ULTRA-HIGH IMPLANT ACTIVATION EFFICIENCY IN GaN USING NOVEL HIGH TEMPERATURE RTP SYSTEM

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ABSTRACT

Si^+ implant activation efficiencies above 90%, even at doses of 5×10^{15} cm^{-2}, have been achieved in GaN by RTP at 1400-1500 °C for 10 secs. The annealing system utilizes with $MoSi_2$ heating elements capable of operation up to 1900 °C , producing high heating and cooling rates (up to 100 °C $\cdot$ s^{-1}). Unencapsulated GaN show severe surface pitting at 1300 °C , and complete loss of the film by evaporation at 1400 °C . Dissociation of nitrogen from the surface is found to occur with an approximate activation energy of 3.8 eV for GaN (compared to 4.4 eV for AlN and 3.4 eV for InN). Encapsulation with either rf-magnetron reactively sputtered or MOMBE-grown AlN thin films provide protection against GaN surface degradation up to 1400 °C, where peak electron concentrations of ~5×10^{20} cm^{-3} can be achieved in Si-implanted GaN. SIMS profiling showed little measurable redistribution of Si, suggesting $D_{Si} \leq 10^{-13}$ cm$^2 \cdot$ s^{-1} at 1400 °C . The implant activation efficiency decreases at higher temperatures, which may result from Si_{Ga} to Si_N site switching and resultant self-compensation.

Introduction

Ion implantation is an enabling technology for fabrication of GaN-based ultra-high power thrysistors, junction field-effect transistors (JFETs) and heterostructure field effect transistors (HFETs)[1-10]. In particular selective area implantation can be used to reduce transistor access resistance by creating highly doped contact regions. Most published device characteristics show evidence of relatively high access resistances[11-14]. To date GaN JFETs formed entirely by implantation into undoped material[2] and GaN light emitting diodes (LEDs) formed by Mg^+ implantation into n-type epi layers[15] are the only devices fabricated using implant doping.

Past work has shown that in compound semiconductors the annealing temperature required for implant activation is a fairly high percentage of the melting temperature of the material, and is also a function of the implant dose[16, 17]. In GaN it has been observed that low dose ($\leq 5 \times10^{14}$ cm^{-2}) implants anneal poorly up to 1100 °C, leaving a coarse network of extended defects, while high dose ($\geq 2\times10^{15}$ cm^{-2}) implants may lead to amorphization. Amorphous layers recrystallize in the range 800-1000 °C to form defective polycrystalline material[18]. Quite good activation efficiencies have been obtained for n-type implanted dopants in spite of high residual damage[19-21]. It is also clear that annealing temperatures above 1300 °C are desirable for optimal electrical properties in the implanted layers[19, 20]. The equilibrium N_2 pressure over GaN at 1400 °C is > 1000 bar[22, 23], and at these temperatures only two methods have proven effective in preventing

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surface decomposition. The first is use of high N_2 pressures (15 kbar)[24], and the second is deposition of AlN encapsulation layers[25] (at 1400 °C the equilibrium N_2 pressure above AlN is only 10^{-8} bar).

In this paper we report use of a new high-temperature rapid thermal processing system for annealing of implanted GaN at temperatures up to 1500 °C. When used in conjunction with AlN cap layers, very high activation efficiencies ($\geq 90\%$) can be obtained even for Si^+ ion doses of 5×10^{15} cm^{-2}. This approach is attractive for processing of GaN devices in a conventional fabrication-line environment, without the need for specialized high-pressure furnaces.

Experimental

Undoped ($n \sim 1\text{-}8 \times 10^{16}$ cm^{-3}) GaN films 2-3 μm thick were grown on Al_2O_3 substrates at ~1040 °C by Metal Organic Chemical Vapor Deposition. Si^+ ions were implanted at 25 °C to a dose of 5×10^{15} cm^{-2} at an energy of 100 keV. This produces a maximum Si concentration at a projected range of 800 Å, according to a Transport-of-Ions-in-Matter calculation. The samples were deposited with AlN by reactive sputtering or by Metal Organic Molecular Beam Epitaxy, and were sealed in quartz ampoules under N_2 gas at 15 psi (the slight negative pressure was to prevent ampoule blow-out at elevated temperature). Annealing was performed in an MHI Zapper RTP furnace containing novel molybdenum intermetallic composite heating elements. These are maintained at constant temperature, and a motor driven actuator is used to achieve high ramp-up and ramp-down rates by inserting or removing the sample. Annealing was performed at 1100-1500 °C for dwell times of 10 secs. The samples were characterized by scanning electron microscopy, atomic force microscopy, Hall measurements (using alloyed 420 °C, 180 secs In-based contacts), and by Secondary Ion Mass Spectrometry (SIMS) using a cameca system and a Cs^+ ion beam.

Results and Discussion

A typical temperature-time profile for an annealing cycle is shown in Figure 1. Excellent temperature uniformity ($\leq \pm 4$ °C over a 9×6" area at 1500 °C) and reproducibility was obtained. When unencapsulated samples were annealed, the GaN surface remained of reasonable quality at 1200 °C, at 1300 °C hexagonal pits at high density ($\sim 10^8$ cm^{-2}) were observed with substantial loss of material, at 1400 °C only the AlN buffer layers remained, while at 1500 °C even this generally peeled away to leave only the Al_2O_3 substrate. By contrast, AlN-capped samples retained good quality surfaces to >1400 °C. Occasional localized cap failures were observed, and potential mechanisms for these are currently under investigation. One possibility is agglomeration of residual H_2 in the AlN to form bubbles which evolve from the material. From temperature-dependent studies we measured activation energies for N_2 loss of ~3.8 eV for GaN and 4.4 eV for AlN[26].

Electrical results for activated samples are shown in Figure 2. Note that in unencapsulated samples the sheet electron density increases with annealing temperature up to 1200 °C, but this was the highest temperature we could obtain data for due to loss of the film. By contrast, the AlN encapsulated samples showed a peak in the sheet electron density at 1400 °C, with a reduction at 1500 °C. Note that the 300 K electron mobility decreases at 1500 °C, indicating that the material is becoming more compensated. This behavior is fairly typical of Si implant activation in III-V materials, and is usually ascribed to self-compensation through Si site-switching, i.e. some of the Si_{Ga} donors move to Si_N sites, producing self-compensation. Note that with a peak Si activation efficiency of ~90%, the corresponding peak electron concentration will be $\sim 5 \times 10^{20} cm^{-3}$. This very high doping level produces extremely good specific contact resistances for W and WSi_x metallization, with values $\leq 10^{-6}$ $\Omega \cdot cm^2$ after annealing in the range 600-900 °C. This demonstrates the efficiency of the implantation approach for reducing contact resistances in GaN electronic devices.

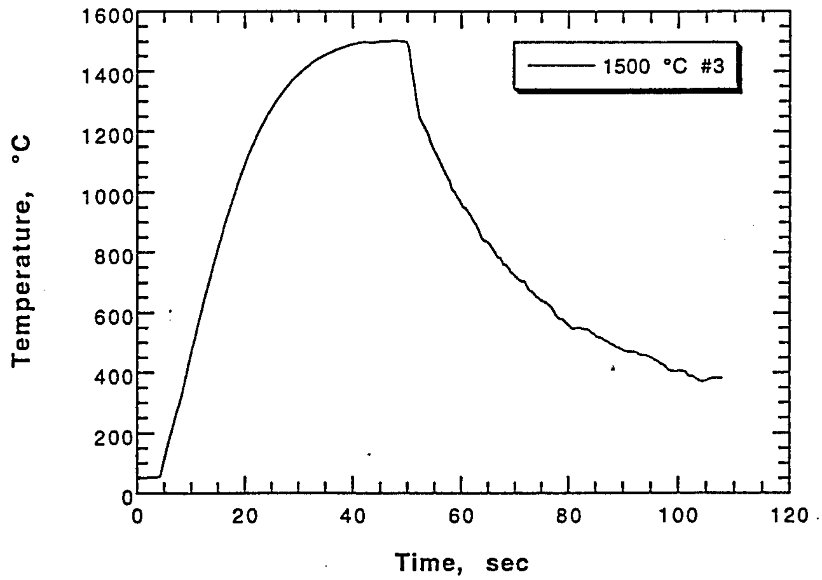

Figure 1. Time-temperature profiles for RTP annealing of GaN at 1500 °C.

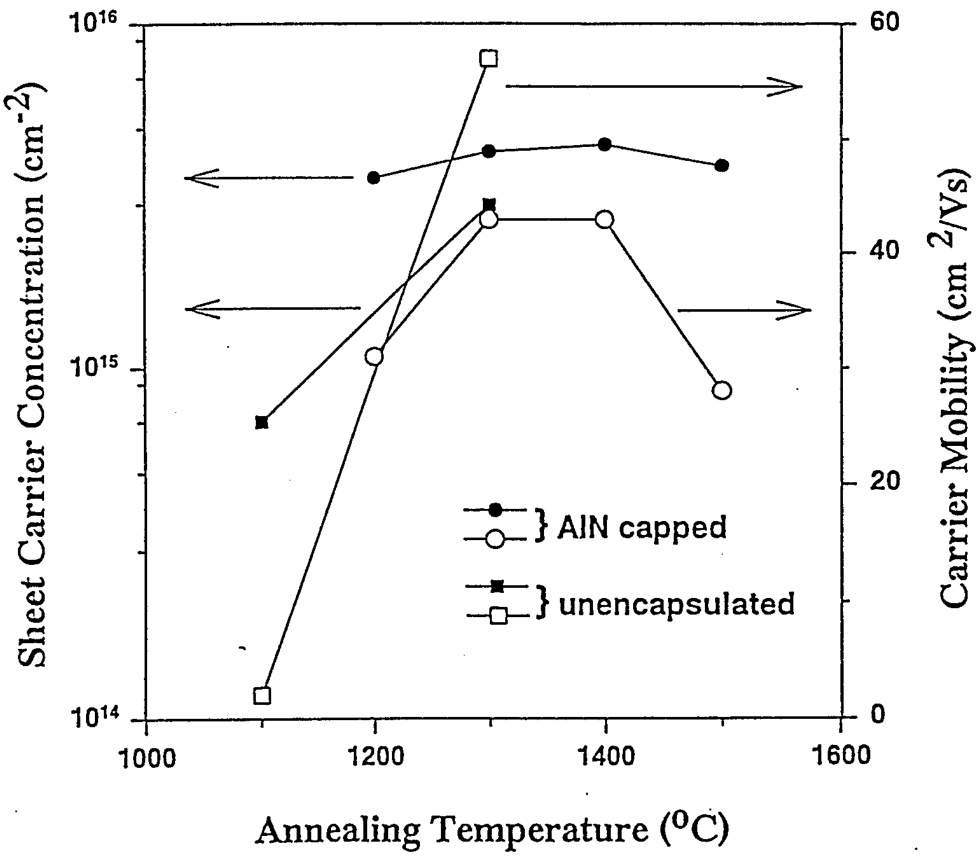

Figure 2. Sheet carrier density and electron mobility in Si implanted GaN after uncapped or AlN-capped annealing.

Figure 3 shows the calculated, as-implanted Si atomic profile, and the SIMS profiles of as-implanted and 1400 °C annealed samples. There are several obvious points in the data. First, the Profile Code algorithm does not produce a good match to the experimental profile, and some work will need to be done to obtain better stopping power data for the ions in GaN. Second, there is little redistribution of the Si at 1400 °C, with $D_{Si} \leq 10^{-13}$ $cm^2 \cdot s^{-1}$ at this temperature calculated from the change in width at half-maximum. This result emphasizes the extremely stable nature of dopants in GaN even at very high processing temperatures.

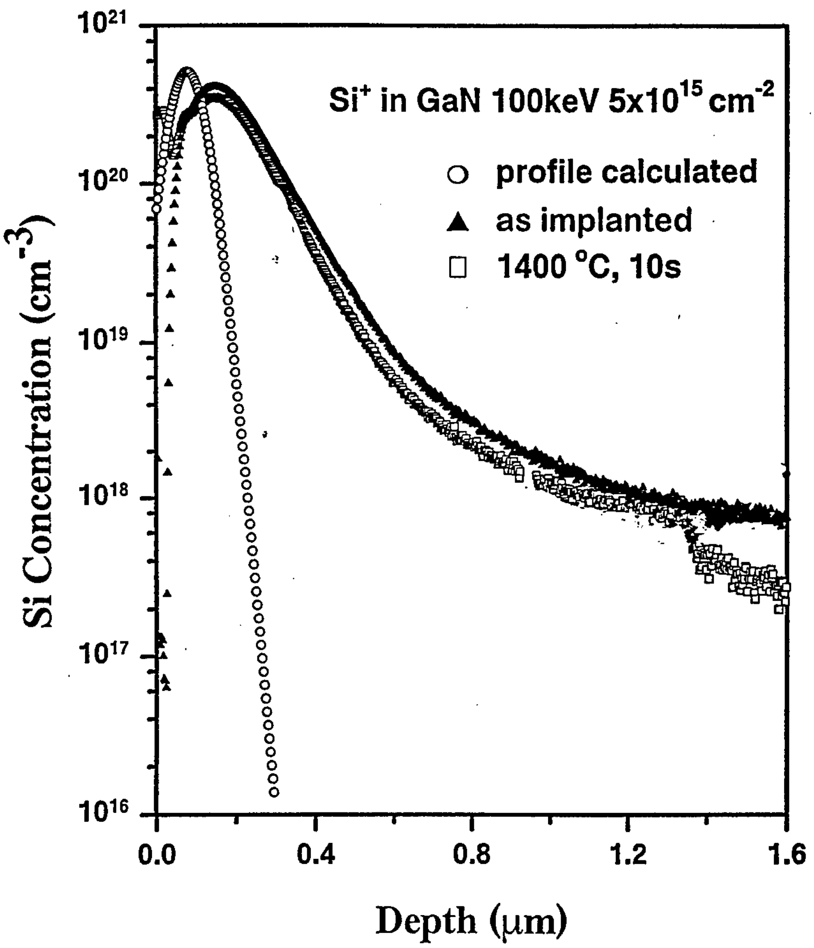

Figure 3. Calculated (from PCODE) and experimentally measured (by SIMS) profiles of implanted Si (100 keV, 5×10^{15} cm^{-2}) in GaN.

SUMMARY AND CONCLUSIONS

To produce low specific contact resistances in selected area of GaN-based electronic devices, ion implantation is an attractive option. However, to achieve high doping levels, high implant doses and therefore high annealing temperatures are required. The major difficulty with processing GaN above ~1150 °C is prevention of surface dissociation. The use of AlN encapsulation works well to temperatures of ≥ 1400 °C, where Si implant activation efficiency is a maximum for high dose (5×10^{15} cm^{-2}) conditions. The activation efficiency decreases at higher temperatures, along with a decrease in electron mobility, which is consistent with Si self-compensation.

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