Reduction in Thermal Boundary Conductance of Direct Wafer Bonded GaN|Si Heterojunction Interfaces Annealed at High Temperatures

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Abstract

The evolution of structural and thermal properties of wafer bonded GaN on Si with annealing are investigated in this study. Formation of an amorphous layer at the interface of wafer bonded samples is commonly observed due to surface preparation techniques prior to bonding. Recrystallization of these interfaces have been shown for several homojunctions, but reconstruction of wafer bonded heterojunctions has additional complexities. Annealing of GaN-Si wafer bonded samples resulted in non-uniform diffusion across the interface and the formation high Ga content pyramidal features within Si. Thermal boundary conductance of the as-bonded and post annealed samples show a factor of two reduction in thermal boundary conductance after annealing. Optimization of wafer bonding techniques and subsequent annealing allows for unique materials combinations that are not limited by crystal structure considerations.

Introduction

Research in wide band gap semiconductors has garnered popularity in an effort to reduce device size, increase efficiency, and allow device operation at higher temperatures.

The interface of direct wafer bonded (0001) GaN on (001) Si was studied as a continuation of a previous effort [1]. In that study, a ~1.5 nm amorphous region is observed at the interface due to surface preparation techniques. Here we investigate the effects of annealing on the evolution of the heterojunction GaN-Si interface and the report preliminary thermal measurements, which we correspond to chemical changes and interdiffusion at the interface.

Experimental Methods

EVG® ComBond® equipment was used for bonding under high vacuum (~10^{-8} mtorr) at room temperature by bombarding the GaN and Si surfaces with an Ar ion beam to remove unwanted native surface oxides prior to bonding [1,2]. The post Ar-beam treated samples are placed face-to-face and pressure is applied to initiate the bond. An FEI Nova 600 Nanolab Dual Beam SEM/FIB was used to prepare cross section TEM samples roughly 100 nm thick using a Ga source and transferred to a TEM grid using a standard lift out procedure. High resolution transmission electron microscopy (HRTEM) images were taken using an FEI Titan at 300 kV. To study the chemical composition of the interface, high spatial resolution energy dispersive x-ray spectroscopy (EDX) was taken with Cs-corrected JEOL GrandARM at 300

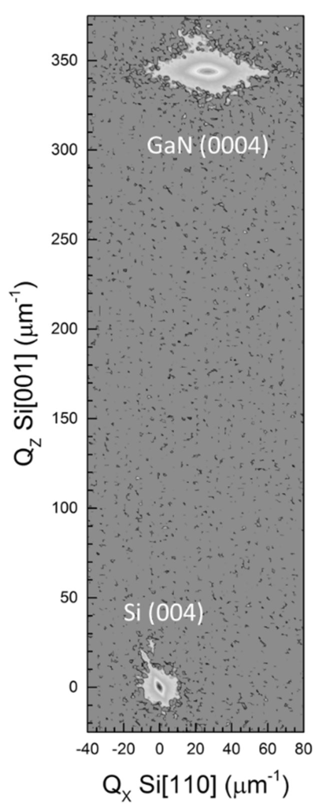

Figure 1: Reciprocal space map of Si (004) and GaN (0004) revealing ~0.2° tilt between the bonded layers

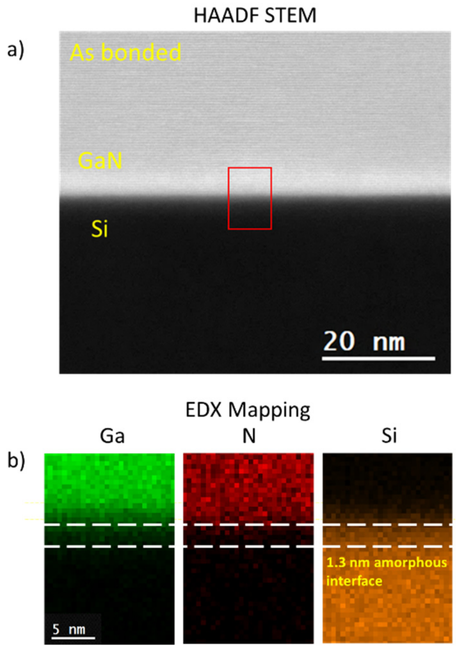

Figure 2: Energy dispersive spectroscopy shows a chemically sharp interface in the as bonded sample. Additionally, comparison with electron microscopy reveals that the amorphous interface lies on the silicon side.

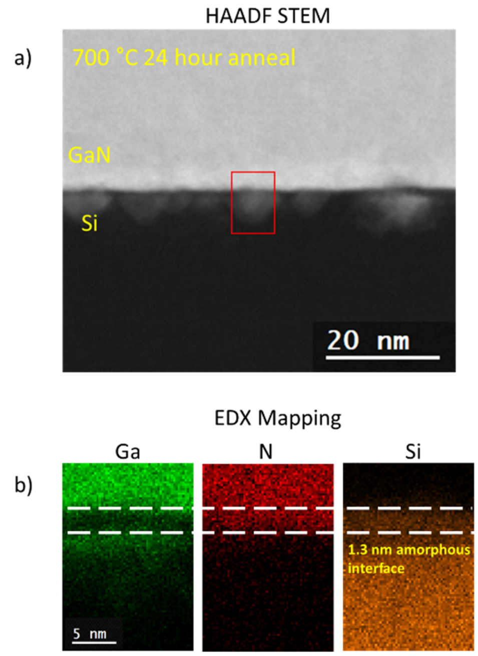

Figure 3: Energy dispersive spectroscopy and transmission electron microscopy reveals an amorphous interface that contains silicon and nitrogen and pyramidal shaped features where the gallium diffused across the interface.

kV. A Bruker D1 diffractometer was used to measure the in-plane misorientation between the bonded substrates. The samples were annealed in a high temperature furnace at 700 °C for 24 hours.

RESULTS AND DISCUSSION

During the bonding process, the $[10\bar{1}0]$ GaN edge was aligned parallel to the Si [110] edge. An X-ray diffraction reciprocal space map of the (004) Si and (0004) GaN revealed that there is a ~0.2° tilt between the GaN and Si layers as seen in Figure 1. Minimal tilt between the bonded layers is expected to minimize effects of misorientation on the bonded interface. The Ar ion bombardment of the surfaces prior to bonding can produce an amorphous or damaged region at the bonded interface that has been seen in many other bonded systems [3-5]. STEM and EDX measurements of the as-bonded interface are shown in Figure 2. Subsequent annealing was done in an effort to recrystallize the interface. Previous work has shown that recrystallization between Si|Si wafer bonded samples occurred when annealed at 450 °C for 12 hours [3]. However, in the GaN-Si system, we found that the disordered interface did not recrystallize when annealed at these temperatures. Annealing at temperatures up to 450 °C and 120 hours showed only initial stages of interdiffusion and a stable interface. After annealing at 700 °C for 24 hours, high resolution EDX revealed the formation of amorphous SiN as well as the diffusion of gallium into silicon as shown in Figure 3. Additionally, the diffusion process is not uniform as noted by the formation of pyramidal structures, alluding to nonuniform diffusion across the interface. The reconstruction of wafer bonded heterogeneous interfaces becomes more complex than the homogenous counterpart due to the potential formation of new compounds at the interface.

Preliminary thermal results show that the thermal boundary conductance (TBC) of the as bonded sample is ~140 MW/(m^2·K). The TBC results of wafer bonded GaN|Si reported here is higher than previously reported TBC values of epitaxially grown interfaces such as GaN on Si [6-7], GaN on SiC [7-8], and GaN on diamond [9]. The TBC for the annealed interface is degraded by a factor of two compared to the as-bonded interface for the sample that was annealed at 700 °C for 24 hours These results demonstrate that high TBC can be achieved through wafer bonding of GaN with materials such as silicon and that such interfaces are stable even up to device operation up to 300 °C. However, chemically rough interfaces formed due to high temperature annealing are detrimental to thermal transport across these interfaces.

CONCLUSION

In this study we show the evolution of the amorphous interface in wafer bonded GaN-Si with annealing. As-bonded samples revealed abrupt interfaces with a ~1.5 nm amorphous interface due to surface preparation techniques prior to bonding. High temperature annealing (700 °C 24 hrs) resulted in non-uniform diffusion across the bonded interface and the formation amorphous SiN, which has deleterious effects on thermal transport across the interface and a reduction in the measured TBC by a factor of two.

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