

## MORPHOLOGY OF CRYSTALLINE STRUCTURE AND ATOMIC BONDS INSIDE $Dy_xO_y$ FILMS GROWN ON Si

**K. Lawniczak-Jablonska<sup>1\*</sup>, E. Dynowska<sup>1</sup>, N.V. Babushkina<sup>2</sup>, S.A. Malyshev<sup>2</sup>,  
L.I. Romanova<sup>2</sup>, M. Heinonen<sup>3</sup>, and T. Laiho<sup>3</sup>**

<sup>1</sup>*Institute of Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02 668 Warsaw, Poland*

<sup>2</sup>*Institute of Electronics, National Academy of Science of Belarus, Minsk, Belarus*

<sup>3</sup>*Laboratory of Materials Science, Department of Physics, University of Turku, FIN-20014 Turku, Finland*

*Keywords: dielectrics, dysprosium oxide, X-ray diffraction, X-ray absorption, atomic force microscopy*

*\*) e-mail: jablo@ifpan.edu.pl*

The continual miniaturization of the metal-oxide-semiconductor (MOS) devices requires the replacement of  $SiO_2$  with dielectrics with high- $k$  constant. In the last decade much attention has been devoted to the study of high- $k$  dielectrics suitable for producing microelectronic devices and integrated circuits and featuring properties equivalent to very thin  $SiO_2$ .

The dielectric films with high- $k$  must satisfy many requirements. A very important requirement is that the atomic structure of the film should be amorphous and has to have low roughness of the dielectric-silicon interface.

It is well known that the formation of crystalline grains in the dielectric films leads to oxygen diffusion along grain boundaries during thermal processing. This can result in the growth of interfacial  $SiO_x$  layer and increase the possible equivalent  $SiO_2$  thickness that should have the high- $k$  materials. Moreover, the grain-boundary diffusion of other impurities deteriorates the electrical performance of the MOS devices. Regarding the roughness it was found that MOS devices with the ultra-thin gate dielectrics are very sensitive to the roughness of the dielectric film surface and dielectric-silicon interface. The increase of the dielectric-silicon interface roughness results in an increased charge state density at the interface  $D_{it}$ , and therefore, in the scattering of the carriers on the silicon surface. The scattering becomes dominant in carrier transport of MOS field-effect transistor (FET) and degrades MOS FET channel mobility. Moreover, the roughness degrades the time-dependent dielectric breakdown characteristics of MOS capacitors, and increases the tunneling current through the dielectric. Therefore, there is a need for elaborating of technology of growing the smooth, amorphous or single crystalline very thin layers of dielectric oxides.

Among the high- $k$  dielectrics under study,  $Dy_xO_y$  appears promising due to its relatively high dielectric constant ( $k = 12$ ) as compared to  $SiO_2$  ( $k = 3.9$ ). Therefore, we have studied the crystalline structure and the surface morphology of the thin  $Dy_xO_y$  films grown on Si as a function of the growth conditions. To examine the crys-

talline structure and range of ordering in  $Dy_xO_y$  layers prepared at different conditions the synchrotron radiation diffraction and absorption was used. To study the roughness and morphology of the surface and interface AFM was employed.

Due to the fact that  $Dy_xO_y$  layers being investigated were very thin ( $50 \div 120 \text{ \AA}$ ) it was not possible to obtain any meaningful diffraction pattern by conventional X-ray diffraction techniques. Only the use of GID geometry and synchrotron radiation resulted in registration of some diffraction peaks from the layers (Fig. 1).

The quality of the diffraction patterns indicates that level of film crystallinity is variable and is a function of the technological conditions. On the base of obtained diffraction patterns we could identify the crystal structure of the films as  $Dy_2O_3$ , cubic of  $Ia\bar{3}$  space group with lattice parameter  $a = 10.665 \text{ \AA}$  (according to the JCPDS-ICDD, 22-0612).

On the base of GID studies one can say that the  $Dy_xO_y$  films obtained with high deposition rate have the best crystalline structure. The thickness of these films is around  $100 \text{ \AA}$ . The decreasing of the deposition rate leads to deterioration of the  $Dy_2O_3$  film crystalline structure (Fig. 1, sample 1).

The shape of XANES is a fingerprint of the compounds formed, and the appearance of the fine structure in a spectrum is evidence of formation of long range ordering. Therefore the L edges of Dy were measured for thin films together with the stoichiometric  $Dy_2O_3$  powder. This method is sampling all volume of layer. To get information about the range of ordering around the Dy atoms spectra of  $L_1$  edge (presented in Fig. 2). Changes observed in the shape of  $L_1$  edges, indicate that the oxides formed have different level of nonstoichiometry but none of them is  $Dy_2O_3$ . The fine structure seen in  $L_1$  edges of  $Dy_2O_3$  was not found in samples 1 and 6 indicating the absence of long range order in these samples in agreement with results of diffraction studies. The reversed intensity in the two peak structures at the first

maximum marked 1 and 2 (Fig. 2) for other samples, is an evidence of a stoichiometry different from that of  $Dy_2O_3$ . In  $L_1$  edge the  $p$ -symmetry states in the conduction band are examined, and it can be seen that these states are very sensitive to the level of ordering in the sample.

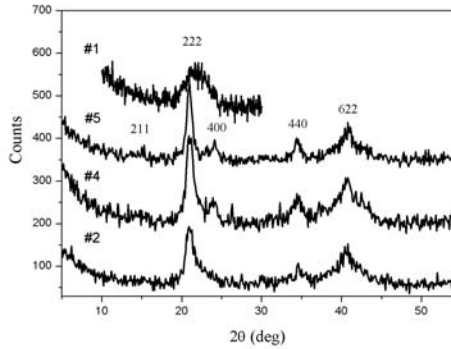


Figure 1. Grazing incident diffraction patterns for different  $Dy_xO_y$  layers.

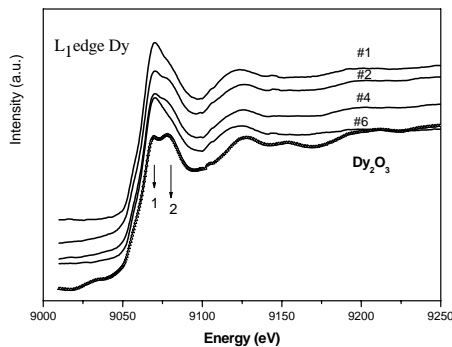


Figure 2.  $L_1$  edges of Dy in  $Dy_xO_y$  layers and  $Dy_2O_3$  powder.

The examples of AFM studies of  $Dy_xO_y$  films morphology are presented in Figures 3 and 4. The morphology of oxide films varies significantly. The surface of the sample 1 is smooth even at the high magnification (Fig. 3) but surface of sample 5 (Fig. 4) shows the well seen crystallites. For a quantitative estimation of the roughness of formed surface a height profile was made from four different line at the surface. The mean height of the roughness was found to be close to  $15 \text{ \AA}$  for the sample 1. Analysis of sample 4 and 5 profiles shows that the  $Dy_xO_y$  grows in the form of crystallites with the height of about  $100 \pm 20 \text{ \AA}$  and the width at the bottom of  $0.3 \pm 0.1 \text{ \mu m}$ . Therefore, the morphology of  $Dy_xO_y$  films strongly depends on the deposition rate. In the case of low deposition rate (sample 1) a fine-grained structure close to amorphous one was obtained, and in the case of high deposition rate (sample 4 and 5) polycrystalline structure with large grain sizes was grown. These results are in agreement with the XRD data.

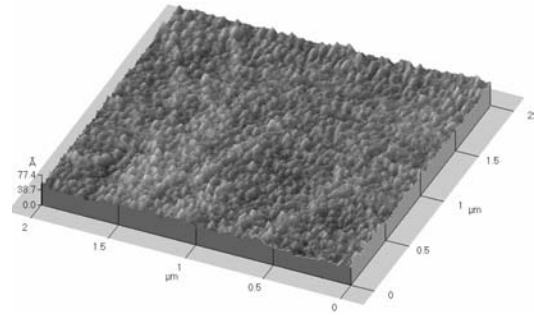


Figure 3. AFM three-dimensional images of  $Dy_xO_y$  film (sample 1) from  $2 \text{ \mu m} \times 2 \text{ \mu m}$  surface.

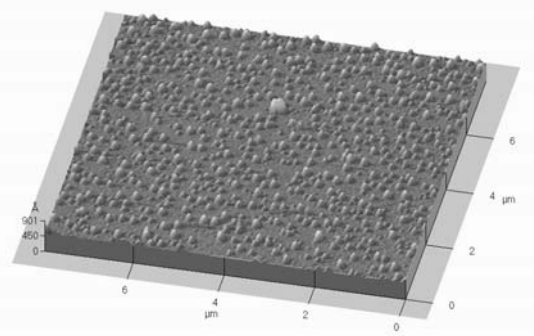


Figure 4. AFM three-dimensional images of  $Dy_xO_y$  film (sample 5) from  $8 \text{ \mu m} \times 8 \text{ \mu m}$  surface.

## Conclusions

$Dy_xO_y$  films prepared by thermal evaporation in mixed  $Ar-O_2$  atmosphere followed by annealing in oxygen can be considered as suitable gate dielectric for MOS devices. It is possible to produce thin amorphous films with the roughness level of about  $15 \text{ \AA}$  and with a very smooth dielectric-silicon interface.

The film structural quality highly depends on the deposition rate. Low deposition rates result in the growth of amorphous film, while an increased deposition rate leads to formation of crystallites inside the layer with the base size of about  $0.3 \text{ \mu m}$  and the height of about  $100 \text{ \AA}$ .

The annealing in the argon leads to the increase of the interface dielectric-silicon roughness.

The crystallographic structure of the films was determined as the phase  $Dy_2O_3$ , cubic of  $Ia\bar{3}$  space group with lattice parameter  $a = 10.665 \text{ \AA}$ , even though the stoichiometry of all films strongly differs from that of  $Dy_2O_3$ . The level of non-stoichiometry is a function of technological conditions.

**Acknowledgements:** This work was partially supported by the State Committee for Scientific Research (Republic of Poland) (Grant No72/E-67/SPB/5.PR UE/DZ 27/2003-2005) and by G1MA-CI-2002-4017 (CEPHEUS) and the IHP-Contract HPRI-CT-2001-00140 of the European Commission.