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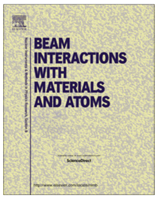

Dynamic defect annealing in wurtzite MgZnO implanted with Ar ions

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ABSTRACT

Successful implementation of ion beams for modification of ternary ZnO-based oxides requires understanding and control of radiation-induced defects. Here, we study structural disorder in wurtzite ZnO and $Mg_xZn_{1-x}O$ ($x \leqslant 0.3$) samples implanted at room and 15 K temperatures with Ar ions in a wide fluence range (5×10^{12}–3×10^{16} cm^{-2}). The samples were characterized by Rutherford backscattering/channeling spectrometry performed *in-situ* without changing the sample temperature. The results show that all the samples exhibit high radiation resistance and cannot be rendered amorphous even for high ion fluences. Increasing the Mg content leads to some damage enhancement near the surface region; however, irrespective of the Mg content, the fluence dependence of bulk damage in the samples displays the so-called IV-stage evolution with a reverse temperature effect for high ion fluences.

1. Introduction

ZnO is wide and direct band gap semiconductor ($E_g = 3.4$ eV) which has received tremendous research interest during the past decade because of its numerous promising applications in optoelectronics for the UV range [1,2]. Band gap modulation is essential for the realization of heterostructures and it has been shown that alloying of ZnO with MgO ($E_g = 7.8$ eV) enables an increase of E_g up to 4.5 eV and still keeping the wurtzite structure [3,4]. Despite that ion implantation has a number of advantages over other doping techniques, energetic particles produce defects affecting almost all materials properties. Understanding and control of implantation-induced defects are crucial for a successful utilization of ion beams in device processing.

Even for pure ZnO the mechanisms of defect formation during ion implantation and subsequent annealing are still not well understood despite large efforts in the past decade [5–9]. In particular, the origin of the high radiation resistance of ZnO, commonly associated to efficient dynamic defect annealing even at cryogenic temperatures [5,6], is not clear. Further, it has been demonstrated that the surface termination affects the radiation tolerance of wurtzite ZnO and samples with non-polar surface terminations exhibit higher radiation resistance as compared to c-plane terminated ones [7]. However, despite that ZnO is generally not amorphized even at high fluences of heavy ions, strong dopant–defect reactions can retard the dynamic annealing resulting in disorder enhancement and eventually amorphization, as has been demonstrated for Si [5] and B [8] ions. A compelling evidence of the important role of the implanted species on the thermal stability of radiation damage in ZnO can also be found in [9]. Hence, in the present contribution we have used noble Ar ions in order to eliminate such dopant-related effects on the damage evolution. However, it should be noted that for high Ar fluences processes related to Ar bubble formation may affect the defect formation.

The incorporation of a third element in a binary compound can also dramatically affect the mechanisms of ion-induced damage formation. For instance, it has been shown that an increase in Al content strongly enhances dynamic annealing in AlGaAs [10] and AlGaN [11], and also that a small amount of Al or In in GaN dramatically suppresses the commonly observed preferential surface disordering in pure GaN [11]. In contrast, our previous studies have shown that an increase in Mg content has a weak effect on the disorder accumulation in wurtzite MgZnO implanted at room temperature (RT) and primarily affects disordering near the surface [12]. In this work, we present a comparative analysis of damage formation in wurtzite $Mg_xZn_{1-x}O$ ($x \leqslant 0.3$) and ZnO implanted at RT and 15 K with Ar^+ ions over a wide range of fluences (5×10^{12}–3×10^{16} cm^{-2}). Thermally-activated dynamic annealing processes are expected to be suppressed to a large extent at 15 K and a comparison of the disorder formation with that at RT provides a possibility to elucidate the fundamental mechanisms involved in the defect formation.

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2. Experimental

Approximately 1 µm thick wurtzite $Mg_xZn_{1-x}O$ ($x = 0.1$ and 0.3) layers were grown by molecular beam epitaxy (MBE) on c-oriented sapphire substrate (the details of the growth process can be found elsewhere [13]). The samples were implanted with 160 keV Ar^+ ions at low temperature (15 K) and RT in a fluence range of 5×10^{12}–3×10^{16} cm^{-2}. The ion flux was kept at 3×10^{11} cm^{-2} s^{-1} for low fluences and was increased up to 6×10^{12} cm^{-2} s^{-1} for the highest fluence used. Note that the flux was kept the same for the samples implanted with the same fluences irrespective of the implantation temperature. According to TRIM code [14] simulations, the projected range (R_p) of 160 keV Ar ions and the maximum of the nuclear energy loss profile (R_{pd}) are estimated to be ~105 and ~65 nm, respectively, in $Mg_xZn_{1-x}O$ ($x = 0.1$ and 0.3). In the simulations we have used a $Mg_xZn_{1-x}O$ density obtained by linear interpolation between the densities of ZnO (5.6 g/cm^3) and MgO (3.58 g/cm^3). In addition, hydrothermally grown ZnO single crystals were implanted under the same conditions with 200 keV Ar^+ ions and used as reference; here, the calculated values of R_p and R_{pd} are ~135 and ~75 nm, respectively. All the implants were carried out at 11° off the [0001] direction in order to minimize channeling.

The structural quality of the implanted samples was analyzed by Rutherford backscattering spectrometry in channeling mode (RBS/C) with 1.4 MeV $^4He^+$ ions incident along the [0001]

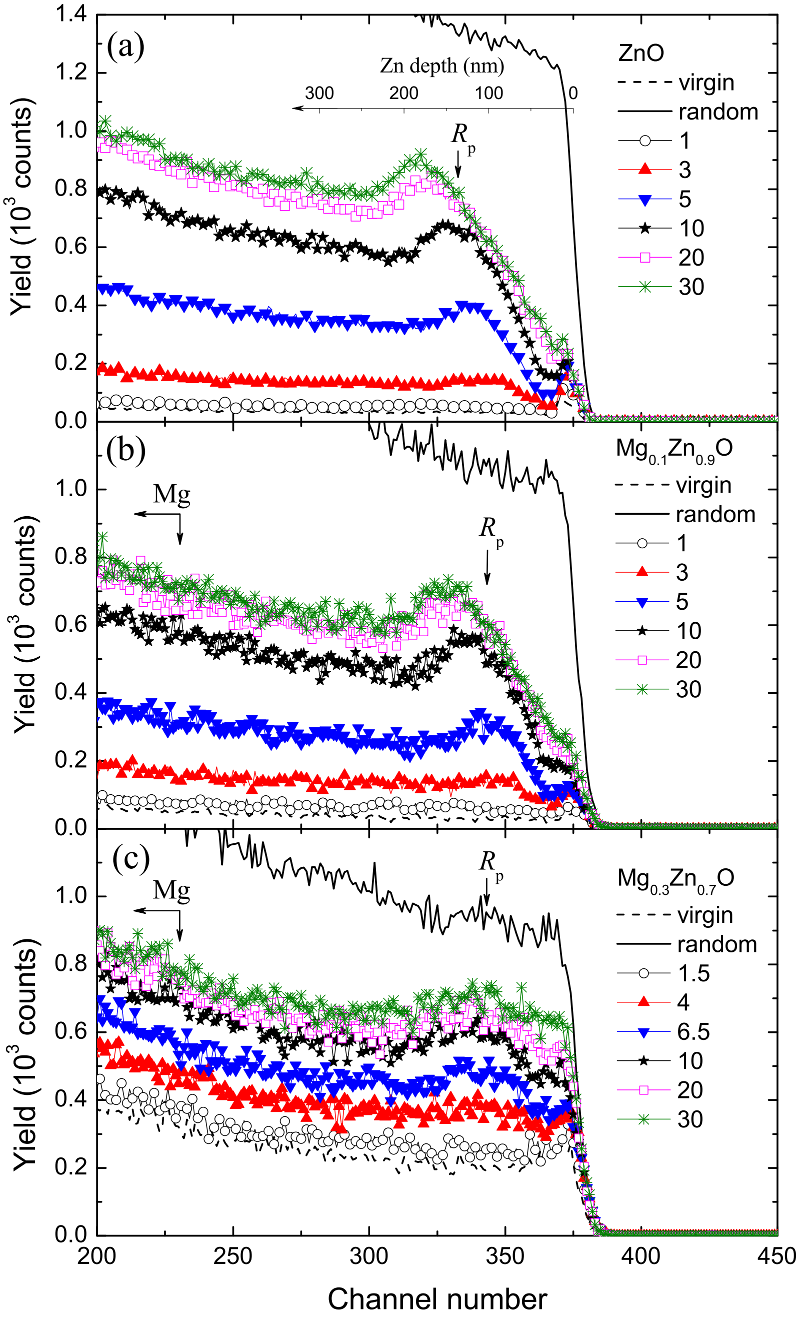

Fig. 1. RBS/C spectra of (a) Zn_0O (b) $Mg_{0.1}Zn_{0.9}O$ and (c) $Mg_{0.3}Zn_{0.7}O$ implanted at 15 K with Ar^+ ions to different fluences as indicated in the legend (in 10^{15} at/cm^2). The projected ranges (R_p) of the implanted ions in correlation with the Zn depth scale and Mg surface position are shown by the arrows. The channeling spectra of virgin samples are also depicted for comparison by the dashed lines.