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Examination of the Native Oxide Layer Using the RBS/NR Method on the Surface of GaAs Samples Before and After Hot-Implanted Al Ions

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The samples employed in the investigation were semi-insulating (SI) GaAs monocrystalline wafers. Aluminum ions have been implanted using the UNIMAS ion implanter with various temperature: 25^0, 300^0 and 500^0 Celsius. 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 3.045 MeV. This resonance provides a useful method for expanding RBS techniques to investigate the concentration of oxygen in oxides. The RBS/NR approach's conclusion indicates that the surface of GaAs samples contains an oxygen-enriched layer. It has also been demonstrated that when the temperature of the Al-implanted process rises, the thickness of this layer decreases.

Keywords: hot-implanted, GaAs, RBS/NR, native oxide

1. INTRODUCTION

The electrical properties of semiconductor materials, which are essential for the progress of modern technology, are significantly affected by surface events, such as the formation of native oxide layers on the surface of materials. This study centers on Gallium Arsenide (GaAs), a semiconductor material widely used in electrical and optoelectronic applications because of its exceptional electron mobility and direct bandgap characteristics [1]. An essential factor influencing the performance of GaAs-based devices is the formation of a native oxide layer on the surface when it comes into contact with air. The presence of this oxide layer can have a substantial impact on the electrical properties, performance, and dependability of the device. Understanding the formation and growth of the native oxide layer

on GaAs surfaces is essential for improving the functionality and integration of GaAs-based devices [2].

This study aims to examine the influence of hot-implanted aluminum (Al) ions on the native oxide layer of GaAs. Our study focuses on investigating the impact of temperature variations during ion implantation on the properties of the oxide layer. In order to examine the samples, we used Rutherford backscattering spectroscopy with nuclear reaction analysis (RBS/NR) [3]. This technique enabled us to accurately measure the thickness and atomic composition of the native oxide layer. The nuclear reaction $^{16}O(\alpha,\alpha)^{16}O$ is particularly noteworthy due to its elastic resonance at approximately 3.045 MeV [4]. This resonance has significantly improved the accuracy of the RBS technique for determining oxygen concentrations. The resonance observed in this nuclear reaction has a backscattering cross-section that is considerably greater than the conventional Rutherford cross-section. This enables a more comprehensive examination of the oxygen-enriched layers.

The results show that after Al ion implantation, the GaAs surface forms an oxygen-enriched layer. Furthermore, we found that the thickness of this layer reduces as the implantation temperature rises. This study not only elucidates the behavior of the native oxide layer on GaAs surfaces under varied implantation settings, but it also opens a pathway for future studies to investigate additional parameters impacting this layer.

2. SAMPLES AND METHODS

2.1. Rutherford backscattering spectroscopy (RBS)

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 process is based on the idea of elastic scattering, where high-energy ions, usually helium ions, collide with the nuclei of atoms in the sample material. RBS offers precise quantitative data on the elemental composition, layer thicknesses, and interface sharpness of a sample by analyzing the energy and angle of the backscattered ions. In addition, RBS exhibits remarkable sensitivity, enabling the detection of trace elements at concentrations as low as parts per million (ppm) and offering depth resolution at the nanoscale scale. 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 [3, 5].

2.2. Nuclear reaction analysis (NR)

It can be difficult to use backscattering techniques to detect small amounts of impurities with low atomic mass within a substrate that has a greater atomic mass. The signals that are obtained from the substrate is usually of such a large magnitude that it is impossible to differentiate the impurity signal from that of the substrate. However, there are specific situations that do allow for the identification of pollutants with a small atomic mass.

The use of nuclear reaction (NR) with resonant scattering can improve the detection sensitivity for small amounts of an impurity with a low atomic mass. Nuclear reactions happen at specific energy levels for specific elements, and this characteristic is used exploited in NR. At the resonant energy, the response takes place on the surface, examining the surface area where the energy loss of the beam matches the width of the resonance. At increased beam energies, the reaction will take place at greater depths within the target, when 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. Depth resolutions of a few nanometers are achieved with typical resonance widths in the range of a few kiloelectron volts. When employing NR, the scattering cross section exhibits a greater in comparison to pure Rutherford scattering [3, 4, 6]. Fig. 1 displays the relationship between the energy and scattering cross section for the collision of ^{4}He with ^{16}O. An evident rise in crop production is observed, namely at an energy level of 3.045 MeV. The resulting yield was 25 times larger than the yield expected based on Rutherford scattering. This approach has been regularly employed to examine thin oxide coatings on the surface of materials.

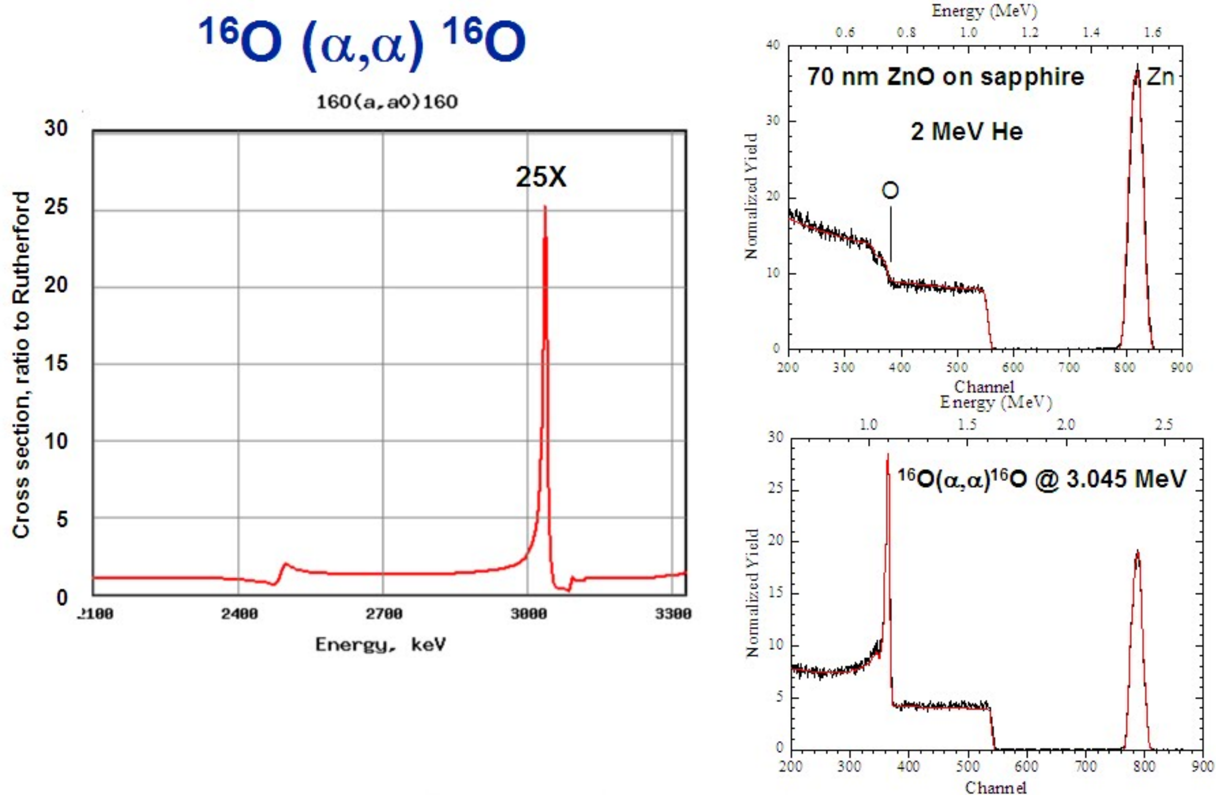

Fig. 1: The scattering cross section for ^{4}He incident on ^{16}O, ratio to Rutherford.

2.3. The samples and hot-implanted

The samples employed in the investigation were semi-insulating (SI) GaAs monocrystalline wafers. Al^{+} ions have been implanted using the UNIMAS ion implanter at Maria Curie-Skłodowska University. The ion beam current density at the collector was maintained at 1.0 mA/cm^{2}. During the implantations, the samples were kept at specific temperatures: about 25°C (room temperature), 300°C, and 500°C. This was achieved by utilizing a custom-made hot stage equipped with the Boraelectric (Tectra)

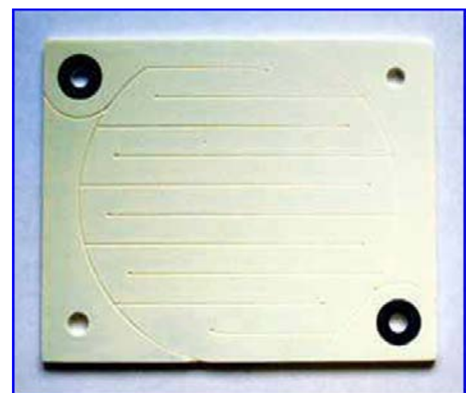

Fig. 2: The Boraelectric (Tectra) HTR 1002 heater.

HTR 1002 heater and the HC-3500 temperature controller. The temperature during the high stage was controlled within a range of 1^0 C. The pressure in the collecting chamber of UNIMAS was approximately 1.0×10^{-4} Pa during the implantation activities. The samples were not subjected to a specialized annealing process. However, they were exposed to oxidation in the air under typical ambient circumstances for at least 5 hours. This exposure ensured that the oxidation effect reached its maximum saturation.

2.4. RBS/NR experiment parameters

The depth profile of the virgin and irradiated GaAs samples was tested by the Rutherford Backscattering Spectroscopy with Nuclear Reactions (RBS/NR) at Frank Laboratory of Neutron Physics (FLNP) at Joint Institute for Nuclear Research (JINR) in Dubna (Russia). An α-beam produced by EG5 accelerator was used. The beam was directed at the samples at a fixed incident angle toward the surface. A semiconductor detector was positioned at a scattering angle to the beam incident direction in order to collect the RBS spectra [7, 8]. The table 1 shows all the experimental setup information.

Table 1

Experimental setup	
Ion beam	
Incident ion	^{4}He
Incident ion energy (MeV)	3.025 ÷ 3.065
IBM geometries	
Incident angle α (degree)	15.0
Scattering angle θ (degree)	170.0
Calibration	
Calibration offset (keV)	± 1
Energy per channel (keV/channel)	3.60
Energy resolution	
Detector resolution (keV)	15 ÷ 20
Energy spread of incident beam	0.0

3. RESULTS AND DISCUSSIONS

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 Al ions are presented in Fig. 3a–d.

These spectra have several characteristics. The first one is a band near channel 300. The intensity of the band was found to rise following ion implantation of the sample surface. The scattering of α particles on oxygen nucleons on GaAs surfaces, both virgin and implanted, reveals the presence of oxygen atoms in thin layers on the sample surface. They are referred to as the native oxide layer. The irradiation of the GaAs surface with Al ions modifies the near-surface layers. Oxygen from the atmosphere reacts differently with atoms on the GaAs crystal surface. In these experiments, the nuclear resonance reaction was used.

An additional prevalent band can be noticed within the channel, ranging from 650 to 700. The recorded spectra displayed comparable morphology and acuity. These spectra are associated with the varying energy of scattering particles on the nucleons of As and Ga. The

results demonstrate a strong association between the sensitivity of measurements and the quality of the surface. The elemental composition and depth distributions were determined by applying the SIMNRA computer algorithm [9] to fit theoretical curves to the RBS/NR experimental spectra. The energy spectra of α particles ranging from 3.025 to 3.065 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 = 3.045 MeV. This phenomenon verifies the presence of tiny layers on the examined surfaces that consist of oxygen atoms. They exhibit homogeneity, with the exception of any measurement error. The obtained spectra at E_α = 3.045 MeV for all samples show variations solely in the intensity of the peak around channel 300. It suggests that the thicknesses of the natural oxide layers in the examined samples vary.

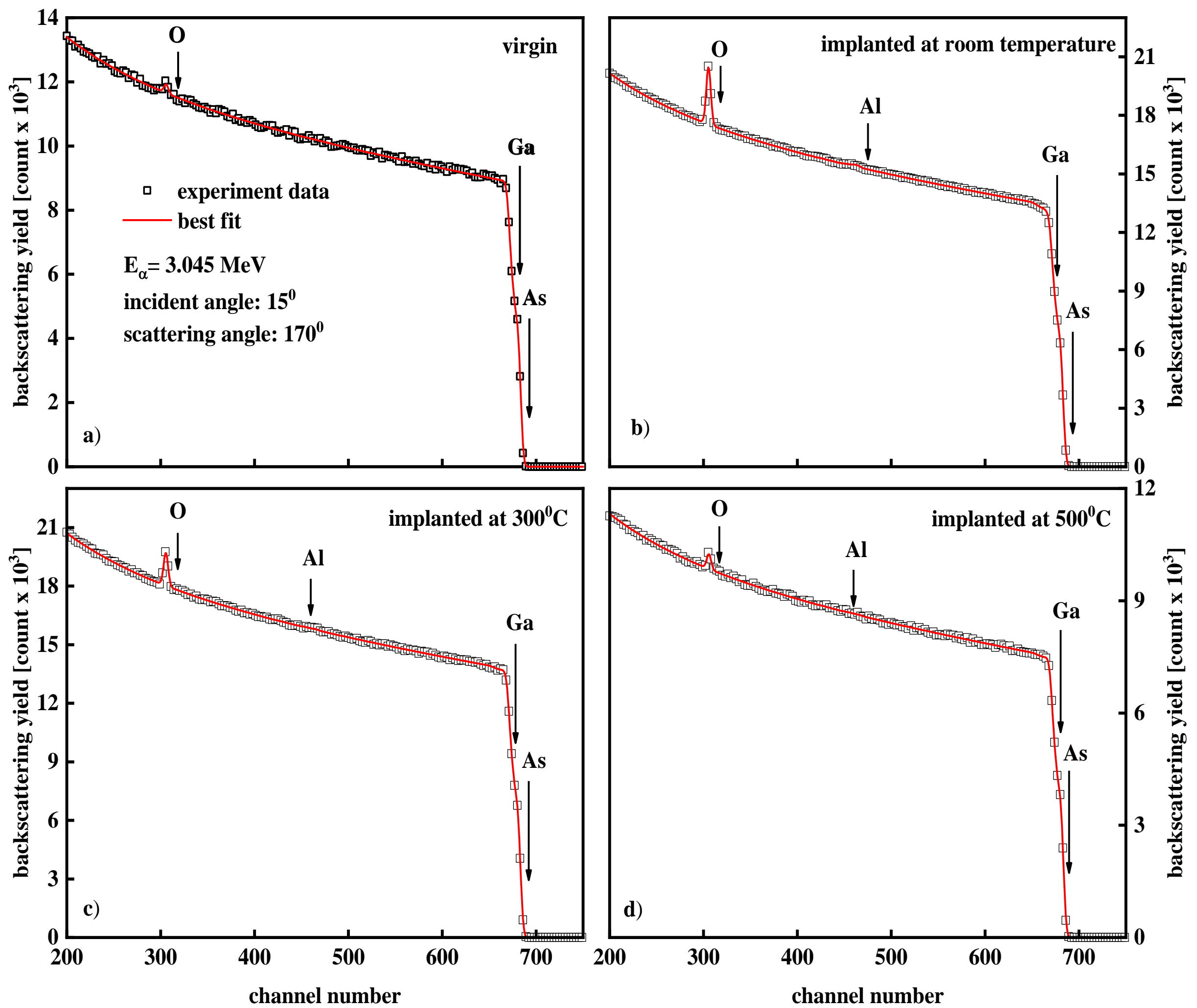

Fig. 3: RBS/NR spectra with a) virgin sample b) sample after implanted at room temperature c) sample after implanted at 300^0C and d) sample after implanted at 500^0C.

4. CONCLUSION

This study gives important insights into the creation and properties of the native oxide layer on GaAs surfaces, particularly after hot-implanted aluminum ion treatment. RBS/NR has been successful in measuring the thickness and elemental content of this oxide layer. The findings show that the GaAs surface generates an oxygen-rich layer during ion implantation and that the thickness of this layer is inversely related to the implantation temperature. Specifically, higher temperatures during the Al-implantation process diminish the thickness of the native oxide layer. This is one of several studies investigating additional aspects that influence the native oxide layer on the surface of GaAs samples.

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