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Secondary ion yield from ion beam sputtered aluminum gallium nitride

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**SECONDARY ION YIELD FROM ION BEAM SPUTTERED
ALUMINUM GALLIUM NITRIDE**

A Thesis

Presented to

The Faculty of the Department of Materials Engineering

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Dale L. Lefforge

July 1998

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ABSTRACT

SECONDARY ION YIELD FROM ION BEAM SPUTTERED ALUMINUM GALLIUM NITRIDE

By Dale L. Lefforge

AlGa_N material is widely used in GaN based optoelectronic devices. Secondary ion mass spectrometry (SIMS) analysis of dopant and impurity distribution require knowledge of relative sensitivity factors (RSFs) and sputter rate variations over the range of compositions being evaluated.

A series of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ films with X ranging from 0 to 0.32 were implanted with O, Si and Mg. The samples were analyzed by SIMS and RSFs generated for the implanted elements in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ materials. Sputter rate decreases and useful ion yield varies as X changes from 0 to 0.32. Different combinations of primary ion beam, cesium or oxygen, and secondary ions were investigated. Information on the relationships of RSFs versus Al composition in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ for O, Si and Mg for the various secondary ion detection methods are presented.

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CHAPTER 1. INTRODUCTION

1.1 The significance of aluminum gallium nitride

Gallium nitride (GaN) has been demonstrated as a promising material for emission in the blue portion of the visible spectrum. GaN is, compared to other semiconductor materials, a large bandgap material. The large bandgap of GaN, 3.4 eV, enables emission of shorter wavelength radiation than is possible in other semiconductor materials with smaller bandgaps. Materials with the capability to emit light in the red and green portion of the spectrum have been available for several years. The addition of aluminum to gallium nitride provides a method of modifying the energy of the bandgap from 3.4 to 6.2 eV.

This material system is being developed as a blue light source for solid state light emitting diodes (LEDs) and lasers. The desirable optoelectronic property of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ is light emission in the blue to blue-green portion of the visible spectrum. Aluminum gallium nitride offers the prospect of being an efficient, inexpensive, and long-lived material with short wavelength emission. The optoelectronic properties of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ have potential in a wide range of applications.

The most attractive aspect of the emission of blue light is that it allows full-color displays to be constructed entirely from semiconductor based materials. Blue light emission in a commercially viable material has been the missing link in the development of a full color display. The production of a full color display

requires the addition of multiple wavelengths of light. In the human perception of color the eye is less sensitive in the blue to violet and the far red portions of the spectrum, shown in Figure 1¹. To overcome the lower sensitivity bright blue and red light sources are needed. Bright red sources are already available in the Al-GaP material system. The $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ system may provide the solution for a bright blue light source.

Figure 1. The normalized response of the human eye to the visible light spectrum.

1.2 Electronic properties

The electronic properties of LEDs and lasers are influenced by the selective control of trace elements in the material. The additions of doping elements, placement of the p/n junction and control of impurities are essential to device performance. A typical device structure for a blue $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ light emitting diode is shown in Figure 2.² The bulk of the device is GaN with a layer of

$(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ providing for charge carrier confinement near the active region of the device. The p/n junction, when positioned properly, is located in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ layer.

The doping levels and proximity of the p to n-type transition to the quantum well are critical to device performance. Measuring the doping level, determining the junction placement and investigating the transition in material composition present challenges to the development of bright and reliable LEDs. Measuring the concentration of trace elements, dopants or impurities, and accurately displaying the location of a p/n junction require developing analysis techniques that can be successfully applied to $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material.

Figure 2. Typical GaN LED device structure.

1.3 Materials analysis

A useful method in the characterization of semiconductor materials, including the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material system, is secondary ion mass spectrometry (SIMS) analysis. A SIMS analysis can relate the distribution of important trace elements, either dopants or undesired impurities, to depth in the material. This information is essential to controlling and modifying the optoelectronic properties of the material. The SIMS technique allows the collection of qualitative and, with appropriate understanding of the material, quantitative information about the material.

When a beam of primary ions of sufficient energy is focused on a condensed phase target, sputtered material will be emitted from the target. The sputtered material will be a combination of neutral and charged particles. The analysis of the spectrum of charged particles, the secondary ions, yields information about the composition of the target material. Collection of data on secondary ion counts versus sputter time yields information on concentration changes with depth in the target.

1.4 Motivation for the project

This thesis is designed to address specific aspects of the effects of the matrix (the primary components of the material) on the yield of secondary ions

ejected from aluminum gallium nitride $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ samples subjected to an impacting ion beam. It is known that the secondary ion yield is determined by material specific properties. Combinations of atomic composition, chemical state, and crystallographic orientation are some of the factors known to have strong influences on net secondary ion yield. The exact physical parameters leading to the production of secondary ions from sputtered material are not well known. A result of the lack of a complete understanding of the ionization process is that no consistent theory exists to describe and predict the yield of secondary ions from sputtered material.³ The purpose of this project is to determine an empirical correlation between the matrix composition and secondary ion yield in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

1.5 Project objective

The objective of this project was to quantify the matrix effect on the secondary ion yield from $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ over a range of Al concentrations. The behavior of ion yield in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ was evaluated. The outcome of this project is the characterization of the material dependence describing the yield of secondary ions as a function of aluminum composition (x) in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material system. Relationships that describe the influence of Al composition on secondary ion yields are presented in Chapter 5.

1.6 Research hypothesis

The primary hypothesis for this project is that ion yield in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ varies as a function of the Al composition. The change in yield can be influenced by combinations of the primary beam used to sputter the material and the secondary ion collected for analysis. The behavior of the yield of trace and matrix ions from $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ as a function of the Al composition has not yet been reported in the literature. The hypothesis does, however, appear reasonable based on reported effects in similar ternary semiconductor materials. The nature of these effects, as reported in the literature, is described in more detail in Chapter 3.

1.7 Preview of the investigation of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$

The $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material system is being developed for its attractive optoelectronic property of emission in the blue to green portion of the visible light spectrum. This semiconductor material presents a number of challenges to material characterization and device fabrication. This thesis addresses the challenges in using SIMS to investigating the material properties of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

Chapter 2 will discuss the SIMS characterization of the material and the difficulty of quantifying trace element concentration in a multi-component semiconductor. Chapter 3 reviews work reported on using SIMS to characterize compound semiconductors, including the limited reports on $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. Chapter 4 describes how the experiments were designed; including epitaxial

material growth, primary composition analysis, preparation of ion implanted material, and the selection of SIMS analysis parameters. Chapter 5 reports on the results of the SIMS investigations and discusses how different approaches to the SIMS analysis can be used to characterize $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material. Chapter 6 presents conclusions on the appropriate use of different analysis methods for the characterization of optoelectronic devices made from $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

CHAPTER 2. SIMS QUANTIFICATION OF TRACE ELEMENT CONCENTRATIONS

2.1 Introduction

SIMS collects information on the number of secondary ions, of a given mass, emitted from a sputtered sample. The data collected are the number of counts of secondary ions and the interval of time used to take the counts. This information is entirely qualitative. Only with sufficient understanding of the sputter yield of secondary ions can the data be converted to quantitative information. In a material system with multiple components sputter yield typically varies with composition. In $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ the change in ion yield with composition complicates the determination of quantitative information on the trace element concentration.

The determination of quantitative information requires reference material to evaluate sputter yield. Ion implantation is the method used to produce reference materials. This chapter describes the SIMS technique and why reference materials are needed. In Chapter 4 the details of simulating ion implants to assist in producing the reference materials for this project are described.

2.2 How SIMS works

SIMS works by selectively sputtering a small area of a sample. The sputtering is accomplished by a primary ion beam. The primary beam is collimated, focused and directed onto the surface of the sample. The beam is rastered

over the surface to sputter or erode material from the sample. Information about the sample is obtained from the ionized component of the sputtered material. The ionized component of the sputtered material is collected, collimated through a separate secondary ion column and directed to a counting system. In the instrument used for this study an adjustable magnetic field in the secondary column separates ions by mass. The secondary ions are counted by detectors at the end of the secondary ion column. Figure 3 shows a diagram of a typical magnetic sector SIMS instrument configured like the Cameca IMS4-f used in this study.⁴

2.3 The information SIMS provides

As the introduction indicated the data collected are the number of counts of secondary ions and the interval of time used to take the counts. The SIMS data provides a method for tracking changes with depth in the material. The data allows correlation of secondary ion counts to be made with changes in the material. The technique provides a method to actively profile the distribution of an element in the material, if measurements of the depth of a sputter crater are taken.

Figure 3. Magnetic sector SIMS

2.4 The technical challenge to characterization

The challenge in using secondary ions for analysis is quantifying the information. The ion counts at any data point in a SIMS profile can be converted to a concentration with a known relative sensitivity factor (RSF). Typically the concentration of a given element in a matrix is calculated according to Eq. (1):

$$Q_{si} = RSF \times \frac{I_{si}}{t_s \times I_m} \quad (\text{Eq. 1})$$

where;

Q_{si} is the concentration of species s at data point i (atoms/cm³),

I_{si} is ion counts of species s at data point i ,

RSF is the relative sensitivity factor of species s in matrix m (atoms/cm³),

t_s is the integration time of the counting cycle for species s (seconds),
 I_m is the matrix ion intensity (counts/second).

In this equation the RSF is assumed to be constant. However, it has been found that atomic composition, chemical state, crystallographic orientation and other attributes influence secondary ion yield. The sample dependent variables that influence sputter yield are called matrix effects.

Any material dependent attribute that alters secondary ion yield from the sputtered material will influence the RSF. The magnitude of the matrix effect is material specific. It is known that matrix effects are not uniform for all secondary ions. Different secondary ions experience different degrees of the matrix effect. The quantification of SIMS data requires matrix effects to be fully evaluated.

2.5 A solution to quantifying secondary ion yield information

The standard approach to quantification in SIMS analysis is to correlate ion yield of a trace element from a reference standard to the ion yield of the most abundant constituent. Reference samples are often ion implanted material. A known dose of an element is implanted into the reference material. The RSF relationship between the ion counts of the element and the target material is established in the reference material. This relationship allows the calculation of a RSF for a given elemental specie in a matrix. The RSF is calculated from Eq. (2)⁵:

$$RSF = \frac{Dose \times n_c \times I_m \times t_s}{Depth \times \sum I_s} \quad (\text{Eq. 2})$$

where;

RSF is the relative sensitivity factor for species *s* and matrix *m*,

Dose is the ion implant atom fluence (atoms/cm²),

n_c is the number of data cycles in the depth range,

I_m is the ion intensity for the matrix ion of isotope *m* (counts/second),

t_s is the integration time per count cycle of species *s* (seconds),

Depth is the analytical depth (cm),

ΣI_s is the integral of species ion counts over all count cycles.

In an elemental matrix with no major secondary constituent a single reference sample can be used to establish a quantifiable relationship between a trace element and the primary matrix ion. This relationship is used in subsequent samples to determine the concentration of the trace element. In a compound matrix the problem of determining concentration is more complex because the material specific properties that influence secondary ion yield are more numerous.

The approach to quantification in SIMS analysis in less complex systems was modified to study the matrix effect influences on the RSF in $(Al_xGa_{1-x})_{0.5}N_{0.5}$. Matrix effects are prevalent in the $(Al_xGa_{1-x})_{0.5}N_{0.5}$ material system but vary by the selection of different types of secondary ions. The approach to quantification in this project, described in Chapter 4, was to correlate the secondary ion yield of a trace constituent to the ion yield of a primary component, not necessarily the most abundant component, in the matrix. The influence of matrix effects and the strength of the effect, under different analysis conditions, are presented in Chapter 5.

Chapter 3. Background and Literature Survey

3.1 Introduction

One of the challenges in this thesis project was gaining the appropriate understanding of the material to allow an evaluation of the matrix effect in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material system. The process to select appropriate elements to evaluate required an understanding of issues relevant to the growth and processing of epitaxial films. This includes ion implantation of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$, a process required to create reference standards for this project.

The literature survey and review for this project were designed to focus on two areas of recent research. The first area of interest focused on articles describing the properties of GaN and $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$, including epitaxial growth and ion implantation. To uncover possible approaches for understanding ion yield behavior in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$, the second area of interest focused on articles addressing the matrix effect in SIMS analysis and how the effects influence material characterization. This included reports on the effects in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ and other compound semiconductors.

3.2 Properties of GaN and $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$

The blue and ultraviolet (UV) portion of the electromagnetic spectrum has, until recently, not been addressed by semiconductor device technology. The use of III-V nitrides, aluminum nitride (AlN), indium nitride (InN) and gallium

nitride (GaN), is allowing construction of semiconductor components that emit in this range of the electromagnetic spectrum. GaN, AlN, and InN form a continuous alloy system with direct band gaps allowing emission in the blue and UV range. The drawback in the early development of these nitrides was an inherently high n-type background from native defects. Complications also resulted from the lack of a lattice matched substrate for epitaxial growth of III-V nitrides.

The review article by Strite and Morkoc describes the basic properties of the III-V nitrides.⁶ The article is a comprehensive review of the methods of III-V thin film growth and characterization. The earliest growth techniques are discussed and development of current epitaxial growth methods, by molecular beam epitaxy (MBE) and chemical vapor depositions (CVD), are described. Also included are descriptions of the band gap, the physical, optical, and electrical properties of the III-V nitrides. The relationship between Al composition and the absorption edge of the bandgap in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ is linear, as shown in Figure 4.

The most useful part of the article, for this work, is a description of the potential n and p-type dopants in GaN and their binding energies. Several group II and IV elements are potential dopants; Mg, Zn, Hg, Cd, Be, and Li are p-type and Si is an n-type dopant in GaN. These elements are possible choices as selective dopants in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. Magnesium and Zn are receiving the most interest for use as p-type dopants. The reported binding energies of potential dopants in GaN is shown schematically in Figure 5.

Figure 4. The influence of Al composition on the bandgap⁶ in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

A difficulty in producing a p-type GaN is that very little of the dopant is electrically active. The hindrance to activating Mg is that it becomes passivated, primarily by H. The H can be introduced into the film by the growth process or by subsequent etch or clean treatments.⁷ In practice the H-Mg bond is broken and the H is removed from the film by a high temperature, 900 °C, anneal. Breaking the H-Mg bond allows the Mg to be electrically active. The importance of understanding and compensating for the influence of H is described by Gotz.⁸

Figure 5. Estimated binding energies of substitutional acceptors and the shallow donor level in GaN.⁶

3.3 Epitaxial growth

Several impurities other than H such as C, O and Si may be introduced during the growth process. The amount of impurity that is introduced is dependent on the details of the growth process. The C is introduced by reactants, trimethylgallium (TMGa) or triethylgallium (TEGa), used to provide Ga to the epitaxial GaN film. An example of the differences in the background C contamination in a GaN film grown with TMGa and TEGa is shown in Figure 6.⁹ Oxygen is introduced as a component of the reactants or by leakage into the reaction chamber. Silicon can be introduced by side reactions with quartz components used to construct epitaxial reactors. The role of the introduction of these impurities is described by Ishibashi.¹⁰

Figure 6. Background contamination concentration of C and O in GaN grown with trimethylgallium and triethylgallium source gasses.⁹

Silicon and O act as electron donors in GaN and have been suggested as contributors to the n-type property of as grown GaN. Careful analysis of the O and Si background concentration in GaN indicate the contribution of O and Si cannot account for the degree of n-type behavior. There is speculation that another unidentified impurity must be present in some epitaxial GaN.¹¹ The importance of these and similar articles suggests the inclusion of Si, C, O and H as elements of primary interest in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

3.4 Ion implantation

Ion implantation was used in this project to produce reference standards for SIMS analysis of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. Ion implants have a more fundamental role in device technology through their use to modify the properties of semiconductor

materials. Ion implants can be used to introduce selected dopants or to produce localized damage to form electrically isolated areas in the material.

Implant ranges for species in GaN have been predicted from TRIM92 calculations. TRIM92 is a program used to model ion implants and to predict sputter yields.¹² Preliminary results of the measured ranges of a number of elements implanted into GaN have been reported by Wilson.¹³ The article reports on the SIMS analysis of the measured range of ion implants into GaN. The SIMS depth profiles show the TRIM92 calculations do not always predict the range of the implant. The discrepancy between calculated and measured ranges becomes greater as the mass of the implanted ion increases.

TRIM92 prediction of implant ranges generally underestimates the range of light elements and overestimates the range of heavy elements implanted into GaN. This project required the use of controlled ion implants into $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. Epitaxial $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ is generally grown to a limited thickness. Knowing the expected range of an implanted ion is critical to obtaining a usable set of ion implant reference standards. The TRIM92 program was used to model the ion implant ranges for the reference standards. The information on the discrepancy between TRIM92 and SIMS measured ranges were considered when selecting implant conditions for specific elements.

The difference in simulated and measured implants in this work were not as severe as those reported by Wilson. This work used an update of the TRIM program. The update to TRIM92 is part of the SRIM96, version 96.01, software

used to simulate implants for this work.¹² The current version of TRIM uses updated values for the nuclear and electronic collisional cross-sections of several light atomic weight elements, including N, that have been revised since the Wilson report. These changes improve the accuracy of the simulation in materials with significant atomic fractions of light elements. The simulation of ion implants is discussed more fully in Chapter 4

3.5 Matrix effects in compound semiconductors

In a multi-component material system the accurate SIMS analysis of dopant and impurity distribution require knowledge of RSFs and sputter rate variations over the range of matrix compositions being evaluated. In the Al containing multi-component materials AlGaInP and AlGaAs that are used in electronic and optoelectronic devices, different combinations of secondary and matrix ions show significant differences in yield with changes in Al composition.^{14, 15}

Extensive work has been published on evaluating ion yields in binary III-V semiconductor materials such as indium phosphide (InP) and gallium arsenide (GaAs). Implant reference material and data of RSFs for a number of elements are commercially available. Little work has been published on evaluating ion yield changes with a change of the aluminum composition in group III-V semiconductors. An article, by Smith, reports on the SIMS evaluation of ion yield

changes with composition in ternary or quaternary (Ga,Al,In)P semiconductor materials.¹⁴

Evaluations of these materials indicated ion yield can be strongly influenced by the composition of the material; a behavior also demonstrated in this study. Wilson has collected information on the dependence of SIMS relative sensitivity factors (RSFs) on electron affinity and ionization potential of 74 elements implanted into 23 different materials.¹⁶ The relationship between RSF and electron affinity and ionization potential is complex. In certain instances, such as with an O_2^+ primary beam and the detection of positive secondary ions, there has been some success in correlating RSF with electron affinity. The correlation strengthens with the selection of sub-groups of elements.

The usefulness of this article is that it attempts to correlate information on electron affinity and ionization potential with RSFs. A set of empirical relationships of RSF values in previously studied materials are presented. Techniques to expand relationships of RSFs of elements in other matrices are also proposed. These techniques offer the possibility of estimating RSFs of elements under similar analysis conditions in other materials. The major limitations of the article, from the perspective of $(Al_xGa_{1-x})_{0.5}N_{0.5}$ analysis, is that it contains little data on any III-V material and no data on III-V nitride material.

Matrix effects can be significant. Previous work reported for aluminum gallium arsenide ($Al_xGa_{1-x}As$) show pronounced matrix effects.¹⁵ In this material system slight changes of Al composition change the RSF. The measured

changes in RSFs of specific elements were found to depend on the type of ion measured. Changes in Be RSF with Al composition were reduced in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ system by selection of an AsBe^- molecular ion.

The ion yield of H, C, N, and O from InP has been investigated by Gaun-eau.¹⁷ The author investigated the useful ion yield of negative secondary ions from InP sputtered by a Cs^+ primary beam. The article reports the ion yield of molecular ions, P_2X^- , PX^- , InX^- , and PX_2^- , where X represents H, C, N, and O. The yield of P_2X^- molecular ions is greater than the yield of any single element or the other molecular ions, PX^- , InX^- , and PX_2^- .

The information in this article was of interest to this project. The yield of molecular ions in other material systems is typically less than the yield of single element ions. The specific behavior of a molecular ion of the form M_2^- , where M is a primary component of the matrix, having a greater yield than an elemental ion or a simpler molecular ion is an interesting feature of InP. This specific feature of enhanced MX_2^- secondary ion yield in InP was not demonstrated in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material system. However, the general attribute of useful ion yield for molecular ions was also demonstrated in this work with III-V nitrides.

Useful information in an article by Gao presents approaches to evaluating matrix effects in SIMS analysis of aluminum gallium arsenide ($\text{Al}_x\text{Ga}_{1-x}\text{As}$) a III-V semiconductor.¹⁵ This ternary system has similarities to $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. Both systems are III-V materials with significant ion yield changes associated with the aluminum fraction. The article describes the strong matrix effects with O_2^+

primary beam analysis of Be in $\text{Al}_x\text{Ga}_{1-x}\text{As}$. The matrix effect dependence on aluminum composition is reduced by selecting a molecular ion, AsBe^- , under a Cs^+ primary beam bombardment of the sample, as shown in Figure 7. In this system the AsBe^- yield is less than Be^+ but the reduced matrix effect in the AsBe^- ion offers distinct advantages in calculating Be concentrations in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ with varying aluminum fractions.

A second article by Gao expands on the ideas developed in the work on $\text{Al}_x\text{Ga}_{1-x}\text{As}$ to describe methods of limiting the extent of matrix effects in SIMS analysis.¹⁸ Molecular or cluster ion combinations can decrease matrix effects

Figure 7. Secondary ion yield from $\text{Al}_x\text{Ga}_{1-x}\text{As}$ of Be^+ elemental ion under O_2^+ primary beam and of AsBe^- molecular ion under Cs^+ primary beam.¹⁵

and, in some cases, increase sensitivity of the detection of certain elements. A use of MCs^+ and MCs_2^+ ions, where M is the element of interest and Cs is the primary beam, reduces matrix effects. The MCs_2^+ yield increases with the electron affinity of M. The MCs_2^+ technique is particularly useful for profiling highly electronegative elements. An added benefit of these approaches to analysis is they allow the simultaneous profiling of n and p-type dopants under conditions that reduce matrix effects.

The articles by Wilson and Gao offered direct benefits to this project.^{13, 15, 16, 18} These articles incorporate analysis methods that were used in the evaluation of matrix effects in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. They had an added benefit in that the descriptions of the experiments include detailed information on the mass spectrometer parameters used to collect data. This was particularly useful because the spectrometer and techniques are identical to those that were used in this project.

3.6 Matrix effects in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$

A demonstration of the significance of the matrix effect in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ can be seen in Figure 8, in the raw data SIMS profile of H and O secondary ion counts in a sample of $(\text{Al}_{0.14}\text{Ga}_{0.86})_{0.5}\text{N}_{0.5}$ grown on GaN⁹. In the profile the Al counts show the transition from the GaN layer to the overlying $(\text{Al}_{0.14}\text{Ga}_{0.86})_{0.5}\text{N}_{0.5}$

Figure 8. Raw data SIMS profile of H and O ion intensity in $(\text{Al}_{0.14}\text{Ga}_{0.86})_{0.5}\text{N}_{0.5}$ on GaN.⁹

layer. The secondary ion counts for H and O show a significant increase in the Al containing layer. Without an evaluation of secondary ion yield in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ system it is not possible to determine any quantitative information on the concentration of H and O in the Al containing layer. The concentrations of H and O in the Al containing layer could be identical, greater, or less than the concentrations of H and O in the GaN layer. In $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material a single article, by Griffis, does report on the SIMS measured influences of elemental ion yield in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.¹⁹

Another aspect of the sputter behavior of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ is a need to understand the influence of the matrix on the sputter rate as the Al composition

changes. Information on the sputter rate dependence on Al content is important for the conversion of raw data into an accurate depth scale. In a single layer film the total depth of the sputter crater can be measured and the raw SIMS data is easily converted to represent depth in the material. In multilayer films the conversion of raw data into depth becomes more difficult. The sputter rate must be known to accurately reflect where the p/n junction is located and where other changes occur in a multilayer film.

Sputter rate changes are independent of secondary ion yield. Secondary ion yield of trace elements does not always scale with sputter rate. Sputter rate as well as RSF changes that occur with differences in Al composition must be evaluated to accurately characterize any changes in trace element concentration through a multilayer film structure.

3.7 Summary of previous work

The literature survey and the review of selected articles offered the benefit of understanding the basic elements of interest in the use of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ as a material for semiconductor devices. This included elements that could be used as dopants, Mg, Zn, Hg, Cd, Be, Li, Si, and elements that interfere with device performance, C, O, H. An item of great practical significance in constructing ion implant reference materials was the reported discrepancy between the TRIM92 program calculation and measured implant ranges in GaN.

A further benefit of the literature survey was the collection of related work on secondary ion yield and the influence of matrix effects in different material systems. This body of work suggested definite approaches to the analysis of secondary ion yield and the calculation of RSFs in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. These articles reported on approaches, such as MX_2^- , MCs^+ , and MCs_2^+ that are non-standard compared to more traditional techniques for the SIMS analysis of semiconductor materials. These approaches offered advantages of limiting the influence of matrix effects and, for specific elements, increasing the sensitivity of SIMS analysis.

A final benefit of the literature search was the mass spectrometer and the TRIM92 program used in a number of the articles are identical to the tools available for this project. The collected experience represented in the literature survey helped reduce the time and cost associated with sample preparation and mass spectrometry. The information from the literature survey was incorporated into the experimental procedures described in the next chapter.

CHAPTER 4. EXPERIMENT DESIGN AND IMPLANT SIMULATION

4.1 Introduction

This project required the completion of several key steps before the secondary ion yield of various elements from $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ could be evaluated. One of the key steps was acquiring $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ samples of various Al compositions. Preparing ion implant reference samples was another key step. This required calculation of the density at different Al compositions and a critical evaluation of implant distribution. To evaluate implant conditions a series of implant simulations was completed. The simulations helped to select the implant energy and dose used in the reference material.

Secondary ion yield was investigated in a set of SIMS experiments. SIMS data can also yield information about the primary composition of a material and any sputter rate dependence on the composition. To obtain a SIMS evaluation of the composition the secondary ion yield data was correlated to Rutherford backscattering spectrometry (RBS) measurements of composition. Sputter rates were calculated for materials with different Al compositions.

4.2 Epitaxial film growth

Epitaxial materials used for this investigation were grown by organometallic vapor phase epitaxy (OMVPE) in a single wafer vertical flow reactor. Films of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ were grown on an underlying buffer layer of OMVPE

GaN. These films were grown by Dr. Mike Ludowise at Hewlett-Packard. The epitaxial material was grown on a sapphire substrate. Films with x varied from 0 to 1 were grown for composition analysis. Films with x ranging from 0 to 0.32, from 1730 to 6970 Å thick, were grown for SIMS investigation of the RSF of O, Mg and Si, Figure 9. Films in this composition range could be grown to thicknesses that were useful for ion implantation of O, Mg and Si. Ion implanted films were used to determine RSFs of O, Mg and Si in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

Figure 9. Film structure for evaluation of SIMS relative sensitivity factors.

Three wafers were deposited with the mass flow controller for the Al precursor set at 25, 50, and 75 percent of the maximum flow rate. The Al containing layers initially were targeted to be 1 µm thick. The slower growth rate at higher Al precursor flow rates produced thinner films. These wafers join a pre-existing sample of GaN $((\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5})$ where $x = 0$ to give a 4 sample set.

The Al composition of the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ does not correspond directly with the setting of the mass flow controller on the reactor. The Al composition and

the thickness of the Al layer must be determined. The composition and thickness were determined by RBS. The RBS analysis was done at Hewlett-Packard by Dr. Chris Nauka.

The individual wafers used in these experiments had surface layers of different thickness. Obtaining thick $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ layers of high aluminum content is difficult because increasing the Al content slows the deposition rate of the growing film. The samples also demonstrated a non-uniformity, approximately 20%, in thickness across the wafer surface. The distribution in layer thickness of the three aluminum containing samples is shown in Table 1. The substrate material has a single flat and the thicknesses reported were taken along a diameter from the middle of the wafer flat to the opposite edge. The pattern of variation is similar in each wafer. The non-uniformity arises from the influence of a temperature gradient in the reactor.

Table 1. Thickness variation in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ surface layer.

Wafer Number	Al Composition	Al containing layer thickness (Å)		
		Wafer Flat	Center Wafer	Opposite Wafer Flat
50M_653	$(\text{Al}_{0.10}\text{Ga}_{0.90})_{0.5}\text{N}_{0.5}$	5680	6690	6970
50M_651	$(\text{Al}_{0.16}\text{Ga}_{0.84})_{0.5}\text{N}_{0.5}$	3490	3900	3850
50M_652	$(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$	1730	2130	2090

The sample of $(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$ had the thinnest aluminum containing layer. This sample at its thinnest measurement, near the wafer edge opposite of

the wafer flat, was 1730Å . The measurement of thickness was done by SIMS profiling for Al on pieces of the wafer. Pieces were taken from three areas; at the wafer edge near the flat, center, and near the wafer edge opposite to the flat. The Al secondary ion count was tracked and the sputtering of the sample stopped when the Al count rate decreased. The thickness of the Al containing layer was taken from the measured depth of the sputter crater.

4.3 Density of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ films

The density of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ film varies with changes in the Al content. The density of a material is an important characteristic influencing the penetration depth of an implanted ion. A value for the density must be provided to the modeling software before an implant is simulated.

The AlN and GaN binary alloy comprise a portion of the ternary alloy system (Al,Ga,In)N. This alloy system has a Wurtzite crystal structure, shown in Figure 10. Each unit cell contains 4 Ga and 4 N atoms. Lattice constants for AlN are $a=3.112 \text{ \AA}$ and $c=4.982 \text{ \AA}$.⁶ Lattice constants for GaN are $a=3.189 \text{ \AA}$ and $c=5.185 \text{ \AA}$.²⁰ Lattice constants for intermediate concentrations of Al are generally not available.

FIGURE 10. The wurtzite crystal structure.²⁰

Density values for the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ series were calculated from literature reports of the crystal structure and the lattice constants of GaN and AlN. The density was calculated as the mass of 2 molecules AlN or GaN per unit cell of the crystal. The volume of a hexagonal unit cell is $\left(\sqrt{3}/2\right)a^2c$. The calculated density of AlN is 3.2573 g/cm^3 and the density of GaN is 6.0877 g/cm^3 . These calculated densities yield values for the number of molecules per cubic centimeter of 4.79×10^{22} for AlN and 4.38×10^{22} for GaN.

The density for $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ was assumed to vary linearly with Al fraction between the AlN and GaN endpoints (density = $[(-2.8304)X + 6.0877]\text{g/cm}^3$, where x is taken from the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ notation). The calculated density of the four samples used for ion implant are listed in Table 2.

Table 2. Aluminum fraction, composition and calculated density of implanted samples of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

Al Fraction x	$(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ Composition	Calculated Density (g/cm ³)
0	$(\text{Al}_0\text{Ga}_1)_{0.5}\text{N}_{0.5} = \text{Ga}_{0.5}\text{N}_{0.5}$	6.0880
0.01	$(\text{Al}_{0.10}\text{Ga}_{0.90})_{0.5}\text{N}_{0.5} = \text{Al}_{0.05}\text{Ga}_{0.45}\text{N}_{0.5}$	5.0850
0.08	$(\text{Al}_{0.16}\text{Ga}_{0.84})_{0.5}\text{N}_{0.5} = \text{Al}_{0.08}\text{Ga}_{0.42}\text{N}_{0.5}$	5.6350
0.16	$(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5} = \text{Al}_{0.16}\text{Ga}_{0.34}\text{N}_{0.5}$	5.1820

4.4 Requirements for reference standards

The depth and peak concentration are important considerations in constructing an ion implant reference for SIMS analysis. The depth of the implant must be targeted to have the entire dose remain within the layer of interest. Typical off-axis implant distributions contain the dose within a distance from the surface of 3 to 5 times the projected range of the implant.

The peak concentration is also important. The major attribute of secondary ion emission that allows SIMS data to be quantitative depends on the emission remaining linear with concentration. At atomic concentrations below one atomic percent the emissions of secondary ions remain linear with concentration.³ An example of a Mg ion, isotope mass 24, implant reference into GaN, Figure 11, shows the peak concentration, depth, and distribution of the Mg ion in the GaN. The concentrations of dopants and impurities important in altering the

optoelectronic properties of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ is generally less than one atomic percent.

Figure 11. ^{24}Mg implant into GaN, dose $1\text{e}15$ atoms/ cm^2 , energy 150 keV.⁹

In GaN one atomic percent is a concentration of approximately 4.4×10^{20} atoms/ cm^3 . The energy and dose selected for the implant references was adjusted to maintain peak concentrations at 10^{19} to 10^{20} atoms/ cm^3 . The energy selected for the implant keeps the projected peak depth at 1/5 the depth of the Al containing layer.

4.5 Modeling of implants

The Stopping and Range of Ions in Matter (SRIM96), version 96.01 was used to model H, O and Si implants in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.²¹ This program allowed the projected range and distribution of implanted ions to be evaluated. The

program was used to select the implant energy and dose for each piece of implanted material.

Accurate modeling of implantation and the effect of an ion on the material requires information about the implant ion, interaction of the ion with the material and the material being implanted. The mass and energy of the impacting ion must be designated. The value of the electronic and nuclear stopping cross sections of elements in the material being implanted must be provided. Material specific properties of surface binding energy, lattice binding energy, lattice displacement energy and density must also be provided. Density is the material specific property that has the greatest influence on the range and distribution of implanted ions.¹²

The SRIM96 software allows two methods of estimating the range, longitudinal and lateral straggle of implanted ions. A quick estimate of the range is calculated using a projected range algorithm (PRAL) program. This program can quickly estimate range and straggle of implants over a set of possible implant energies. The program will calculate and display a table of range and straggle values within a few seconds.

A more complete treatment of the implant simulation is available in the SRIM96 software in a Monte-Carlo program, the transport of ions in matter (TRIM). The TRIM program calculates the path and distribution of an individual ion as it interacts with the material. To develop a better simulation of the implant many individual ions, typically several thousand, must be evaluated. Only ions

of a single energy are tracked in a given simulation. A single simulation can take several hours.

The PRAL program was used to obtain quick estimates of the range of implant energy that could be useful. Useful implant energies keep the range and straggle of an implant within the layer of interest. In the implant samples the layer of interest was at the surface of the wafer. In the three samples containing aluminum the surface layers ranged from 1730 Å to 6970 Å in thickness. The GaN sample with no aluminum containing layer was several microns thick.

The selection of the optimum implant energy in thin surface layers requires evaluation of the range and the distribution of the implant. The range is the depth of the peak concentration of implanted ions. The straggle is the distribution of ions around the peak concentration. In SIMS samples it is desirable to have the implant range be a few hundred angstroms below the surface while maintaining the final distribution of ions completely within the surface layer.

Information from the modeling program allows calculation of the expected peak concentration of the implant according to Eq. 3.²²

$$\hat{n} = \frac{\phi}{\sigma_p \sqrt{2\pi}} \approx \frac{0.4\phi}{\sigma_p} \quad (\text{Eq. 3})$$

where,

$\hat{n}$ is the peak concentration (atoms/cm³),

ϕ is the implanted dose (atoms/cm²),

σ_p is the standard deviation in projected range (cm).

The full Monte-Carlo simulation of the TRIM program requires several hours to show the range and straggle at a single implant energy. When multiple energies are being considered a separate simulation must be done for each energy. In the SRIM96 software the PRAL program can be used to quickly, within a few seconds, obtain estimates of the range and straggle at multiple energies. The PRAL program typically produces results that are within 5 percent of the TRIM simulation. Concentrations expected at the peak of the implant distribution indicated by the PRAL program can easily be estimated from Eq. 3.

To evaluate a range of possible implant energies the PRAL program is very useful. The program yields results that are acceptable for some applications and can be used effectively as a tool to screen implant parameters. Appendix A, obtained from PRAL simulations, includes tables of energy, range and straggle for O, Mg and Si implanted into $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material. The tables provide a reference to quickly evaluate implants over a range of energies.

To develop the most accurate picture of an implant, full Monte-Carlo TRIM simulations were run on the set of useful implant energies identified by the PRAL program. Several simulations were run for each implant specie. The simulations were used to evaluate how different energies distributed the ion within the layer of interest.

Complete TRIM simulations were run for ^{18}O , ^{24}Mg and ^{29}Si into the $(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$ sample, and these results are shown in Figure 12. All implants were modeled with an Al containing layer of 1640 Å, which is less than the

Figure 12. SRIM96 simulations of ^{18}O , ^{24}Mg and ^{29}Si implants in $(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$.

thinnest dimension expected, 1730 Å, for an Al containing layer. Implant energies that allowed the ions to remain within the 1640 Å layer were also used for the samples with thicker Al containing layers. Table 3 shows the energy and dose selected for each element, based on the simulations.

4.6 Ion implants

The wafers were divided into several pieces before being implanted. A single element was implanted into individual pieces obtained from each wafer. The implants were done at IICO Wafer Services.²³ Individual implants of ^{18}O , ^{24}Mg and ^{29}Si into $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ with x equal to 0, 0.10, 0.16, and 0.32 were used to investigate secondary ion yield. Table 3 lists implant dose and energy selected for the reference sample. The table also lists the projected range (the depth to the peak in the profile) and the peak concentration expected from the TRIM simulations of implants into $(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$.

Table 3. Ion implantation in $(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$ reference material.

Implant specie	Dose (atoms/cm ²)	Energy (keV)	Projected Range (Å)	Peak Concentration (atoms/cm ³)
^{18}O	4×10^{14}	50	750	5.17×10^{19}
^{24}Mg	4×10^{14}	60	700	5.04×10^{19}
^{29}Si	4×10^{14}	80	750	4.99×10^{19}

The dose was selected to produce peak concentrations near 5×10^{19} atoms/cm³. The implant energies were selected to yield peak depths of 700 - 800 Å while maintaining the dose in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ layer. The thinnest

sample, $(\text{Al}_{0.32}\text{Ga}_{0.68})_{0.5}\text{N}_{0.5}$, retained 97% of the implanted dose in the Al containing layer.

4.7 Implant dose verification

With the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material sent for implant companion pieces of either a silicon or a gallium-arsenide wafer were provided. A piece of silicon was implanted with pieces of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ receiving the ^{18}O and the ^{24}Mg implant. A piece of gallium-arsenide wafer was implanted with the pieces receiving the ^{29}Si implant. All pieces of material receiving a given implant were placed on a common carrier plate and implanted together. Processing the pieces in a batch lowers the cost of sample preparation and assures uniformity in dose across the sample set.

The companion pieces were used to verify the implant dose and energy. Silicon and gallium-arsenide have SIMS reference materials, prepared by implantation, that are characterized and commercially available. The ^{18}O , ^{24}Mg and ^{29}Si implant into the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ samples were verified, for correct dose, by comparing SIMS profiles in the companion pieces to existing reference material.

4.8 Sputter crater depth measurement

The total sputter depth is required for a complete description of the RSF, Eq. 2. In this SIMS work a Dektak II surface profilometer was used to measure the sputtered crater depth. Each crater was measured 2 to 4 times, in the x

direction and in the y direction, and an average sputter depth calculated. The profilometer is calibrated to a height standard traceable to the National Institute of Standards and Technology. The 10,000 Å step height standard is within 5 percent of the absolute value. The Dektak profilometer is maintained to have its reading deviate by less than 2 percent of the nominal step height.

4.9 RBS composition measurements

Rutherford backscattering spectrometry is commonly used to measure the primary component composition and thickness of epitaxial films. A He^{++} ion beam of a single and very high (1-2 meV) energy strikes the film. Some of the ions will elastically scatter from atoms in the film. The energy lost in the scattering is related to the mass of the atom being struck and the depth in the material where scattering occurs. The number of ions scattered is a function of the number of atoms present in the film. Measuring the energies of scattered ions identifies the elements present in the film. Counting the number of ions at each energy identify the number of each type of atom that is present in the material. The method is used to measure composition and calculate either film thickness or film density. RBS measurements were used to measure the Al composition in the samples of epitaxial $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ used in this project.

4.10 SIMS analysis methods

The literature survey indicated a number of possible analysis methods that could be useful in evaluating the secondary ion yield in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. The selections of specific analysis parameters affect calculated RSFs. These effects influence the final calculation of concentration. An evaluation of the analysis parameters including primary beam, secondary ion charge, and the specific ion combination being counted was performed for each implant.

Standard methods of SIMS analysis have trends associated with the selection of primary beam and the detection of a positive or negative secondary ion. The use of an O_2^+ primary beam tends to promote the formation of positive secondary ions. The use of a Cs^+ primary beam tends to promote negative secondary ions.³ These trends are related to the electronegativity of the element of interest. When elements of lower electronegativity, generally below 5 eV, are analyzed an O_2^+ primary beam is used and positive secondary ions are collected. When elements of higher electronegativity, generally above 5 eV, are analyzed a Cs^+ primary beam is used and negative secondary ions are collected. The standard method of analysis uses single ions with single negative or positive charge.

The literature survey indicated alternative methods of SIMS analysis could be useful in evaluating III-V semiconductor material. Unlike the standard methods of analysis the alternative methods use molecular ions. The molecular ions reported are combinations of the element of interest plus Cs, from the primary

ion beam, or a major component of the matrix. The abundance of the secondary ion that is formed has trends that follow the electronegativity of the element of interest.¹⁶

With the ion implant reference standards a set of preliminary SIMS evaluations were run to establish the analysis protocol to use for evaluating the secondary ion yield in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. The GaN sample and the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ sample with the greatest Al composition was used for the evaluations. The standard SIMS analysis methods, shown in Table 4, were compared to the alternative methods shown in Table 5. The trends in the formation of molecular positive and negative ions, reported in Chapter 5, are different from the standard methods of analyzing single atom ions.

Table 4. SIMS analysis using elemental secondary ions.

Element M	Electroneg.	Primary beam/Ion	
		Cs ⁺ /M ⁻	O ₂ ⁺ /M ⁺
O	9.65	+	
Mg	4.09		+
Si	7.3	+	

Table 5. SIMS analysis using a Cs⁺ primary ion beam and molecular secondary ions.

Element M	Electroneg.	Secondary ion		
		MCs ⁺	MCs ₂ ⁺	XM ⁺ X=Ga or N
O	9.65		+	
Mg	4.09	+		+
Si	7.3		+	

The evaluations determined which of the possible primary beam and secondary ion combinations had adequate ion yield to be useful for SIMS analysis. Determination of adequate ion yield depends on the overall count rate of secondary ions. The secondary ion intensity must be great enough to allow the collection of sufficient data to analyze. In SIMS analysis this generally requires a secondary ion intensity of a few hundred to several thousand ions per second. The count rate required must be sufficient to adequately track, record, and differentiate the counts of secondary ions of the element of interest. Sufficient counts are needed to differentiate against any background of secondary ions of similar mass to charge ratios. The influence of background counts on the detection and analysis of secondary ion data is discussed in Chapter 5.

The initial SIMS analysis to determine the appropriate use of a given analysis condition employed a single set of profiles. The primary beam and secondary ion selections listed in Tables 3 and 4 were used for the analysis. From the initial evaluations a set of conditions to use in the analysis of the complete set of samples was determined. Complete evaluations included from 1 to 3 repetitions of the analysis for every ion implant, on each of the four $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ samples.

4.11 Sputter rates and composition

SIMS measurements were made with a Cameca IMS4-f magnetic sector SIMS with a 10 keV Cs^+ or O_2^+ primary ion beam, which corresponds to impact

energies of 4.5 keV for positive secondary ions and 14.5 keV for negative secondary ions. Measurements of the depth of SIMS sputter craters were made with a Dektak II surface profilometer. The depth measurements allow the calculation of the sputter rate for the SIMS crater.

The primary components were profiled using an MCs^+ technique. Positive secondary ions of MCs^+ , with $\text{M} = \text{Al, Ga and N}$, were collected. This technique is less susceptible to changes in ion yield that occur with composition and have been shown to be useful for the measurement of composition in nitrides of group III elements.^{24 25} Samples were analyzed using a 10 keV Cs^+ primary beam of 24 to 38 nA rastered over an area of $(100 \mu\text{m})^2$ to $(112.5 \mu\text{m})^2$. The secondary ions were collected using a 150 μm field aperture, 30 μm contrast aperture and 150 μm image field. Counts of AlCs^+ , GaCs^+ and NCs^+ secondary ions were collected from the sputtered crater. In collecting the molecular ion data the most abundant isotope of an element was counted.

4.12 SIMS of trace elements

Films implanted with O, Si and Mg were used to evaluate matrix composition influences on ion yield. Useful ion yield and RSFs of different elements vary as composition changes. Different combinations of primary ion beam, cesium and oxygen, and polarity and type of secondary ion were investigated. Relative sensitivity factors were determined by the method described in Chapter 2.

A combination of different secondary ions was selected for analysis. A 10 keV Cs⁺ primary beam was used to analyze positive secondary ions of ²⁴Mg, ²⁴MgCs, ²⁹Si, ²⁹SiCs and ¹⁸O and negative secondary ions of ¹⁸O and ²⁹Si. Positive secondary ions of ²⁴Mg and ²⁹Si were analyzed with a 10 keV O₂⁺ primary beam. A normal incidence electron flood was used, when required, to compensate for sample charging. A 150 μm image field was used for all analyses. Single element and molecular ions containing the implant specie as well as the primary components were analyzed.

The instrument configurations used in the analyses are listed in Table 6. Individual analysis sessions occurred on separate days. The range in beam currents used for the analyses are listed. Where multiple raster dimensions, field aperture and contrast aperture sizes are listed in the table they correspond to the selections used at the lowest and highest beam current settings.

Table 6. Instrument configurations used in the SIMS analysis of (Al_xGa_{1-x})_{0.5}N_{0.5}.

Primary Beam	Secondary Ion	Beam Current (nA)	Raster Dimension (μm)	Field Aperture (μm)	Contrast Aperture (μm)
Cs ⁺	²⁴ MgCs ⁺	22 - 51	125	150, 400	150, 85
Cs ⁺	²⁹ SiCs ⁺	20 - 32	100, 125	150	150, 400
Cs ⁺	¹⁸ O ⁺ ¹⁸ ON ⁺	13	125, 100	150	150, 85
Cs ⁺	¹⁸ O ⁻ ¹⁸ ON ⁻	31 - 107	125, 100	150	150, 85
Cs ⁺	²⁹ Si ⁻	35 - 110	125, 175	150	150
O ₂ ⁺	²⁴ Mg ⁺	220 - 270	150	150	150
O ₂ ⁺	²⁹ Si ⁺ ²⁹ SiO ⁺	340 - 360	150	150	400

4.13 Research approach

The approach for this research was designed to evaluate appropriate methods of SIMS analysis in the $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material system. Collections of data on the secondary ion yield, of trace elements and matrix elements, as the Al fraction changes were used to determine RSFs of various elements sputtered from $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. From this data a relationship between secondary ion yield, calculated RSF, and Al fraction in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ has been determined.

CHAPTER 5. EXPERIMENTAL RESULTS AND DISCUSSION

5.1 Introduction

This chapter presents the results of the SIMS analysis of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material. Results of the correlation of secondary ion yield of the primary constituents to the RBS measured composition is presented. Sputter rates vary with Al content of the material. Sputter rates are also dependent on the selection of the primary beam. The RSF values calculated from the collection of SIMS analysis conditions described in Chapter 4 are presented. A discussion of the use of the RSFs and examples of applying the information to quantitative evaluation of material is presented in specific examples of SIMS depth profiles.

5.2 SIMS correlation with RBS

SIMS is not typically used as a technique for measuring primary component composition. The benefit of the calibration plot is it provides a method to evaluate primary composition changes in a SIMS analysis. This information can be useful when investigating multi-layer films where an underlying layer is not easily investigated by other techniques. The method also provides a means to address problems with composition that may occur in the epitaxial growth of the material. The ratios of the secondary ion counts, $\text{AlCs}^+/\text{GaCs}^+$, were calculated from the SIMS data and plotted versus RBS values of the Al composition as shown in Figure 13. With this calibration plot the composition of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$

material was obtained. This calibrated SIMS data can be used to measure changes in composition in multi-layer films. The collection of molecular secondary ions has utility to the characterization of trace element composition, described later in the chapter.

Figure 13. Calibration plot of RBS measured composition to SIMS AlCs⁺/GaCs⁺ ratio in (Al_xGa_{1-x})_{0.5}N_{0.5}.

5.3 Sputter rate with Cs⁺ and O₂⁺ primary beams

Figure 14 shows the volume of material sputtered by either a Cs⁺ or O₂⁺ primary beam, as a function of the Al fraction. For Al fractions up to 0.32 the sputter rate decreases linearly with Al fraction. Sputter rate at compositions greater than 0.32 appear to be independent of Al fraction. The Cs⁺ beam provides, because of its greater mass, a much greater sputter rate than the O₂⁺

beam. The Cs^+ beam is also more sensitive than is the O_2^+ beam to the Al fraction.

Figure 14. Dependence of volume ($\text{\AA}^3$) of material removed per second, as a function of beam current (Amp), beam type (Cs^+ , O_2^+), and secondary ion polarity (+/-) on Al content in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

5.4 Cs^+ RSFs of trace elements with positive secondary ions

The RSFs for the combinations of a Cs^+ primary beam with positive secondary ions of Mg, Si and O are shown, respectively, in Figures 15, 16 and 17. In the figures the GaCs, Ga, NCs and N lines indicate the RSFs determined using these positive matrix reference ions.

Figure 15. Cs⁺ beam RSFs of ²⁴Mg⁺ and ²⁴MgCs⁺ in (Al_xGa_{1-x})_{0.5}N_{0.5} using GaCs⁺, Ga⁺, NCs⁺, and N⁺ matrix references.

Figure 16. Cs⁺ beam RSFs of ²⁹Si⁺ and ²⁹SiCs⁺ in (Al_xGa_{1-x})_{0.5}N_{0.5} using GaCs⁺, Ga⁺, NCs⁺, and N⁺ matrix references.

Figure 17. Cs⁺ beam RSFs of ¹⁸O⁺, ¹⁸ON⁺, ¹⁸OCs⁺ using GaCs⁺, Ga⁺, NCs⁺, and N⁺ matrix references.

For a Cs⁺ primary beam with positive secondary ions the intensity of matrix counts falls in the sequence of GaCs⁺, Ga⁺, NCs⁺ and N⁺. The NCs⁺ and N⁺ intensities are much lower, and the N⁺ count more variable, than GaCs⁺ and Ga⁺. The low count rate of NCs⁺ and N⁺ can be limiting in a SIMS analysis when

smaller field and contrast apertures reduce secondary ion transmission. With a Cs^+ primary beam the comparisons of RSFs for all positive secondary ions display similar trends in terms of the matrix ion count. The RSFs with a GaCs^+ reference decrease with increasing Al composition. The RSFs with a N^+ reference increase with increasing Al composition in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. The RSFs with Ga^+ and NCs^+ reference generally have less dependence on the Al composition in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

5.5 Cs^+ RSFs of trace elements with negative secondary ions

The RSFs for the combinations of a Cs^+ primary beam with negative secondary ions of Si and O are shown, respectively, in Figures 18 and 19. In the figures the GaN, Ga and N_2 lines indicate the RSFs determined using these negative matrix reference ions.

Figure 18. Cs^+ beam RSFs of $^{29}\text{Si}^-$ using GaN^- , Ga^- and N_2^- matrix references.

Figure 19. Cs⁺ beam RSFs of ¹⁸O⁻ and ¹⁸ON⁻ using GaN⁻, Ga⁻ and N₂⁻ matrix references.

The RSFs for combinations of a Cs⁺ primary beam with ²⁹Si⁻ and ¹⁸O⁻ secondary ions show the intensity of matrix counts fall in the order of GaN⁻, Ga⁻ and N₂⁻. The Cs⁺ primary beam with O⁻ secondary ions provided the most useful combination for the detection of low concentration levels of O. The secondary ion yield, and count rate, is less for ON⁻. The low count rate for ON⁻ ions limit their use for the detection of low concentration levels of O. A discussion of the merits of the different analysis methods for the detection of O follows in section 5.7.

5.6 O_2^+ RSFs of trace elements

The RSFs for the combinations of a O_2^+ primary beam with positive secondary ions of Mg and Si are shown, respectively, in Figures 20 and 21. The figures show plots of the calculated RSFs versus the Al for the different combinations of primary beam and secondary ion.

Figure 20. O_2^+ beam RSFs of $^{24}Mg^+$ using Ga $^+$, GaN $^+$ and N $^+$ matrix references.

Figure 21. O_2^+ beam RSFs of $^{29}Si^+$ and $^{29}SiO^+$ using Ga^+ , GaN^+ and N^+ matrix references.

For a O_2^+ primary beam with positive secondary ions the intensity of matrix counts fall in the sequence of Ga^+ , GaN^+ and N^+ . The GaN^+ and N^+ intensities are much lower and more variable than Ga^+ . The low count rate of GaN^+ and N^+ can be limiting in a SIMS analysis when smaller field and contrast apertures reduce secondary ion transmission. With a O_2^+ primary beam the RSFs for all positive secondary ions decrease with increasing Al composition.

5.7 Matrix effects and comparison of SIMS analysis methods

The wide differences in matrix ion yields and the choice of different trace element ions that can be detected provide choices of several analysis methods. The selection of a particular analysis method will be directed by the material issue being investigated. Delineation of junction placement and investigation of

composition changes can be determined with positive secondary ion detection. The investigation of material purity requires the highest sensitivity to trace element ions. These investigations require, for O and Si, the use of a Cs primary beam and the detection of negative secondary ions. The greatest sensitivity to Mg comes with the use of an O₂ beam and detection of positive secondary ions.

The matrix ion count rates for the different matrix ions can differ by several orders of magnitude. The higher count rate matrix will produce many secondary ions. The typical protocol in SIMS analysis of a homogeneous material is to take a matrix ion count only once during the depth profile. In practice the high count rate matrix will yield an RSF that is less susceptible to slight variations in the count rate. In a homogeneous material with stable and uniform secondary ion yield the high count rate matrix is generally the preferred reference ion. Matrix ions typically require a separate detector from that used to monitor trace elements. Matrix ions are commonly detected with a Faraday cup detector and trace element ions with an electron multiplier. However, the tracking of both the matrix and the trace element is more difficult if two different detectors are required.

In a multi-layered material or a non-homogeneous layer it is often an advantage to take a matrix ion depth profile. The constant tracking of the matrix ion yields information on significant changes that may occur in different layers of the material. In this case a depth profile of the matrix yields useful information about the material. In a material with a matrix ion yield comparable to the trace

element yield both the matrix and trace element ions can be measured with the same detector.

Matrix ions with lower yields were present in analyses detecting positive and negative secondary ions from $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. With a Cs primary beam and positive secondary ion detection the NCs and N ions can be used to actively track matrix composition changes. Positive ions of GaN or N can be used to monitor the matrix composition when an O_2 beam is used to sputter the material. When a Cs beam is used and negative secondaries are detected Ga and N_2 ions can be used to monitor the matrix.

The use of a Cs^+ primary beam with Si^- and O^- and of a O_2^+ primary beam with Mg^+ secondary ions and a Ga matrix have been the standard method of analysis for Si, O and Mg in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material. The limited reports of RSFs in this material utilized these analysis methods. The RSFs calculated here for Mg^+ , O^- , and Si^- in AlGaN material using a Ga matrix generally match the trends previously reported in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.^{20, 26}

A comparison of the Mg concentration profiles in GaN with a Cs^+ and an O_2^+ beam is presented in Figure 22. Both beams provided useful count rates and similar detection limits for Mg. The O_2^+ beam did produce a higher yield and count rate for Mg ions. The O_2^+ beam has advantages for Mg detection when sputter rate, instrument configuration, or concentration levels in the material reduce the count rate.

Figure 22. Depth versus concentration profiles of Mg in GaN.

A comparison of the Si concentration profiles in GaN with a Cs⁺ and an O₂⁺ beam is presented in Figure 23. Some combinations of primary beam and secondary ion detection have high background count rates for the secondary ions. This is seen by the leveling of the profile at higher concentrations in the profiles of a Cs⁺ primary beam with Si⁺ and SiCs⁺ secondary ions and with the O₂⁺ beam with Si⁺ secondary ions. High background counts result when ionized components other than the ion of interest are present in the sputtered material. Any ionized component with the same mass to charge ratio as the ion of interest will add to the count rate.

Figure 23. Comparison of Si profile in GaN under different analysis conditions.

Potential background counts can come from molecular combinations of the primary beam, the matrix elements, or any trace elements present in the material. Examples of molecular ions at mass 162 that coincide with the mass of $^{29}\text{Si}^{133}\text{Cs}^+$ are: $(^{69}\text{Ga}_2^{12}\text{C}_2)^+$, $(^{133}\text{Cs}^{14}\text{N}^{15}\text{N})^+$, $(^{133}\text{Cs}^{16}\text{O}^{13}\text{C})^+$, and $(^{133}\text{Cs}^{17}\text{O}^{12}\text{C})^+$. Components that are uniformly distributed in the material contribute counts at a constant rate. In a material that has been implanted the constant portion of the count rate can be subtracted from the data. In Figure 24 the background counts have been subtracted for the profiles of a Cs^+ primary beam with Si^+ and SiCs^+ secondary ions and with the O_2^+ beam with Si^+ secondary ions. In the figure a profile of $^{29}\text{Si}^-$ taken with a Cs^+ primary beam is also shown for comparison. The background subtraction allows more of the implant distribution to be displayed. Background subtraction can be useful when delineating implant profiles into the

material. However, the best sensitivity to low levels of impurities, often required in device characterization, is obtained when the detection of the element is achieved without the subtraction of background counts.

Figure 24. The ^{29}Si implant profile in GaN with background counts subtracted.

A comparison of the O concentration profiles in GaN with a Cs^+ beam is presented in Figure 25. The O profile can be obtained with both positive and negative secondary ions. The negative O secondary ions have a higher count rate than the positive secondary ions. The higher count rate makes data collection easier and the detection to O more sensitive.

Figure 25. Comparison of ^{18}O implant profile in GaN under different analysis conditions.

A summary of the analysis methods is presented in Table 7. This table lists the detection limit obtained under the analysis conditions investigated for this work. The detection limits are those detected in the GaN sample. In samples containing Al the distributions to the end of the Al containing layer were similar to GaN. The GaN sample was the only sample thick enough to allow the complete tail of the implant distribution to be detected. Secondary ions with significant background interference had the background contribution subtracted.

Table 7. Detection limits of O, Mg and Si in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$.

Implant Species	Primary Beam	Ion Detected	Detection Limit (cm^{-3})	Background Subtraction
^{18}O	Cs^+	$^{18}\text{O}^-$	1E15	
	Cs^+	$^{18}\text{ON}^-$	1E17	Y
	Cs^+	$^{18}\text{O}^+$	1E17	
	Cs^+	$^{18}\text{ON}^+$	2E17	Y
	Cs^+	$^{18}\text{OCs}^+$	3E17	Y
^{24}Mg	Cs^+	$^{24}\text{Mg}^+$	5E16	
	Cs^+	$^{24}\text{MgCs}^+$	3E16	
	O_2^+	$^{24}\text{Mg}^+$	3E16	
^{29}Si	Cs^+	$^{29}\text{Si}^+$	1E17	
	Cs^+	$^{29}\text{SiCs}^+$	1E17	Y
	Cs^+	$^{29}\text{Si}^-$	3E16	
	O_2^+	$^{29}\text{SiO}^+$	5E16	Y
	O_2^+	$^{29}\text{Si}^+$	5E16	Y

5.8 Summary of results

The results demonstrate several combinations of primary beam and secondary ions which are useful in the SIMS analysis of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material. The use of alternative methods, described in Chapter 5 and reported here, provide enhancements to device characterization that are not available with the traditional approach to analysis. While secondary ion yield and instrumental count

rates are lower with alternative methods of analysis the count rates were not limiting. In Si and Mg analysis the use of alternate methods allows good sensitivity at concentrations relevant to device performance. The methods allow the delineation of p and n-type dopants under identical instrument configurations. This is a benefit in characterizing junction placement in device material. Another benefit is the methods provide an alternative that allows compositional changes to be measured. A significant benefit to device characterization comes with the improved depth resolution resulting from the analysis.

The traditional analysis methods do provide benefits for the detection of O, Mg and Si. The benefit is primarily in the higher secondary ion yield. The Cs^+ primary beam with Si^- secondary ions has a greater intensity of secondary ions than a Cs^+ primary beam with either Si^+ or SiCs^+ . The Cs^+ primary beam with O^- secondary ions has a greater intensity of secondary ions than a Cs^+ primary beam with either O^+ or ON^+ . In the detection of Mg secondary ions the O_2^+ beam with Mg^+ has a greater intensity than a Cs^+ beam with Mg^+ or MgCs^+ ions. The benefit of the traditional methods is that detection sensitivity is increased under conditions where secondary ion count rates are limited.

CHAPTER 6. CONCLUSIONS

The $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ system produces many types of secondary ions. The yield of secondary ions, both of trace elements and matrix elements, varies with the composition of the material. The magnitude of the change in ion yield with a change in composition varies depending on the type of secondary ion being evaluated. The relationship of the secondary ion yield for trace elements and matrix elements has been investigated.

Both single element and molecular ions are produced from sputtered material. The yield of secondary ions was evaluated when the material was sputtered with a Cs^+ and an O_2^+ ion beam. Several O, Mg and Si ion combinations have sufficient yield to be useful for the characterization of these elements in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. The investigation of ion yield provides a method for the quantitative evaluation of the trace element composition in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ material.

The positive secondary ions provide alternative methods of detecting dopant level concentrations of Si and Mg, n and p-type dopants, in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. In the implanted reference material Si and Mg concentrations of 1×10^{17} atoms/cm³ could be detected. This provides a method, in a single analysis, to characterize the n and p-type dopants using conditions that are less susceptible to variation when calculating the concentration profile. The detection of molecular MgCs^+ and SiCs^+ secondary ions also favor the best depth resolution. In the characterization of device material this improves tracking the concentration and

depth profile of n and p-type doping. An additional economic advantage in employing this method of analysis is it reduces the time and cost associated with characterization. The time and economic advantages can be significant.

With a correlation to RBS determination of composition SIMS data can be used to measure primary composition. The understanding of the dependence of sputter rates, by primary beam, on Al composition allows an accurate representation of trace element concentration or primary matrix composition with sputter depth. In the characterization of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ this allows composition and doping levels to be investigated.

The SIMS investigation of RSFs provides several alternatives for the successful determination of trace element concentration. The combination of a Cs^+ primary beam with Mg^+ , MgCs^+ , Si^+ and SiCs^+ secondary ions are very useful for the analysis of Mg and Si doping in device structures using $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. These methods complement the traditional approaches to SIMS measurements of trace element composition and improve ability to resolve junction placement and compositional changes that occur in epitaxial material deposited for the fabrication of optoelectronic devices.

APPENDIX A: Range statistics for O, Mg and Si in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$

The following tables list the SRIM96 output of the projected range, longitudinal straggle and lateral straggle of selected ion implants into $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. The tables list the results for implants of ^{18}O , ^{24}Mg , and ^{29}Si for five different compositions of $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$. The Al composition, x , was set at values of 0, 10, 20, 30 and 40. In this work the Al composition in the group III portion of the material (the $\text{Al}_x\text{Ga}_{1-x}$ portion) is noted in any chart or table as the atomic percent Al. This is consistent with the notation used by epitaxial material growers. These compositions correspond to an Al fraction in the total material of 0, 5, 10, 15 and 20 atomic percent.

Target = Ga(50 %) + N (50 %)
Density = 6.0877g/cm3 = 8.7571E+22 atoms/cm3

Ion = O (Mass = 17.99916)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	1.36E+02	2.94E+02	137 A	96 A	71 A
11.00 keV	1.42E+02	2.93E+02	149 A	104 A	77 A
12.00 keV	1.48E+02	2.91E+02	161 A	111 A	83 A
13.00 keV	1.54E+02	2.89E+02	173 A	118 A	88 A
14.00 keV	1.60E+02	2.87E+02	185 A	125 A	93 A
15.00 keV	1.65E+02	2.84E+02	197 A	133 A	99 A
16.00 keV	1.70E+02	2.82E+02	210 A	140 A	104 A
17.00 keV	1.75E+02	2.80E+02	222 A	147 A	109 A
18.00 keV	1.80E+02	2.77E+02	234 A	154 A	115 A
20.00 keV	1.89E+02	2.73E+02	259 A	167 A	125 A
22.00 keV	1.97E+02	2.68E+02	283 A	181 A	135 A
24.00 keV	2.06E+02	2.64E+02	308 A	194 A	146 A
26.00 keV	2.13E+02	2.59E+02	333 A	207 A	156 A
28.00 keV	2.21E+02	2.55E+02	358 A	220 A	166 A
30.00 keV	2.28E+02	2.51E+02	383 A	232 A	176 A
33.00 keV	2.39E+02	2.45E+02	421 A	251 A	190 A
36.00 keV	2.49E+02	2.39E+02	458 A	270 A	205 A
40.00 keV	2.61E+02	2.32E+02	509 A	293 A	224 A
45.00 keV	2.76E+02	2.23E+02	573 A	322 A	248 A
50.00 keV	2.90E+02	2.16E+02	637 A	351 A	271 A
55.00 keV	3.03E+02	2.09E+02	701 A	378 A	294 A
60.00 keV	3.16E+02	2.02E+02	765 A	405 A	317 A
65.00 keV	3.28E+02	1.96E+02	829 A	431 A	339 A
70.00 keV	3.40E+02	1.91E+02	893 A	456 A	361 A
80.00 keV	3.62E+02	1.80E+02	1021 A	504 A	403 A
90.00 keV	3.82E+02	1.71E+02	1149 A	550 A	445 A
100.00 keV	4.02E+02	1.64E+02	1277 A	594 A	485 A
110.00 keV	4.20E+02	1.58E+02	1404 A	635 A	523 A
120.00 keV	4.38E+02	1.50E+02	1530 A	675 A	561 A
130.00 keV	4.55E+02	1.44E+02	1656 A	713 A	598 A
140.00 keV	4.71E+02	1.39E+02	1780 A	749 A	633 A
150.00 keV	4.86E+02	1.34E+02	1904 A	784 A	668 A
160.00 keV	5.01E+02	1.30E+02	2027 A	817 A	702 A
170.00 keV	5.16E+02	1.25E+02	2149 A	849 A	734 A
180.00 keV	5.30E+02	1.22E+02	2270 A	880 A	766 A
200.00 keV	5.57E+02	1.15E+02	2510 A	938 A	828 A
220.00 keV	5.83E+02	1.09E+02	2746 A	992 A	886 A
240.00 keV	6.09E+02	1.03E+02	2977 A	1042 A	941 A
260.00 keV	6.35E+02	9.86E+01	3205 A	1089 A	994 A
280.00 keV	6.60E+02	9.43E+01	3428 A	1133 A	1045 A
300.00 keV	6.84E+02	9.04E+01	3648 A	1174 A	1093 A
330.00 keV	7.27E+02	8.53E+01	3968 A	1230 A	1161 A
360.00 keV	7.73E+02	8.08E+01	4276 A	1281 A	1224 A
400.00 keV	8.33E+02	7.56E+01	4669 A	1341 A	1301 A
450.00 keV	9.08E+02	7.00E+01	5134 A	1407 A	1388 A
500.00 keV	9.82E+02	6.53E+01	5572 A	1463 A	1465 A
550.00 keV	1.05E+03	6.13E+01	5986 A	1511 A	1534 A
600.00 keV	1.12E+03	5.78E+01	6380 A	1553 A	1596 A
650.00 keV	1.18E+03	5.47E+01	6758 A	1591 A	1653 A
700.00 keV	1.23E+03	5.20E+01	7123 A	1625 A	1705 A
800.00 keV	1.32E+03	4.74E+01	7822 A	1685 A	1798 A
900.00 keV	1.41E+03	4.38E+01	8483 A	1736 A	1879 A
1.00 MeV	1.49E+03	4.04E+01	9112 A	1779 A	1950 A

Target = Al (5 %) + Ga (44 %) + N (50 %)
Density = 5.8047g/cm3 = 8.7991E+22 atoms/cm3

Ion = O (Mass = 17.99916)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	1.36E+02	2.94E+02	140 A	96 A	71 A
11.00 keV	1.42E+02	2.92E+02	153 A	103 A	77 A
12.00 keV	1.48E+02	2.90E+02	165 A	111 A	82 A
13.00 keV	1.54E+02	2.88E+02	178 A	118 A	88 A
14.00 keV	1.60E+02	2.86E+02	190 A	125 A	93 A
15.00 keV	1.65E+02	2.83E+02	203 A	132 A	98 A
16.00 keV	1.70E+02	2.81E+02	215 A	139 A	104 A
17.00 keV	1.75E+02	2.78E+02	228 A	146 A	109 A
18.00 keV	1.79E+02	2.76E+02	240 A	153 A	114 A
20.00 keV	1.89E+02	2.71E+02	266 A	167 A	125 A
22.00 keV	1.97E+02	2.66E+02	291 A	180 A	135 A
24.00 keV	2.05E+02	2.61E+02	317 A	193 A	145 A
26.00 keV	2.13E+02	2.57E+02	342 A	207 A	155 A
28.00 keV	2.21E+02	2.52E+02	368 A	219 A	165 A
30.00 keV	2.28E+02	2.48E+02	394 A	232 A	175 A
33.00 keV	2.39E+02	2.42E+02	432 A	251 A	190 A
36.00 keV	2.49E+02	2.36E+02	471 A	269 A	205 A
40.00 keV	2.61E+02	2.29E+02	523 A	293 A	224 A
45.00 keV	2.76E+02	2.21E+02	588 A	322 A	248 A
50.00 keV	2.90E+02	2.13E+02	654 A	350 A	271 A
55.00 keV	3.03E+02	2.06E+02	720 A	377 A	294 A
60.00 keV	3.16E+02	1.99E+02	785 A	404 A	316 A
65.00 keV	3.28E+02	1.93E+02	851 A	430 A	339 A
70.00 keV	3.40E+02	1.87E+02	917 A	455 A	360 A
80.00 keV	3.62E+02	1.77E+02	1048 A	502 A	403 A
90.00 keV	3.82E+02	1.68E+02	1179 A	548 A	444 A
100.00 keV	4.02E+02	1.60E+02	1309 A	591 A	484 A
110.00 keV	4.20E+02	1.53E+02	1439 A	632 A	523 A
120.00 keV	4.38E+02	1.47E+02	1568 A	671 A	560 A
130.00 keV	4.55E+02	1.41E+02	1696 A	709 A	596 A
140.00 keV	4.71E+02	1.36E+02	1823 A	744 A	632 A
150.00 keV	4.86E+02	1.31E+02	1949 A	779 A	666 A
160.00 keV	5.01E+02	1.27E+02	2074 A	811 A	699 A
170.00 keV	5.16E+02	1.23E+02	2198 A	843 A	732 A
180.00 keV	5.30E+02	1.19E+02	2321 A	873 A	763 A
200.00 keV	5.57E+02	1.12E+02	2565 A	930 A	824 A
220.00 keV	5.83E+02	1.06E+02	2804 A	983 A	882 A
240.00 keV	6.09E+02	1.01E+02	3039 A	1032 A	937 A
260.00 keV	6.35E+02	9.62E+01	3270 A	1077 A	989 A
280.00 keV	6.60E+02	9.20E+01	3496 A	1120 A	1039 A
300.00 keV	6.85E+02	8.82E+01	3718 A	1160 A	1086 A
330.00 keV	7.28E+02	8.31E+01	4042 A	1215 A	1153 A
360.00 keV	7.73E+02	7.87E+01	4353 A	1264 A	1215 A
400.00 keV	8.33E+02	7.36E+01	4750 A	1323 A	1291 A
450.00 keV	9.07E+02	6.81E+01	5220 A	1386 A	1375 A
500.00 keV	9.81E+02	6.36E+01	5662 A	1440 A	1451 A
550.00 keV	1.05E+03	5.96E+01	6080 A	1487 A	1518 A
600.00 keV	1.12E+03	5.62E+01	6477 A	1528 A	1579 A
650.00 keV	1.18E+03	5.32E+01	6859 A	1564 A	1634 A
700.00 keV	1.22E+03	5.05E+01	7227 A	1597 A	1685 A
800.00 keV	1.32E+03	4.60E+01	7931 A	1655 A	1776 A
900.00 keV	1.41E+03	4.23E+01	8598 A	1704 A	1855 A
1.00 MeV	1.49E+03	3.93E+01	9233 A	1747 A	1925 A

Target = Al (10 %) + Ga (40 %) + N (50 %)
Density = 5.5216g/cm3 = 8.8458E+22 atoms/cm3

Ion = O (Mass = 17.99916)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	1.36E+02	2.94E+02	144 A	96 A	71 A
11.00 keV	1.42E+02	2.92E+02	157 A	103 A	76 A
12.00 keV	1.48E+02	2.89E+02	170 A	110 A	82 A
13.00 keV	1.54E+02	2.87E+02	183 A	118 A	87 A
14.00 keV	1.60E+02	2.85E+02	195 A	125 A	93 A
15.00 keV	1.65E+02	2.82E+02	208 A	132 A	98 A
16.00 keV	1.70E+02	2.79E+02	221 A	139 A	103 A
17.00 keV	1.75E+02	2.77E+02	234 A	146 A	109 A
18.00 keV	1.80E+02	2.74E+02	247 A	153 A	114 A
20.00 keV	1.89E+02	2.69E+02	273 A	166 A	124 A
22.00 keV	1.97E+02	2.64E+02	299 A	180 A	135 A
24.00 keV	2.06E+02	2.59E+02	325 A	193 A	145 A
26.00 keV	2.13E+02	2.55E+02	352 A	206 A	155 A
28.00 keV	2.21E+02	2.50E+02	378 A	219 A	165 A
30.00 keV	2.28E+02	2.46E+02	405 A	231 A	175 A
33.00 keV	2.39E+02	2.39E+02	444 A	250 A	190 A
36.00 keV	2.49E+02	2.34E+02	484 A	268 A	204 A
40.00 keV	2.61E+02	2.26E+02	538 A	292 A	224 A
45.00 keV	2.76E+02	2.18E+02	605 A	321 A	247 A
50.00 keV	2.90E+02	2.10E+02	672 A	349 A	270 A
55.00 keV	3.03E+02	2.03E+02	740 A	376 A	293 A
60.00 keV	3.16E+02	1.96E+02	807 A	402 A	316 A
65.00 keV	3.28E+02	1.90E+02	874 A	427 A	338 A
70.00 keV	3.40E+02	1.84E+02	942 A	452 A	359 A
80.00 keV	3.62E+02	1.74E+02	1076 A	500 A	402 A
90.00 keV	3.83E+02	1.65E+02	1210 A	544 A	443 A
100.00 keV	4.02E+02	1.57E+02	1343 A	587 A	482 A
110.00 keV	4.20E+02	1.50E+02	1476 A	628 A	521 A
120.00 keV	4.38E+02	1.44E+02	1607 A	666 A	558 A
130.00 keV	4.55E+02	1.38E+02	1738 A	703 A	594 A
140.00 keV	4.71E+02	1.33E+02	1867 A	738 A	629 A
150.00 keV	4.86E+02	1.28E+02	1996 A	771 A	663 A
160.00 keV	5.01E+02	1.24E+02	2123 A	803 A	696 A
170.00 keV	5.16E+02	1.20E+02	2249 A	834 A	728 A
180.00 keV	5.30E+02	1.16E+02	2375 A	864 A	759 A
200.00 keV	5.57E+02	1.09E+02	2622 A	919 A	819 A
220.00 keV	5.83E+02	1.04E+02	2865 A	971 A	876 A
240.00 keV	6.09E+02	9.84E+01	3104 A	1019 A	930 A
260.00 keV	6.35E+02	9.38E+01	3337 A	1063 A	981 A
280.00 keV	6.60E+02	8.97E+01	3567 A	1104 A	1030 A
300.00 keV	6.85E+02	8.59E+01	3791 A	1143 A	1077 A
330.00 keV	7.28E+02	8.10E+01	4118 A	1196 A	1142 A
360.00 keV	7.73E+02	7.66E+01	4433 A	1244 A	1203 A
400.00 keV	8.33E+02	7.16E+01	4834 A	1301 A	1277 A
450.00 keV	9.07E+02	6.63E+01	5308 A	1362 A	1360 A
500.00 keV	9.80E+02	6.18E+01	5754 A	1414 A	1433 A
550.00 keV	1.05E+03	5.80E+01	6176 A	1459 A	1499 A
600.00 keV	1.12E+03	5.46E+01	6577 A	1499 A	1558 A
650.00 keV	1.17E+03	5.17E+01	6961 A	1534 A	1612 A
700.00 keV	1.22E+03	4.91E+01	7332 A	1565 A	1662 A
800.00 keV	1.31E+03	4.47E+01	8042 A	1622 A	1750 A
900.00 keV	1.40E+03	4.11E+01	8714 A	1669 A	1828 A
1.00 MeV	1.48E+03	3.81E+01	9354 A	1710 A	1896 A

Target = Al (15 %) + Ga (34 %) + N (50 %)
Density = 5.2386g/cm3 = 8.8983E+22 atoms/cm3

Ion = O (Mass = 17.99916)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	1.36E+02	2.94E+02	148 A	95 A	70 A
11.00 keV	1.43E+02	2.91E+02	161 A	102 A	76 A
12.00 keV	1.49E+02	2.89E+02	174 A	110 A	81 A
13.00 keV	1.54E+02	2.86E+02	188 A	117 A	87 A
14.00 keV	1.60E+02	2.84E+02	201 A	124 A	92 A
15.00 keV	1.65E+02	2.81E+02	214 A	131 A	98 A
16.00 keV	1.70E+02	2.78E+02	227 A	138 A	103 A
17.00 keV	1.75E+02	2.76E+02	241 A	145 A	108 A
18.00 keV	1.80E+02	2.73E+02	254 A	152 A	113 A
20.00 keV	1.89E+02	2.68E+02	281 A	166 A	124 A
22.00 keV	1.97E+02	2.63E+02	308 A	179 A	134 A
24.00 keV	2.06E+02	2.57E+02	335 A	192 A	144 A
26.00 keV	2.14E+02	2.53E+02	362 A	205 A	154 A
28.00 keV	2.21E+02	2.48E+02	389 A	218 A	164 A
30.00 keV	2.28E+02	2.43E+02	416 A	230 A	174 A
33.00 keV	2.39E+02	2.37E+02	457 A	249 A	189 A
36.00 keV	2.49E+02	2.31E+02	498 A	267 A	203 A
40.00 keV	2.62E+02	2.23E+02	553 A	290 A	222 A
45.00 keV	2.76E+02	2.15E+02	622 A	319 A	246 A
50.00 keV	2.90E+02	2.07E+02	691 A	346 A	269 A
55.00 keV	3.04E+02	2.00E+02	761 A	373 A	292 A
60.00 keV	3.16E+02	1.93E+02	830 A	399 A	314 A
65.00 keV	3.29E+02	1.87E+02	899 A	424 A	336 A
70.00 keV	3.40E+02	1.81E+02	968 A	449 A	358 A
80.00 keV	3.62E+02	1.71E+02	1106 A	496 A	400 A
90.00 keV	3.83E+02	1.62E+02	1243 A	540 A	441 A
100.00 keV	4.02E+02	1.54E+02	1379 A	582 A	480 A
110.00 keV	4.21E+02	1.47E+02	1514 A	621 A	518 A
120.00 keV	4.38E+02	1.41E+02	1648 A	659 A	555 A
130.00 keV	4.55E+02	1.35E+02	1781 A	695 A	590 A
140.00 keV	4.71E+02	1.30E+02	1913 A	729 A	625 A
150.00 keV	4.87E+02	1.25E+02	2044 A	762 A	658 A
160.00 keV	5.02E+02	1.21E+02	2174 A	793 A	691 A
170.00 keV	5.16E+02	1.17E+02	2302 A	823 A	722 A
180.00 keV	5.30E+02	1.13E+02	2430 A	852 A	753 A
200.00 keV	5.57E+02	1.07E+02	2681 A	906 A	812 A
220.00 keV	5.83E+02	1.01E+02	2928 A	956 A	868 A
240.00 keV	6.10E+02	9.60E+01	3170 A	1002 A	921 A
260.00 keV	6.35E+02	9.14E+01	3407 A	1045 A	971 A
280.00 keV	6.61E+02	8.74E+01	3639 A	1085 A	1019 A
300.00 keV	6.86E+02	8.37E+01	3866 A	1123 A	1064 A
330.00 keV	7.30E+02	7.89E+01	4197 A	1174 A	1128 A
360.00 keV	7.74E+02	7.46E+01	4515 A	1220 A	1188 A
400.00 keV	8.34E+02	6.97E+01	4920 A	1275 A	1260 A
450.00 keV	9.08E+02	6.45E+01	5398 A	1333 A	1341 A
500.00 keV	9.81E+02	6.01E+01	5848 A	1384 A	1412 A
550.00 keV	1.05E+03	5.63E+01	6273 A	1427 A	1476 A
600.00 keV	1.12E+03	5.31E+01	6677 A	1465 A	1534 A
650.00 keV	1.17E+03	5.02E+01	7065 A	1498 A	1586 A
700.00 keV	1.22E+03	4.77E+01	7439 A	1529 A	1634 A
800.00 keV	1.31E+03	4.34E+01	8154 A	1583 A	1720 A
900.00 keV	1.40E+03	3.99E+01	8832 A	1628 A	1795 A
1.00 MeV	1.48E+03	3.69E+01	9477 A	1667 A	1861 A

Target = Al (20 %) + Ga (30 %) + N (50 %)
Density = 4.9555g/cm3 = 8.9573E+22 atoms/cm3

Ion = O (Mass = 17.99916)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	1.37E+02	2.94E+02	152 A	94 A	70 A
11.00 keV	1.43E+02	2.91E+02	166 A	102 A	75 A
12.00 keV	1.49E+02	2.89E+02	179 A	109 A	81 A
13.00 keV	1.54E+02	2.86E+02	193 A	116 A	86 A
14.00 keV	1.60E+02	2.83E+02	206 A	123 A	91 A
15.00 keV	1.65E+02	2.80E+02	220 A	130 A	97 A
16.00 keV	1.70E+02	2.77E+02	234 A	137 A	102 A
17.00 keV	1.75E+02	2.75E+02	248 A	144 A	107 A
18.00 keV	1.80E+02	2.72E+02	261 A	151 A	112 A
20.00 keV	1.89E+02	2.66E+02	289 A	164 A	123 A
22.00 keV	1.98E+02	2.61E+02	317 A	178 A	133 A
24.00 keV	2.06E+02	2.56E+02	344 A	191 A	143 A
26.00 keV	2.14E+02	2.51E+02	372 A	203 A	153 A
28.00 keV	2.22E+02	2.46E+02	400 A	216 A	163 A
30.00 keV	2.29E+02	2.41E+02	428 A	229 A	173 A
33.00 keV	2.39E+02	2.35E+02	471 A	247 A	187 A
36.00 keV	2.49E+02	2.29E+02	513 A	265 A	202 A
40.00 keV	2.62E+02	2.21E+02	569 A	288 A	221 A
45.00 keV	2.77E+02	2.12E+02	640 A	316 A	244 A
50.00 keV	2.91E+02	2.04E+02	711 A	343 A	267 A
55.00 keV	3.04E+02	1.97E+02	782 A	370 A	290 A
60.00 keV	3.17E+02	1.90E+02	853 A	395 A	312 A
65.00 keV	3.29E+02	1.84E+02	924 A	420 A	334 A
70.00 keV	3.41E+02	1.78E+02	995 A	444 A	355 A
80.00 keV	3.63E+02	1.68E+02	1136 A	490 A	397 A
90.00 keV	3.84E+02	1.59E+02	1277 A	533 A	437 A
100.00 keV	4.03E+02	1.51E+02	1416 A	574 A	476 A
110.00 keV	4.21E+02	1.44E+02	1554 A	613 A	513 A
120.00 keV	4.39E+02	1.38E+02	1691 A	650 A	550 A
130.00 keV	4.56E+02	1.33E+02	1827 A	685 A	585 A
140.00 keV	4.72E+02	1.27E+02	1961 A	718 A	619 A
150.00 keV	4.88E+02	1.23E+02	2095 A	750 A	652 A
160.00 keV	5.03E+02	1.18E+02	2227 A	780 A	684 A
170.00 keV	5.17E+02	1.14E+02	2358 A	809 A	715 A
180.00 keV	5.31E+02	1.11E+02	2487 A	837 A	745 A
200.00 keV	5.58E+02	1.04E+02	2742 A	890 A	802 A
220.00 keV	5.84E+02	9.86E+01	2993 A	938 A	857 A
240.00 keV	6.11E+02	9.36E+01	3238 A	983 A	909 A
260.00 keV	6.37E+02	8.91E+01	3478 A	1024 A	958 A
280.00 keV	6.62E+02	8.51E+01	3713 A	1063 A	1005 A
300.00 keV	6.88E+02	8.15E+01	3943 A	1099 A	1049 A
330.00 keV	7.31E+02	7.68E+01	4278 A	1148 A	1111 A
360.00 keV	7.75E+02	7.26E+01	4599 A	1192 A	1169 A
400.00 keV	8.35E+02	6.77E+01	5008 A	1244 A	1239 A
450.00 keV	9.09E+02	6.27E+01	5490 A	1300 A	1317 A
500.00 keV	9.81E+02	5.84E+01	5944 A	1348 A	1386 A
550.00 keV	1.05E+03	5.47E+01	6372 A	1390 A	1448 A
600.00 keV	1.12E+03	5.15E+01	6779 A	1426 A	1504 A
650.00 keV	1.17E+03	4.87E+01	7170 A	1458 A	1554 A
700.00 keV	1.22E+03	4.62E+01	7547 A	1487 A	1601 A
800.00 keV	1.31E+03	4.21E+01	8267 A	1538 A	1684 A
900.00 keV	1.39E+03	3.86E+01	8950 A	1582 A	1756 A
1.00 MeV	1.47E+03	3.58E+01	9599 A	1619 A	1820 A

Target = Ga(50 %) + N (50 %)
Density =6.0877g/cm3 = 8.7571E+22atoms/cm3

Ion = Mg (Mass = 23.985)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	9.28E+01	5.08E+02	104 A	72 A	53 A
11.00 keV	9.70E+01	5.10E+02	113 A	78 A	57 A
12.00 keV	1.01E+02	5.11E+02	122 A	83 A	61 A
13.00 keV	1.05E+02	5.11E+02	131 A	89 A	65 A
14.00 keV	1.09E+02	5.11E+02	139 A	94 A	68 A
15.00 keV	1.12E+02	5.11E+02	148 A	99 A	72 A
16.00 keV	1.16E+02	5.10E+02	157 A	105 A	76 A
17.00 keV	1.19E+02	5.09E+02	166 A	110 A	80 A
18.00 keV	1.22E+02	5.07E+02	174 A	115 A	84 A
20.00 keV	1.29E+02	5.04E+02	192 A	125 A	91 A
22.00 keV	1.34E+02	5.01E+02	210 A	136 A	99 A
24.00 keV	1.40E+02	4.97E+02	228 A	146 A	106 A
26.00 keV	1.45E+02	4.92E+02	246 A	156 A	114 A
28.00 keV	1.51E+02	4.88E+02	264 A	167 A	121 A
30.00 keV	1.56E+02	4.84E+02	282 A	177 A	128 A
33.00 keV	1.63E+02	4.77E+02	310 A	192 A	139 A
36.00 keV	1.69E+02	4.70E+02	338 A	207 A	150 A
40.00 keV	1.78E+02	4.61E+02	375 A	227 A	165 A
45.00 keV	1.88E+02	4.50E+02	422 A	252 A	183 A
50.00 keV	1.98E+02	4.40E+02	470 A	276 A	202 A
55.00 keV	2.07E+02	4.29E+02	519 A	301 A	220 A
60.00 keV	2.15E+02	4.20E+02	568 A	326 A	238 A
65.00 keV	2.24E+02	4.11E+02	618 A	350 A	257 A
70.00 keV	2.32E+02	4.02E+02	668 A	374 A	275 A
80.00 keV	2.47E+02	3.85E+02	770 A	421 A	312 A
90.00 keV	2.61E+02	3.71E+02	873 A	468 A	349 A
100.00 keV	2.74E+02	3.57E+02	978 A	514 A	386 A
110.00 keV	2.86E+02	3.45E+02	1084 A	560 A	423 A
120.00 keV	2.98E+02	3.33E+02	1192 A	605 A	459 A
130.00 keV	3.10E+02	3.22E+02	1300 A	649 A	496 A
140.00 keV	3.21E+02	3.13E+02	1409 A	693 A	532 A
150.00 keV	3.31E+02	3.04E+02	1519 A	735 A	569 A
160.00 keV	3.42E+02	2.95E+02	1629 A	777 A	605 A
170.00 keV	3.51E+02	2.87E+02	1740 A	818 A	640 A
180.00 keV	3.61E+02	2.80E+02	1851 A	859 A	676 A
200.00 keV	3.79E+02	2.66E+02	2075 A	938 A	747 A
220.00 keV	3.97E+02	2.54E+02	2300 A	1014 A	816 A
240.00 keV	4.13E+02	2.43E+02	2526 A	1088 A	885 A
260.00 keV	4.29E+02	2.33E+02	2752 A	1160 A	952 A
280.00 keV	4.44E+02	2.24E+02	2979 A	1229 A	1019 A
300.00 keV	4.61E+02	2.16E+02	3205 A	1296 A	1084 A
330.00 keV	4.85E+02	2.05E+02	3542 A	1392 A	1179 A
360.00 keV	5.09E+02	1.95E+02	3876 A	1482 A	1271 A
400.00 keV	5.41E+02	1.84E+02	4316 A	1596 A	1390 A
450.00 keV	5.91E+02	1.72E+02	4853 A	1725 A	1530 A
500.00 keV	6.45E+02	1.61E+02	5369 A	1841 A	1661 A
550.00 keV	7.00E+02	1.52E+02	5864 A	1944 A	1782 A
600.00 keV	7.56E+02	1.44E+02	6337 A	2036 A	1893 A
650.00 keV	8.14E+02	1.37E+02	6791 A	2119 A	1996 A
700.00 keV	8.72E+02	1.31E+02	7225 A	2193 A	2091 A
800.00 keV	9.88E+02	1.20E+02	8039 A	2321 A	2260 A
900.00 keV	1.10E+03	1.11E+02	8790 A	2426 A	2406 A
1.00 MeV	1.22E+03	1.03E+02	9487 A	2513 A	2532 A

Target = Al (5 %) + Ga (44 %) + N (50 %)

Density = 5.8047g/cm3 = 8.7991E+22 atoms/cm3

Ion = Mg (Mass = 23.985)

Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	9.28E+01	5.07E+02	107 A	72 A	53 A
11.00 keV	9.71E+01	5.09E+02	116 A	78 A	57 A
12.00 keV	1.01E+02	5.09E+02	125 A	83 A	61 A
13.00 keV	1.05E+02	5.10E+02	134 A	89 A	64 A
14.00 keV	1.09E+02	5.09E+02	143 A	94 A	68 A
15.00 keV	1.12E+02	5.09E+02	152 A	99 A	72 A
16.00 keV	1.16E+02	5.08E+02	161 A	104 A	76 A
17.00 keV	1.19E+02	5.08E+02	170 A	110 A	80 A
18.00 keV	1.22E+02	5.05E+02	179 A	115 A	84 A
20.00 keV	1.29E+02	5.01E+02	197 A	125 A	91 A
22.00 keV	1.34E+02	4.97E+02	216 A	136 A	99 A
24.00 keV	1.40E+02	4.93E+02	234 A	146 A	106 A
26.00 keV	1.45E+02	4.89E+02	253 A	156 A	113 A
28.00 keV	1.51E+02	4.84E+02	271 A	166 A	121 A
30.00 keV	1.56E+02	4.79E+02	290 A	177 A	128 A
33.00 keV	1.63E+02	4.72E+02	319 A	192 A	139 A
36.00 keV	1.70E+02	4.65E+02	347 A	207 A	150 A
40.00 keV	1.78E+02	4.56E+02	386 A	227 A	165 A
45.00 keV	1.88E+02	4.45E+02	435 A	252 A	183 A
50.00 keV	1.98E+02	4.34E+02	484 A	277 A	202 A
55.00 keV	2.07E+02	4.24E+02	534 A	301 A	220 A
60.00 keV	2.16E+02	4.14E+02	585 A	326 A	239 A
65.00 keV	2.24E+02	4.05E+02	636 A	350 A	257 A
70.00 keV	2.32E+02	3.96E+02	688 A	374 A	275 A
80.00 keV	2.47E+02	3.79E+02	792 A	422 A	313 A
90.00 keV	2.61E+02	3.64E+02	899 A	468 A	349 A
100.00 keV	2.74E+02	3.51E+02	1007 A	515 A	386 A
110.00 keV	2.87E+02	3.38E+02	1116 A	560 A	423 A
120.00 keV	2.98E+02	3.27E+02	1226 A	605 A	460 A
130.00 keV	3.10E+02	3.16E+02	1337 A	649 A	497 A
140.00 keV	3.21E+02	3.06E+02	1449 A	692 A	533 A
150.00 keV	3.31E+02	2.97E+02	1562 A	735 A	569 A
160.00 keV	3.42E+02	2.89E+02	1675 A	776 A	605 A
170.00 keV	3.52E+02	2.81E+02	1789 A	818 A	641 A
180.00 keV	3.61E+02	2.74E+02	1903 A	858 A	677 A
200.00 keV	3.79E+02	2.60E+02	2132 A	936 A	748 A
220.00 keV	3.97E+02	2.48E+02	2363 A	1012 A	817 A
240.00 keV	4.13E+02	2.37E+02	2594 A	1085 A	885 A
260.00 keV	4.29E+02	2.28E+02	2825 A	1156 A	953 A
280.00 keV	4.45E+02	2.19E+02	3056 A	1224 A	1019 A
300.00 keV	4.61E+02	2.11E+02	3287 A	1290 A	1083 A
330.00 keV	4.86E+02	2.00E+02	3631 A	1385 A	1178 A
360.00 keV	5.10E+02	1.91E+02	3971 A	1474 A	1270 A
400.00 keV	5.41E+02	1.79E+02	4420 A	1585 A	1387 A
450.00 keV	5.92E+02	1.67E+02	4965 A	1712 A	1526 A
500.00 keV	6.46E+02	1.57E+02	5489 A	1825 A	1655 A
550.00 keV	7.01E+02	1.48E+02	5991 A	1926 A	1775 A
600.00 keV	7.57E+02	1.40E+02	6471 A	2016 A	1885 A
650.00 keV	8.14E+02	1.33E+02	6930 A	2096 A	1986 A
700.00 keV	8.71E+02	1.27E+02	7369 A	2169 A	2080 A
800.00 keV	9.87E+02	1.16E+02	8194 A	2293 A	2246 A
900.00 keV	1.10E+03	1.08E+02	8953 A	2395 A	2389 A
1.00 MeV	1.22E+03	1.00E+02	9658 A	2480 A	2512 A

Target = Al (10 %) + Ga (40 %) + N (50 %)
Density = 5.5216g/cm3 = 8.8458E+22 atoms/cm3

Ion = Mg (Mass = 23.985)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	9.29E+01	5.07E+02	110 A	72 A	52 A
11.00 keV	9.72E+01	5.08E+02	119 A	77 A	56 A
12.00 keV	1.01E+02	5.08E+02	128 A	83 A	60 A
13.00 keV	1.05E+02	5.08E+02	138 A	88 A	64 A
14.00 keV	1.09E+02	5.08E+02	147 A	94 A	68 A
15.00 keV	1.12E+02	5.07E+02	156 A	99 A	72 A
16.00 keV	1.16E+02	5.05E+02	165 A	104 A	76 A
17.00 keV	1.19E+02	5.04E+02	175 A	109 A	79 A
18.00 keV	1.23E+02	5.02E+02	184 A	115 A	83 A
20.00 keV	1.29E+02	4.98E+02	203 A	125 A	91 A
22.00 keV	1.35E+02	4.94E+02	222 A	135 A	98 A
24.00 keV	1.40E+02	4.90E+02	241 A	146 A	106 A
26.00 keV	1.46E+02	4.85E+02	260 A	156 A	113 A
28.00 keV	1.51E+02	4.80E+02	279 A	166 A	120 A
30.00 keV	1.56E+02	4.75E+02	299 A	176 A	128 A
33.00 keV	1.63E+02	4.68E+02	328 A	192 A	139 A
36.00 keV	1.70E+02	4.61E+02	357 A	207 A	150 A
40.00 keV	1.78E+02	4.51E+02	397 A	227 A	165 A
45.00 keV	1.88E+02	4.40E+02	447 A	252 A	183 A
50.00 keV	1.98E+02	4.29E+02	498 A	276 A	201 A
55.00 keV	2.07E+02	4.18E+02	550 A	301 A	220 A
60.00 keV	2.16E+02	4.08E+02	602 A	325 A	238 A
65.00 keV	2.24E+02	3.99E+02	655 A	350 A	257 A
70.00 keV	2.32E+02	3.90E+02	708 A	374 A	275 A
80.00 keV	2.47E+02	3.73E+02	816 A	421 A	312 A
90.00 keV	2.61E+02	3.58E+02	926 A	468 A	349 A
100.00 keV	2.74E+02	3.45E+02	1037 A	514 A	386 A
110.00 keV	2.87E+02	3.32E+02	1149 A	559 A	423 A
120.00 keV	2.99E+02	3.21E+02	1262 A	604 A	460 A
130.00 keV	3.10E+02	3.10E+02	1376 A	648 A	496 A
140.00 keV	3.21E+02	3.00E+02	1491 A	691 A	533 A
150.00 keV	3.32E+02	2.91E+02	1607 A	733 A	569 A
160.00 keV	3.42E+02	2.83E+02	1723 A	774 A	605 A
170.00 keV	3.52E+02	2.75E+02	1840 A	815 A	641 A
180.00 keV	3.61E+02	2.68E+02	1957 A	855 A	676 A
200.00 keV	3.80E+02	2.54E+02	2192 A	932 A	747 A
220.00 keV	3.97E+02	2.43E+02	2428 A	1007 A	816 A
240.00 keV	4.14E+02	2.32E+02	2664 A	1080 A	884 A
260.00 keV	4.30E+02	2.22E+02	2901 A	1149 A	951 A
280.00 keV	4.45E+02	2.14E+02	3137 A	1217 A	1017 A
300.00 keV	4.62E+02	2.06E+02	3373 A	1282 A	1081 A
330.00 keV	4.86E+02	1.95E+02	3724 A	1374 A	1175 A
360.00 keV	5.10E+02	1.86E+02	4071 A	1462 A	1266 A
400.00 keV	5.42E+02	1.75E+02	4527 A	1571 A	1382 A
450.00 keV	5.93E+02	1.63E+02	5082 A	1695 A	1519 A
500.00 keV	6.47E+02	1.53E+02	5614 A	1805 A	1646 A
550.00 keV	7.02E+02	1.44E+02	6123 A	1903 A	1764 A
600.00 keV	7.57E+02	1.36E+02	6609 A	1991 A	1872 A
650.00 keV	8.14E+02	1.29E+02	7075 A	2069 A	1972 A
700.00 keV	8.72E+02	1.23E+02	7519 A	2139 A	2064 A
800.00 keV	9.87E+02	1.13E+02	8353 A	2259 A	2227 A
900.00 keV	1.10E+03	1.05E+02	9121 A	2358 A	2366 A
1.00 MeV	1.22E+03	9.73E+01	9833 A	2440 A	2487 A

Target = Al (15 %) + Ge (34 %) + N (50 %)
Density = 5.2386g/cm3 = 8.8983E+22 atoms/cm3

Ion = Mg (Mass = 23.985)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	9.30E+01	5.06E+02	113 A	72 A	52 A
11.00 keV	9.73E+01	5.07E+02	122 A	77 A	56 A
12.00 keV	1.01E+02	5.07E+02	132 A	82 A	60 A
13.00 keV	1.05E+02	5.07E+02	141 A	88 A	64 A
14.00 keV	1.09E+02	5.06E+02	151 A	93 A	68 A
15.00 keV	1.13E+02	5.05E+02	160 A	98 A	71 A
16.00 keV	1.16E+02	5.04E+02	170 A	104 A	75 A
17.00 keV	1.19E+02	5.02E+02	180 A	109 A	79 A
18.00 keV	1.23E+02	5.00E+02	189 A	114 A	83 A
20.00 keV	1.29E+02	4.96E+02	209 A	125 A	90 A
22.00 keV	1.35E+02	4.91E+02	228 A	135 A	98 A
24.00 keV	1.40E+02	4.87E+02	248 A	145 A	105 A
26.00 keV	1.46E+02	4.82E+02	267 A	155 A	112 A
28.00 keV	1.51E+02	4.77E+02	287 A	166 A	120 A
30.00 keV	1.56E+02	4.71E+02	307 A	176 A	127 A
33.00 keV	1.63E+02	4.64E+02	337 A	191 A	138 A
36.00 keV	1.70E+02	4.56E+02	368 A	206 A	149 A
40.00 keV	1.79E+02	4.47E+02	409 A	226 A	164 A
45.00 keV	1.89E+02	4.35E+02	461 A	251 A	182 A
50.00 keV	1.98E+02	4.23E+02	513 A	276 A	201 A
55.00 keV	2.07E+02	4.13E+02	567 A	300 A	219 A
60.00 keV	2.16E+02	4.03E+02	620 A	324 A	237 A
65.00 keV	2.24E+02	3.93E+02	675 A	349 A	256 A
70.00 keV	2.32E+02	3.84E+02	730 A	373 A	274 A
80.00 keV	2.47E+02	3.67E+02	841 A	420 A	311 A
90.00 keV	2.61E+02	3.52E+02	954 A	466 A	348 A
100.00 keV	2.75E+02	3.39E+02	1068 A	512 A	385 A
110.00 keV	2.87E+02	3.26E+02	1184 A	557 A	422 A
120.00 keV	2.99E+02	3.15E+02	1300 A	601 A	459 A
130.00 keV	3.11E+02	3.04E+02	1418 A	645 A	495 A
140.00 keV	3.22E+02	2.94E+02	1536 A	687 A	531 A
150.00 keV	3.32E+02	2.85E+02	1655 A	729 A	568 A
160.00 keV	3.43E+02	2.77E+02	1774 A	770 A	603 A
170.00 keV	3.52E+02	2.69E+02	1894 A	810 A	639 A
180.00 keV	3.62E+02	2.62E+02	2014 A	850 A	674 A
200.00 keV	3.80E+02	2.49E+02	2255 A	926 A	745 A
220.00 keV	3.98E+02	2.37E+02	2497 A	1000 A	813 A
240.00 keV	4.14E+02	2.27E+02	2739 A	1071 A	881 A
260.00 keV	4.30E+02	2.17E+02	2981 A	1140 A	947 A
280.00 keV	4.46E+02	2.09E+02	3222 A	1206 A	1012 A
300.00 keV	4.62E+02	2.01E+02	3463 A	1269 A	1076 A
330.00 keV	4.87E+02	1.90E+02	3821 A	1360 A	1169 A
360.00 keV	5.11E+02	1.81E+02	4175 A	1446 A	1258 A
400.00 keV	5.44E+02	1.70E+02	4639 A	1552 A	1373 A
450.00 keV	5.95E+02	1.58E+02	5203 A	1673 A	1508 A
500.00 keV	6.48E+02	1.49E+02	5743 A	1780 A	1633 A
550.00 keV	7.03E+02	1.40E+02	6260 A	1875 A	1748 A
600.00 keV	7.59E+02	1.32E+02	6753 A	1959 A	1854 A
650.00 keV	8.15E+02	1.26E+02	7224 A	2035 A	1952 A
700.00 keV	8.73E+02	1.20E+02	7674 A	2102 A	2042 A
800.00 keV	9.87E+02	1.10E+02	8518 A	2218 A	2201 A
900.00 keV	1.10E+03	1.01E+02	9294 A	2313 A	2338 A
1.00 MeV	1.21E+03	9.44E+01	1.00 um	2392 A	2456 A

Target = Al (20 %) + Ga (30 %) + N (50 %)
Density = 4.9555g/cm3 = 8.9573E+22 atoms/cm3

Ion = Mg (Mass = 23.985)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	9.33E+01	5.06E+02	116 A	71 A	52 A
11.00 keV	9.75E+01	5.07E+02	126 A	76 A	56 A
12.00 keV	1.02E+02	5.07E+02	135 A	82 A	59 A
13.00 keV	1.06E+02	5.06E+02	145 A	87 A	63 A
14.00 keV	1.09E+02	5.05E+02	155 A	92 A	67 A
15.00 keV	1.13E+02	5.04E+02	165 A	98 A	71 A
16.00 keV	1.16E+02	5.02E+02	175 A	103 A	75 A
17.00 keV	1.20E+02	5.00E+02	185 A	108 A	78 A
18.00 keV	1.23E+02	4.98E+02	195 A	113 A	82 A
20.00 keV	1.29E+02	4.94E+02	215 A	124 A	90 A
22.00 keV	1.35E+02	4.89E+02	235 A	134 A	97 A
24.00 keV	1.41E+02	4.84E+02	255 A	144 A	104 A
26.00 keV	1.46E+02	4.78E+02	275 A	154 A	112 A
28.00 keV	1.51E+02	4.73E+02	296 A	165 A	119 A
30.00 keV	1.56E+02	4.68E+02	316 A	175 A	126 A
33.00 keV	1.63E+02	4.60E+02	347 A	190 A	137 A
36.00 keV	1.70E+02	4.52E+02	379 A	205 A	148 A
40.00 keV	1.79E+02	4.42E+02	421 A	225 A	163 A
45.00 keV	1.89E+02	4.30E+02	475 A	249 A	181 A
50.00 keV	1.99E+02	4.19E+02	529 A	274 A	199 A
55.00 keV	2.08E+02	4.08E+02	584 A	298 A	218 A
60.00 keV	2.17E+02	3.97E+02	640 A	323 A	236 A
65.00 keV	2.25E+02	3.88E+02	696 A	347 A	254 A
70.00 keV	2.33E+02	3.79E+02	752 A	371 A	273 A
80.00 keV	2.48E+02	3.62E+02	867 A	417 A	310 A
90.00 keV	2.62E+02	3.46E+02	984 A	463 A	346 A
100.00 keV	2.75E+02	3.33E+02	1101 A	509 A	383 A
110.00 keV	2.88E+02	3.20E+02	1220 A	553 A	420 A
120.00 keV	3.00E+02	3.09E+02	1340 A	597 A	456 A
130.00 keV	3.11E+02	2.98E+02	1461 A	640 A	492 A
140.00 keV	3.22E+02	2.89E+02	1583 A	682 A	529 A
150.00 keV	3.33E+02	2.80E+02	1705 A	723 A	564 A
160.00 keV	3.43E+02	2.71E+02	1827 A	763 A	600 A
170.00 keV	3.53E+02	2.64E+02	1950 A	803 A	635 A
180.00 keV	3.63E+02	2.56E+02	2074 A	842 A	671 A
200.00 keV	3.81E+02	2.43E+02	2321 A	917 A	740 A
220.00 keV	3.99E+02	2.32E+02	2569 A	989 A	808 A
240.00 keV	4.15E+02	2.21E+02	2816 A	1059 A	875 A
260.00 keV	4.31E+02	2.12E+02	3064 A	1126 A	941 A
280.00 keV	4.47E+02	2.03E+02	3311 A	1191 A	1005 A
300.00 keV	4.63E+02	1.96E+02	3557 A	1253 A	1067 A
330.00 keV	4.88E+02	1.85E+02	3922 A	1341 A	1159 A
360.00 keV	5.12E+02	1.76E+02	4283 A	1424 A	1247 A
400.00 keV	5.46E+02	1.66E+02	4756 A	1528 A	1360 A
450.00 keV	5.97E+02	1.54E+02	5329 A	1645 A	1493 A
500.00 keV	6.50E+02	1.44E+02	5878 A	1748 A	1615 A
550.00 keV	7.05E+02	1.36E+02	6402 A	1839 A	1728 A
600.00 keV	7.60E+02	1.29E+02	6901 A	1921 A	1831 A
650.00 keV	8.17E+02	1.22E+02	7379 A	1993 A	1926 A
700.00 keV	8.74E+02	1.16E+02	7834 A	2058 A	2014 A
800.00 keV	9.88E+02	1.07E+02	8687 A	2169 A	2169 A
900.00 keV	1.10E+03	9.83E+01	9472 A	2260 A	2301 A
1.00 MeV	1.21E+03	9.15E+01	1.02 um	2335 A	2416 A

Target = Ga(50 %) + N (50 %)
Density = 8.0877g/cm3 = 8.7571E+22atoms/cm3

Ion = Si (Mass = 28.9765)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	1.13E+02	6.41E+02	92 A	60 A	44 A
11.00 keV	1.18E+02	6.45E+02	99 A	65 A	47 A
12.00 keV	1.23E+02	6.49E+02	107 A	69 A	50 A
13.00 keV	1.28E+02	6.52E+02	114 A	73 A	53 A
14.00 keV	1.32E+02	6.54E+02	121 A	77 A	56 A
15.00 keV	1.37E+02	6.55E+02	129 A	81 A	59 A
16.00 keV	1.41E+02	6.56E+02	136 A	86 A	62 A
17.00 keV	1.45E+02	6.56E+02	143 A	90 A	65 A
18.00 keV	1.49E+02	6.56E+02	151 A	94 A	68 A
20.00 keV	1.56E+02	6.55E+02	165 A	102 A	74 A
22.00 keV	1.63E+02	6.53E+02	180 A	110 A	79 A
24.00 keV	1.70E+02	6.50E+02	194 A	118 A	85 A
26.00 keV	1.77E+02	6.47E+02	209 A	126 A	91 A
28.00 keV	1.83E+02	6.44E+02	224 A	133 A	96 A
30.00 keV	1.89E+02	6.40E+02	238 A	141 A	102 A
33.00 keV	1.98E+02	6.34E+02	261 A	153 A	110 A
36.00 keV	2.06E+02	6.28E+02	283 A	164 A	119 A
40.00 keV	2.16E+02	6.19E+02	313 A	179 A	130 A
45.00 keV	2.29E+02	6.08E+02	351 A	198 A	143 A
50.00 keV	2.40E+02	5.96E+02	389 A	217 A	157 A
55.00 keV	2.51E+02	5.85E+02	428 A	236 A	170 A
60.00 keV	2.62E+02	5.75E+02	467 A	254 A	184 A
65.00 keV	2.72E+02	5.64E+02	506 A	273 A	197 A
70.00 keV	2.82E+02	5.54E+02	546 A	291 A	211 A
80.00 keV	3.00E+02	5.35E+02	626 A	327 A	238 A
90.00 keV	3.17E+02	5.17E+02	707 A	363 A	265 A
100.00 keV	3.33E+02	5.01E+02	789 A	398 A	292 A
110.00 keV	3.48E+02	4.85E+02	872 A	432 A	319 A
120.00 keV	3.63E+02	4.71E+02	956 A	466 A	346 A
130.00 keV	3.77E+02	4.58E+02	1041 A	500 A	372 A
140.00 keV	3.90E+02	4.45E+02	1126 A	533 A	399 A
150.00 keV	4.03E+02	4.34E+02	1211 A	565 A	426 A
160.00 keV	4.15E+02	4.23E+02	1298 A	597 A	452 A
170.00 keV	4.27E+02	4.12E+02	1384 A	629 A	478 A
180.00 keV	4.39E+02	4.03E+02	1471 A	660 A	505 A
200.00 keV	4.61E+02	3.85E+02	1646 A	721 A	557 A
220.00 keV	4.82E+02	3.68E+02	1822 A	780 A	608 A
240.00 keV	5.02E+02	3.54E+02	1998 A	837 A	659 A
260.00 keV	5.22E+02	3.41E+02	2175 A	892 A	710 A
280.00 keV	5.40E+02	3.28E+02	2352 A	946 A	759 A
300.00 keV	5.58E+02	3.17E+02	2530 A	998 A	808 A
330.00 keV	5.83E+02	3.02E+02	2796 A	1074 A	880 A
360.00 keV	6.09E+02	2.89E+02	3061 A	1146 A	951 A
400.00 keV	6.43E+02	2.73E+02	3413 A	1238 A	1042 A
450.00 keV	6.85E+02	2.55E+02	3848 A	1345 A	1152 A
500.00 keV	7.26E+02	2.40E+02	4276 A	1444 A	1257 A
550.00 keV	7.77E+02	2.27E+02	4695 A	1536 A	1357 A
600.00 keV	8.27E+02	2.16E+02	5102 A	1620 A	1452 A
650.00 keV	8.78E+02	2.06E+02	5498 A	1696 A	1542 A
700.00 keV	9.30E+02	1.97E+02	5882 A	1767 A	1627 A
800.00 keV	1.03E+03	1.81E+02	6616 A	1893 A	1782 A
900.00 keV	1.14E+03	1.68E+02	7307 A	2000 A	1920 A
1.00 MeV	1.25E+03	1.57E+02	7957 A	2091 A	2043 A

Target = Al (5 %) + Ga (44 %) + N (50 %)
Density = 5.8047g/cm3 = 8.7991E+22 atoms/cm3

Ion = Si (Mass = 28.9765)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	1.13E+02	6.39E+02	94 A	60 A	44 A
11.00 keV	1.18E+02	6.43E+02	102 A	64 A	47 A
12.00 keV	1.23E+02	6.46E+02	109 A	69 A	50 A
13.00 keV	1.28E+02	6.49E+02	117 A	73 A	53 A
14.00 keV	1.32E+02	6.50E+02	125 A	77 A	56 A
15.00 keV	1.37E+02	6.51E+02	132 A	81 A	59 A
16.00 keV	1.41E+02	6.52E+02	140 A	85 A	62 A
17.00 keV	1.45E+02	6.52E+02	147 A	89 A	65 A
18.00 keV	1.49E+02	6.52E+02	154 A	94 A	68 A
20.00 keV	1.56E+02	6.50E+02	169 A	102 A	74 A
22.00 keV	1.63E+02	6.48E+02	184 A	110 A	79 A
24.00 keV	1.70E+02	6.45E+02	200 A	117 A	85 A
26.00 keV	1.77E+02	6.42E+02	215 A	125 A	91 A
28.00 keV	1.83E+02	6.38E+02	230 A	133 A	96 A
30.00 keV	1.89E+02	6.34E+02	245 A	141 A	102 A
33.00 keV	1.98E+02	6.28E+02	268 A	153 A	110 A
36.00 keV	2.06E+02	6.21E+02	291 A	164 A	118 A
40.00 keV	2.17E+02	6.12E+02	322 A	179 A	129 A
45.00 keV	2.29E+02	6.00E+02	361 A	198 A	143 A
50.00 keV	2.40E+02	5.89E+02	400 A	217 A	157 A
55.00 keV	2.51E+02	5.78E+02	440 A	236 A	170 A
60.00 keV	2.62E+02	5.67E+02	480 A	254 A	184 A
65.00 keV	2.72E+02	5.56E+02	520 A	273 A	197 A
70.00 keV	2.82E+02	5.46E+02	561 A	291 A	211 A
80.00 keV	3.00E+02	5.27E+02	643 A	327 A	238 A
90.00 keV	3.17E+02	5.09E+02	727 A	362 A	265 A
100.00 keV	3.33E+02	4.92E+02	811 A	398 A	292 A
110.00 keV	3.48E+02	4.77E+02	897 A	432 A	319 A
120.00 keV	3.63E+02	4.62E+02	983 A	466 A	346 A
130.00 keV	3.77E+02	4.49E+02	1069 A	499 A	373 A
140.00 keV	3.90E+02	4.37E+02	1157 A	532 A	399 A
150.00 keV	4.03E+02	4.25E+02	1245 A	565 A	426 A
160.00 keV	4.15E+02	4.14E+02	1333 A	597 A	452 A
170.00 keV	4.27E+02	4.04E+02	1422 A	628 A	479 A
180.00 keV	4.39E+02	3.94E+02	1511 A	659 A	505 A
200.00 keV	4.61E+02	3.76E+02	1690 A	719 A	557 A
220.00 keV	4.82E+02	3.60E+02	1870 A	778 A	609 A
240.00 keV	5.03E+02	3.46E+02	2051 A	834 A	659 A
260.00 keV	5.22E+02	3.33E+02	2232 A	889 A	710 A
280.00 keV	5.40E+02	3.21E+02	2413 A	943 A	759 A
300.00 keV	5.58E+02	3.10E+02	2594 A	994 A	808 A
330.00 keV	5.83E+02	2.95E+02	2865 A	1069 A	880 A
360.00 keV	6.09E+02	2.81E+02	3136 A	1140 A	950 A
400.00 keV	6.43E+02	2.66E+02	3494 A	1230 A	1040 A
450.00 keV	6.85E+02	2.49E+02	3937 A	1336 A	1149 A
500.00 keV	7.27E+02	2.34E+02	4372 A	1433 A	1254 A
550.00 keV	7.77E+02	2.21E+02	4798 A	1523 A	1353 A
600.00 keV	8.28E+02	2.10E+02	5211 A	1605 A	1446 A
650.00 keV	8.79E+02	2.00E+02	5612 A	1680 A	1535 A
700.00 keV	9.30E+02	1.91E+02	6001 A	1749 A	1618 A
800.00 keV	1.03E+03	1.76E+02	6745 A	1871 A	1771 A
900.00 keV	1.14E+03	1.63E+02	7444 A	1975 A	1907 A
1.00 MeV	1.25E+03	1.52E+02	8101 A	2064 A	2028 A

Target = Al (10 %) + Ga (40 %) + N (50 %)
Density = 5.5216g/cm3 = 8.8458E+22 atoms/cm3

Ion = Si (Mass = 28.9765)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Straggling	Lateral Straggling
10.00 keV	1.13E+02	6.37E+02	97 A	60 A	44 A
11.00 keV	1.18E+02	6.41E+02	105 A	64 A	47 A
12.00 keV	1.23E+02	6.44E+02	112 A	68 A	50 A
13.00 keV	1.28E+02	6.46E+02	120 A	73 A	53 A
14.00 keV	1.32E+02	6.47E+02	128 A	77 A	56 A
15.00 keV	1.37E+02	6.48E+02	136 A	81 A	59 A
16.00 keV	1.41E+02	6.49E+02	143 A	85 A	62 A
17.00 keV	1.45E+02	6.48E+02	151 A	89 A	65 A
18.00 keV	1.49E+02	6.48E+02	159 A	93 A	68 A
20.00 keV	1.56E+02	6.46E+02	174 A	101 A	73 A
22.00 keV	1.64E+02	6.44E+02	189 A	109 A	79 A
24.00 keV	1.70E+02	6.40E+02	205 A	117 A	85 A
26.00 keV	1.77E+02	6.37E+02	220 A	125 A	90 A
28.00 keV	1.83E+02	6.33E+02	236 A	133 A	96 A
30.00 keV	1.89E+02	6.28E+02	252 A	141 A	102 A
33.00 keV	1.98E+02	6.22E+02	275 A	152 A	110 A
36.00 keV	2.06E+02	6.15E+02	299 A	164 A	118 A
40.00 keV	2.17E+02	6.05E+02	331 A	179 A	129 A
45.00 keV	2.29E+02	5.93E+02	371 A	198 A	143 A
50.00 keV	2.41E+02	5.81E+02	411 A	217 A	156 A
55.00 keV	2.52E+02	5.70E+02	452 A	235 A	170 A
60.00 keV	2.62E+02	5.59E+02	494 A	254 A	184 A
65.00 keV	2.72E+02	5.48E+02	535 A	272 A	197 A
70.00 keV	2.82E+02	5.38E+02	577 A	291 A	211 A
80.00 keV	3.00E+02	5.18E+02	662 A	326 A	238 A
90.00 keV	3.17E+02	5.00E+02	748 A	362 A	265 A
100.00 keV	3.33E+02	4.83E+02	834 A	397 A	292 A
110.00 keV	3.48E+02	4.68E+02	922 A	431 A	319 A
120.00 keV	3.63E+02	4.54E+02	1011 A	465 A	345 A
130.00 keV	3.77E+02	4.40E+02	1100 A	498 A	372 A
140.00 keV	3.90E+02	4.28E+02	1189 A	531 A	399 A
150.00 keV	4.03E+02	4.16E+02	1280 A	563 A	425 A
160.00 keV	4.16E+02	4.05E+02	1370 A	595 A	452 A
170.00 keV	4.28E+02	3.95E+02	1461 A	626 A	478 A
180.00 keV	4.39E+02	3.86E+02	1553 A	657 A	504 A
200.00 keV	4.62E+02	3.68E+02	1736 A	716 A	556 A
220.00 keV	4.83E+02	3.52E+02	1921 A	774 A	608 A
240.00 keV	5.03E+02	3.38E+02	2105 A	830 A	658 A
260.00 keV	5.22E+02	3.25E+02	2290 A	884 A	708 A
280.00 keV	5.41E+02	3.13E+02	2476 A	937 A	757 A
300.00 keV	5.58E+02	3.02E+02	2661 A	988 A	806 A
330.00 keV	5.83E+02	2.87E+02	2938 A	1061 A	877 A
360.00 keV	6.10E+02	2.74E+02	3214 A	1132 A	946 A
400.00 keV	6.44E+02	2.59E+02	3579 A	1220 A	1036 A
450.00 keV	6.85E+02	2.42E+02	4029 A	1323 A	1144 A
500.00 keV	7.28E+02	2.28E+02	4472 A	1418 A	1247 A
550.00 keV	7.78E+02	2.15E+02	4904 A	1506 A	1345 A
600.00 keV	8.28E+02	2.04E+02	5324 A	1586 A	1437 A
650.00 keV	8.79E+02	1.95E+02	5731 A	1659 A	1524 A
700.00 keV	9.30E+02	1.86E+02	6125 A	1726 A	1606 A
800.00 keV	1.03E+03	1.71E+02	6878 A	1845 A	1756 A
900.00 keV	1.14E+03	1.58E+02	7585 A	1946 A	1890 A
1.00 MeV	1.24E+03	1.48E+02	8250 A	2032 A	2008 A

Target = Al(15 %) + Ga (34 %) + N (50 %)
Density = 5.2386g/cm3 = 8.8983E+22 atoms/cm3

Ion = Si (Mass = 28.9765)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	1.13E+02	6.35E+02	99 A	59 A	43 A
11.00 keV	1.18E+02	6.39E+02	107 A	64 A	46 A
12.00 keV	1.23E+02	6.42E+02	115 A	68 A	49 A
13.00 keV	1.28E+02	6.44E+02	123 A	72 A	53 A
14.00 keV	1.32E+02	6.45E+02	131 A	76 A	55 A
15.00 keV	1.37E+02	6.45E+02	139 A	81 A	58 A
16.00 keV	1.41E+02	6.45E+02	147 A	85 A	61 A
17.00 keV	1.45E+02	6.45E+02	155 A	89 A	64 A
18.00 keV	1.49E+02	6.44E+02	163 A	93 A	67 A
20.00 keV	1.57E+02	6.42E+02	179 A	101 A	73 A
22.00 keV	1.64E+02	6.39E+02	195 A	109 A	79 A
24.00 keV	1.71E+02	6.36E+02	211 A	117 A	84 A
26.00 keV	1.77E+02	6.32E+02	227 A	124 A	90 A
28.00 keV	1.83E+02	6.27E+02	243 A	132 A	95 A
30.00 keV	1.89E+02	6.23E+02	259 A	140 A	101 A
33.00 keV	1.98E+02	6.16E+02	283 A	152 A	109 A
36.00 keV	2.06E+02	6.08E+02	307 A	163 A	118 A
40.00 keV	2.17E+02	5.99E+02	340 A	178 A	129 A
45.00 keV	2.29E+02	5.86E+02	382 A	197 A	142 A
50.00 keV	2.41E+02	5.74E+02	423 A	216 A	156 A
55.00 keV	2.52E+02	5.62E+02	465 A	234 A	169 A
60.00 keV	2.62E+02	5.51E+02	508 A	253 A	183 A
65.00 keV	2.72E+02	5.40E+02	551 A	271 A	196 A
70.00 keV	2.82E+02	5.30E+02	594 A	289 A	210 A
80.00 keV	3.00E+02	5.10E+02	681 A	325 A	237 A
90.00 keV	3.18E+02	4.92E+02	769 A	360 A	264 A
100.00 keV	3.34E+02	4.75E+02	859 A	395 A	291 A
110.00 keV	3.49E+02	4.60E+02	949 A	429 A	318 A
120.00 keV	3.63E+02	4.45E+02	1040 A	463 A	344 A
130.00 keV	3.77E+02	4.32E+02	1131 A	496 A	371 A
140.00 keV	3.91E+02	4.19E+02	1224 A	528 A	397 A
150.00 keV	4.04E+02	4.08E+02	1316 A	560 A	424 A
160.00 keV	4.16E+02	3.97E+02	1409 A	591 A	450 A
170.00 keV	4.28E+02	3.87E+02	1503 A	622 A	476 A
180.00 keV	4.40E+02	3.77E+02	1596 A	652 A	503 A
200.00 keV	4.62E+02	3.60E+02	1785 A	711 A	554 A
220.00 keV	4.83E+02	3.44E+02	1973 A	768 A	605 A
240.00 keV	5.03E+02	3.30E+02	2163 A	824 A	656 A
260.00 keV	5.23E+02	3.17E+02	2352 A	877 A	705 A
280.00 keV	5.41E+02	3.05E+02	2541 A	929 A	754 A
300.00 keV	5.59E+02	2.95E+02	2730 A	979 A	802 A
330.00 keV	5.84E+02	2.80E+02	3013 A	1051 A	872 A
360.00 keV	6.10E+02	2.67E+02	3295 A	1119 A	941 A
400.00 keV	6.45E+02	2.52E+02	3667 A	1206 A	1030 A
450.00 keV	6.86E+02	2.36E+02	4126 A	1307 A	1136 A
500.00 keV	7.29E+02	2.22E+02	4576 A	1400 A	1237 A
550.00 keV	7.79E+02	2.09E+02	5015 A	1485 A	1333 A
600.00 keV	8.30E+02	1.99E+02	5440 A	1562 A	1424 A
650.00 keV	8.80E+02	1.89E+02	5853 A	1633 A	1509 A
700.00 keV	9.31E+02	1.81E+02	6253 A	1698 A	1590 A
800.00 keV	1.03E+03	1.66E+02	7015 A	1813 A	1737 A
900.00 keV	1.14E+03	1.54E+02	7731 A	1910 A	1867 A
1.00 MeV	1.24E+03	1.43E+02	8403 A	1993 A	1983 A

Target = Al (20 %) + Ga (30 %) + N (50 %)
Density = 4.9555g/cm3 = 8.9573E+22 atoms/cm3

Ion = Si (Mass = 28.9765)
Stopping Units = keV/ micron

Ion Energy	dE/dx Elec.	dE/dx Nuclear	Projected Range	Longitudinal Stopping	Lateral Stopping
10.00 keV	1.13E+02	6.34E+02	102 A	59 A	43 A
11.00 keV	1.18E+02	6.38E+02	110 A	63 A	46 A
12.00 keV	1.23E+02	6.40E+02	118 A	67 A	49 A
13.00 keV	1.28E+02	6.42E+02	127 A	72 A	52 A
14.00 keV	1.33E+02	6.43E+02	135 A	76 A	55 A
15.00 keV	1.37E+02	6.43E+02	143 A	80 A	58 A
16.00 keV	1.41E+02	6.43E+02	151 A	84 A	61 A
17.00 keV	1.45E+02	6.42E+02	159 A	88 A	64 A
18.00 keV	1.49E+02	6.41E+02	167 A	92 A	67 A
20.00 keV	1.57E+02	6.39E+02	184 A	100 A	72 A
22.00 keV	1.64E+02	6.35E+02	200 A	108 A	78 A
24.00 keV	1.71E+02	6.32E+02	217 A	116 A	84 A
26.00 keV	1.77E+02	6.27E+02	233 A	124 A	89 A
28.00 keV	1.84E+02	6.23E+02	250 A	131 A	95 A
30.00 keV	1.90E+02	6.18E+02	266 A	139 A	100 A
33.00 keV	1.99E+02	6.10E+02	291 A	151 A	109 A
36.00 keV	2.07E+02	6.03E+02	316 A	162 A	117 A
40.00 keV	2.17E+02	5.92E+02	350 A	177 A	128 A
45.00 keV	2.30E+02	5.80E+02	393 A	196 A	141 A
50.00 keV	2.41E+02	5.67E+02	436 A	214 A	155 A
55.00 keV	2.52E+02	5.55E+02	479 A	233 A	168 A
60.00 keV	2.63E+02	5.44E+02	523 A	251 A	182 A
65.00 keV	2.73E+02	5.33E+02	567 A	269 A	195 A
70.00 keV	2.83E+02	5.22E+02	611 A	287 A	208 A
80.00 keV	3.01E+02	5.02E+02	701 A	323 A	235 A
90.00 keV	3.18E+02	4.84E+02	792 A	358 A	262 A
100.00 keV	3.34E+02	4.67E+02	884 A	392 A	289 A
110.00 keV	3.50E+02	4.51E+02	977 A	426 A	316 A
120.00 keV	3.64E+02	4.37E+02	1071 A	459 A	342 A
130.00 keV	3.78E+02	4.24E+02	1165 A	492 A	369 A
140.00 keV	3.92E+02	4.11E+02	1259 A	524 A	395 A
150.00 keV	4.04E+02	4.00E+02	1355 A	555 A	421 A
160.00 keV	4.17E+02	3.89E+02	1450 A	586 A	447 A
170.00 keV	4.29E+02	3.79E+02	1546 A	616 A	473 A
180.00 keV	4.41E+02	3.69E+02	1642 A	646 A	499 A
200.00 keV	4.63E+02	3.52E+02	1835 A	704 A	551 A
220.00 keV	4.84E+02	3.36E+02	2029 A	760 A	601 A
240.00 keV	5.04E+02	3.22E+02	2223 A	814 A	651 A
260.00 keV	5.24E+02	3.09E+02	2416 A	867 A	700 A
280.00 keV	5.42E+02	2.98E+02	2610 A	917 A	748 A
300.00 keV	5.60E+02	2.87E+02	2803 A	966 A	795 A
330.00 keV	5.85E+02	2.73E+02	3092 A	1036 A	865 A
360.00 keV	6.12E+02	2.60E+02	3379 A	1103 A	933 A
400.00 keV	6.46E+02	2.45E+02	3759 A	1188 A	1020 A
450.00 keV	6.87E+02	2.29E+02	4226 A	1285 A	1125 A
500.00 keV	7.32E+02	2.16E+02	4683 A	1375 A	1224 A
550.00 keV	7.81E+02	2.04E+02	5129 A	1458 A	1318 A
600.00 keV	8.31E+02	1.93E+02	5561 A	1532 A	1406 A
650.00 keV	8.82E+02	1.84E+02	5979 A	1601 A	1490 A
700.00 keV	9.33E+02	1.75E+02	6384 A	1663 A	1568 A
800.00 keV	1.03E+03	1.61E+02	7156 A	1774 A	1711 A
900.00 keV	1.14E+03	1.49E+02	7880 A	1867 A	1838 A
1.00 MeV	1.24E+03	1.39E+02	8559 A	1947 A	1950 A

APPENDIX B: RSF values for O, Mg and Si in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$

The table lists the equations of the linear fit to the RSF values as a function of the Al composition, x , in $(\text{Al}_x\text{Ga}_{1-x})_{0.5}\text{N}_{0.5}$ for the indicated primary beam, secondary ion and matrix ions. The correlation, R^2 value, is listed for each equation. The equations were obtained from the graphs of RSF values reported in Chapter 5, Figures 15 through 21.

Primary Beam	Secondary Ion	Matrix Ion	Linear fit to RSF data	R^2 value
Cs ⁺	²⁸ Si ⁺	GaCs ⁺	$-2e22x + 1e24$	0.7770
		Ga ⁺	$6e20x + 4e22$	0.6398
		NCs ⁺	$8e19x + 2e21$	0.7874
		N ⁺	$4e19x + 3e20$	0.8958
Cs ⁺	²⁸ SiCa ⁺	GaCs ⁺	$-1e22x + 9e23$	0.7113
		Ga ⁺	$1e21x + 4e22$	0.7578
		NCs ⁺	$1e20x + 1e21$	0.8414
		N ⁺	$5e19x + 2e20$	0.9042
Cs ⁺	²⁴ Mg ⁺	GaCs ⁺	$-5e21x + 2e23$	0.5960
		Ga ⁺	$-9e19x + 1e22$	0.2953
		NCs ⁺	$-3e18x + 6e20$	0.2106
		N ⁺	$2e18x + 9e19$	0.1825
Cs ⁺	²⁴ MgCa ⁺	GaCs ⁺	$-6e20x + 3e22$	0.8724
		Ga ⁺	$3e19x + 2e21$	0.1828
		NCs ⁺	$2e18x + 1e20$	0.3390
		N ⁺	$1e18x + 1e19$	0.4147
Cs ⁺	¹⁶ O ⁺	GaCs ⁺	$-3e23x + 1e25$	0.8280
		Ga ⁺	$1e21x + 6e23$	0.0144
		NCs ⁺	$-3e18x + 2e22$	0.0004
		N ⁺	$5e20x + 4e21$	0.8426
Cs ⁺	¹⁶ ON ⁺	GaCs ⁺	$-4e23x + 1e25$	0.8216
		Ga ⁺	$-2e21x + 8e23$	0.0178
		NCs ⁺	$-1e20x + 2e22$	0.2836
		N ⁺	$5e20x + 6e21$	0.8049

Cs ⁺	¹⁶ OCs ⁺	GaCs ⁺	-1e23x + 8e24	0.8497
		Ga ⁺	4e22x + 3e23	0.8804
		NCs ⁺	1e21x + 1e22	0.9684
		N ⁺	2e23x - 3e23	0.8857
Cs ⁺	²⁸ Si ⁻	Ga ⁺	-6e19x + 4e21	0.8708
		NCs ⁺	-2e18x + 1e20	0.5697
		N ⁺	2e17x + 3e17	0.9440
Cs ⁺	¹⁶ O ⁻	GaN ⁻	-3e18x + 3e20	0.3809
		Ga ⁻	-2e17x + 1e19	0.4030
		N ₂ ⁻	3e15x + 6e17	0.0079
Cs ⁺	¹⁸ ON ⁻	GaN ⁻	-6e18x + 3e22	0.0237
		Ga ⁻	-2e19x + 1e21	0.3686
		N ₂ ⁻	1e18x + 5e19	0.1470
O ₂ ⁺	²⁴ Mg ⁺	Ga ⁺	-3e20x + 4e22	0.0244
		GaN ⁺	-6e16x + 7e18	0.0398
		N ⁺	-9e16x + 6e18	0.0705
O ₂ ⁺	²⁸ Si ⁺	Ga ⁺	-4e22x + 2e24	0.5288
		GaN ⁺	-8e18x + 3e20	0.6877
		N ⁺	-7e18x + 3e20	0.5982
O ₂ ⁺	²⁸ SiO ⁺	Ga ⁺	-3e23 + 2e25	0.2766
		GaN ⁺	-5e19x + 3e21	0.4544
		N ⁺	-5e19x + 3e21	0.3503

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IMAGE EVALUATION TEST TARGET (QA-3)

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