

Structural and optical properties of Er implanted AlN thin films: Green and infrared photoluminescence at room temperature

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ABSTRACT

In this work erbium ions were implanted into AlN films grown on sapphire with fluence range: $(0.5-2) \times 10^{15}$ at/cm², ion energy range: 150–350 keV and tilt angle: 0°, 10°, 20°, 30°. The optical and structural properties of the films are studied by means of photoluminescence and Raman spectroscopy in combination with Rutherford backscattering/channeling (RBS/C) measurements. The photoluminescence spectra of the Er³⁺ were recorded in the visible and infrared region between 9 and 300 K after thermal annealing treatments of the samples. The emission spectrum of the AlN:Er films consists of two series of green lines centered at 538 and 558 nm with typical Er³⁺ emission in the infrared at 1.54 μm. The green lines have been identified as Er³⁺ transitions from the ²H_{11/2} and ⁴S_{3/2} levels to the ⁴I_{15/2} ground state. Different erbium centers in the matrix are suggested by the change of infrared photoluminescence relative intensity of some of the emission lines when different excitation wavelengths are used. The relative abundances of these centers can be varied by using different implantation parameters. The Raman and RBS/C measurements show good crystalline quality for all the studied films.

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1. Introduction

Infrared (IR) and visible luminescence from rare earth (RE) doped AlN brings significant interest of this material for possible applications in optical communications – IR wavelengths at 1.54 μm is coincident with minima in the optical loss of silica-based glass fibers utilized in telecommunications – and full color displays [1]. AlN with its large band gap allows energetically high lying RE levels to be exploited and thermal quenching of the luminescence is expected to be small [2–5].

Ion implantation is a very attractive technological tool for device fabrication steps such as selective-area doping, electrical isolation, etc. However, in all of these fabrication steps, limitations may arise due to ion-beam-produced lattice disorder and its undesirable consequences [6]. In this work a set of AlN samples were implanted with different fluencies of Er³⁺ ions, ion energies and tilt angles. The as-implanted samples were further submitted to thermal annealing treatments to optically activate the Er³⁺ ions and visible and infrared intraionic luminescence was measured. Surface, lattice damage and the lattice location of the implanted ions

were characterized by Raman spectroscopy, Rutherford backscattering/channeling (RBS/C) and correlated to the optical properties of the samples measured by photoluminescence.

2. Experimental

AlN films with thickness of 3 μm grown by hydride vapor phase epitaxy (HVPE) on sapphire substrates purchased from TDI. The AlN films were implanted with Er³⁺ ions with a fluence range: $(0.5-2) \times 10^{15}$ at/cm², ion energy range: 150–350 keV and tilt angle between the ion beam and the surface normal: 0°, 10°, 20°, 30°. After the implantation the samples were annealed during 20 min at temperatures up to 1300 °C in a conventional tube furnace with an overpressure of 4×10^5 Pa nitrogen gas. RBS/C measurements were performed with 2.0 MeV He⁺ ions and the backscattered particles were detected with solid state detectors at 140° and close to 180°. Steady state infrared photoluminescence (IR-PL) was generated using a 514.5 nm line from an Ar⁺ ion laser. The samples were placed on a cold finger of a continuous flow cryostat in vacuum and the sample temperature could be controlled in the range from 5 K up to room temperature (RT). The IR-PL was measured using a Bruker 66 V Fourier transform spectrometer equipped with a liquid nitrogen cooled germanium

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detector. Steady state visible photoluminescence (VIS-PL) was carried out between 9 K and RT. The excitation source was the 514.5 nm line of an Ar⁺ ion laser. The luminescence was measured using a JobinYvon T64000 spectrometer equipped with a liquid nitrogen cooled CCD. Raman spectroscopy was performed with a LabRam HR and T64 000 spectrometers and the excitation sources were the 325 and 514.5 nm lines of HeCd and Ar⁺ lasers, respectively.

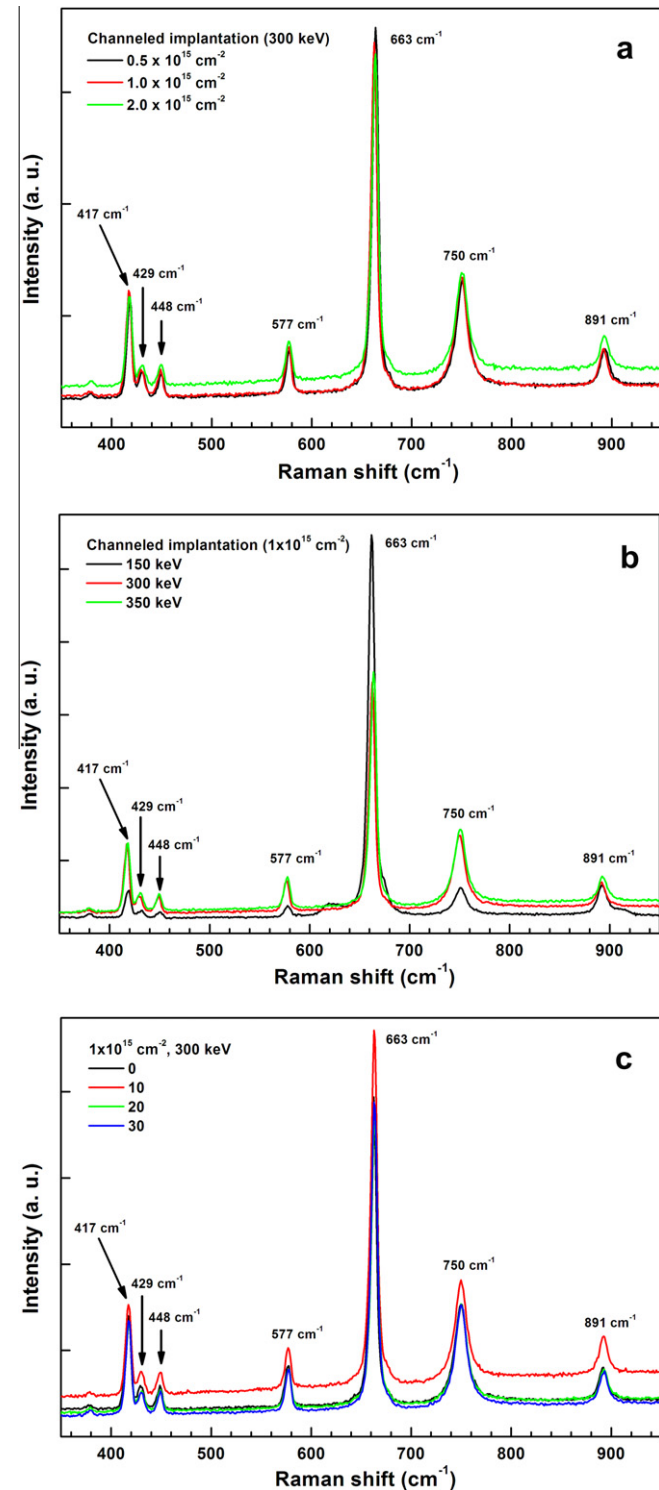


Fig. 1. Raman spectra of the films as a function of Er³⁺ ions implanted parameters: fluence range: (0.5–2) × 10¹⁵ at/cm² (a), ion energy range: 150–350 keV (b) and tilt angle: 0°, 10°, 20°, 30° (c).

3. Results and discussion

The Fig. 1 shows the Raman spectra of the films as a function of Er³⁺ ion implantation parameters: fluence range of (0.5–2) × 10¹⁵ at/cm² (a), ion energy range of 150–350 keV (b) and tilt angle of 0°, 10°, 20°, 30° (c). The peaks at ~660 cm and 890 cm⁻¹ with full width at half maximum of ~7 and ~10 cm⁻¹, respectively, are attributed to the E₂(TO) and A₁(LO) AlN phonon modes. These are allowed by the Raman selection rules for the backscattering geometry [Z(x, x)–Z] used in the experiment [7]. The peaks at 417, 429, 448, 577, 750 cm⁻¹ are attributed to phonon modes from the sapphire substrate. The observed phonon mode energies are close to the values measured for the AlN bulk [8,9] which show good crystalline quality for all the studied films. RBS/C random and ⟨0001⟩ aligned spectra (not shown) clearly prove a strong reduction of implantation damage when the implantation is performed in channelled geometry along the *c*-axis (0 tilt) as previously reported for Eu-implantation [10]. Fig. 2 presents full angular scans across the ⟨0001⟩ and the tilted ⟨2̄113⟩ axes for samples implanted with 1 × 10¹⁵ at/cm² along the *c*-axis (Fig. 2a and b) and tilted by 10° (Fig. 2c and d). For the sample implanted without tilt an almost complete overlap of the scans for Al and Er are observed for both crystal directions showing that Er is incorporated on substitutional Al-sites. For the tilted implantation, on the other hand, a clear narrowing of the Er-scan, in particular for the ⟨2̄113⟩ axis, reveals a displacement of Er from the substitutional site possibly due to an interaction of Er with implantation defects. Furthermore, the near substitutional fraction is slightly lower as seen in the increased minimum yields for Er.

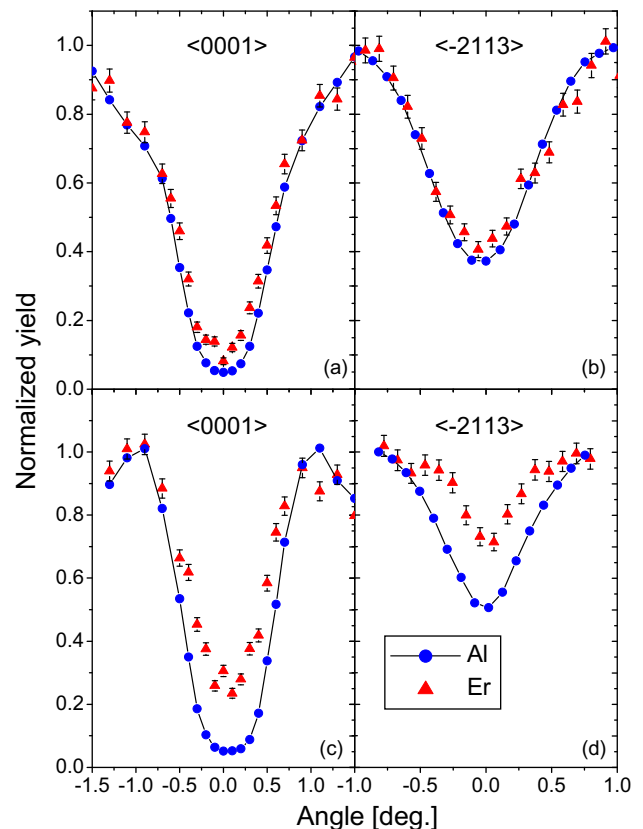


Fig. 2. Channeling scans for the ⟨0001⟩ and ⟨2̄113⟩ crystal directions for the AlN sample implanted with a fluence of 1 × 10¹⁵ Er/cm² directly after implantation with 0° tilt (a + b) and 10° tilt (c + d).

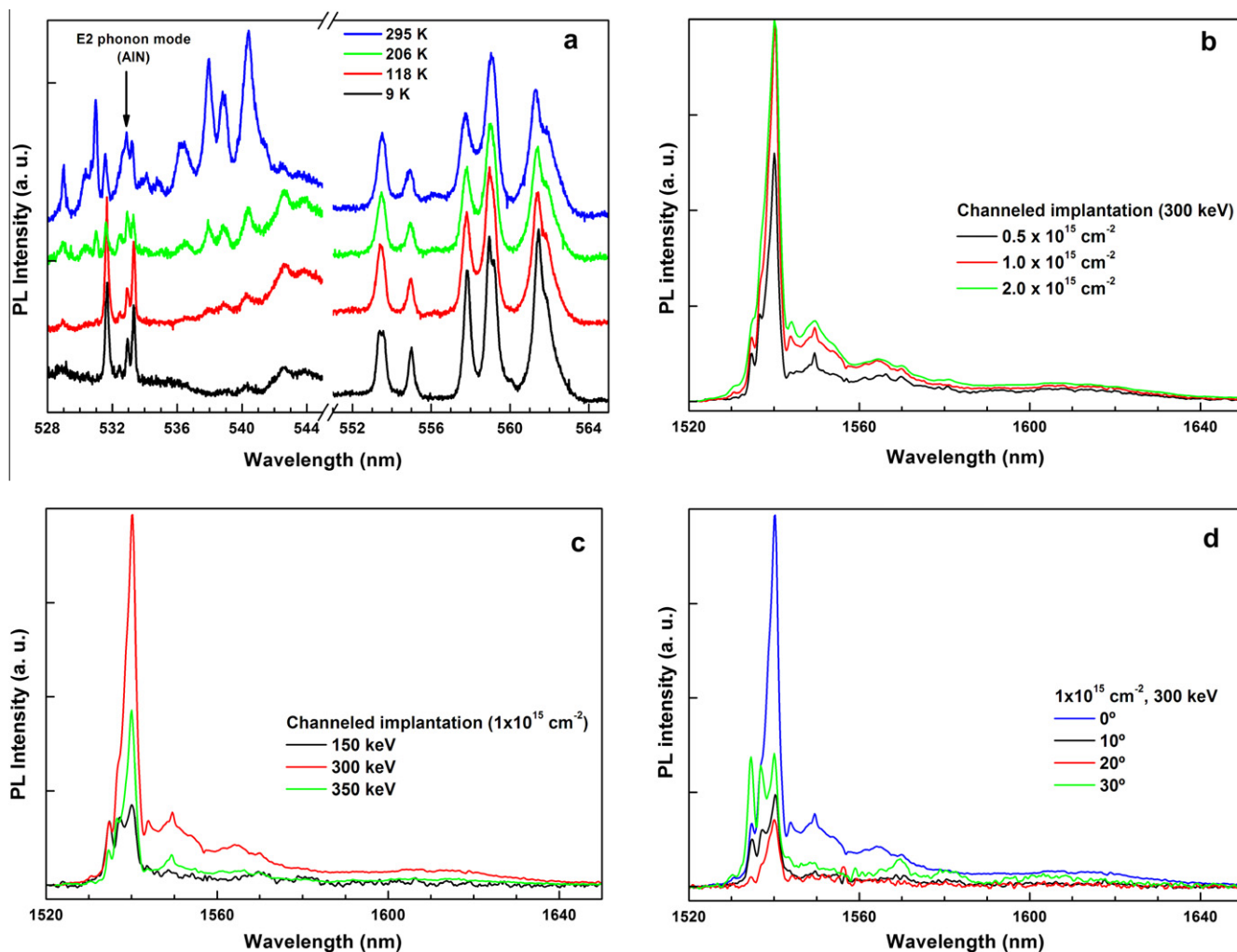


Fig. 3. (a) Visible Er^{3+} luminescence as a function of temperature and (b–d) 10 K infrared PL as a function of the implantation parameters.

Fig. 3 shows the PL characterization in the visible and infrared spectral range of the AlN samples implanted with different fluencies, ion energies and tilt angles. The samples luminescence was obtained with excitation (514.5 nm) below the AlN band gap. This excitation wavelength is close to an intra $4f$ Er^{3+} absorption line ($^4I_{15/2} \rightarrow ^4F_{7/2}$) leading to resonant excitation of the Er^{3+} ions [2].

Fig. 3a shows the temperature dependent PL of the AlN:Er sample obtained with below band gap excitation (514.5 nm). Two sets of sharp lines centered at ~ 538 nm and the other at ~ 558 nm could be identified and assigned to transitions from the excited state multiplets $^2H_{11/2}$ and $^4S_{3/2}$ to the fundamental one $^4I_{15/2}$, respectively. The lines at lower temperature arise from the phonon modes in the sapphire substrate and the E_2 (TO) mode in AlN. As the temperature is increased, the intensity of the transitions $^4S_{3/2} \rightarrow ^4I_{15/2}$ slightly decreases whereas a new thermally populated set of lines, centered at ~ 538 nm, appears. This temperature dependent PL was observed from Er doped GaN samples prepared by metalorganic molecular beam epitaxy (MOMBE) [11,12]. Visible luminescence from Er^{3+} ions was reported in an earlier work by using cathodoluminescence [13]. In this case the excitation is always performed above the AlN bandgap as well as by direct impact. Up to our knowledge, visible PL from Er^{3+} was reported from AlN:Er films and nanostructures grown by magnetron sputtering [14,15] but in implanted samples with Er^{3+} ions this is the first time.

In the range 1530–1545 nm, corresponding to the transition between the $^4I_{13/2}$ multiplet lowest excited state to the $^4I_{15/2}$ multiplet ground at least three sharp lines are observed which suggest the presence of different optical centers due to different neighborhoods of the Er^{3+} ion [16]. In fact, the relative intensity of the three lines in the above range is critically influenced by the used implantation energy and the tilt angle (Fig. 3c and d) and in minor extend by the implantation fluence (Fig. 3b). These findings are in good agreement with the RBS/C scans that suggest that for tilted implantation Er is interacting with lattice defects that cause a displacement of the ion. Different optically active centers may therefore correspond to undisturbed substitutional Er and to Er coupled to defects that change the symmetry of its microscopic environment. As seen from Fig. 3(b–d), the implantation parameters that maximize the PL intensity around the 1.54 μm in the studied samples correspond to implantation energy of 300 keV, fluence range $(1-2) \times 10^{15} \text{ cm}^{-2}$ and a tilt angle of 0° .

4. Conclusions

The Er implantation in AlN resulted in the formation of more than one optical center. Evidence for a good recovery of the lattice was found for all implantation parameters considered in this work. RBS/channeling measurements showed the presence of Er atoms in substitutional positions when the implantation was carried out

along the *c*-axis and displaced from the substitutional site for tilted implantation. In addition to the infrared emission from the $^4I_{13/2}$ multiplet lowest excited state to the $^4I_{15/2}$ multiplet ground state, the large band gap of the AlN allowed the observation of visible intraionic photoluminescence. In the former at least three sharp lines were observed in the 1530–1545 nm range and its dependence on excitation energy suggests the presence of different optical centers related to the Er^{3+} ion. The relative abundance of these centers can be influenced by the implantation angle in good agreement with RBS/C results showing changes in the Er incorporation sites for different implantation geometries. In the visible range transitions from the lowest excited state multiplets $^2H_{11/2}$ and $^4S_{3/2}$ to the fundamental one $^4I_{15/2}$ were detected.

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