Investigations of depth profile of native oxide layers covering GaAs implanted with noble gas by Rutherford Backscattering Spectroscopy with Nuclear Reaction

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Abstract

The samples employed in the investigation were semi-insulating GaAs wafers. Noble gas has been implanted using the UNIMAS ion implanter at energy 100 keV, fluence of 3 x 10^{15} ions/cm^2. Rutherford backscattering spectroscopy with nuclear reaction analysis (RBS/NR) method was used to determine the thickness and atomic composition of elements in the samples. The nuclear reaction $^{16}O(\alpha,\alpha)^{16}O$ exhibits elastic resonance at around energy 3.05 MeV. This resonance provides a useful method for expanding RBS techniques to investigate the concentration of oxygen present on sample surfaces. The RBS/NR approach's conclusion indicates that the surface of GaAs samples contains an oxygen-enriched layer. It has also been shown that the thickness of native oxide layer influence by the type of ion.

Keywords: GaAs, RBS/NR, native oxide.

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INTRODUCTION

Gallium arsenide (GaAs) is a semiconductor material that has garnered extensive application in high-frequency electronics, optoelectronic devices, and photovoltaic systems due to its superior electron mobility and direct bandgap [1]. However, like most semiconductors, the surface of GaAs is highly susceptible to oxidation upon exposure to the ambient atmosphere, leading to the formation of a native oxide layer [2]. The presence of this native oxide is often detrimental to the performance and long-term reliability of GaAs-based devices. It can introduce surface states that pin the Fermi level, leading to increased surface recombination velocities, reduced charge carrier lifetimes, and ultimately, the degradation of electronic and optoelectronic

properties [3]. Consequently, understanding the formation, composition, and evolution of this native oxide layer is critical for enhancing device performance, stability, and integration.

Ion implantation is a fundamental technique in semiconductor technology, widely used for doping, modifying material properties, and synthesizing buried layers [4]. The interaction of implanted ions with a semiconductor substrate can induce significant microstructural changes, including defect formation, amorphization, and alterations in the composition and growth kinetics of surface layers [4]. Noble gas ions, being chemically inert, are particularly useful for studying such radiation-induced effects without introducing additional chemical doping. Despite its importance, the specific impact of noble gas ion implantation on the characteristics of the native oxide layer on GaAs remains an area requiring further detailed investigation.

Analytical techniques with high sensitivity to light elements, especially oxygen, are essential for characterizing thin surface layers. Rutherford Backscattering Spectroscopy (RBS) is a powerful ion-beam analysis method for determining elemental composition and depth profiles [5]. However, its sensitivity for light elements on heavier substrates can be limited. This limitation can be overcome by coupling RBS with resonant Nuclear Reaction (NR) analysis. The NR of $^{16}O(\alpha,\alpha)^{16}O$ provides a highly sensitive and specific means for quantifying oxygen [6].

In this study, we investigate the depth profile of the native oxide layer on GaAs surfaces before and after implantation with various noble gas ions. The primary objectives are to: confirm the existence and quantify the composition of the oxygen-enriched native oxide layer on GaAs, and systematically examine how the thickness and structure of this layer are influenced by the mass of the implanted noble gas ions.

SAMPLES AND METHODS

Rutherford backscattering spectroscopy and nuclear reaction (RBS/NR)

Rutherford backscattering spectroscopy (RBS) is a highly effective analytical method employed for accurately determining the elemental composition and depth profiles of thin films and multilayer structures. The non-destructive and highly sensitive nature of RBS makes it an essential tool for analyzing semiconductor devices, thin film coatings, and surface modification procedures in materials science and engineering [7]. However, the RBS can be difficult to detect small amounts of impurities with low atomic mass within a substrate that has a greater atomic mass. The use of nuclear reaction (NR) with resonant scattering can improve the detection sensitivity of RBS for this situation. At the resonant energy, examining the surface area where the

energy loss of the beam matches the width of the resonance. When the beam energies increased, the reaction will take place at higher depths within the samples, until the resonance energy is attained. Therefore, this technique can be utilized to determine the concentrations of the specific atom engaged in the resonance, relative to depth, thereby providing a depth profile of the particular element. When employing NR, the scattering cross section becomes greater than that of pure Rutherford scattering - about 23 times larger at energy 3.05 MeV [6]. This approach has been regularly employed to examine thin oxide coatings on the surface of materials.

The samples and ion implantation

The samples employed in the investigation were semi-insulating GaAs wafers. The GaAs samples with the dimension of 10 x 10 x 1 (mm) were studied. First of all, the surface of the samples was chemically cleaned using the Bromine Methanol (BrM) Chemo-Mechanical Polishing Process [2]. One sample was kept as the virgin sample; the others were implanted with noble gas ions. The implantation was performed using three different ion species: neon (Ne^+), krypton (Kr^+), and xenon (Xe^+). All implantations were carried out under the same conditions: the ion energy was 100 keV and the ion fluence was 3×10^{15} ions/cm² at room temperature. Implantation was performed using the UNIMAS ion implanter at Maria Curie-Sklodowska University, Poland. After implantation, the samples were removed from the chamber and exposed to oxidation in air with normal condition together with virgin sample about 5 hours [2].

RBS/NR experiment parameters

The depth profile of the virgin and implanted samples was tested by the RBS/NR at Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research (JINR) in Dubna, Russia. An α-beam with the energy ranging from 3.02 to 3.07 MeV produced by the EG5 Van de Graaff accelerator was used. The beam was directed to the samples under an incident angle of 15^0 toward the surface normal. A semiconductor detector with 20 keV energy resolution was positioned at a scattering angle of 170^0 to the beam incident direction in order to collect the spectra. The elemental composition and depth distributions were calculated by fitting theoretical curves to the experimental spectra using the SIMNRA program [8, 9].

RESULT AND DICUSSIONS

The typical spectra of scattered α particles on the nucleons of the atoms located in the near surface layers of virgin and implanted GaAs with noble gas are presented in Fig. 1.

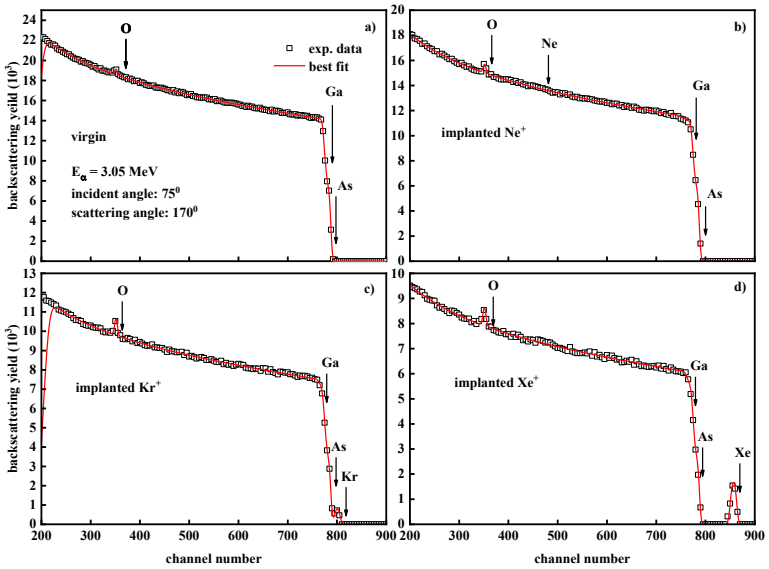

Fig. 1. RBS/NR spectra at 3.05 MeV a) virgin sample b) sample after implanted Ne^+ c) sample after implanted Kr^+ and d) sample after implanted Xe^+

These spectra have several characteristics. The first one is the border from channel 750 to 800. The results demonstrate a strong association between the sensitivity of measurements and the surface quality. The spectrum of the virgin GaAs sample (Fig. 1-a) serves as the reference. It exhibits a sharp, well-defined step with a high-energy edge at approximately in this region, corresponding to backscattering from Ga and As atoms at the surface. The stable and constant yield behind the step indicates a high-quality, crystalline substrate with minimal energy straggling. All implanted samples (Fig. 1-b, c, d) exhibit a significant broadening and steepening of the GaAs substrate step relative to the virgin sample. This phenomenon partly indicates the presence of implanted ions on the sample surface and may also reflect surface damage caused by ion implantation. The incident ions create cascades of collisions, displacing atoms from their lattice sites and forming an amorphous layer. In this disordered layer, backscattered particles experience greater and more variable energy loss, smearing the otherwise sharp interface signal from the crystalline substrate.

Critically, a kinematic border is observed at a band near channel 350. This energy corresponds to the kinematic edge for oxygen. Its significant intensity, far exceeding standard RBS expectations, is direct evidence of the resonant enhancement of the $^{16}O(\alpha,\alpha)^{16}O$ reaction. This border is attributed to a native oxide layer on the GaAs surface. The elemental composition and

depth distributions were determined by applying the SIMNRA computer algorithm to fit theoretical curves to the RBS/NR experimental spectra. The energy spectra of α particles ranging from 3.02 to 3.07 MeV have been gathered for each sample under investigation. For all samples, it was observed that the strength of the oxygen band varies with the energy of α particles, both below and above the resonance energy E_α = 3.05 MeV. This phenomenon verifies the presence of thin layers on the examined surfaces that consist of oxygen atoms. The obtained spectra at E_α = 3.05 MeV for all samples show variations only in the intensity of the peak around this energy. This observation suggests that the thicknesses of the natural oxide layers in the examined samples differ.

CONCLUSION

This RBS/NR analysis using alpha beam with varies energy successfully characterized the effects of noble gas implantation in GaAs. The technique unambiguously identified the implanted species, revealing distinct spectral signatures: a high-energy peak for heavy elements (Kr, Xe) and a low-energy signal for light Ne. Furthermore, the results provide direct evidence of significant lattice damage, the severity of which scaled with the implant mass, being most substantial for Xe. RBS/NR has been successful in measuring the thickness and elemental composition of this oxide layer. The findings show that the GaAs surface forms an oxygen-rich layer before and after ion implantation and that the thickness of this layer is related to the mass of ion implanted. In summary, this analysis delivers insights into elemental composition, depth profiles, and structural damage, underscoring the power of RBS/NR for semiconductor materials characterization.

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