RBS analyses of the composition and structure of thin films synthesized using the pulsed laser deposition technique

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Flexible or transparent electronics are among the most exciting applications for transparent conducting oxides (TCO) [1-4]. Some TCO materials [5] (e.g. ITO, AZO, or SnO2) used as contact electrodes in solar cell structures, may lead to an improvement of the solar cell efficiency, according to their performance. Furthermore, the flexible substrate used to obtain flexible solar cells, offer numerous advantages, including mechanical flexibility, freedom of design, optical transparency, low weight and cost [6]. Metal oxide-based thin film transistors (TFT) are used in displays as switching components in the active-matrix over a large area and can be deposited at room temperature on plastic substrates. The best TCO for TFT are amorphous indium zinc oxide (IZO) [2, 3], zinc indium tin oxide (ZITO) or indium gallium zinc oxide (IGZO) [3,4], which have the added benefit on using less In than ITO. The major basic materials science questions with these oxides are:

1) what are the best compositions (In/(In+Zn) or In/(In+Zn+Ga) values, type and concentration of dopants) of IZO and IGZO layers for displays or TFTs applications;

2) what are the best gate dielectrics for TFT fabricated using IGZO channels and IZO electrodes;

3) what is the effect of channel and dielectric composition and interface roughness on band offset or interface state density;

4) how the performance and stability of such devices is affected by low-temperature processing.

Using several elemental characterization techniques we were able to accurately determine the composition of IZO thin films deposited by the combinatorial pulsed laser deposition (C-PLD) technique [7]. The main result we obtained was the use of calibration free LIBS (laser induced breakdown spectroscopy) to determine the In/(In+Zn) values under ambient conditions. The use of Rutherford backscattering spectrometry was essential for these studies ensuring an initial calibration of the LIBS technique and afterwards providing comparative results. Also, the thickness values were compared with those obtained by ellipsometry and X-ray reflectivity allowing for accurate determinations of the films density too.

Since the RBS analyzing area is rather small it was possible to investigate lateral variations of the elemental composition in films deposited by PLD.

The next objectives of our project are the synthesis using the combinatorial pulsed laser deposition technique of variable Ga concentrations IGZO, doped IZO and high-k dielectric layers that have various chemical compositions.

The main difference with respect to conventional PLD, is that in the case of C-PLD the laser beam is divided into two beams (Fig. 1) by an optical beam-splitter. The two beams are separately directed by mirrors and focused by lenses inside the deposition chamber onto the surfaces of two or more targets. Accordingly, on the facing substrates we will obtain a perfectly controllable gradient of composition along the longitudinal direction from almost 100% of a material A (e.g. IZO) to almost 100% of a material B (e.g. dopant) over well-defined areas, by changing the separation distance (D) between targets, or the specific irradiation sites. Our expertise in this direction was mainly applied in case of IZO compositional libraries for tuning the structural, optical and electrical properties [7-9], in case of materials with complex stoechiometry like calcium phosphates doped with Ag for biomedical applications [10], but also for the synthesis of biopolymer compositional gradient thin films by Combinatorial Matrix-Assisted Pulsed Laser Evaporation (C-MAPLE) [11].
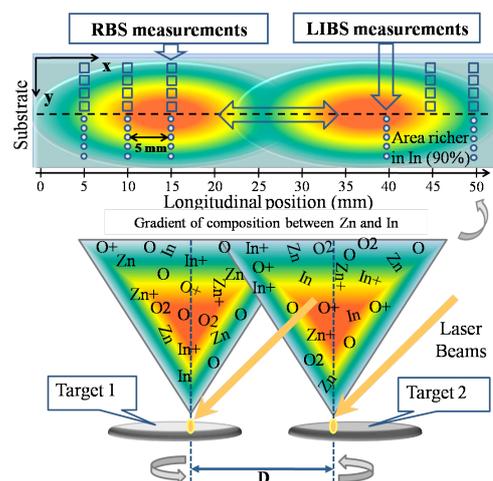
Figure 1. *Typical set up for Combinatorial Pulsed Laser Deposition*

The experimental conditions (laser fluence, number of pulses, repetition rate, target-substrate separation distance, ambient pressure inside reaction chamber, substrates temperature) will be optimized in order to obtain the best quality coatings.

The analysis of IGZO and high-k dielectric thin films synthesized using a Combinatorial Pulsed Laser Deposition technique will be firstly performed via laser-induced breakdown spectroscopy (LIBS) based on the calculation of the spectral radiance of the laser-produced plasma. The plasma emission spectra were characterized using time-resolved optical emission spectroscopy. The recorded spectra were then compared to the spectral radiance computed for plasmas in local thermal equilibrium. The metal fractions measured via LIBS were compared to values obtained by complementary measurements using RBS, X-ray florescence (XRF), energy dispersive X-ray spectroscopy (EDAX). Also, the thickness/density of these films will be measured using RBS, XRR, and ellipsometry.
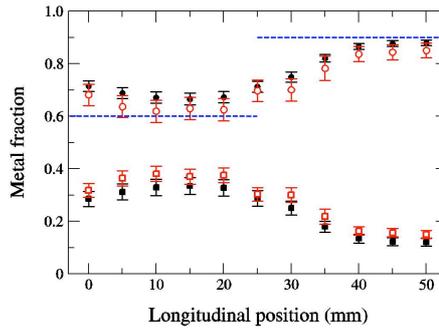
Figure 2. *Atomic fractions of indium (circles) and zinc (squares) measured by LIBS (empty red symbols) and by EDS (filled black symbols). The dashed lines represent the In/(In+Zn) fractions of the targets used for thin film synthesis by C-PLD.*

However, the precise investigation of the dopants concentration along the longitudinal direction of the samples as well as their 3D spatial distribution is mandatory. Since complementary characterization techniques suffers due to limited accuracy (EDAX), or very limited depth resolution (XPS), the chemical stoichiometry of the grown films is very important and must be achieved using a reliable technique such as Rutherford Backscattering Spectrometry (RBS) or non-Rutherford Backscattering Spectrometry (NRBS).

Other compounds of interest to be investigated by RBS to obtain the depth profiles and thickness are thin layers of transition metal carbides (ZrC, TiC), nitrides (ZrN, TiN) and carbonitrides (ZrC_xN_y, TiC_xN_y) used as hard and protective coatings for field emission tips, nuclear fuel encapsulation, or outer space thermal radiators. The hard coatings were deposited by PLD under optimized experimental conditions. X-ray reflectivity investigations showed that films exhibited mass densities similar to bulk values. X-ray diffraction investigations found that films were nanocristalline, exhibiting a (1 1 1) texture and high micro-strain values. Auger electron spectroscopy investigations indicated that films contained in bulk a relatively low oxygen concentration, usually below 2.0% [12].

AES survey spectra recorded after removal of more than 10 nm of surface material by Ar ion sputtering indicated low oxygen concentrations within the deposited films. The Zr to N or Zr to C ratios were higher than 1, indicating either a strong preferential sputtering of the light atoms (C, O, N) or a substoichiometric compound. The ZrN film also contained C atoms. High resolution XPS investigations showed that the binding energy of C atoms, when present in bulk, was around 282.5 eV, corresponding to C bonded in a metallic carbide type of compound [13].

Rutherford backscattering spectrometry with light ions, typically 1–2 MeV ^{1}H or [4]He ions, is a often used technique for depth profiling of elements concentrations. In the extensive use of elastic backscattering for materials characterization purposes, [4]He particles up to several MeV have been for long considered as most convenient projectile. This often gives sufficient mass and depth resolution. However, the cases of more complex film structures, with compound materials, have put higher demands on both the mass and the depth resolution in the analysis.

The RBS technique has also its limitations. Mass resolution for heavy elements and sensitivity for light elements are poor, and, except for the surface, mass determination is not unambiguously possible. The analysis of light elements in a heavier matrix is often

impossible, because of the energy overlap of the beam ions scattered by light surface atoms and by heavier bulk atoms deeper in the sample. Furthermore, small amounts of light elements are difficult to analyze, because of the Z^2 dependence of the Rutherford cross section.

It is well known that the mass and depth resolution, as well as the sensitivity may be improved by using heavier and more energetic ions. In particular, mass separation for medium and heavy elements is improved significantly by heavy ions RBS. The expression for the energy separation as a function of the projectile mass M_1, the projectile energy E_0 and the target mass M_2 can be written as:

$$\Delta E \cong \frac{2M_1E_0}{M_2^2}\left(1-\cos\theta\right) \tag{1}$$

where θ is the backscattering angle [14]. This is valid for $M_1/M_2 << 1$. The expression suggests the use of higher mass projectiles and higher bombarding energies. There are, however, some drawbacks, because the resolution of the silicon detector is worsened and, due to $1/E_0^2$ dependency of the cross section, the counting rate reduces. Subsequently, longer analyzing time has to be used if higher energies are needed. In order to avoid the worsened resolution of silicon detectors for heavy ions the measurement of backscattered ions energy using a time of flight spectrometer can be used.

A severe disadvantage of conventional RBS is low sensitivity for light elements. The Rutherford scattering cross section is proportional to the square of the nuclear charge of the target nucleus. Therefore, the scattering peaks from light elements such as C, N and O are superimposed on a relatively high background due to backscattering from heavy elements in the sample. In recent years, high energy ^{1}H and ^{4}H backscattering has been utilized to overcome this difficulty and to quantify the stoichiometry or to profile the light elements in the heavy bulk samples. In the high energy backscattering experiments, ^{1}H and ^{4}He ions of *3–9 MeV* (or even more) are used as incident projectiles. The elastic scattering cross section for light elements becomes a nuclear rather than a Rutherford interaction, called non–Rutherford backscattering or nuclear resonance elastic scattering. The non–Rutherford backscattering can be used to enhance the sensitivity for light elements. For example, at ^{4}He energies of *3.045*, *4.265* and *3.72 MeV* the elastic backscattering cross sections for O, C and N are 25, 150 and 6 times larger than their corresponding Rutherford cross sections, respectively [15, 16].

We intend to use RBS and NRA techniques to characterize the thin layers of the above mentioned materials. Both RBS and NRBS with ^{4}He will be used. The measurements will be performed using a dedicated target chamber at the new 3 MV Tandetron accelerator. The energy of the ^{4}He beam used for measurements will be calibrated. The method adopted for calibration of the accelerator consists simply of comparing the energies of alpha particles from a radioactive source with the energies of ^{4}He projectiles back-scattered into an silicon detector by thin carbon and gold layers. The ions scattered at 165^0 will be detected by a Si detector having 15 keV resolution.

The results obtained so far were recently published in collaboration with the team from IFIN-HH as a paper in Applied Physics A: Materials Science & Processing (DOI 10.1007/s00339-014-8427-y) entitled: "Quantitative analysis of amorphous indium zinc oxide

thin films synthesized by Combinatorial Pulsed Laser Deposition", by E. Axente, G. Socol, S.A. Beldjilali, L. Mercadier, C.R. Luculescu, L.M. Trinca, A.C. Galca, D. Pantelica, P. Ionescu, N. Becherescu, J. Hermann, and V. Craciun. Several other disseminations were performed at national and international conferences as: E-MRS 2014 SPRING MEETING, Symposium H – „Analytical techniques for precise characterization of nanomaterials", Lille France, International Conference "MODERN LASER APPLICATIONS" 4th Edition, Bran, Romania, IUMRS 2014 Taiwan. Another contribution was submitted to Advanced Laser Technologies (ALT) Conference, to be held in Cassis, France, from 6 to 10 October 2014.

We need 8 days (24 shifts) at the 3 MV Tandetron .

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