Investigation of laser ablated ZnO thin films grown with Zn metal target: a structural study.

A. Fouchet, W. Prellier* and B. Mercey

Laboratoire CRISMAT, CNRS UMR 6508, 6 Bd du Maréchal Juin,
F-14050 Caen Cedex, FRANCE.

L. Méchin

Laboratoire GREYC, CNRS UMR 6072, ENSICAEN et Université de Caen,
6 Bd du Maréchal Juin, F-14050 Caen Cedex, FRANCE.

V. N. Kulkarni† and T. Venkatesan

Center for Superconductivity Research, University of Maryland,
College Park, Maryland 20742-4111, USA
(March 22, 2022)

Abstract

High quality ZnO thin films were grown using the pulsed laser deposition technique on (0001) Al$_2$O$_3$ substrates in an oxidizing atmosphere, using a Zn metallic target. We varied the growth conditions such as the deposition temperature and the oxygen pressure. First, using a battery of techniques such as x-rays diffraction, Rutherford Backscattering spectroscopy and atomic force microscopy, we evaluated the structural quality, the stress and the degree of epitaxy of the films. Second, the relations between the deposition conditions

*prellier@ismra.fr

†On leave from Indian Institute of Technology, Kanpur, India.
and the structural properties, that are directly related to the nature of the thin films, are discussed qualitatively. Finally, a number of issues on how to get good-quality ZnO films are addressed.
I. INTRODUCTION

Zinc oxide (ZnO) is a II-VI semiconductor highly transparent (85-95%) in the visible region with a wide and direct band-gap of about 3.3eV at room temperature and a high exciton binding energy of 60 meV\textsuperscript{1}. This semiconductor is very attractive because it has many applications such as transparent conductive contacts, solar cells, laser diodes, ultraviolet lasers, thin films transistors and others\textsuperscript{2-8}.

ZnO is an oxide that can be grown, as a thin film, by many deposition techniques including chemical vapor deposition, radio frequency sputtering, magnetron sputtering, sol-gel, ion-beam assisted, molecular beam epitaxy and pulsed laser deposition\textsuperscript{9-16}. The zinc oxide shows a $n$-type conduction, without intentional doping, and crystallizes in a wurtzite structure that contains large voids that can easily accommodate interstitial atoms. The intrinsic point defects i.e. zinc interstitials have been proposed to be the donors causing $n$-type conduction\textsuperscript{20}. However, in order to control the doping content, it is necessary to remove oxygen vacancies (since the lack of oxygen and an excess of zinc leads to a $n$-type semiconductor). For this reason, the pulsed laser deposition (PLD) technique is interesting because it gives the advantage of carrying out the growth in a high-oxygen partial pressure (typically around 0.2 torr)\textsuperscript{16}. Usually, the films are obtained from a ZnO target\textsuperscript{16,21,22} but we have recently developed a variant technique in which the oxide films are grown from a metal target\textsuperscript{17,18}. We have also used this technique to synthesis ZnO films described in this article.

Fabricating high quality epitaxial thin films with a perfect $c$-axis texture, a low density of defects (i.e. low strained films) and an extremely smooth surfaces, are important for many applications. Thus, it is necessary to understand the growth mechanisms of ZnO films that influence the structural and the optical properties. Here, we report the growth of ZnO films on sapphire (0001)-oriented by PLD, using a Zn metal target. A number of issues on how to control the growth conditions in order to get good-quality ZnO films are addressed in this paper. In particular, the effects of the deposition parameters on the degree of epitaxy
II. EXPERIMENTAL

The ZnO films were grown utilizing the pulsed laser deposition technique (Lambda Physik, KrF laser λ=248nm)\(^{19}\) by firing a zinc metal target (99.995\%) as purchased (NEYCO, France) and without further preparations. The films are deposited on (0001) \(\text{Al}_2\text{O}_3\) substrates at a constant temperature under a flux of pure oxygen. These two parameters (temperature and oxygen pressure) were systematically varied. The substrate temperature ranged from 400 to 750\(^\circ\)C and the pressure was changed from 0.03 to 0.2 torr of \(\text{O}_2\). Thus, different series of films are obtained. At the end of the deposition, the films were slowly cooled to room temperature (20\(^\circ\)C/min) under 225 torr of oxygen.

The structural study was done by X-Ray diffraction (XRD) using a Seifert XRD 3000P for the \(\Theta - 2\Theta\) scans and the \(\omega\)-scan (tilting). An X’Pert Phillips was also employed for the in-plane measurements (\(\Phi\)-scans). Both diffractometers utilized the Cu, Ka1 radiation (\(\lambda = 0.15406\)nm). In order to obtain additional information on the structural properties of the ZnO films, we have determined the thin film strains. This technique used the distance between the atomic planes of a crystalline specimen as an internal strain gage\(^{29}\). The plane spacing \(d_{hkl}\) is normal to the diffraction vector \(\mathbf{L}\). One can define a strain \(\varepsilon\), along this diffraction vector \(d_{hkl}\), 

\[
\varepsilon = (d_{hkl} - d_0)/d_0 
\]

where \(d_0\) is the unstressed plane spacing of the \((hkl)\) planes (i.e. the value of the bulk). To measure the stress, we used the sin\(^2\)\(\Psi\) technique\(^{29}\). Briefly, in this model, the strain is defined as follows: 

\[
\varepsilon = A \sin^2 \Psi + B 
\]

where \(A\) and \(B\) are constants that depend on the strain along the surface direction, the Young’s modulus, Poisson’s ratio and the stress along the direction, for details see Ref.15). Additional informations are given from the XRD measurements by calculating the grain size of the crystallites along the \(c\)-axis using the Scherrer’s formula\(^{30}\):

\[
\beta_{1/2} = \frac{0.9\lambda}{D \cos \theta} 
\]
where $\lambda$ is the X-ray wavelength, $\beta_{2}$ is the (0002) peak width (in radian), $D$ the crystal size and $\theta$ the Bragg diffraction angle.

Rutherford back scattering spectroscopy (RBS)/ion channeling using a well-collimated 1.5-3 MeV He$^+$ ions has been used to determine the epitaxy quality and the film thickness. Surface morphology and roughness measurements were determined by Atomic Force Microscopy (AFM) in tapping mode using a Multimode Nanoscope III (Digitalis Instruments).

Optical measurements were investigated with an UV-Visible spectrophotometer (Cary 100 scan) to determine the energy band gap of the different films. In this method, the fundamental absorption, which corresponds to electron excitation from the valence band to conduction band, is used to determine the value of the optical band gap through the following relation:

$$(h\nu \alpha)^2 = C(h\nu - E_g)$$ (2)

where $\alpha$ is the absorption coefficient, $C$ is a constant, $h\nu$ is the incident photon energy and $E_g$ the band gap.

III. RESULTS

A. Study as a function of the deposition temperature

A series of films grown in 0.1 torr of O$_2$ were investigated. The resulting XRD patterns of ZnO exhibit two diffraction peaks observed around $2\Theta$ close to 34.48° and 72.66°. They are characteristic of the hexagonal ZnO wurtzite, the $c$-axis being perpendicular to the substrate plane$^{25-27}$. The out-of-plane lattice parameter is calculated to be close to 5.205 Å which corresponds to the theoretical bulk value$^{28}$. Moreover, the out-of-plane lattice parameter is almost constant, equal to 5.198±0.004 Å in the temperature range 500-700°C, which is slightly shorten, as compared to the bulk, but in agreement with a tensile stress within the plane (see below in the text). Below 500°C and above 700°C, the out-of-plane lattice parameter is much lower (5.185 Å). Nevertheless, the full-with-at-half-maximum (FWHM)
of the rocking-curve $\omega$-scan measured around the 0002 reflection (tilting) is decreasing from $1.8^\circ$ at 400$^\circ$C to $0.3^\circ$ at 600$^\circ$C. It remains constant from 600$^\circ$C to 750$^\circ$C (see Fig.1). The in-plane epitaxy was investigated by measuring the $\Phi$-scan (recorded around the 2113 reflection) at different deposition temperatures. The resulting plot is given in Fig.3. While the films grown above 600$^\circ$C exhibit 6 diffraction peaks separated of 60$^\circ$ in agreement of the six-fold symmetry of the hexagonal lattice of the ZnO, the films deposited below display 12 diffraction peaks separated of 30$^\circ$. In fact, these 12 peaks correspond most probably to two different series of 6 peaks i.e. two series of crystallites (or oriented domains) that are epitaxially different. The FWHM of the $\Phi$-scan (twisting) is also indicated on the left part of Fig.3. It confirms the degradation of the epitaxy as the deposition temperature is decreasing (see also Fig.1).

In order to evaluate the stress of the ZnO films, we have used the $\sin^2\Psi$ model\textsuperscript{29} that allows to determine the residual stress in epitaxial plane. The stress (determined as the slope of the curve when plotting the strain $\varepsilon$ vs. $\sin^2\Psi$) is decreasing when increasing the substrate temperature. The residual stress is calculated to be 107 MPa at 600$^\circ$C and 100.5 MPa at 700$^\circ$C. Note that the decrease of the residual stress when increasing the deposition temperature is in a perfect agreement with the decrease of the FWHM of both the (0002) and the (2113) reflections (see Fig.1). In addition, this value is much lower than previously reported ones (330-500 MPa)\textsuperscript{22} but these films were grown from a ZnO target and the deposition performed at 550$^\circ$C under $3.75 \times 10^{-4}$ torr.

The absorbance measurements investigated between 200 and 900 nm show that the films are highly transparent in the visible region and present a steep fall off around 380 nm. This fundamental absorption can be used to determine the value of the optical band gap. Its dependence on the deposition temperature, is given in Fig. 2a. The band gap energy is increasing with the temperature as a result of an increase of the number of defects\textsuperscript{23}. However, between 550-700$^\circ$C, the energy gap is almost constant and close to 3.20 eV, a characteristic of high quality ZnO films. The grain size has also been calculated using the Sherrer’s formula. The grain size increases with the temperature in the range of 600-700 $^\circ$C.
up to 25 nm (see Fig.2). As a result, when the grain size is increasing, the epitaxy of the films is improving and the energy band gap is increasing to a constant value.

These experiments suggest that at a pressure of 0.1 torr of O₂, the deposition temperature should be around 600°C. Thus, in a second step, we have investigated the influence of the oxygen pressure for a fixed temperature of 600°C.

B. Study as a function of the oxygen pressure

Basically, the XRD of the films (Θ − 2Θ), grown at various oxygen pressure, resemble the previous one. Two diffraction peaks corresponding to 0002 and the 0004 reflections are predominant and indicate that the film has a c-axis orientation with an out-of-plane lattice parameter around 5.2 Å. In Fig.2b, the grain size and the band gap exhibits a maximum indicating an optimum value of the oxygen pressure close to 0.1 torr 24. In the same way, the FWHM of rocking curve (tilting) presents a minimum (0.3°) for a pressure of 0.1 torr (see Fig.1). Similar behavior is observed when plotting the FWHM of the Φ-scan (twisting): the minimum value (0.9°) is also seen at a pressure close to 0.1 torr of O₂ (see Fig.1). Such values are comparable to the results of other groups which used ceramic targets 25–27. These results also confirm that a pressure of 0.1 torr will give the better epitaxy (as seen from Φ-scan), better texture (see the values of the FWHM) and larger nano-crystallites (30 nm using Sherrer’s formula) of the ZnO films. The low value obtained at 0.2 torr for the twisting angle will be explained latter. We have also noted that the measured value of the out-of-plane lattice parameter is 5.1982 Å, which is lower than the bulk value (5.2066 Å 28). This indicates a compression ( ~0.1%) of the out-of-plane parameter and an expansion of the in-plane lattice parameter (3.253 Å in the film to be compared with 3.2498 Å in bulk 28) as observed for many oxide films 31,32. The tensile stress within the plane of the substrate is confirming by the positive slope of the curve (strain ε versus sin²Ψ). The resulting data are given in Table 1 for a series of films. At 0.1 torr, the residual stress is minimum (107 MPa) as compared to the films grown at 0.2 torr (334 MPa) or 0.03 torr (232 MPa). In addition,
the film prepared at 0.1 torr approached the c-axis value of the bulk\textsuperscript{28} in agreement with a low residual compressive stress. This is also in perfect accordance with the evolution of the FWHM along both $\omega$ (tilting) and $\Psi$ (twisting) scans (Fig.1) where the minimum values are obtained for a pressure of 0.1 torr.

The structural analysis was completed using the measurements of ion channeling using RBS and the results spectra (random and aligned) recorded for three different oxygen pressures are given in Fig.4. The $\chi_{\text{min}}$ value, which indicates the quality of the film is given a minimum at 0.1 torr (Aligned yield of 8.7%) as compared to the film grown at 0.03 torr (aligned yield: 24%). Surprisingly the film grown at 0.2 torr is not epitaxied (no alignment). The low experimental $\chi_{\text{min}}$ value indicates a very low level of structural defects in this film. On the contrary, a high $\chi_{\text{min}}$ value is correlated to a presence of large amount of defects in the crystallites. The presence of defects leads to a broadening of the diffraction peaks as observed in the plot of the FWHM vs. oxygen pressure (Fig.3). Note also, that the thickness of the film was also determined with the simulation of the structure and we found that it is increasing with the increase of the oxygen pressure.

The morphology and the surface roughness, determined by AFM measurements, are represented in Fig.5. The roughness seems to decrease with the increase of oxygen concentration and in the same time, the grains size on the surface is changing. For the film grown at low pressure (0.07 torr), the grains size is around 250 nm and seems relatively constant. Furthermore the roughness of this film is about 50 nm. On the contrary, the film grown at higher pressure (0.1 torr) shows two types of grains with two different sizes: higher 500 nm and smaller 160 nm than for the film at low pressure. The roughness is around 50 nm. Finally for the film grown at 0.2 torr, the grains size is larger and seems inhomogeneous, but the roughness (rms) being of only 23 nm.

These studies were followed by the determination of the energy band gap, plotted in Fig.2b versus the pressure of oxygen. The film deposited under 0.1 torr presents the widest energy band gap with the value of 3.20 eV. Furthermore the comparison of the gap with
the grain size shows the same tendency than with the temperature: when the grains size is larger, the energy band gap between the conduction band and valence band is increased.

C. Discussion

These experiments performed on a series of ZnO thin films clearly show that there is a correlation between the deposition parameters (substrate temperature, oxygen pressure) and many structural parameters including crystallinity, grain size, epitaxy in-the-plane of the substrate, texture along the out-of-plane direction, residual stress, roughness and defects. As observed from the experiments, the best compromise for formation of ZnO films is obtained with a deposition temperature of \(600 ^\circ\text{C}\) and an oxygen pressure of \(0.1\) torr. In this section, we will discuss the effects of the pressure and the temperature upon the formation of ZnO. To understand the influence of these parameters, two conditions must be taken into account: the dynamics of the ablation materials and the nucleation\(^{33}\).

At the beginning, the zinc target, is in the metal state and the vapor species ablated out are constituted by zinc element only. The ZnO formation is due to the reaction with the ambient gas of the chamber. The collisions between the ejected species and the oxygen increases with the oxygen pressure. On one hand, if the pressure of oxygen is low, the ion fraction and the kinetic energy of the evaporated target material are not really reduced. Furthermore the oxidation could not be completed, allowing some defects in the film and some interstitial zinc. This number of defects is confirmed with the \((2\overline{1}3)\) \(\Phi\)-scan of the film grown at \(0.03\) torr which shows 12 peaks separated by \(30^\circ\) and confirms the low epitaxial quality. On the other hand, if the quantity of oxygen is too high, the vapor species can undergo enough collisions that nucleation and growth of these vapor species form particulates before their arrival at the substrate. In order to understand the number of collisions, the mean free path is approximately \(5\) cm for a pressure of \(10^{-3}\) torr and \(0.05\) cm at a higher pressure of \(0.1\) torr. Thus, a high ambient pressure increases the size of ultrafine particulates (which are deposited in the film) and the thickness layer, and creates a large number of defect.
Furthermore, the nucleation process depends on the interfacial energies between the three existing phases: substrate, the condensing material and the vapor. The minimum-energy shape of a nucleus is like a cap. The critical size of the nucleus depending on the driving force, *i.e.*, the substrate temperature (fixed: first part of the study) and the deposition rate. A characteristic of small supersaturation (0.03 torr) for large nuclei is the creation of isolated patches (islands) of the film onto the substrate which subsequently grow and coalesce together. As the supersaturation increases, the critical nucleus shrinks until its height reaches on atomic diameter, resulting in a two-dimensional layer (0.1 torr). For large supersaturation, the PLD process would cause rapid nucleation of very small clusters. This is confirmed with the calculation of grain size (see Fig.2b) which indicates small crystallites: 18 nm and 20.5 nm along the c-axis for the films grown at 0.03 torr and 0.2 torr, respectively, compared with the films grown at 0.07 torr and 0.1 torr (around 30 nm). Furthermore, the crystalline film growth depends on the surface mobility of the adatom (vapor atoms). Normally, the adatoms will diffuse through several atomic distances before sticking to a stable position within the newly formed film. The surface temperature of the substrate determines the adatom’s surface diffusion ability and a full oxidation of the zinc atom. The high temperature (see first part) favors rapid and defect-free crystal growth; whereas, low temperature (between 400 and 450 °C) or large supersaturation crystal growth may be overwhelmed by energetic particle impingement, resulting in disordered or even poor crystallized structures.

Finally, the dependance of the number of defects from the gap calculation can be observed with optical measurements. The two films deposited at 0.2 torr (no epitaxy) and 0.03 torr (oriented domains) show very low energy band gaps. Thus, optical results follow the same trend as the structural analysis.
IV. CONCLUSION

High quality ZnO thin films were grown using the pulsed laser deposition technique on (0001) Al$_2$O$_3$ substrates starting from a Zn metal target. The growth was performed under high oxygen pressure (0.03-.2 torr) in the temperature range 400-750°C. We have studied the influence of the growth conditions (deposition temperature, oxygen pressure) upon the structural properties that are directly related to the nature of a thin films: out-of-plane alignments, in-plane epitaxy, grain size, distribution of the stress in the different directions etc...

We concluded that the optimum deposition conditions leading to high quality ZnO thin films with good optical properties when using a Zn metal target are 600°C and 0.1 torr of O$_2$. This new alternative method of using a Zn metal target, as compared to ceramic target, allows a better control of the zinc oxidation and lead to good structural properties that can be used to many interesting oxides such as VO$_2$, WO$_3$ or TiO$_2$.

Acknowledgments

W.P. acknowledges the Centre Franco-Indien pour la Promotion de la Recherche Avancée/Indo-French Centre for the Promotion of Advance Research (CEFIPRA/IFCPAR) for its partial financial support (Project N°2808-1). A.F. also thanks the "Centre National de la Recherche Scientifique" (CNRS) and the "Conseil Regional de Basse Normandie" for his BDI fellowship.

We also thank Dr. H. Eng for careful reading of the article.
REFERENCES

1 D. G. Thomas, J. Phys. Chem. Solids 15 (1960) 86.

2 T. Mitsuyu, S. Ono, K. Wasa, J. Appl. Phys. 51 (1980) 2646.

3 W. W. Wenas, A. Yamada and K. Takahashi, J. Appl. Phys. 70 (1991) 7119.

4 H. Ohta, K. Kawamura, M. Orita, M. Hirano, N. Sarukura and H. Hosono, Appl. Phys. Lett. 77 (2000) 475.

5 A. S. Juarez, A.T. Silver, A. Ortiz, E.P. Zironi, J. Richiards, Thin Solid Films 333 (1998) 135.

6 M. Joseph, H. Tabata and T. Kawai, Appl. Phys. Lett. 74 (1999) 2534.

7 H. Jeon, J. Ding, A.V. Nurmiiko, H. Luo, N. Samarth, J.K. Furdyna, W.A. Bonner and R.E. Nahory, Appl. Phys. Lett. 57 (1990) 2413.

8 S. Nakamura, M. Senoh, S. Nakahana, N. Iwasa, T. Yamada, T. Matsushita, Y. Sugimoto and H. Kiyoku, Appl. Phys. Lett. 69 (1996) 1477.

9 Z.K. Tang, G.K.L. Wang, P. Yu, Kawasaki, A. Ohtomo, H. Koinuma and Y. Segawa, Appl. Phys. Lett. 72 (1998) 3270.

10 D. M. Bagnall, Y.F. Chan, Z. Zhu, T. Yao, S. Koyoama, M.Y. Shen and T. Goto, Appl. Phys. Lett. 70 (1997) 230.

11 W. Tang and D.C. Camron, Thin Solid Films 238 (1994) 83.

12 L. Bahadur, T.N. Rao and J.P. Pandey, Semicond. Sci. Tech. 9 (1994) 275.

13 K. Minegishi, Y. Koiwai, Y. Kikuchi, K. Yano, M. Kasuga and A. Shimizu, Jpn. J. Appl. Phys. 36 (1997) 1453.

14 M. Joseph, H. Tanaka and T. Kawai, Jpn. J. Appl. Phys. 38 (1999) (1997) 1205.

15 V. Craciun, R.K. Singh, J. Perriere, J. Spear and D. Craciund, J. Electrochemical Soc. 147
(2000) 1077.

16 R.D. Vispute, V. Talyansky, S. Choopun, M. Downes, R.P. Sharma, T. Venkatesan, M.C. Wood, R.T. Lareau, K.A. Jones and A.A. Iliadis, Appl. Phys. Lett. 70 (1997) 2735.

17 M.B. Korzenksi, Ph. Lecoeur, B. Mercey, D. Chippaux and B. Raveau, Chem. Mater. 12 (2000) 3139.

18 W. Prellier, A. Fouchet, B. Mercey, Ch. Simon and B. Raveau, Appl. Phys. Lett. 82 (2003) 3490.

19 E. Rauwel Buzin, W. Prellier, Ch. Simon, S. Mercone, B. Mercey, B. Raveau, J. Sebek and J. Hejtmanek, Appl. Phys. Lett. 79 (2001) 674.

20 D.C. Look, J.W. Hemskey and J.R. Sozeloove, Phys. Rev. Lett. 82 (1999) 2552.

21 K. Tamura, A. Ohtomo, K. Saikusa, Y. Osaka, T. Makino, Y. Segawa, M. Sumiya, S. Fuke, H. Koinuma, M. Kawasaki, J. Cryst. Growth 214-215 (2000) 59.

22 E. Millon, O. Albert, J. C. Loulergue, J. Etchepare, D. Hulin, W. Seiler and J. Perrière, J. Appl. Phys. 88 (2000) 6937.

23 V. Srikant and D. R. Clarke, J. Appl. Phys. 81 (1997) 6357.

24 J.J. Chen, Y. Gao, F. Zeng, D.M.li, F. Pan, Appl. Surf. Sci. 223 (2004) 318.

25 S. Choopun, R. D. Vispute, W. Noch, A. Balsamo, R. P. Sharma, and T. Venkatesan, A. Iliadis D. C. Look, Appl. Phys. Lett. 75 (1999) 3947.

26 Y.-Z. Yoo, T. Fukumura, Zhengwu Jin, K. Hasegawa, and M. Kawasaki, P. Ahmet and T. Chikyow, H. Koinuma, J. Appl. Phys. 90 (2001) 4246.

27 J. Perrière and E. Millon, W. Seiler, C. Boulmer-Leborgne, V. Craciun, O. Albert, J. C. Loulergue, and J. Etchepare, J. Appl. Phys. 91 (2002) 690.

28 JCPDS-International Center for diffraction Data, Card No. 05-0664 (2001), R.R. Reeber,
J. Appl. Phys. 41 (1970) 5063.

29 I. C. Noyan, T. C. Huang and B. R. York, Crit. Rev. Sol. State Mater Sci. 20 (1995) 125.

30 W. L. Bragg, The crystalline state 1 (1946) 189, M. A. Herman, H. Sitter, Molecular Beam Epitaxy, Springer Verlag (1989) p 177.

31 W. Prellier, Ch. Simon, B. Mercey, M. Hervieu, A.M. Haghiri-Gosnet, D. Saurel, Ph. Lecoeur and B. Raveau, J. Appl. Phys. 89 (2001) 6612.

32 W. Prellier, A.M. Haghiri-Gosnet, B. Mercey, Ph. Lecoeur, M. Hervieu, Ch. Simon and B. Raveau, Appl. Phys. Lett. 77 (2000) 1023.

33 D. B. Chrisey and G. K. Hubler, Pulsed Laser Deposition of Thin Films, Wiley Interscience, New York (1994).
Figures Captions:

Figure 1: FWHM of the $\omega$-scan (recorded around (0002) reflection, see left axis) and $\Phi$-scan (recorded around the (2113) reflection, see right axis) plotted as a function of the oxygen pressure (for a deposition temperature of 600°C, see bottom axis) and as a function of the deposition temperature (for an oxygen pressure of 0.1 torr, see top axis).

Figure 2: Energy band gap (square) and crystal size (circle) as a function (a) of the deposition temperature (the oxygen pressure is fixed at 0.1 torr) and (b) of the oxygen pressure (the temperature is 600 °C). see text for details.

Figure 3: $\Phi$-scan recorded around the (2113) diffraction peaks for different ZnO films grown under 0.1 Torr of O$_2$ at various substrate temperatures. The FWHM of the peaks in the $\Phi$-scan is indicated in the left panel of the graph.

Figure 4: Rutherford backscattering random (open circle) and aligned (full square) for a series of films grown under different oxygen pressures at 600°C. The aligned yield and the thickness of the films are given. The simulation of the structure is also indicated (black line).

Figure 5: AFM images of ZnO films deposited at 600 °C with (a), (b), (c) the height of the film grown under 0.2 torr, 0.1 torr and 0.03 torr of O$_2$, respectively and (d), (e), (f) the amplitude signal recorded in the same scans.
Tables:

Table 1: Evolution of various structural parameters for a series of films.
This figure "Figures.jpg" is available in "jpg" format from:

http://arxiv.org/ps/cond-mat/0405629v1