Paper

Reliability of MIS transistors with plasma deposited Al_2O_3 gate dielectric film

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Abstract — The paper presents the parameters of MIS transistors with plasma deposited thin film aluminum oxide gate insulator. Al_2O_3 films were synthesized by means of the low-energy, low-temperature reactive pulse plasma (RPP) method. Investigated transistors, with channel width to length (*W/L*) ratios of 200/10 [μm/μm] and 200/20 [μm/μm] were manufactured in a standard microelectronic technological laboratory. In order to determine the most important parameters of produced devices there were measured their electrical characteristics. The distribution of the threshold voltage values was studied on a representative set of over two hundred structures.

Keywords — MIS transistor, reliability, Al_2O_3 films, RPP method.

1. Introduction

Dielectric films perform various functions in MIS devices. They are used as: semiconductor surface passivation layers, masks in ion diffusion processes, protective layers against environment and electric isolation in some areas of MIS structures. In this paper, we would like to present the results of investigation of the performance of MIS transistors with aluminum oxide Al_2O_3 dielectric film playing the role of the gate insulator. Since the properties of gate insulator substantially determine the electrical characteristics of transistors, fabrication technology of dielectric films must ensure their highest quality. Currently the basic semiconductor materials are silicon (Si) and its natural dielectric – silicon dioxide (SiO_2). However, besides well-known advantages, SiO_2 has also certain shortcomings, among which the most important are:

1) easiness of ion and impurity migration, particularly at elevated temperatures and strong electric fields;
2) low radiation resistance.

Under certain circumstances, these features may result in instability of parameters of Si-SiO_2 structures and in effect – in instability of their electrical characteristics. Therefore, one can observe a growing interest in alternative dielectric materials, among which is aluminum oxide. Today Al_2O_3 is the third (after SiO_2 and Si_3N_4) most explored and simultaneously very promising dielectric material. As compared to SiO_2, aluminum oxide is characterized by much lower ion and impurity migration, is more radiation resistant [1] (it can be used in nuclear medicine and aerospace applications), shows higher dielectric constant value and its technology is less complicated. Al_2O_3 has been investigated at least since the late 60-ties [2], mainly as the one of insulating films in nonvolatile memories (in MAOS devices) [3]. Now electronics again is witnessing a comeback of the interest in this material. Primarily, because its dielectric constant value ($7.5 \div 9$) is higher than that of SiO_2 ($3.5 \div 4.3$) what is very attractive from the point of view of advanced MIS devices (like for instance DRAM structures). Moreover, Al_2O_3 has a large bandgap width (9.5 eV) which makes it very promising dielectric material for wide bandgap semiconductors (such as SiC, GaN or diamond), particularly in heterojunction bipolar transistor (HBT) structures and high-power and high-temperature electronic devices. Finally, the renaissance of the interest in Al_2O_3 can be also to some extent attributed to very dynamic development of its deposition methods, particularly the plasma-based ones. These techniques, in general, enable obtaining (at low-temperature and low-energy conditions) of sufficiently pure and stoichiometric dielectric layers.

Table 1
Properties of SiO_2, Si_3N_4 and Al_2O_3 films

Parameter	Material		
	SiO_2	Si_3N_4	Al_2O_3
Energy gap E_G [eV]	8.5	5.1	9.5
Density [g/cm^3]	$1.8 \div 2.4$	$3.0 \div 3.2$	$3.43 \div 3.9$
Dielectric constant	$3.5 \div 4.3$	$4.8 \div 7.4$	$7.0 \div 9.0$
Resistivity [Ωcm]	$10^{12} \div 10^{17}$	$10^{13} \div 10^{15}$	$10^{11} \div 10^{16}$
Dielectric strength [V/cm]	$1 \div 20 \cdot 10^6$	10^7	$2 \div 12 \cdot 10^6$
Thermal coefficient of linear expansion k [10^{-6}K^{-1}]	0.5	$2 \div 4$	8
Refractive index n	$1.32 \div 1.5$	$1.95 \div 2.05$	$1.55 \div 1.8$

Unfortunately, aluminum oxide has also a few disadvantages. Perhaps the most important is its large thermal coefficient of linear expansion with respect to Si. It makes that Al_2O_3 films cannot be used in situations when the gradient of the temperature during technological processes or during device operation is changing, what practically occurs usually. However, from the point of view of wide bandgap semiconductors this problem is less critical, as their thermal coefficients of linear expansion k are higher as well (e.g.

for SiC $k \geq 4 \cdot 10^{-6}$ [K^{-1}], for GaN $\geq 5.6 \cdot 10^{-6}$ [K^{-1}] whereas for SiO_2 $k = 0.5 \cdot 10^{-6}$ [K^{-1}]).

For all these reasons, in certain applications Al_2O_3 may be seriously considered an alternative to SiO_2. Table 1 shows a comparison of the most important properties of SiO_2, Si_3N_4 and Al_2O_3 dielectric films.

2. Experimental details

As substrates, there were used Si p-type <100> 8.7 ÷ 9.8 Ωcm wafers. Prior to Al_2O_3 deposition process they were chemically cleaned according to the standard procedure, consisting of the following steps:

- preliminary cleaning in a solution of hydrogen dioxide and sulfuric acid $H_2O_2 + H_2SO_4$ mixed at the ratio1:2,
- removal of organic impurities in a mixture of $H_2O + NH_4OH + H_2O_2$ (5:1:1),
- removal of thin silicon dioxide layer in a mixture of $HF + H_2O$ (1:50),
- removal of other impurities in a mixture of $H_2O + HCl + H_2O_2$ (6:1:1).

Aluminum oxide films were obtained by means of reactive-pulse-plasma technique [4]. Characteristic of this method is the specific way of plasma generation. It is induced at room temperature in a coaxial accelerator by electrical impulses of controlled frequency and voltage, what results in formation of small crystallites of synthesized material, which subsequently are being „frozen” on the substrate's surface. In the case of Al_2O_3 films deposition, the Al source is an aluminum internal electrode and alundum bushing. The plasma-generating gas is oxygen (O_2) [5]. In order to ensure a higher uniformity of produced layers, during the deposition process the substrates are kept on a rotation table. The process parameters are presented in Table 2.

Table 2
Technological parameters of Al_2O_3 films synthesis process (RPP method)

Parameter	Value
Pressure [Pa]	40
Temperature [°C]	< 150
Plasma-generating gas	O_2
Voltage [kV]	3.5
Number of plasma impulses	2000
Frequency [Hz]	0.2

After deposition, the thickness and refractive index of Al_2O_3 film was measured ellipsometrically (Gaertner L116). Other technological processes (photolithography I, etching of Al_2O_3 film, diffusion of phosphorus, aluminum metallization, photolithography II) were carried out in a clean-room standard technological laboratory. It is worth noting, that aluminum oxide dielectric films can be efficiently and selectively etched in a buffer of hydrofluoric acid (Fig. 1).

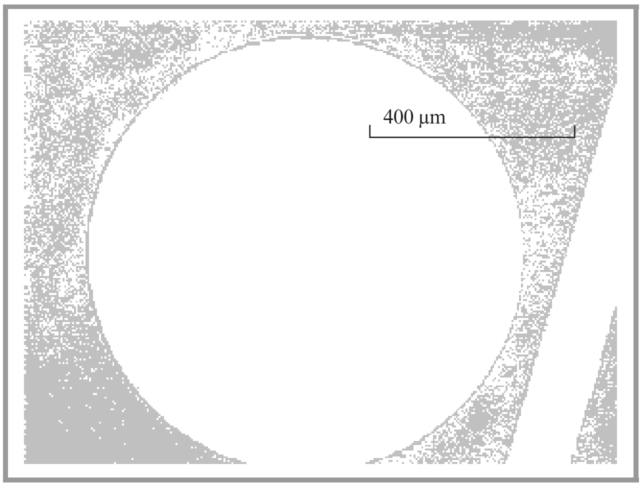

Fig. 1. Al_2O_3 film etched in HF buffer.

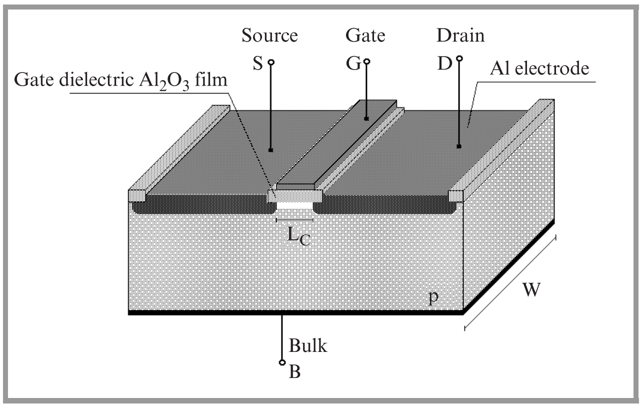

Fig. 2. The structure of investigated MIS transistor.

As a result of the processes mentioned above, on several wafers there were obtained chips containing transistors (Fig. 2) with varying channel dimensions. Under the same technological conditions and on the identical Si substrates there was also produced a number of simple MIS capacitor test structures with Al_2O_3 dielectric layers and metal (Al) dot contacts (each of 0.75 mm diameter). Measurements of their electrical characteristics as well as measurements of transient and output electrical characteristics of 211 transistors enabled extraction and analysis of some of the most important parameters of produced structures.

3. Results and discussion

Obtained Al_2O_3 dielectric films had mixed amorphous-nanocrystalline structure with predominant γ – type phase of aluminum oxide [5]. Measurements of electrical characteristics of MIS capacitors allowed extraction of some parameters of investigated material (dielectric constant ε_{ri}, effective charge Q_{eff}, resistivity ρ and interface trap density D_{it} – see Table 3) from well-known relationships:

$$\varepsilon_{ri} = \frac{C_{\max} t_i}{\varepsilon_0 A} , \tag{1}$$

where $C_{\max}$ is the capacitance of a MIS structure in accumulation, t_i is dielectric film thickness and A denotes the gate area of a MIS structure (in our case $A = 4.42 \cdot 10^{-3}$ cm^2);

$$Q_{eff} = \frac{\varepsilon_{ri} \left(\varphi_{MS} - U_{FB}\right)}{t_i} , \tag{2}$$

where φ_{MS} is the work-function difference (as the Si substrates and Al gate electrodes were used, the φ_{MS} was assumed to be equal to $-\,0.6 - \varphi_F$) whereas U_{FB} denotes the flat band voltage of MIS structure;

$$\rho\,|_{U=\text{const}} = \frac{UA}{It_i} . \tag{3}$$

Table 3
Properties of produced Al_2O_3 films

Parameter	Value
Thickness t_{ox} [nm]	317
Refractive index n	1.6
Dielectric constant ε_{ri}	$4.8 \div 11.8$
Effective charge Q_{eff} [C/cm^2]	$1.76 \cdot 10^{-7}$
Resistivity ρ [Ωcm]	$\sim 10^9$
Interface trap density D_{it} [eV^{-1}cm^{-2}]	$2.62 \cdot 10^{12}$

Interface trap density D_{it} was estimated by means of simplified version of so-called Terman method, proposed in [6], which allows determining D_{it} in the middle-band voltage state of MIS structure.

Output conductances g_D, transconductances g_m, threshold voltage values V_{TH} of the obtained MIS transistors as well as the mean yield for the whole batch were extracted from the measurements of their transient and output characteristics.

Figures $3 \div 6$ show the electrical characteristics and conductances of the investigated structures. As it can be seen, in general they do not depart in character from the curves usually observed for typical MOS transistor structures. The value of transconductance g_m (Fig. 4) is quite high and in accord with the theory. Note that characteristics presented in Fig. 4 are the extreme ones, what demonstrates relatively small scattering of all measured curves. Similar remarks apply to observed output conductance g_D characteristics (Fig. 6). Thus, the basic parameters of the MIS transistor with plasma deposited Al_2O_3 films can be considered satisfactory.

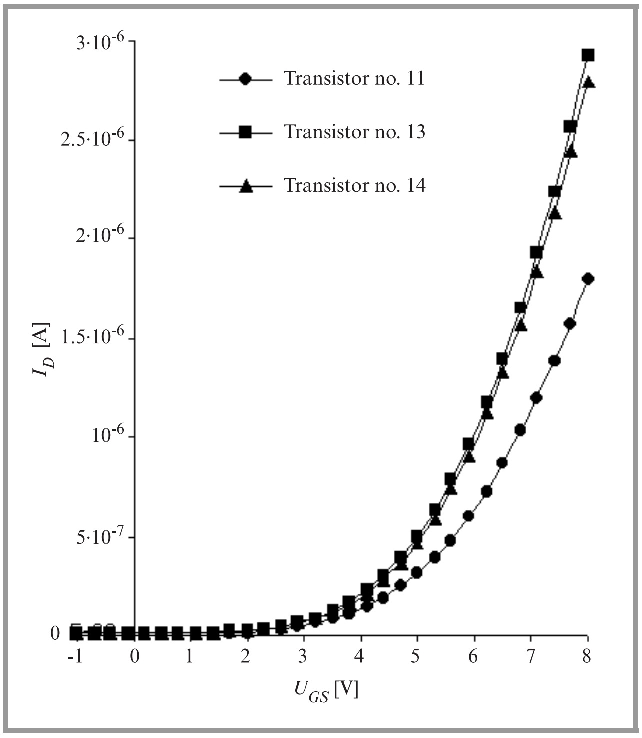

Fig. 3. Transient $I_D = f\,(U_{GS})$ characteristics of investigated MIS transistors.

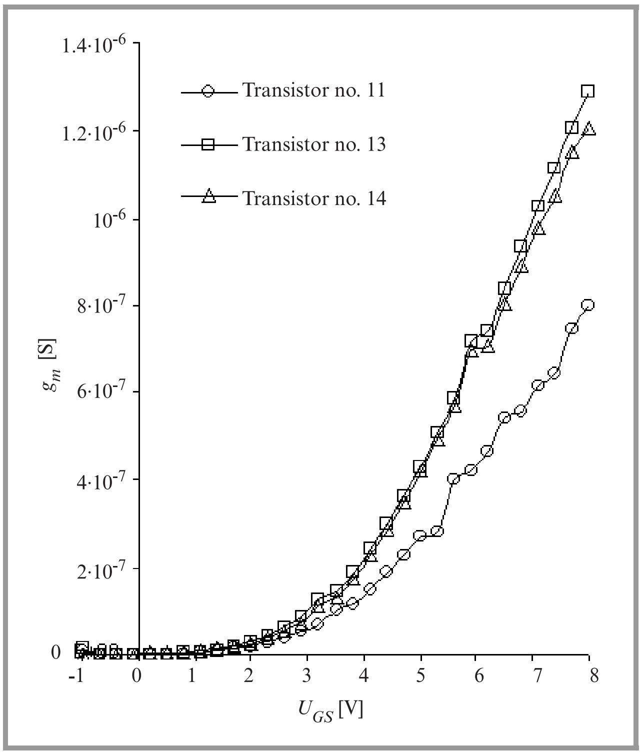

Fig. 4. Transconductance $g_m = f\,(U_{GS})$ characteristics of investigated MIS transistors.

Another problem analysed was the quality of obtained transistors. Characteristic of the RPP process is step-like (pulse) film growth. Additionally, the propagation of plasma has also a certain influence on the film thickness and quality, which both depend on the distance between the electrodes and the substrate. In order to ensure the better

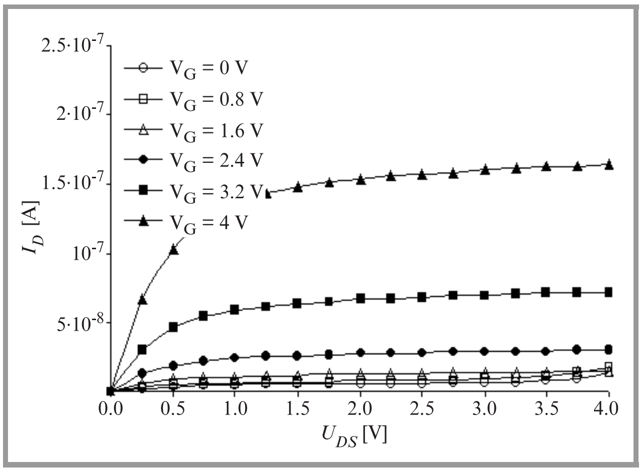

Fig. 5. Output $I_D = f(U_{DS})$ characteristics of investigated MIS transistors.

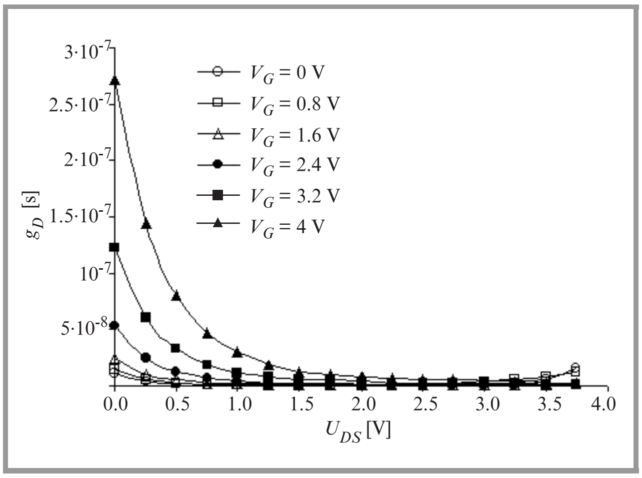

Fig. 6. Conductance $g_D = f(U_{DS})$ characteristics of investigated MIS transistors.

quality of layers and higher homogeneity of their thickness, the rotation table was used. The distribution of transistor threshold voltage V_{TH} values was assumed to be the determinant of the homogeneity of the electrical properties of investigated devices. Corresponding results are shown in Figs. $7 \div 9$. The histogram in Fig. 7 shows typical distribution of V_{TH} values. It has well-marked maximum around $2.5 \div 3$ V. Obviously, the situation pictured in this figure leaves much to be desired, especially because of the considerable scatter of results. Undoubtedly, more accurate adjusting of the technological process parameters might bring the substantial improvement here.

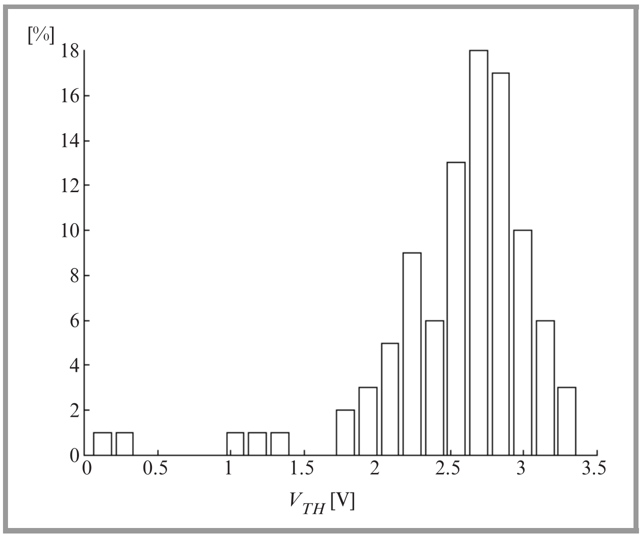

Fig. 7. Histogram of the threshold voltage V_{TH} values (for measured 107 transistors with 200/20 W/L ratio).

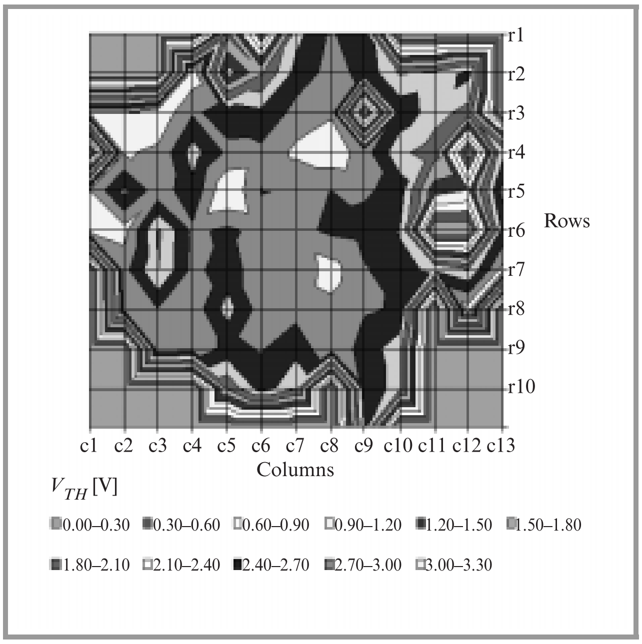

Fig. 8. 3D distribution map of the threshold voltage V_{TH} value variations over the substrate's surface.

3D and 2D distribution maps of the V_{TH} values variation over the surface show that despite substrate's rotation during Al_2O_3 deposition process there are observed dramatic changes in V_{TH} even between neighboring transistors. On the other hand, especially in the central part of the wafer there are relatively large areas with structures of similar threshold voltage values (V_{TH} variations visible in the vicinity of the substrate's border can be considered a fringe effect). All these effect, most likely should be attributed to the lack of structural uniformity of produced layers, what certainly indicates the necessity of some improvements in technology (e.g. changing of wafers rotation rate etc.). But this task can be not that easy, as inhomogeneity of the material structure is closely associated with the very nature of the applied plasma-chemical processes. Relationships between plasma properties and particularly between its homogeneity, chemical reactions occurring in such environment and homogeneity of deposited film are very difficult to be grasped and modeled. So far, it has not been a very important problem, but there is no doubt that it will be.

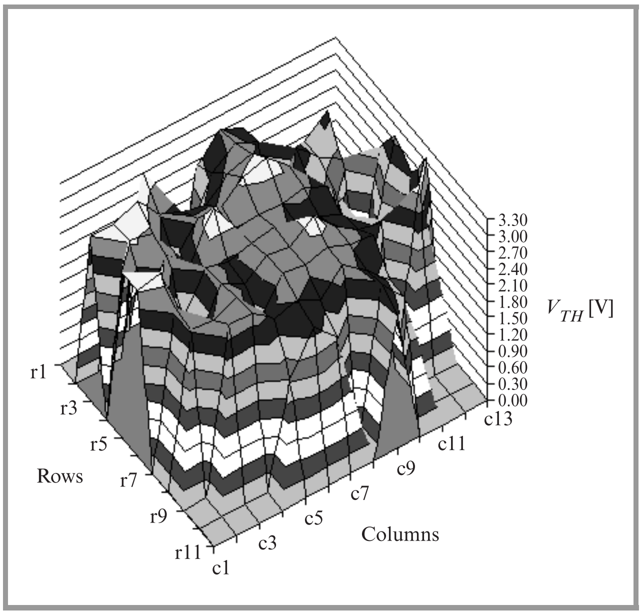

Fig. 9. 2D distribution map of the threshold voltage V_{TH} value variations over the substrate's surface.

It is also worth noting that the yield of the whole batch of investigated transistors was 73%. It is very promising result, indicating that the RPP technique can be applied to fabrication of that kind of electronic structures.

To sum up, it should be stated that as for the present stage of the research on Al_2O_3 gate dielectric films, the obtained results are quite satisfactory. However, the practical application of this material requires further improvement of the deposition process and better understanding of some fundamental issues related to the physics and chemistry of used technology.

4. Conclusions

After measuring of 211 MIS transistors with plasma deposited Al_2O_3 films (104 pcs with W/L ratio = = 200/10 [μm/μm] and 107 pcs with W/L ratio = = 200/20 [μm/μm]), we found that:

1) fabricated transistors have reproducible electrical characteristics (Figs. 3 and 5) and Al_2O_3 films show satisfactory properties and parameters (Table 3);

2) Al_2O_3 films can be selectively etched in HF buffer (there also exists possibility of their selective removal by means of so-called „lift off" process);

3) examined MIS transistors with Al_2O_3 films show satisfactory values of V_{TH}, g_m and g_D parameters (Figs. 4, 6 and 7);

4) as for the present stage of the technology development the distribution of the threshold voltage V_{TH} values is acceptable;

5) though a certain number of produced transistors did not work, the mean yield for the whole batch was 73%.

Acknowledgements

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