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Characterization of lutetium oxide-based thin-film capacitors by impedance spectroscopy

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ABSTRACT

The impedance spectroscopy method has been applied for diagnostics of lutetium oxide-based MIM (metal–insulator–metal) thin-film structures with a different insulator thickness, from 0.2 μm to 0.55 μm. For frequencies 10 μHz–10 MHz and temperatures 300 K–500 K, the total impedance response of examined specimens comes from: Lu_2O_3 film, near-electrode regions and resistance of electrodes and leads. The equivalent electrical circuit models containing the following elements: series resistance of electrodes and leads; resistance, capacitance and constant phase element, which characterize the volume of the film; and resistance and constant phase element, which characterize near-electrode regions, have been proposed to describe the dielectric response of $Al/Lu_2O_3/Al$ thin-film capacitors. The values of characteristic parameters of these elements have been determined and discussed.

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1. Introduction

Over the last decade, an intensive search is observed for candidates to substitute conventional dielectric materials as SiO_2, Si_3N_4 or Al_2O_3 in metal–insulator–metal (MIM) structures or in metal–insulator–semiconductor (MIS) structures [1–10]. Some high dielectric permittivity oxide films have attracted much attention as respective candidates for this substitution in various microelectronic and nanoelectronic devices.

In this class, films of rare earth metal oxides (REO) and transition metal oxides are alternative candidates for the mentioned above applications and are currently intensively being examined [8–17]. Lutetium oxide (Lu_2O_3) belongs to the REO group. Thin films of Lu_2O_3 have been recently extensively examined [13–17]. Dielectric and electrical studies have been carried out on samples with MIS-type and MIM-type electrodes configuration.

We have applied the impedance spectroscopy to characterization of REO-based thin-film sandwiches [8,17]. This method has been frequently applied as a useful diagnostic method in material engineering [8,19–23]. In our previous paper [17] we have reported the results of introductory dielectric studies of $Al/Lu_2O_3/Al$ structures. In this report, the broadband impedance spectroscopy has been applied for electrical diagnostics of lutetium oxide-based thin-film structures of different film thickness. We have tried to describe $Al/Lu_2O_3/Al$ thin-film structures taking into account different equivalent models that enable to estimate the fundamental material parameters and properties of these structures.

2. Experimental details

Lutetium oxide-based thin-film structures were prepared on quartz plates by the physical vapour deposition method (PVD) with the help of an electron beam gun. All examined samples had sandwich-type configuration (see Fig. 1). The specimens exhibited the following geometry: sample area in the range of 0.8 mm^2–1.2 mm^2 and sample thickness from 0.2 μm to 0.55 μm, specified in Table 1.

All impedance measurements were carried out in the temperature range from about 300 K to about 500 K on samples placed in a specially designed measurement cell. Alpha type Novocontrol Frequency Response Analyser (FRA), working at a small measurement signal (U_{ac} = 10–100 mV), was applied for impedance measurements in the frequency range of 10^{-5} Hz–10^7 Hz.

3. Experimental results

It is well known that the complex impedance diagnostics is a very useful examination method for inhomogeneous structures. In Fig. 2 we have shown in the form of complex impedance graphs (Nyquist graphs) the experimental data for $Al/Lu_2O_3/Al$ samples measured at temperatures T = 480–493 K. These results deal with specimens of different film thickness, from 0.2 μm to 0.55 μm. Since specimen's impedances extended for over more than 10 orders of magnitude, a double logarithmic scale was used for data presentation. In the frequency range of 10^{-5} Hz–10^7 Hz, all structures exhibit a similar impedance response. Two well-separated regions were distinguished in each $Z'' = F(Z')$ plot. They were denoted as regions I and II, for high and low frequencies, respectively.

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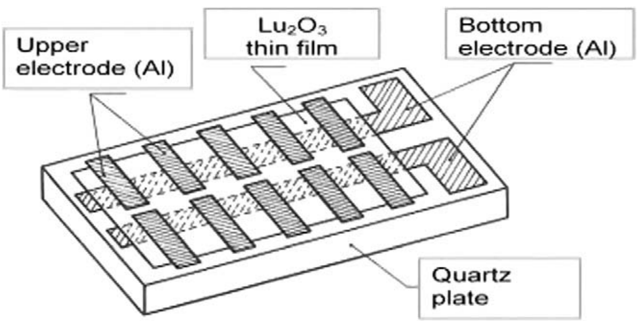

Fig. 1. Typical configuration of $Al/Lu_2O_3/Al$ structures.

Table 1
Parameters of $Al/Lu_2O_3/Al$ thin-film capacitors.

	Film thickness (nm)	Sample area (mm^2)
Sample A	203 ± 1.5	1.11 ± 0.01
Sample B	223 ± 2	0.88 ± 0.01
Sample C	334 ± 1	0.98 ± 0.01
Sample D	546 ± 2.5	0.95 ± 0.02

An example of the frequency dependent dielectric response of the capacitance C and the dielectric loss factor tan δ, for examined samples, is shown in Fig. 3. The introduced regions I and II can also be distinguished in these characteristics. Fig. 4 shows a thickness test for the capacitance–frequency characteristics of $Al/Lu_2O_3/Al$ capacitors at 410 K. All $C(f)$ curves exhibit almost the same capacitance in the region II. In the region I, the changes of $C(f)$ characteristics versus insulator thickness follow the parallel-plate capacitor formula.

Fig. 5 presents the $Z'' = F(Z')$ plots for samples measured at different temperatures. These results show an increasing contribution of region I (in comparison with region II) with temperature decreasing.

4. Discussion

4.1. The dielectric and impedance response of $Al/Lu_2O_3/Al$ structures

Experimental data presented in the previous chapter, as well as the results of our previous reports [8,17] strongly suggest that the total dielectric (impedance) response of $Al/Lu_2O_3/Al$ thin-film sandwiches is associated with inhomogeneity of examined samples. For such structures, dielectric properties are connected with the interior of the insulator and near-electrodes barriers.

The dielectric film is characterized here by its capacitance C_v ($C_v = \varepsilon_0 \cdot \varepsilon' \cdot s \cdot d^{-1}$, where ε_0 is the dielectric permittivity of a free space, ε' denotes the dielectric permittivity of the film, s is the sample area and d its thickness) and by the resistance R_v ($R_v = R_{v0} \cdot \exp(E_v/kT)$, where E_v is the activation energy of Lu_2O_3 film, k is Boltzmann constant, T is the temperature and R_{v0} is a constant).

The near-electrode regions can be expressed by the capacitance C_b ($C_b = \varepsilon_0 \cdot \varepsilon' \cdot s \cdot \lambda^{-1}$) and resistance R_b $R_b = R_{b0} \cdot \exp(E_b/kT)$, where λ denotes the thickness of near-electrode regions, E_b is the activation energy for near-electrode processes and R_{b0} is a constant.

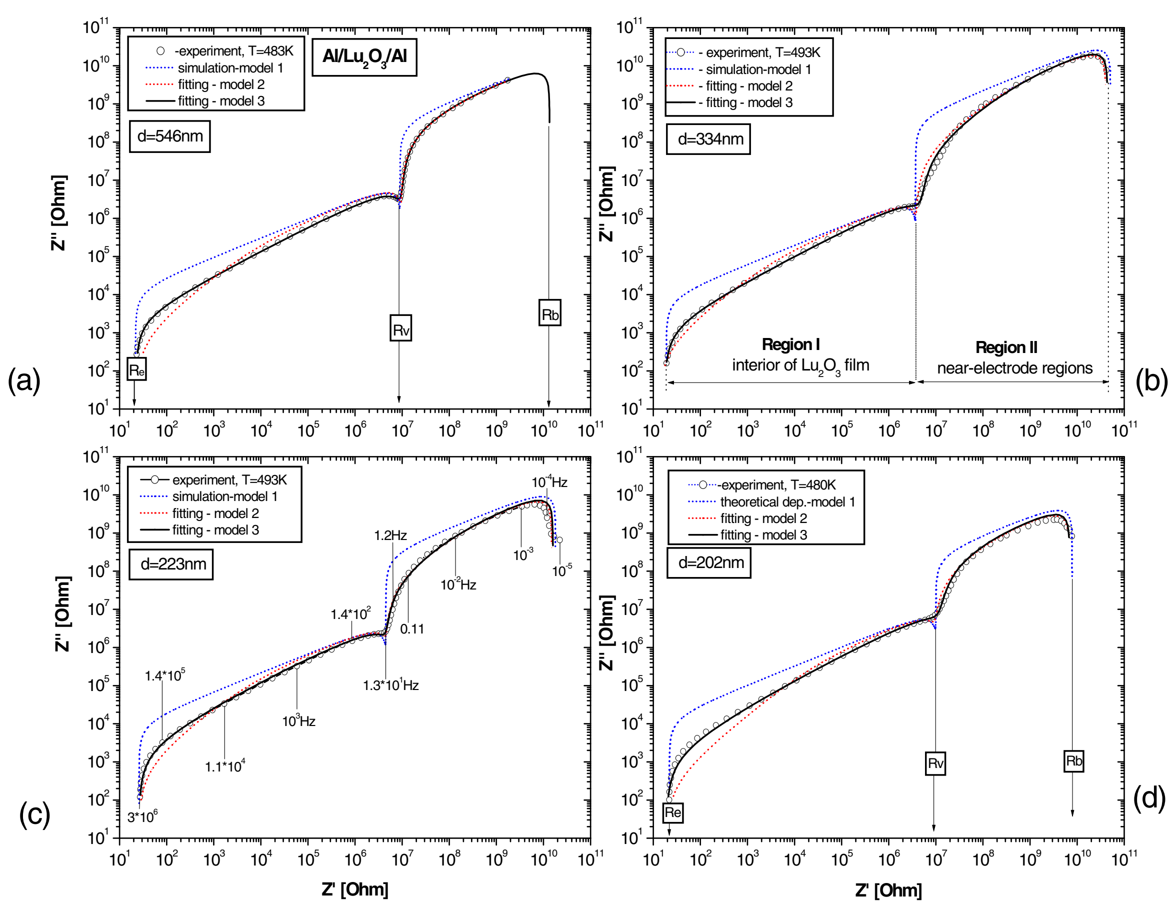

Fig. 2. Complex impedance graphs of $Al/Lu_2O_3/Al$ thin-film capacitors for different insulator thickness: (a) d = 546 nm, (b) d = 334 nm, (c) d = 223 nm and (d) d = 202 nm.

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