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Waveguide effect in ZnO crystal by He^+ ions implantation: Analysis of optical confinement from implant-induced lattice damage

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ABSTRACT

Waveguide effect was observed in He^+ implantation ZnO with different energies and doses. Computer code was used to simulate the process of ion implantation into ZnO crystal and the implantation-produced damage distribution is extracted according to RBS experimental result. The prism coupling and end-face coupling technique are used to investigate the waveguide properties. The reconstructed refractive index profile shows that the ordinary index decreases at the near surface region after He^+ implantation under different conditions. The damage layer, which is governed by nuclear energy deposition of He^+ ions, makes itself a reduced index barrier for guiding light. Ion-implantation, generally used for electrical isolation, may play a role for optical confinement in ZnO light emitting devices.

1. Introduction

ZnO is a II-VI semiconductor with a room temperature direct band gap of 3.37 eV [1]. Over the past several decades, ZnO material has many successful applications, such as piezoelectric transducers and phosphors [2,3]; many studies on ZnO only involves in polycrystalline or amorphous materials. However, recent successes in producing large bulk single crystals [4] have opened up extensive research interest and ZnO has been considered as a potential candidate for a range of short wavelength light emitters [5], laser diodes and other optoelectronic devices due to practical advantages over its major rival GaN—another wide gap semiconductor which currently dominates the market of short wavelength devices. In addition to desired excellent properties of ZnO, the fabrication of optoelectronic devices obviously requires a device processing technology. In the fabrication of such GaN/ZnO-based devices, ion implantation is usually employed [6,7], especially for doping or for electrical isolation. Ion implantation can offer possibility of introducing any given impurity with accurate control of both the depth and lateral concentrations of the ions.

Implantation of light ions, such as O^+ or H^+, into ZnO devices is often used to produce electrical isolation [8]. However, introduction of exotic ions into a host transparency crystal will cause distinct change not only for its electrical properties, but optical properties as well [7]. One of the possible results is the modulation of refractive index of material. In the letter we report the optical effect of He^+ implantation into ZnO crystal with different He^+ doses and energies. These implantation conditions are chosen by consulting the comparable implantation parameters used for electrical isolation in ZnO device with light ions implantation. We present a detailed study of possible optics waveguide in He^+-implanted ZnO. Together, a physics description is given for a better understanding of the formation mechanism.

2. Experiments

The Z-cut ZnO crystals with the dimensions $10 \times 5 \times 0.5$ mm^3 were optically polished before He^+ implantation. The detailed parameters in experiments are listed in Table 1. The implantation was performed at room temperature by an implanter in the Institute of Semiconductor, Chinese Academy of Sciences and a 1.7 MV tandem accelerator at Peking University. In order to minimize the channeling effect during the implantation the samples were tilted by 7° off the incident beam direction. The near-field intensity profile of propagation mode from waveguide was obtained by the end-face coupling arrangement. The m-line spectra were measured by the prism coupling method with a Model 2010 Prism Coupler (Metricon 2010, USA). The He–Ne laser at 633 nm acts as a light beam in the measurements. The Rutherford backscattering/channeling (RBS/C) measurements were performed using a 2.1 MeV He^+ beam generated by a 1.7 MV tandem accelerator at

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Table 1
Experiment parameters for samples suffered He^+ irradiation.

Samples	Ion	Energy	Dose
1#	He^+	500 KeV	2×10^{16} ions/cm^2
2#	He^+	500 KeV	4×10^{16} ions/cm^2
3#	He^+	2 MeV	2×10^{16} ions/cm^2

Shandong University. The backscattering of He^+ particles was detected with a surface barrier detector placed at 165° to the incident beam direction.

3. Results and discussion

The stopping and range of ions in matters (SRIM) code [9] were used to simulate the process of He^+ implantation into ZnO. Fig. 1 shows the energy loss of the 500 KeV and 2 MeV He^+ into ZnO. As we can see, the He^+ lose most of their energies by electronic ionizations along the path of He^+ traveling inside the target, usually with occurrence of the formation of color centers. While at the end of the He^+ track, the nuclear collisions result in both lattice disorder in ZnO and a decrease of physical density in this region, which will cause a reduction of the refractive index.

The RBS spectra of samples in the channeling and non-channeling directions were measured for detecting the lattice damage in the implanted-ZnO. For comparison the virgin and random spectra are also measured from the virgin ZnO. As is shown in Fig. 2(a), a significant bulge can be found around channel number ~100 for both samples 1# and 2#, which corresponds to the lattice disorder caused by implantation. For the implantation at high energy of 2 MeV, no obvious damage is found in the near surface region, even at the fluence as high as 4×10^{16} ions/cm^2. In this case, the depth of damage layer is far beyond the scope of detectable depth of RBS, so the damage of sample 3# cannot be obtained directly in our experiment.

After He^+ implantation, a damage peak is formed below the crystal surface for all the implanted samples. By comparing the yields of RBS spectra from the virgin and as-implanted samples 1# and 2# respectively, the lattice damage levels can be determined using multiple scattering formulas of Feldman and Rodgers [10]. The profile of damage caused by implantation is extracted and shown in Fig. 2(b). It can be seen that a broad damage peak located at 1.4 μm below the sample surface is formed in ZnO. By comparing the experimental result in Fig. 2(b) with the simulation result in Fig. 1, it can be found that the shape of the damage profile is similar to that of nuclear energy loss distribution. It is suggested that the nuclear energy loss has more influence on the refractive index change than that from electronic energy.

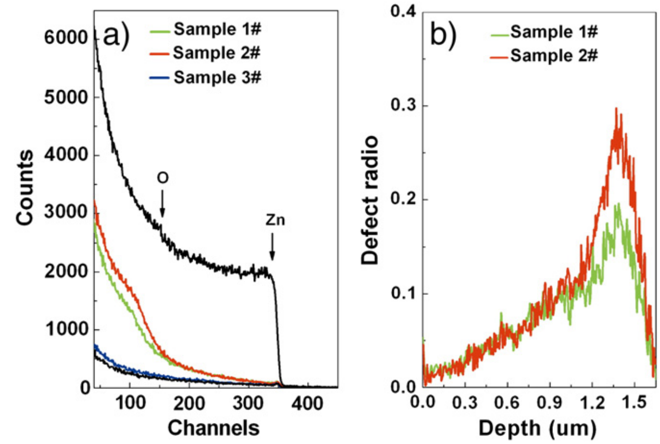

Fig.2. (a) RBS/channeling spectra of He^+ ions implanted ZnO. The random and channel spectra of the virgin ZnO are also presented. (b) Disorder profiles of samples 1# and 2#.

Fig. 3 is the result from prism-coupling measurement for three He^+ implanted ZnO. According to the principle of m-line measurement, when the waveguide condition is met, some light will propagate in waveguide and result in lack of reflected light (intensity dips in m-line spectrum). Usually each intensity dip corresponds to a waveguide mode. As indicated in Fig. 3, TE modes were observed in all samples, but only those in Fig. 3(b) and (c) were relatively obvious. Deep and sharp dip means a good confinement of the light, which represents a real propagating waveguide mode. According to our prism-coupling results, the optical confinement in the samples is relative poor, especially for sample 1#. It is mainly because of the small waveguide thickness (for samples 1# and 2#) and the small index contrast in the implanted waveguide, a detailed analysis will be given later. Another reason is due to the high transmission loss in waveguide; introduction of point defects is a typical result of ion implantation. The transverse magnetic (TM) polarized modes in the He^+-implanted ZnO were also measured in our experiments, and similar results have been obtained.

In order to investigate light propagation property in the implanted ZnO, the near-field intensity distribution of output from waveguide was also measured using the end-face coupling setup with He–Ne laser at wavelength of 633 nm. The input and output facets of ZnO, with cross section dimensions of 5×0.5 mm^2, were polished to

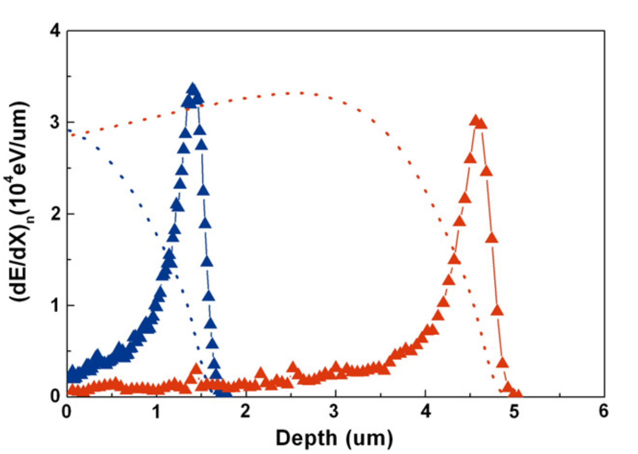

Fig.1. SRIM simulation: electronic energy loss (dotted line, divided by 15) and nuclear energy loss (triangle) of 500 KeV He (the blue) and 2 MeV He^+ (the red) implantation.

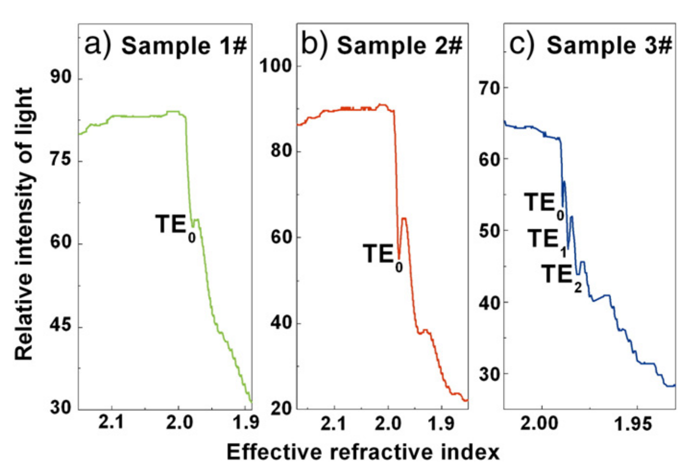

Fig.3. M-line spectra: relative intensity of TE light reflected from the prism versus the effective refractive index of the incident light in ZnO waveguide.