Chapter 1. Introduction

1.1. Wafer Fusion of Lattice-mismatched Materials

In describing the first reported transistor formed via wafer fusion, this dissertation demonstrates the potential of wafer fusion for the production of otherwise unobtainable, electrically active heterointerfaces between lattice-mismatched materials. Wafer fusion (also called direct wafer bonding) is an attractive technique for integrating disparate materials, as the conventional method of epitaxial growth has had little success in integrating lattice-mismatched crystals. Consider the epitaxial growth of a crystal film onto a crystal substrate. During growth, if the two crystals have lattice constants that differ by even one percent, the film will grow elastically strained until it reaches its critical thickness. At that point, "threading" dislocations are likely to form at the growth interface and glide (i.e. "thread") through the film, to the heterointerface between the two materials, forming "misfit"

dislocations at the heterointerface. Generally, threading dislocations drastically degrade a crystal's electronic and optoelectronic properties. In contrast, wafer fusion allows a single crystal to be transferred from one substrate to another, where the new substrate can be an amorphous material, a polycrystal, or a single crystal of different lattice constant, crystal structure, or crystallographic orientation.[1] The wafer-fused interface will still have misfit dislocations, due to the difference in lattice constants of the two constituent crystals. However, the transferred film will have no threading dislocations, and would hence maintain its beneficial electronic or optoelectronic properties.

Wafer fusion, which joins two materials placed in intimate contact under elevated temperature and pressure, has proven to be effective in forming a number of heterogeneous devices from lattice-mismatched materials. These devices include GaAs-InP vertical-cavity[2] and microdisk[3] lasers, InGaAs-Si avalanche photodiodes,[4] and InGaAsP-AlGaAs photonic crystal lasers.[5] Such a variety of thick-layer material combinations would not have been obtainable, thus far, via conventional all-epitaxial formation methods. This issue of integrating disparate materials is particularly important for GaN, as progress in GaN research is presently limited by the lack of an appropriate epitaxial growth substrate.[6, 7] Hence, the novel technique of wafer fusion is a promising alternative to an all-epitaxial GaN device formation process.[8, 9]

1.2. GaN for Electronic Devices

GaN is a relatively new semiconductor, widely studied and reported in numerous applied physics, materials science, and electrical engineering journals and conferences. There is even a peer-reviewed journal devoted solely to nitride research, the Materials Research Society's *MRS Internet Journal of Nitride Semiconductor Research*. GaN has had a remarkable history, as it initially advanced quickly from research to commercialization. Due to pioneering research in the 1970s-1990s of Amano, Akasaki, Pankove, and Nakamura [10-17], GaN light-emitting diodes (LEDs) recently emerged as a long-awaited, strong, and efficient light source capable of blue, green, and ultraviolet emission. By complementing the already commercialized red and yellow LEDs, the new GaN LEDs finally rendered the full color spectrum achievable via energy-efficient and long-lifetime LEDs. From this auspicious beginning, GaN research has expanded to now encompass a wide variety of areas, including high-power electronics [18-38], spintronics[39], nanostructures [40], microphotonics [41], and of course green, blue, and ultraviolet photoelectronics [42-52].

1.3. Motivation for the n-AlGaAs/p-GaAs/n-GaN HBT

The large breakdown field and anticipated saturation velocity of GaN make this novel material particularly promising for high-frequency, high-power devices. With this goal in mind, quite a few researchers are working to develop GaN-based

heterojunction bipolar transistors (HBTs).[22-37] Although results thus far have been promising, there are still a number of outstanding material issues, related to the p-GaN material. For example, AlGaN-GaN HBTs appear to be limited by large Mg acceptor ionization energies and low hole mobilities.[36]

This dissertation describes the use of wafer fusion to form HBTs with an AlGaAs-GaAs emitter-base and a GaN collector. By avoiding the use of p-GaN, this transistor design avoided the problems presently limiting bipolar transistors made entirely of III-N materials. GaN was used as the collector material, because its larger energy bandgap ($E_{g,\ GaN}$ = 3.39eV) implied that it could withstand a higher electric field than GaAs ($E_{g,\ GaAs}$ = 1.42eV). Compared to a p-GaAs/n-GaAs base-collector, the p-GaAs/n-GaN base-collector junction was expected to withstand a higher reverse bias, allowing the HBT to operate at higher voltages and current levels without breakdown. AlGaAs-GaAs was chosen as the emitter-base material system, due to its high emitter injection efficiency, low base transit time, high current gain, and widely reported success in HBT applications.[53-55] In contrast to GaN growth technology, AlGaAs-GaAs growth was already well developed, producing uniform low-defect material layers, which led to reproducible electrical features such as turn-on voltage. Because the high degree of lattice mismatch between GaAs (lattice constant of 5.65A) and GaN (3.19A) precluded an all-epitaxial formation of this device, the GaAs-GaN heterostructure was formed via the novel technique of wafer fusion. Thus, this project demonstrated the integration of device materials, chosen for

their optimal electronic properties, unrestricted by the conventional (and very limiting) requirement of lattice-matching.

1.4. Challenges of GaN Wafer Fusion

As discussed in Section 1.1, wafer fusion has proven to be effective in forming a number of heterogeneous devices from lattice-mismatched materials. However, those devices did not require the wafer-fused interface to serve as a critical device active region. Instead, those device active regions were located far from the crystallographic imperfection of the fused interface. In contrast, the device described in this dissertation placed stringent demands on the electronic quality of the fused interface, as it served also as the base-collector junction of an HBT. Uncontrolled bond reconstruction or residual impurities at the fused interface may have produced electronic traps or barriers, which in turn may have produced the low common-emitter current gain observed in these wafer-fused HBTs.

Bond reconstruction is indeed a primary issue in the wafer fusion of GaN. Ideally, during the fusion process, Ga-As and Ga-N bonds would break on the wafer surfaces, and new bonds would form between the two wafers. However, the melting point of GaN at atmospheric pressure is very high (>1200°C) relative to the fusion process temperature (500-750°C) for this dissertation study. Prior to this dissertation study, GaN fusion was reported at temperatures up to 1000°C.[56-59] Even at these elevated fusion temperatures, the resulting fused interface was

notoriously non-uniform and irreproducible. Moreover, only junctions fused at 700-1000°C were proven to be electrically conducting. At the start of this dissertation study, it was uncertain if temperatures less than 700°C would provide enough thermal energy to form a mechanically strong and electrically active junction between GaAs and GaN. This endeavor seemed all the more challenging, as the GaAs surface was non-polar (Ga- and As-terminated (100)) while the GaN surface was polar (Ga-terminated (001)). It was remarkable that fusion did occur at temperatures as low as 500°C, and that the resulting interfaces were suitable as base-collector junctions of functioning HBTs (Chapters 4-6). However, TEM studies (Section 2.5) indicated that bond reconstruction at the fused interface was less than ideal. The observed disorder was common to other fused semiconductor junctions [60-62], but the disorder of these other fused junctions was not correlated with systematically varied fusion process conditions. In this dissertation study, the disorder was found to vary with the fusion process temperature, and may have contributed to variations in HBT electrical performance observed for HBTs fused over a wide range of temperatures (500-750°C).

Aside from the issue of electronic traps and barriers at the fused interface, the elevated temperature of the fusion process (500-750°C) may itself have accelerated dopant and defect diffusion, potentially degrading the entire material structure and hence the entire energy band structure as well. It is important to note that the fusion temperature was often higher than the growth temperature of the AlGaAs-GaAs materials (585°C); hence, diffusion was most likely occurring in these structures

during the fusion process. Lower fusion temperatures would thus seem to be desirable, but for the device application in this dissertation, the fusion process conditions were required to provide enough thermal energy to form a mechanically robust and electrically active fused interface. In fact, TEM and electrical (I-V) studies did reveal a thicker and less electrically active disordered layer at the interface (1.5-2 nm), when formed via fusion at a lower temperature (550°C). Due to these two competing factors, of diffusion at high temperature vs. interfacial disorder at low temperature, wafer fusion studies must include a systematic variation of process conditions, in order to achieve proper characterization and optimization. In this dissertation study, fusion conditions were systematically varied over a wide range (500-750°C, 0.25-2hours) and were correlated with the electrical, chemical, and structural quality of the resulting interface.

1.5. References

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