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ULTRA HIGH TEMPERATURE RAPID THERMAL ANNEALING OF GaN

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ABSTRACT

All of the major acceptor (Mg, C, Be) and donor (Si, S, Se and Te) dopants have been implanted into GaN films grown on Al_2O_3 substrates. Annealing was performed at 1100-1500 °C, using AlN encapsulation. Activation percentages of ≥90% were obtained for Si^+ implantation annealed at 1400 °C, while higher temperatures led to a decrease in both carrier concentration and electron mobility. No measurable redistribution of any of the implanted dopants was observed at 1450 °C.

INTRODUCTION

The use of selective area implantation to create channel and/or contact regions is the basis of standard metal semiconductor field effect transistor (MESFET) technology in GaAs, and a similar process is desirable for GaN electronics.(1,2) Currently, most GaN-based electronic devices for high power, high frequency, high temperature applications are heterostructure FETs,(3-7) and for these devices implantation is also useful for increasing doping in the source/drain regions for improved contact resistance.(8)

Past work has shown that anneal temperatures of 1100-1150 °C produce reasonably good activation efficiencies for Si^+ or Mg^+ implant doses up to $\sim 10^{14}$ cm^{-2}.(8-11) However considerable lattice damage remains for higher dose implants annealed at these temperatures, producing a clear need for furnaces capable of 1400-1500 °C.(11-16) Conventional rapid thermal processing(RTP) systems generally reach a maximum temperature of ~1300°C. It is desirable that the time at elevated temperature be minimized because of the high vapor pressure of N_2 above GaN and the need to prevent dissociation of the surface.(17,18) Several different surface protection schemes have been reported for high temperature annealing of GaN, including provision of NH_3 ambients, high pressure N_2 ambients, AlN encapsulation or use of granulated InN or GaN powder within the reservoirs of a graphite susceptor in which the implanted sample is contained.(19,20) In terms of utility in a fabrication line, the AlN cap approach seems the most effective. The AlN can be deposited by reactive sputtering and selectively removed after the annealing processing by KOH etching.(21)

In this paper we describe the use of a novel high temperature RTP system for annealing of implanted GaN at temperatures up to 1500 °C. Extremely good activation

DISCLAIMER

efficiencies for Si^+ implants were obtained (≥90%), while little redistribution was observed for all the common donors(Si, S, Se, Te) and acceptor(Mg, C, Be) species.

EXPERIMENTAL

Epitaxial GaN layers 2-3 μm thick were grown on c-axis Al_2O_3 substrates at ~1040 °C by Metal Organic Chemical Vapor Deposition. The layers were nominally undoped ($n=1\text{-}8\times10^{16}$ cm^{-3}). Implantation of Si^+, S^+, Se^+, Te^+, Be^+, C^+ or Mg^+ ions was performed at 25 °C, at doses of $1\text{-}5\times10^{15}$ cm^{-2} and energies designed to place the projected range at 1200-1500 Å. The samples were deposited with 1000 Å of AlN by reactive sputtering.

Annealing was performed in an MHI Zapper RTP furnace, which employs molybdenum intermetallic composite heating elements. These are maintained at constant temperature with the sample inserted and removed via a motor-driven actuator to achieve high ramp-up and ramp-down rates. Annealing was performed at 1100-1500 °C for dwell times of 10 secs. Typical time-temperature profiles for 1400 and 1500 °C are shown in Figure 1. After annealing the AlN was removed by etching in 0.1 M KOH solution at 70 °C. The electrical properties of the Si^+ implanted samples were obtained from Van der Pauw geometry Hall measurements using HgIn contacts alloyed at 420°C for 3 mins. Redistribution of the implanted species was examined by performing Secondary Ion Mass Spectrometry (SIMS) using a Cameca system.

RESULTS AND DISCUSSION

Figure 2 shows an Arrhenius plot of sheet carrier concentration in Si^+ implanted material. In the AlN encapsulated samples activation occurs with an activation energy of

~5.2 eV before saturating at ~1400 °C. We interpret this activation energy as the average required to move the interstitial Si atom to a vacant substitutional site by short-range diffusion and to simultaneously remove compensating point defects so that the Si is electrically active. Note that at 1500 °C the sheet electron density decreases, and this was accompanied by a decrease in carrier mobility. This increase in compensation is consistent with Si beginning to occupy both Ga sites(where it is a donor), and N sites(where it is an acceptor). This is commonly observed with Si implantation in other III-V materials.(22) The peak n-type doping level we obtained is $\sim 5\times10^{20}$ cm^{-3}. This high carrier concentration enhances emission over the barrier on metal contacts deposited on the material. For example, for both W and WSi_x sputter deposited on Si-implanted material activated by annealing, we obtained specific contact resistances of $\sim 10^{-6}$ $\Omega\cdot$cm^2 after annealing in the range 600-900 °C. This combination is particularly effective for producing high quality, stable ohmic contacts on GaN, since there is no measurable reaction of the W or WSi_x with the semiconductor at 900 °C. This is superior to the more commonly employed Ti/Al and Ni/Au metallizations on GaN.

Si^+ implantation produces the best n-type doping of GaN, but there is also interest in the group VI donors: S, Se and Te. From preliminary measurements, we obtained $\leq$40% activation for these dopants under the same conditions that produced 90% activation with Si. There was basically no redistribution of any of the dopants to 1450 °C; given the resolution of the SIMS measurements, this indicates that the diffusivity for each of these elements at 1450 °C is $\leq 10^{-13}$ cm$^2\cdot$s^{-1}. These are clearly the lowest diffusivities of these elements in any compound semiconductor, and emphasize the stable nature of implanted GaN devices. Figure 3 shows the data for S^+ implants. In a similar fashion, the atomic profiles of Mg, C and Be were measured before and after annealing at 1450 °C, there was no detectable redistribution for Mg and C. Figure 4 shows the data for Mg^+ implants. Thus, the diffusivities of these acceptor species are also $\leq 10^{-13}\ cm^2 \cdot s^{-1}$ at 1450 °C. For Be, a slight amount of diffusion was observed at 900 °C (~300 Å at full-width-half-maximum), but no motion at higher temperatures. This is consistent with defect-assisted motion of the Be, which ceases once the implant damage is annealed.

SUMMARY AND CONCLUSIONS

The most common acceptor and donor dopants have been implanted into GaN, and annealed at 1100-1500 °C for dwell times of 10 secs at the peak temperatures. No measurable redistribution was observed for any of the implanted species at 1450 °C. AlN has proven to be an effective encapsulant at these high temperatures, and can be selectively removed in KOH solutions, there was no evidence of interdiffusion between the AlN and GaN. Annealing at 1400 °C produced the highest activation for implanted Si(~90%), while higher temperatures led to an increase in self compensation.

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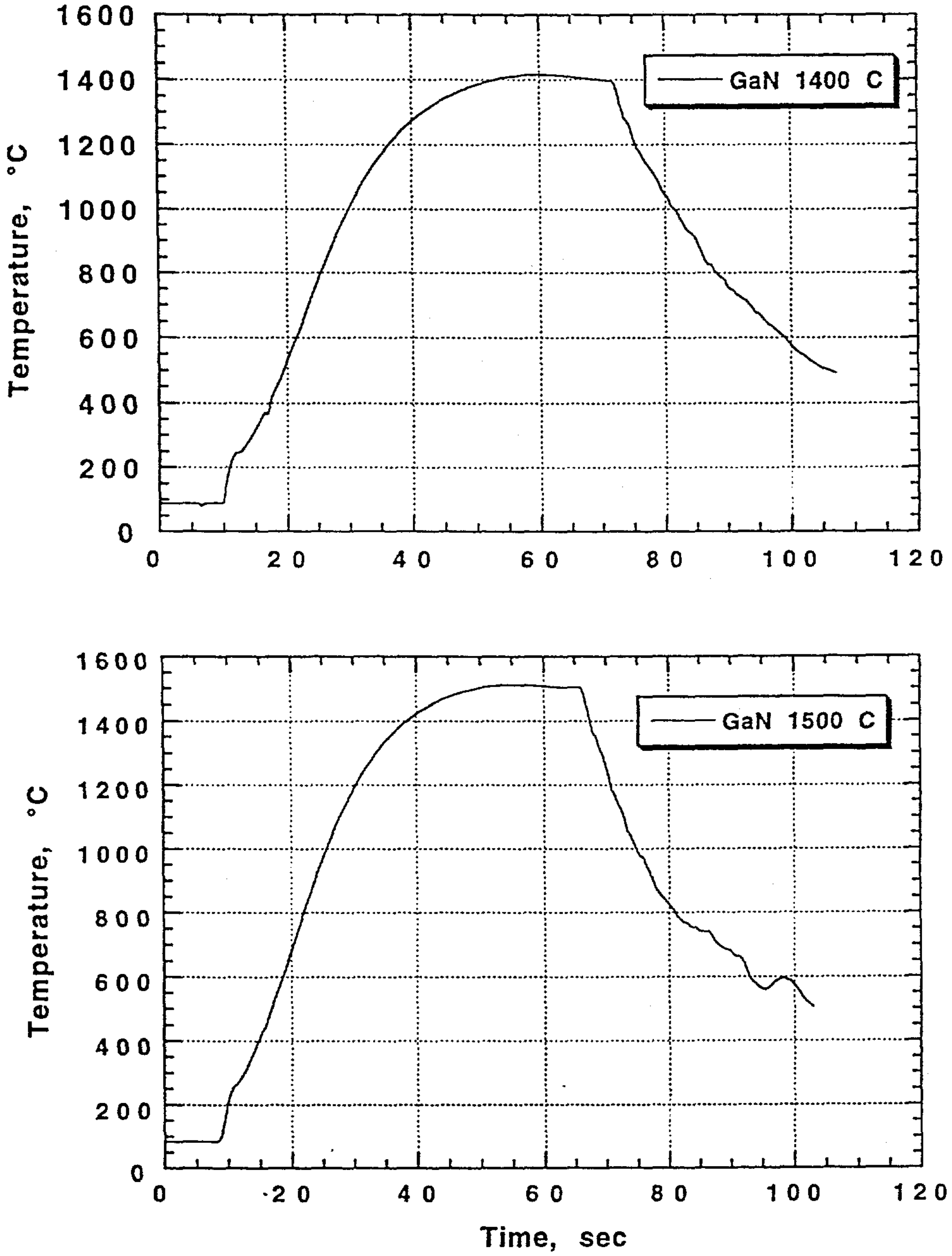
Figure Captions

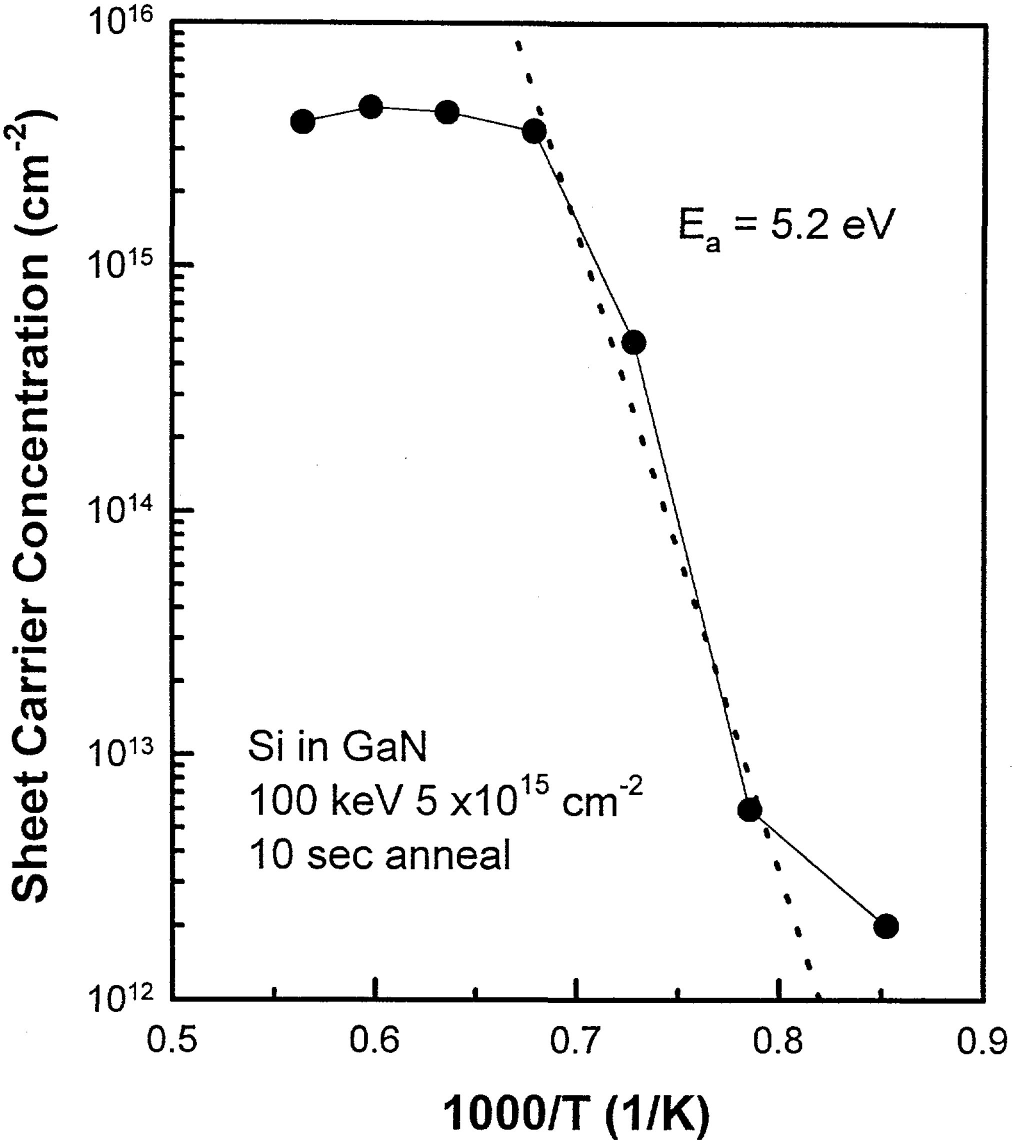
Figure 1. Time-temperature profiles for 10 sec anneals at both 1400 and 1500 °C.

Figure 2. Arrhenius plot of sheet electron concentration versus inverse anneal temperature for Si^+ implanted GaN..

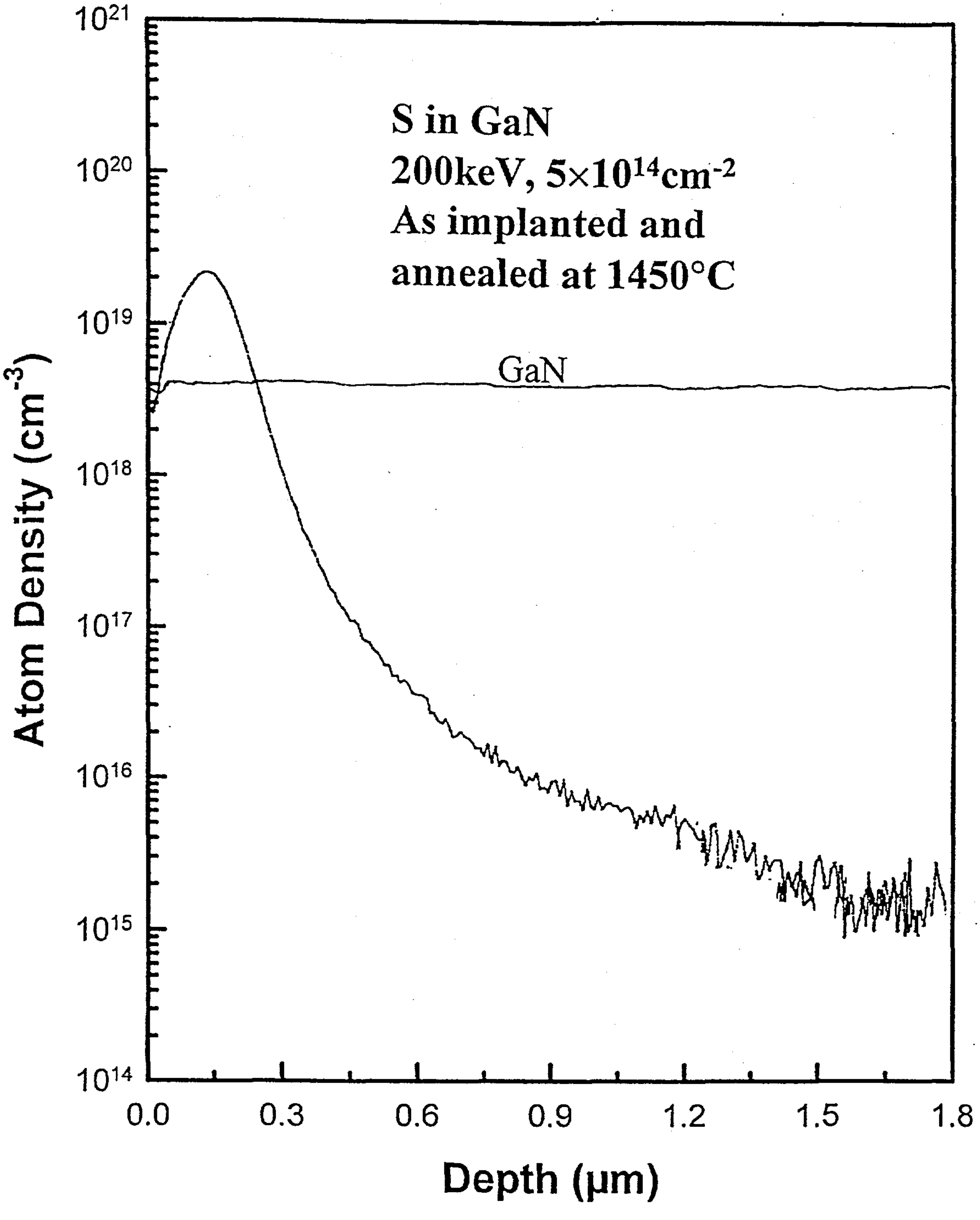
Figure 3. SIMS profiles of 200 keV S^+ implants in GaN before and after annealing at 1450 °C for 10 secs.

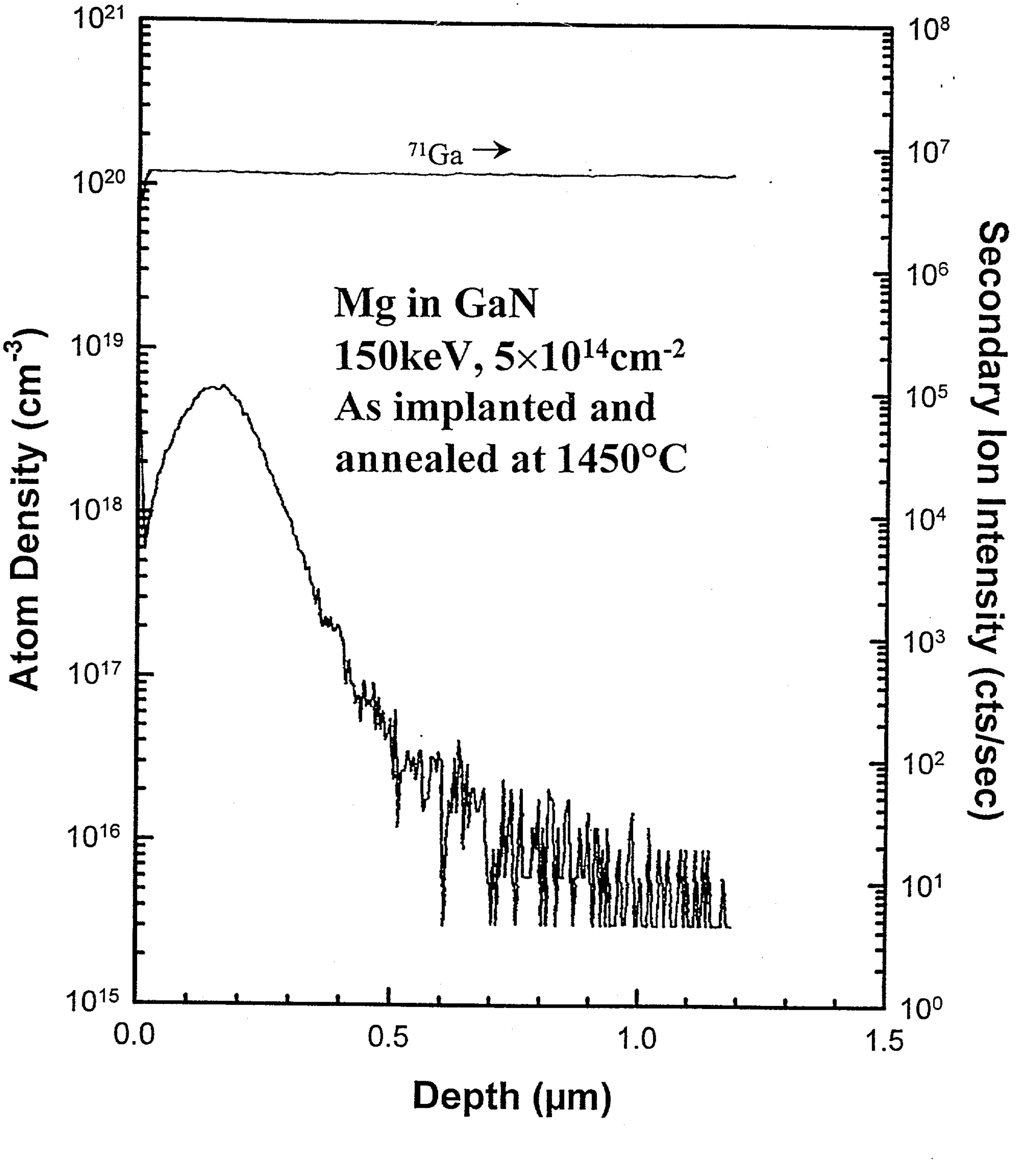
Figure 4. SIMS profiles of 150 keV Mg^+ implants in GaN before and after annealing at 1450 °C for 10 secs.


GaN 1400 C
Temperature, °C
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
GaN 1500 C
Temperature, °C
0
200
400
600
800
1000
1200
1400
1600
0
20
40
60
80
100
120
Time, sec



10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
Sheet Carrier Concentration (cm^{-2})
E_a = 5.2 eV
Si in GaN
100 keV 5 x10^{15} cm^{-2}
10 sec anneal
0.5
0.6
0.7
0.8
0.9
1000/T (1/K)


S in GaN
200keV, 5×10¹⁴cm⁻²
As implanted and
annealed at 1450°C
GaN
Atom Density (cm⁻³)
10²¹
10²⁰
10¹⁹
10¹⁸
10¹⁷
10¹⁶
10¹⁵
10¹⁴
0.0
0.3
0.6
0.9
1.2
1.5
1.8
Depth (μm)


^{71}Ga →
Mg in GaN
150keV, 5×10^{14}cm^{-2}
As implanted and
annealed at 1450°C
Atom Density (cm^{-3})
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
Secondary Ion Intensity (cts/sec)
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
0.0
0.5
1.0
1.5
Depth (μm)