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Electrical and dielectric characteristics of Al/Dy_2O_3/p-Si heterostructure

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ABSTRACT

In this work we report the electrical characteristics of high-*k* Dy_2O_3 dielectric deposited on p-Si substrate by electron beam deposition under ultra vacuum. The surface morphology of Dy_2O_3 is investigated by scanning electron microscopy (SEM) and atomic force microscopy (AFM). The surface topography analysis reveals that the Dy_2O_3 film is nanograined and contains numerous contacts between columnar grains. The electrical properties of Al/Dy_2O_3/p-Si heterostructure are further analyzed by current–voltage (*I–V*), capacitance–voltage (*C–V*), capacitance–frequency (*C–f*) and conductance–frequency (*G–f*) measurements. The dominant conduction mechanisms which governed the Al/Dy_2O_3/p-Si heterostructure are determined. The hetrostructure induces a significant value of leakage current: 1.1×10^{-5} A at flat-band voltage -1 V which is linked to the structural properties of the elaborated structure. The effects of grain boundaries and oxygen vacancies within the dielectric are observed in term of leakage current. Indeed, the $C(V)$ characteristics measured at different applied voltage show a large frequency–dispersion, indicative of the presence of a continuous distribution of interface states. So, the interface state densities are determined from the $C(V)$ characteristics to be around 10^{13} eV^{-1} cm^{-2}. $C(f)$ measurements elucidate that the capacitance behavior is typical of material with traps. From $G(f)$ and $C(f)$ measurement the trap density and relaxation time are also determined. It is suggested that the interface states series resistance are important parameters that strongly influence the electrical properties of Al/Dy_2O_3/p-Si heterostrucure.

1. Introduction

Rare-earth oxides as dielectric materials find their most important use in microelectronics as gate oxides in transistors. High-*k* dielectrics have been studied extensively as an alternative to silicon dioxide in the next generation of MOSFETs [1].The requirements of the high-*k* material properties [2] also include stability on silicon, low interface trap densities, smooth film morphology, and high dielectric constant [3]. Rare-earth oxide thin films can find numerous applications, for example, as luminescent materials, catalysts, buffer and protecting layers, and as constituents in oxide superconductors and solid oxide fuel cells [4].

Anyway, high dielectric constant materials are the potential candidates because a thicker film is utilized to reduce the leakage current while maintaining the same gate capacitance. Such a suitable high-*k* material should have a wide band gap, high barrier height for both electrons and holes, and good thermal stability. Rare earth oxides have the most of the fundamental requirements for the alternative gate dielectric in order to achieve performance comparable to SiO_2. Among those requirements are band gap, dielectric constant, higher crystallization temperature, thermodynamic stability in contact with silicon at temperature exceeding 800 °C, high quality interface with Si with low interfacial state density D_{it} and lower leakage conduction than SiO_2 at an equivalent oxide thickness [5]. Recently, Dy_2O_3 has attracted considerable attentions as promising dielectric materiel with superior electrical properties. In this study, the Dy_2O_3 was deposited on p-Si substrate by electron beam deposition to well clarify the electrical properties of the Al/Dy_2O_3/p-Si heterostructure. However, the performance of an MIS structure depends on various factors, such as the presence of localized interface states at the Dy_2O_3/p-Si interface, cleaning, the interface preparation process, the metal–semiconductor barrier height, the interfacial dielectric layer formation, and the series resistance [6,7]. Therefore, if these issues are to be better understood, a more detailed investigation of the interface state of the Dy_2O_3/p-Si structure based on frequency

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dependence is required. Furthermore, Dy_2O_3, like most rare earth oxides, are not usually stoichiometric and often contain significant concentrations of oxygen vacancies which can contribute to leakage current [8]. Thus, it is important to study the different defects such us oxygen vacancies and grain boundaries which may significantly affect the electrical properties of our structure.

In the present study, the electrical and dielectric properties of Al/Dy_2O_3/p-Si heterostruture are investigated by means $I(V)$, $C(V)$, $C(f)$ and $G(f)$ measurements.

2. Experimental procedure

P-type silicon wafer with $2\,\Omega\,cm$ and (100) orientation was used as the starting substrate. Before processing, the substrate was purified by successively immersing in acetone, propanol and de-ionized water to remove the native oxide. Then, the Dy_2O_3 film (~80 nm) was deposited on p-Si substrate by electron beam deposition under ultra vacuum and under a pressure of $\sim 10^{-9}$ Torr, with a growth rate of $0.02\ nm\,s^{-1}$. The thickness of the oxide film was monitored in situ using oscillating layers quartz. After that the sample was subjected to rapid thermal annealing (RTA) in Ar at temperature 600 °C.

Then, in order to characterize the electrical properties, a 2 mm diameter aluminum contact was deposed by vacuum evaporation technique at pressure $\sim 5 \times 10^{-6}$ Torr.

The surface morphology of Dy_2O_3 film was analyzed by a scanning electron microscopy (SEM) and atomic force microscopy (AFM) techniques. The AFM measurements were performed in the tapping mode.

The $I(V)$ characteristic of the Al/Dy_2O_3/p-Si heterostructure is measured by a set up consisted of a computer-controlled KEITHLY 236 (as a DC source measure unit), the $C(V)$, $G(f)$ and $C(f)$ characteristics are performed using a HP 4192 A (5–13 MHz) LF impedance analyzer (as a AC source measure unit). All measurements were carried out in the dark under ambient conditions.

3. Results and discussions

3.1. Morphology characterization

Fig. 1 shows a SEM image of the top surface of the oxide film deposited on p-Si substrate. This figure exhibits a smooth surface morphology and gives evidence for the presence of a continuous prepared oxide film on the p-Si substrate. It is clearly seen that the Dy_2O_3 oxide film consists of uniform distribution of small grains with a mean grain size of about 20–25 nm. Besides, the surface morphology of Dy_2O_3 film seems to be almost homogenous and polycrystalline.

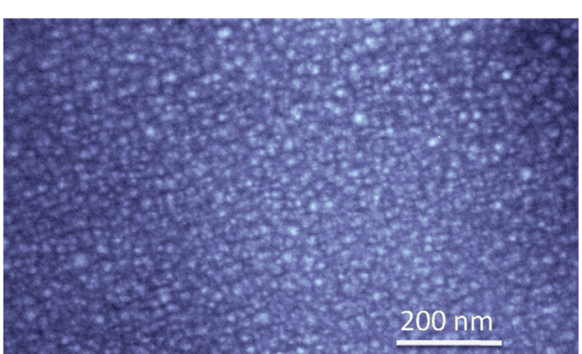

Fig. 1. Top view SEM image of the Dy_2O_3 oxide film.

On the other hand, since SEM is not very effective in nanoscale resolution, the nanostructural nature of the Dy_2O_3 oxide film was also investigated by AFM imaging, using a scanning area of $2 \times 2\ \mu m^2$. Fig. 2 reveals the AFM imaging (a) 2D view and (b) 3D view of the oxide surface. The oxide film exhibits a fairly homogenous nanostructured surface morphology, which consists of spheroid shaped nanocrystallites. The average diameter of these grains is around of 25 nm which is consistent with SEM analysis. Also, the root mean square of the roughness (RMS roughness) can be determined to be around 5.15 nm. This rough surface may influence the electrical behavior, i.e. it can increase the leakage current across the Dy_2O_3/p-Si interface.

In fact, as shown, micrographs in Figs. 1 and 2 witness that the Dy_2O_3 oxide film is nanograined and contain numerous contacts between columnar grains. Although, it has been recently demonstrated that the physical properties of nanograined oxides are strongly depend on the presence of defects like grain boundaries [9] and oxygen vacancies. Thus, it is important to consider how oxygen vacancies interact with the grain boundaries. Generally, metal-oxide materials are an essential component of many electronic devices and there have speculations that the increased concentration of defects, such as oxygen vacancies, near grain boundaries can contribute to electron tunneling and lead to dielectric breakdown [10,11]. Therefore, the segregation and diffusion of defects to grain boundaries [12] may affect the electrical properties of the Al/Dy_2O_3/p-Si heterostructure.

3.2. Electrical characterization

3.2.1. Current–voltage characteristics

To evaluate the leakage current performance of the device, Fig. 3(a) displays the $I(V)$ characteristic for Al/Dy_2O_3/p-Si heterostructure measured in both positive and negative bias voltages. The leakage current as a function of bias voltage exhibits a significant value of leakage current around 1.1×10^{-5} A at $V_{FB} = -1$ V. The leakage current slightly increased up to a level of 2×10^{-4} A at an initial stage of applied bias. However, an abrupt increase of leakage current was observed when the applied voltage was gradually increased. Therefore, it would be of great concern to find out how electrical properties are influenced in the elaborated structure. So, there are several effects can affect considerably the leakage current.

In fact, it was found that grain boundary may affect both the leakage current and breakdown field [13]. It is noticed that leakage current characteristics are determined by grain boundary intersection and breakdown field by grain boundary itself. In general, grain boundaries in dielectrics show higher resistance than the bulk of grains, therefore, high electric field will evolve across these grain boundaries under a DC field, which may cause local breakdown or field-assisted emission of trapped charge carriers [14,15]. Space charges like oxygen vacancies in the oxide film pile up at the grain boundaries during the deposition process [16] and eventually, the potential barrier height of grain boundary decreases to reduction in the density of states at the grain boundary [17]. Since the height of the grain boundary potential barrier (activation energy for electronic conduction) can control the current level [18], the resultant leakage current increases with the enlarge area of grain boundaries.

On the other hand, to explain the current transport in Dy_2O_3 oxide, there are mainly several mechanisms which can control metal–oxide–semiconductor structure, Schottky, Poole–Frenkel and Fowler–Nordheim emission mechanisms. In the present case, two possible mechanisms are explored in the metal-oxide interface i.e. Richardson–Schottky and Poole–Frenkel emissions [19]. The R–Schottky emission generated by the thermionic effect is caused by electron transport across the potential energy barrier