oxygen flow rate possess poor electrical properties due to the presence of oxygen vacancies or nonstoichiometry. Comparisons of the physical and electrical properties of YSZ films with various oxygen flow rate have been discussed. We also discussed the mechanism of how different oxygen flow rate influence the leakage current of the YSZ thin films.

2. Experiment

The YSZ films were prepared on ITO substrate by the e-beam deposition technique with electron energy of 10 keV in vacuum. The electron beam was focused on the target with a diameter of 16 mm and a thickness of 6 mm. The system was evacuated by a cryopump up to a pressure of 5.0×10^{-7} torr. The substrate was placed parallel to the target surface at a distance of 500 mm. The YSZ target was prepared from a pressed pure YSZ grain (ZrO_2-8mol%Y_2O_3) and was mounted on a water-cooled holder. Characteristics of YSZ films, such as microstructure, stoichiometry, and dielectric properties are dependent on the deposition method and the details of the conditions such as deposition rate, substrate temperature, oxygen partial pressure, etc. The thickness and deposition rate of the YSZ films were measured, respectively, with a crystal quartz monitor. The thickness and the deposition rate of YSZ films were set at 3000Å and 0.1 nm/s. For many advanced device applications, low processing temperatures are required, so the substrates were not intentionally heated during deposition, and the influence of annealing was not studied in this work. The YSZ films deposited by electron beam evaporation at different oxygen flow rate were analyzed. Oxygen flow rate in the process of evaporation drastically affects the oxygen concentration in the films. During the evaporation, the pure O_2 gas was introduced into the surrounding of the sample holder at various flow rates. The flow rate of oxygen gas was independently controlled using a mass-flow controller.

The structural properties of the YSZ thin films have been analyzed by X-ray diffraction (XRD) using Cu Ka radiation and the root-mean-square (rms) surface roughness of the films was calculated by AFM under ambient conditions. XPS is preferred as a powerful diagnostic technique to yield information on the chemical characteristics of the surface of the films. Thus, we used XPS as a tool to investigate the charge states of the films. All current-voltage (I-V) measurements were performed with a semiconductor parameter analyzer (Agilent 4155C) and the electrical properties of the YSZ films also evaluated from current density-electric field (J-E) measurements with Au/YSZ/ITO structure.

3. Results and Discussion

In general, the polycrystalline gate dielectrics may be problematic because grain boundaries serve as high leakage paths. In addition, grain size and orientation changes throughout a polycrystalline film can cause significant variations in *k*, leading to irreproducible properties. Crystallites in the polycrystalline film could also cause uniformity and surface topography problems. In contrast, amorphous films will exhibit isotropic electrical properties, will not suffer from grain boundaries, and can be easily deposited by manufacturable techniques. Therefore, the amorphous film is preferred for the gate dielectric application [15,16].

Figure 1 displays the XRD patterns of the YSZ films as a function of oxygen flow rate. Up to an oxygen flow rate of 40sccm, no diffraction peaks can be observed, indicating the amorphous structure is maintained in the YSZ films. These results clearly suggest that crystallization of the YSZ composite structure is effectively suppressed. It is due to the fact that addition of Y_2O_3 into ZrO_2 matrix affects nucleation and growth of ZrO_2 grains from the composite matrix, so mixing of Y_2O_3 with ZrO_2 will raise the crystallization onset temperature. This is because the dopant can distort the ordered structure in the original film.

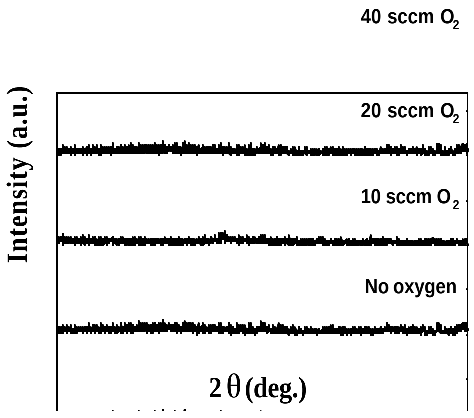

Fig. 1. XRD patterns of the YSZ films as a function of oxygen flow rate.

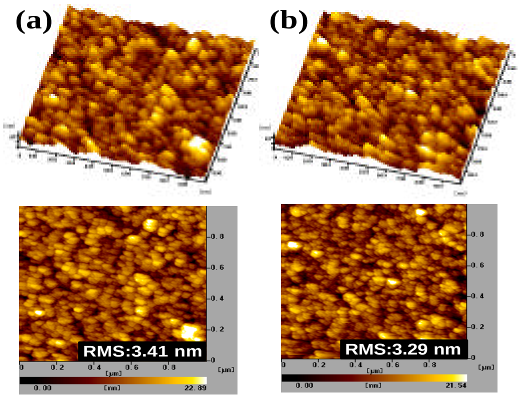

Fig. 2. AFM surface images of the YSZ films as a function of oxygen flow rate : (a) No oxygen, (b) 40sccm

The surface morphology and surface roughness of the oxide films was measured by atomic force microscopy (AFM). The AFM surface morphology of YSZ thin films deposited at without and with 40sccm oxygen flow rate is shown in Figure 2(a) and 2(b).

The surface rms (root mean squared) roughness are 3.41 nm and 3.29 nm for samples without and with 40sccm oxygen flow rate, respectively, indicating that a relatively smooth surface, uniform grain size and very similar features in surface topography can be obtained either without or with 40sccm oxygen flow rate. Therefore, no significant change in the YSZ surface roughness is noticed after oxygen flow rate. Other previous work has also shown that the oxide films fabricated by electron-beam evaporation with different oxygen flow rate have similar phenomenon [17,18].

Oxygen vacancies are expected to be the most predominant type of defect in metal-oxide dielectrics. There have been studies demonstrating that the interaction of these defects results in trap creation, which causes deleterious effects on the electrical performance of the device [19–21]. Fig. 3 shows the O 1s core level XPS spectra of YSZ films deposited at various oxygen flow rate. A carbon C 1s peal at a binding energy of 284.5eV is observed on all samples before ion beam bombardment. The presence of this peak is related to surface contamination which corresponds to the fact that the samples are exposed to air before the XPS measurements. All carbon peaks from the surface of YSZ films which almost disappear after the first sputtering runs, and thus were attributed to organic contaminations. Thus, the XPS spectra for the films were obtained after a sputter cleaning using 3 keV Ar^+ ion beam for 1 min in order to remove surface contaminants. As shown in Fig. 3, the binding energy of O 1s in YSZ is 529.4 eV. Under a high oxygen flow rate of 40 sccm, the kinetic energy and internal energy of the flying particles are easily lost by frequent collisions between the evaporated particles and the oxygen gas. Consequently, the migration energy of the deposited particles is lowered and the interaction with the substrate is reduced. As a result, the film was highly oxidized, and fewer oxygen vacancies and structural defects are introduced. On the contrary, insufficient oxidation due to the low oxygen flow rate causes lots of oxygen vacancies. The variation of the stoichiometry ratio of the YSZ films indicated that a higher oxygen flow rate during the evaporation promoted the fabrication of highly oxidized films, and consequently reduced the concentration of the oxygen vacancies in the films.

The electrical properties of the YSZ films were investigated by current density-electric field (J-E) and current-voltage (I-V) characteristics of the Au/YSZ/ITO structures. As shown in Fig. 4, with increasing oxygen flow rate, the leakage current density of the YSZ thin films decreases steeply. In general, the oxygen vacancies of an oxide material form a donor level [22,23]. Electrons trapped at the donor level are emitted due to the Schottky effect, elevating the leakage current exponentially with the applied voltage. It could be concluded that the leakage current density decreased mainly because of the reduction of oxygen vacancies with increasing oxygen flow rate and oxygen vacancies role as charge traps and carriers in a leakage current mechanism.

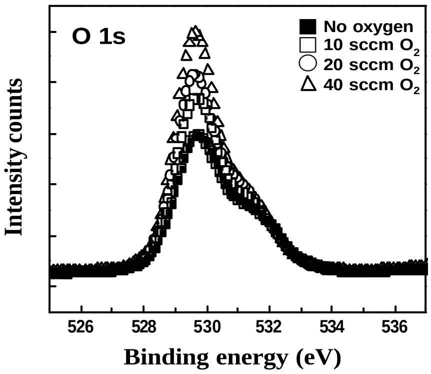

Figure 3. XPS O 1s core-level spectra of the YSZ films as a function of oxygen flow rate.

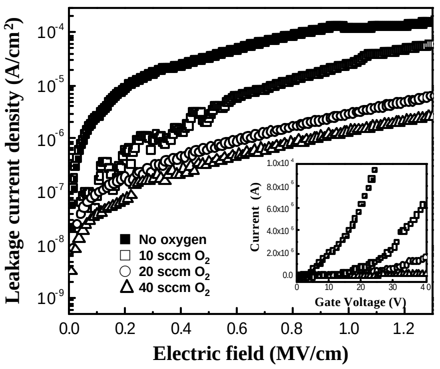

Figure 4. Plots of J-E & I-V (inset) characteristics measured from the Au/YSZ/ITO structure

4. Conclusion

In summary, the amorphous YSZ thin films were deposited on ITO substrates by E-beam evaporation under various oxygen flow rate. The effects of the different oxygen flow rate on the structural and electrical characteristics of YSZ thin films were investigated. Oxygen vacancies are expected to be the most predominant type of defect in metal-oxide dielectrics. The leakage current density decreased mainly because of the reduction of oxygen vacancies with increasing oxygen flow rate. It is concluded that the e-beam evaporated YSZ oxides are promising as a gate dielectric of an OTFT device if fabricated under an optimum process condition.

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6. References

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