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Thin dysprosium oxide films formed by rapid thermal annealing on porous SiC substrates

Yu.Yu. Bacherikov[1], R.V. Konakova[1], O.B. Okhrimenko[1,*], N.I. Berezovska[2], O.S. Lytvyn[3], L.M. Kapitanchuk[4], A.M. Svetlichnyi[5]

[1] *V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kyiv, Ukraine*
[*] *E-mail: olga@isp.kiev.ua*

[2] *Taras Shevchenko Kyiv National University, Physics Department, Kyiv, Ukraine*

[3] *Borys Grinchenko Kyiv University Kyiv, Ukraine*

[4] *Paton Institute of Electric Welding, NAS of Ukraine, Kyiv, Ukraine*

[5] *Institute of Nanotechnologies, Electronics, and Electronic Equipment Engineering, Southern Federal University, Taganrog, Russia*

Abstract. In this paper, we consider the effect of rapid thermal annealing (RTA) on the properties of Dy_2O_3 film formed on the surface of a substrate with a por-SiC/SiC structure. The atomic composition of the films under study was analyzed as a function of the RTA time. It is shown that the RTA method makes it possible to obtain thin Dy oxide films with a composition close to the stoichiometric one. In this case, an increase in the RTA time leads to improving the quality of film-substrate interface and increasing the optical transmission of Dy_2O_3/por-SiC/SiC structure.

Keywords: thin dysprosium oxide films, rapid thermal annealing, SiC substrates, interface, porous layer.

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1. Introduction

Development of microelectronics necessitates the use of materials that are characterized by high chemical and thermal resistance, large values of dielectric constant (ε = 8…20) and specific resistance (ρ = 10^{13}…10^{16} Ω·cm), such as rare-earth oxides (REO). As a rule, REO oxides are used in metal–dielectric–semiconductor (MDS) transistors, heat-resistant and effective antireflection and passivating dielectric coatings for photoelectric devices [1-3]. At the same time, REO have high transparency in the visible spectral region, chemical and thermal durability and have an optimal refractive index for these purposes [4-7]. In addition, the use of two-layer dielectric films such as REO–SiO_2 in microelectronics allows improving the electrical stability of MDS devices [1]. However, despite the large number of works devoted to the study of the properties of rare-earth oxide films and MDS systems obtained on their basis [2, 8-12], search and development of new REO-semiconductor systems remains topical task.

Modern requirements of microelectronics, related with the miniaturization of devices, lead to the need to take into account the physical limits of the minimum permissible dimensions for materials used in MDS structures. As it is known, a decrease in the thickness of SiO_2 traditionally used in silicon and silicon carbide MDS structures up to 10…15 Å is accompanied by an unacceptably high leakage current [10, 11]. A decrease in leakage current through the gate dielectric is achieved by replacing silicon dioxide with the so-called alternative dielectrics (dielectrics with high dielectric constant – high-k dielectrics) [10, 11]. The use of alternative dielectrics allows to increase the physical thickness of the dielectric and thus suppress the tunnel current [10, 11]. In addition, when using REO as alternative oxides, the absence of a “thick” disturbed transition oxide-substrate layer is observed, which in the work [9] is associated with relatively low temperatures for obtaining the dielectric films based on rare-earth oxides that do not cause significant mechanical stresses at the oxide – substrate interface.

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The structural, optical, and electrical characteristics of REO films can significantly depend on the methods and conditions of preparation, on following processing, as well as on the type of substrates used [2]. So, for example, depending on the method of oxidation in the transition layer 'a film of dysprosium oxide – silicon', formation of dysprosium pyrosilicates [13] is possible, and the structure of the Dy_2O_3 itself can significantly depend on the quality of the substrate [14, 15].

One way to decrease the value of mechanical stresses at the oxide – substrate interface, as well as reducing the influence of structural defects of a semiconductor substrate, which penetrate during high temperature process into a thin oxide film grown on this substrate, is to create a porous interlayer between the substrate and epitaxial layer [16, 17].

In this regard, the purpose of this work was to study the characteristics of silicon carbide MDS structures with dielectric films of dysprosium oxide Dy_2O_3 formed using the RTA method on silicon carbide substrates with an intermediate porous layer of por-SiC.

2. Samples and measurement techniques

To obtain the Dy_2O_3/por-SiC/SiC structure, first of all, a por-SiC layer was obtained on the silicon carbide substrate. Porous silicon carbide was created using the anodic etching of silicon carbide in an aqueous-alcoholic solution of hydrofluoric acid: H_2O:HF:C_2H_5OH = 1:1:2, the current density was 20 mA/cm^2, the etching time was 5 min. Then, the material was processed in the KNO_3 + KOH etchant to open pores. Formation of the oxide film Dy_2O_3 was carried out as follows. A dysprosium film was deposited on the surface of porous silicon carbide by using the thermal deposition method. Then, samples of porous SiC with the deposited metal film were annealed in vacuum at the temperature close to 850 °C for 8 min and after that were subjected to rapid thermal annealing in dry oxygen atmosphere at the temperature 400 °C for 1…5 s.

The absorption spectra were measured at room temperature and recorded on a SPECORD UV VIS setup within the region λ = 400-800 nm. In all the samples, morphology of the coating was studied on an atomic

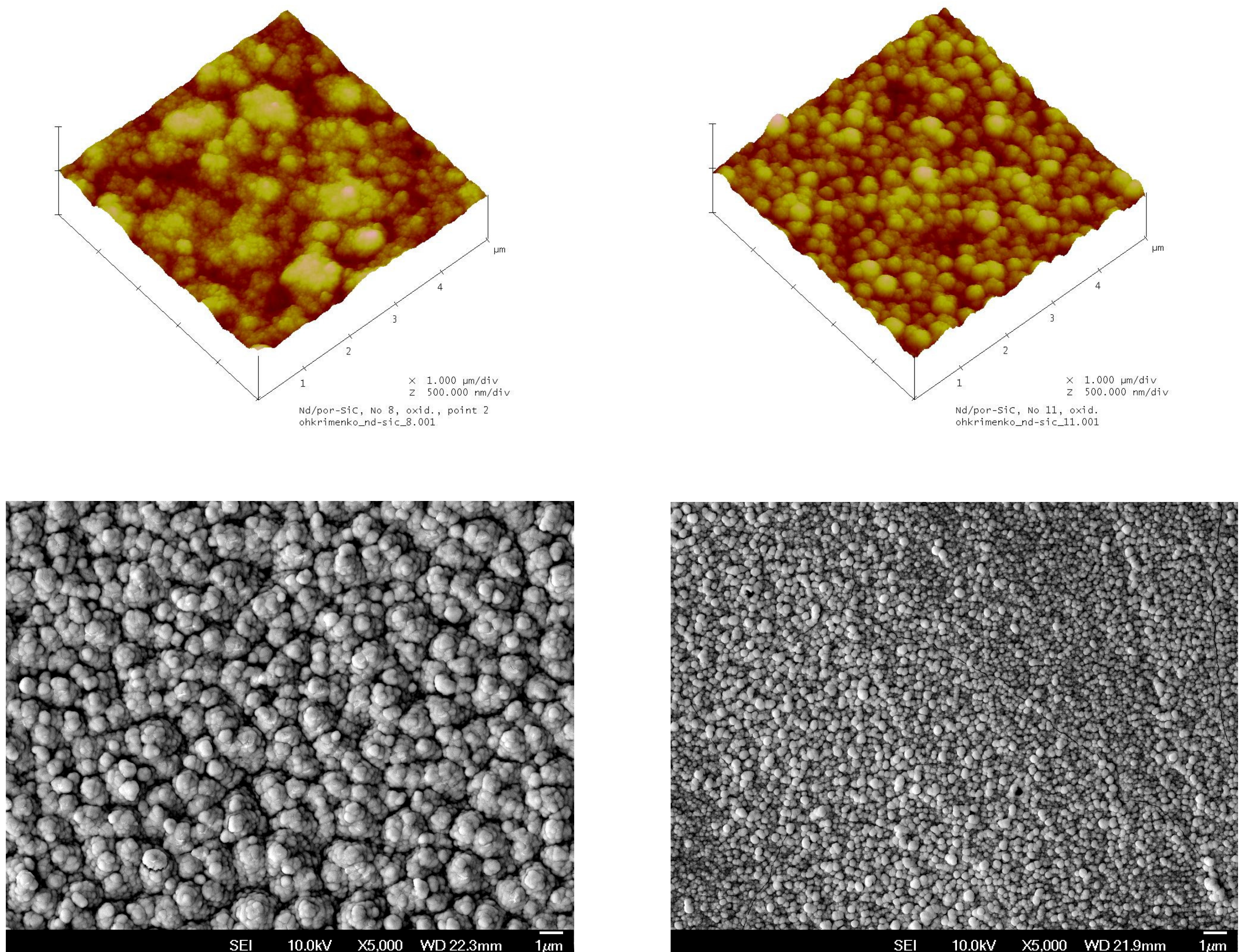

Fig. 1. Images of the surface of the Dy_2O_3/por-SiC/SiC structure obtained using AFM (a) and scanning electron microscopy (b). The RTA time is 1 s (1), 5 s (2).

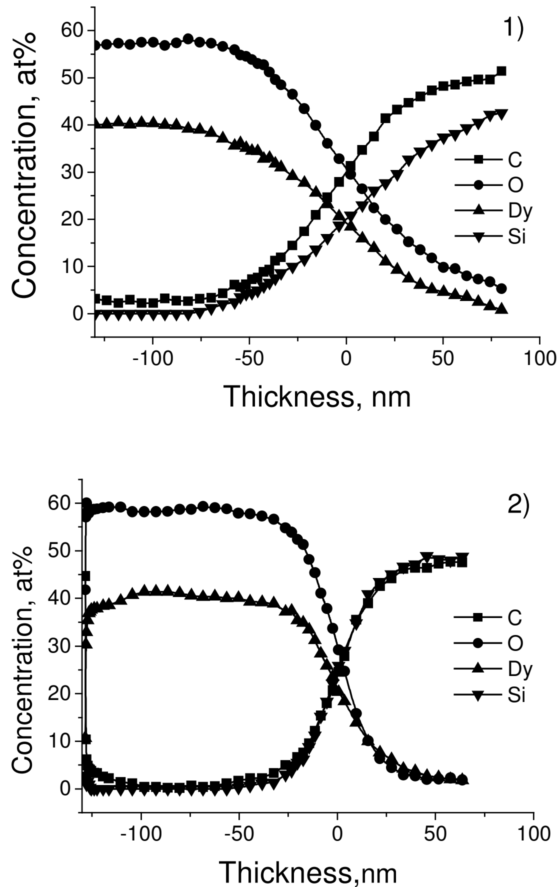

Fig. 2. Content of elements (in atomic percents) in the Dy_2O_3/por-SiC/SiC samples. The RTA time is 1 s (1), 5 s (2).

force microscope (AFM) NanoScopeIIIa (DJ). The atomic composition of the structures under study was measured using the LAS-2000 Auger spectrometer with the layer-by-layer etching of the samples with Ar ions possessing the energy 1 keV.

3. Experimental results and discussion

The thickness of the oxide layers was determined by the Auger spectroscopy method and was approximately 130…170 nm. The pore size determined using the scanning electron microscopy method was 30 nm.

Fig. 1 shows images of the surface of the Dy_2O_3/por-SiC/SiC structure obtained using AFM and scanning electron microscopy.

As can be seen from Fig. 1, the oxide film has a non-homogeneous character and granular structure. An increase in the RTA time contributes to a decrease in the grain size and formation of an oxide film with a more homogeneous structure.

Fig. 2 shows the atomic profiles of the structures formed by dysprosium oxides on a por-SiC/SiC substrate in the region of the ‘oxide layer – substrate’ interface.

As it follows from the Auger spectrometry data obtained in the process of growing the dysprosium oxides, heat treatment allows to form uniformly thick oxide layers of Dy_2O_3, the composition of which is close to the stoichiometric one. As can be seen from Fig. 2, the ratio of the Dy_2O_3 components formed on the SiC substrate in the presence of a por-SiC buffer layer practically corresponds to the stoichiometric composition of the sesquialteral dysprosium oxide: $N_O/N_{Dy} \approx 1.4$ regardless of the oxidation time.

The observed changes in the composition of the oxide phases in the near-boundary layers and their depth are related to the conditions of oxide growth. As can be seen from Fig. 2, the chemical composition of the transition areas ‘oxide film – substrate’ differs from that in the oxide bulk. An increase in the RTA time, like to the case of erbium and titanium oxides formation [18-21], leads to formation of a sharper interface ‘oxide film – substrate’. This formation of the sharper interface ‘oxide film – substrate’ with increasing the RTA time is most likely due to the fact that, with the RTA time increasing, dysprosium silicates [13] formed in the intermediate layer ‘oxide film – porous layer’ break down.

Fig. 3 shows the transmission spectra of the Dy_2O_3/por-SiC/SiC structures at different RTA times, as well as the transmission spectrum of the 4H-SiC substrate.

The minimum in the transmission spectrum of the Dy_2O_3/por-SiC/SiC structures is caused by the presence of nitrogen impurity in the 4H-SiC substrate (Fig. 2, curve 3). The sharp decrease in the optical transmission in the Dy_2O_3/por-SiC/SiC structures as compared to that in 4H-SiC substrate is due to the presence of a porous layer and occurs due to an increase in scattering in the porous layer.

As seen from Fig. 3, an increase in the RTA time also leads to an increase in optical transmission within the spectral range 400…800 nm, as well as in the Er_2O_3/por-SiC/SiC [20, 21] and TiO_2/por-SiC/SiC [18, 19] structures. The growth of optical transmission for oxidized dysprosium films, as well as a decrease in the thickness of the transition layer at the ‘oxide film – substrate’ interface, is most likely caused by the same reasons, namely: destruction of dysprosium silicates at the interface [13], which correlates with the Auger spectroscopy data.

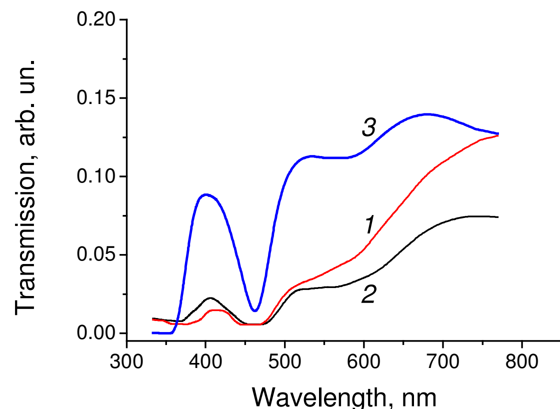

Fig. 3. Optical transmission spectra of the Dy_2O_3/por-SiC/SiC structures. The RTA time is 1 s (*1*), 5 s (*2*), transmission spectrum of the initial 4H-SiC substrate (*3*). The intensity of the transmission spectra of the Dy_2O_3/por-SiC/SiC structures is five-fold increased.

4. Conclusions

Thus, as seen from the experimental data, the RTA method allows to obtain thin Dy oxide films with a composition close to stoichiometric on the por-SiC – SiC surface. At the same time, the increasing the RTA time leads to improvement in the quality of the film-substrate interface. In this case, the presence of a porous interlayer between the substrate and epitaxial layer makes it possible to reduce the influence of structural defects of the semiconductor substrate and improve the quality of the whole structure.

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Authors and CV

Yuriy Yu. Bacherikov, born in 1960, defended his Doctoral Dissertation in Physics and Mathematics in 2010. Leading scientific collaborator at V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Authored over 300 publications, 6 patent, 1 monograph. The area of his scientific interests includes physics and applications of wide-band semiconductor compounds and devices based on them.
V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kyiv, Ukraine

Raisa V. Konakova Doctor of science in Technical field. Professor at Laboratory of Physical and Technological Problems of Solid-State Microwave Electronics, ISP of NAS, Ukraine. Authored over 600 publications, 85 patents, 14 textbooks. The area of her scientific interests includes physics, technology and diagnostics of microwave semiconductor devices.
V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kyiv, Ukraine

Olga B. Okhrimenko, Doctor of science in Physics and Mathematics. Leading senior researcher at V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine. Authored over 140 publications, 1 patent, 1 monograph. The area of her scientific interests includes investigation of the patterns and physical mechanisms of the formation and rearrangement of the defect-impurity system of the thin-film dielectric-semiconductor structures, depending on the technology of obtaining, the composition of the thin film, additional processing and the introduction of buffer layers.
V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kyiv, Ukraine

Nataliya I. Berezovska, PhD in Physics and Mathematics. Senior researcher at Experimental Physics Division, Faculty of Physics, Kyiv National Taras Shevchenko University. Authored over 113 publications. The area of her scientific interests includes fundamental and applied problems in the field of spectroscopy of phonon, exciton and plasmon states in crystals, nano-sized semiconductor and metal structures. Recent studies deal with the study of the mechanisms of self-organization of quasi-perioidic structures on the surface of materials of various types under the influence of femtosecond laser radiation and the prospects of their application for photovoltaics and sensorics.
Taras Shevchenko Kyiv National University, Physics Department, Kyiv, Ukraine

Oksana S. Lytvyn, PhD in Physics and Mathematics, Senior Researcher. Head of Information technologies and mathematic disciplines Chair of Borys Grinchenko Kyiv University. Authored over 200 publications, 2 patents. The area of her scientific interests includes scanning probe microscopy diagnostic of physics and mechanical surface properties of various materials (thin films and low-dimensional systems, composite).
Borys Grinchenko Kyiv University Kyiv, Ukraine

Leonid M. Kapitanchuk. Researcher at E.O. Paton Electric Welding Institute, National Academy of Science of Ukraine. Authored over 82 publications and 2 patents. The area of his scientific interests includes materials science, Auger electron spectroscopy, X-ray spectroscopy.
Paton Institute of Electric Welding, NAS of Ukraine, Kyiv, Ukraine

Aleksandr M. Svetlichnyi PhD in Technical sciences. Associate Professor at Institute of Nanotechnologies, Electronics and Equipment Engineering. Authored over 300 publications, 30 patents, 6 textbooks. The area of his scientific interests includes defects in the crystal structure of semiconductors and their influence on the instrument parameters, quality control of manufacturing processes of integrated circuits on the noise characteristics, the development of equipment and manufacturing processes of integrated circuits on the basis of coherent (laser) and non-coherent radiation sources.
Institute of Nanotechnologies, Electronics, and Electronic Equipment Engineering, Southern Federal University, Taganrog, Russia