Chapter 6. AlGaAs/GaAs/GaAs Wafer-fusedHBTs

6.1. Overview

Previous chapters described an AlGaAs-GaAs-GaN HBT, in which an epitaxially grown AlGaAs-GaAs emitter-base was wafer-fused to a GaN collector. The motivation for using a wafer fusion process was the universal lack of success in using all-epitaxial methods to form a high-quality heterojunction between highly lattice-mismatched crystals, such as GaAs and GaN. The wafer-fused GaAs-GaN junction could not be compared to an epitaxially grown GaAs-GaN junction, in order to directly assess the effects of fusion on the electrical properties of that heterojunction. Although the inherent GaAs-GaN energy band line-up (free of fusion-induced artifacts) was unknown, the GaAs-GaAs energy band structure had been widely known for years, allowing for the isolation of fusion effects on a high-quality, well understood GaAs-GaAs junction.

This chapter describes the comparison of epitaxially grown, annealed, and wafer-fused AlGaAs-GaAs-GaAs HBTs. This study assessed the effects of fusion, and of high temperature alone (without the presence of a fused interface), on the electrical performance of the epitaxially grown HBT. These experiments were similar to those involving the epitaxially grown AlGaAs-GaAs emitter-base diodes, discussed in Chapter 4. Similar to the findings of Chapter 4, the electrical performance of the as-grown device (β=48 at I_B=0.6mA and V_{CE}=2V) was far superior to the performance of the device fused at 750^{o}C for one hour (β=0.32). However, unlike the findings of Chapter 4, the electrical performance was also degraded (albeit to a lesser extent) for a device merely annealed at those same thermal conditions, 750^{o}C for one hour, (β=0.68) and for a device fused at a lower temperature of 600^{o}C for one hour (β=0.32). The discrepancy was most likely due to the increase of defect-assisted diffusion (perhaps of H, a passivating agent) in the HBT structure (of three thin layers), as compared to the diode structure (of two thick layers) discussed in Chapter 4. In the InP-GaAs material system [1], both annealing and fusion were shown to be high-temperature processes that ultimately degraded device performance. However, defect-assisted diffusion was shown to exacerbate degradation in fused samples, as compared to annealed samples.

Finally, fused AlGaAs-GaAs-GaAs HBTs were compared to fused AlGaAs-GaAs-GaN HBTs, demonstrating that the use of a wider bandgap collector ($E_{g,GaN}$ >

$E_{g,GaAs}$) did indeed improve HBT performance at high applied voltages. Given the same I_B (10mA) and the same fusion process conditions (600^{o}C for one hour), the AlGaAs-GaAs-GaN HBT was operable to a high V_{CE} of 40V (Figure 6.6.b.i), while the AlGaAs-GaAs-GaAs HBT exhibited much more leakage when operated to a V_{CE} of only 15V (Figure 6.6.a.i).

6.2. Transistor Design & Fabrication

This chapter describes and compares an AlGaAs-GaAs-GaAs HBT subjected to various thermal processes. The "as-grown" HBT was grown epitaxially via MBE, and was not subjected to additional thermal processing prior to I-V testing. The "annealed" HBTs were grown epitaxially via MBE, and then capped and annealed at 600-750^{o}C for one hour. The "fused" HBTs were formed via wafer fusion at 600-750^{o}C for one hour, using the process described in Section 2.2. The starting materials for the fused HBT were grown epitaxially via MBE (Figure 6.1.a). Figure 6.1.b. shows the material structure of the AlGaAs-GaAs-GaAs HBT. All HBTs had the same material structure, whether the HBTs were as grown, annealed, or formed via wafer fusion. The material structure of the AlGaAs-GaAs-GaAs HBT was identical to the structure of the AlGaAs-GaAs-GaN HBT described in Chapter 4 (Figure 4.1), except for the GaAs-GaAs vs. GaN-sapphire collector-substrate. Both collectors had the same width and n-type (Si) doping concentration.

The samples described in this chapter were fused by S. Estrada (using the procedure described in Section 2.2) and processed into I-V test structures by K. McGroddy (using the procedure described in Section 2.3).

6.3. Chemical Profiles

SIMS analysis confirmed that the doping profiles of the n-p-n emitter-base-collector were preserved during the fusion anneal. Figure 6.2 shows the Si, C, O, and H profiles of different samples of the same HBT structure (Figure 6.1), subjected to various thermal processes as described in Section 6.2. In all SIMS data discussed thus far (for the fused diodes of Chapter 3 and the fused HBTs of Chapter 4), all dopants and impurities were seen to peak at the fused interface. It is notable that in Figure 6.2, only the fused sample exhibited concentration peaks at the interface. The as-grown and annealed samples did not show concentration peaks, even after both the annealed samples and the fused samples were exposed to the same temperature (600-750^{o}C) for the same duration (1 hour). Whether the contamination of the fused interface was due to residual pre-fusion impurities, or to gettering properties of the fused interface, it is interesting to compare the device characteristics (Sections 6.4-6.6) of the fused samples to the other samples, which did not have highly contaminated base-collector junctions.

As mentioned in Chapter 4, it is notable that high levels of hydrogen were present at the fused junction, even when these device materials were grown exclusively via MBE, and not MOCVD. Thus, it is likely that a significant amount of hydrogen remained on the surfaces of the adjoining wafers, prior to fusion and after the cleaning procedure described in Table 2.2. The hydrogen may have been present in a hydrocarbon form, for example from the methanol used in the bonding process described in Table 2.2. In future work, the reduction of residual pre-fusion impurities may greatly improve HBT electrical characteristics -- especially the reduction of hydrogen, a known passivating agent of C, the p-GaAs base dopant.[2]

6.4. Emitter-Base Diode Characteristics

Since the performance of the n-p-n HBT depended on the behavior of its two constituent back-to-back diodes, this study first examined the I-V characteristics of the emitter-base and base-collector diodes independently. Figure 6.3 shows the I-V characteristics of the emitter-base diodes in the AlGaAs-GaAs-GaAs HBTs. Emitter-base data were taken with the collector open.

As discussed in Chapter 4, the AlGaAs-GaAs emitter-base junction was (in all cases) formed directly through MBE growth, but it was important to isolate the effects of the fusion or anneal conditions on the electrical characteristics of that junction (i.e. the elevated temperature for one hour, either with or without the presence of the gettering fused interface). In Figure 6.3, each curve represents a different sample, exposed to one of three thermal processes described in Section 6.2: as-grown, annealed at 600-750^{o}C for one hour, and formed via fusion at 600-750^{o}C for one hour. All emitter-base I-V characteristics (Figure 6.3) exhibited a similar turn-on voltage (1.2V), ideality factor (1.1-1.3), and breakdown voltage (8.2-8.8V). All emitter-base I-Vs were nearly identical to those of the as-grown sample, except for an apparent series resistance. In forward bias, the annealed and as-grown samples exhibited similar behavior regardless of process temperature (750^{o}C, 600^{o}C, or none). However, the fused samples were more resistive than the as-grown and annealed samples. Because the diode characteristics were nearly identical (in ideality factor, turn-on voltage, reverse-bias leakage current, breakdown), it was unlikely that the emitter-base junction itself was degraded during fusion. However, given the additional series resistance observed for the fused samples, it was likely that the base of the fused samples was somehow degraded by the fusion process.

A similar discrepancy was seen in studies of GaAs-InP wafer-fused interfaces, involving structures that were similarly fused, annealed, or as-grown; device characteristics of the as-grown material were somewhat degraded after annealing, but were degraded even further after wafer fusion at the same temperature (i.e. annealed in the presence of a nearby fused interface).[1] Thus, the elevated temperature alone did not account entirely for the increased diffusion and device degradation. It was the presence of the disordered fused interface (both a source and sink for defects, such as impurities and vacancies) which greatly enhanced diffusion under elevated temperature.

In the fused samples described in this chapter, it is likely that defects (such as vacancies) or impurities (such as hydrogen) were present at the fused interface, and diffused from the fused interface into the surrounding materials, most critically into the base. For instance, hydrogen was certainly present at the fused interface (Figure 6.2). Hydrogen may have diffused into the base and passivated some of the C base doping, hence increasing the base resistance and causing the additional series resistance observed in the diode characteristics of Figure 6.3. (Presently, a series of similar samples are being prepared by S. Estrada and K. McGroddy for base resistance studies.) Similar experiments were discussed in Section 4.4 (regarding emitter-base diodes of AlGaAs-GaAs-GaN HBTs), where reduced fusion temperatures were seen to successfully mitigate the additionalseries resistance .

It was interesting to compare the emitter-base diodes of these AlGaAs-GaAs-GaAs HBTs (Figure 6.3) to those of the fused AlGaAs-GaAs-GaN HBTs (Figure 4.4.b and 4.4.c). The two different HBT structures (Figures 4.1 and 6.1) had the same emitter-base structure and differ only in the collector-substrate material choice. The emitter-base diode characteristics were similar for both HBT structures, regardless of thermal process (whether as-grown, annealed at 600-750^{o}C, or fused at 550-750^{o}C). All diodes displayed an ideality factor of 1.1-1.3. The fused GaN-collector HBTs exhibited a slightly lower emitter-base breakdown voltage (7.3-7.9V), as compared to the GaAs-collector HBTs (8.2-8.8V). The GaN-collector HBTs also demonstrated slightly higher turn-on voltage (1.4-1.7V), than did the GaAs-collector HBTs (1.2V).

6.5. Wafer-fused Base-Collector Diode Characteristics

Figure 6.4 shows the I-V characteristics of the base-collector diodes in the AlGaAs-GaAs-GaAs HBTs. All data were taken with the emitter open. In comparing the GaAs-collector HBTs (Figure 6.1) with the GaN-collector HBTs (Figure 4.1), the GaAs-collector diodes (Figure 6.4) were much more uniform than were the GaN-collector diodes (Figure 4.4.a). All GaAs-collector diodes demonstrated a turn-on voltage of 0.6V, whereas the fused GaN-collector diodes exhibited higher turn-on voltages of 0.7-2.8V. All GaAs-collector diodes exhibited much lower ideality factors (n=1.1 for as-grown diodes, n=1.3-1.5 for annealed and fused diodes) than the fused GaN-collector diodes (n=2.3-5.9). Thus, the high ideality factors of the GaN-collector diodes were not inherent to the fusion process itself, but were likely due to the GaN material. It is important to note that epitaxially grown GaN p-n junctions were also reported with high ideality factors (n~1.5-9.0).[3, 4]

As discussed in Section 4.2, GaN was chosen 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. This was indeed the case, as the GaAs-collector diodes (as-grown, annealed, or fused) broke down at 16-18V, whereas the GaN-collector diodes (fused at 550-650^{o}C) did not breakdown when tested up to 40V. It is interesting that the GaN-collector diodes fused at 700-750^{o}C were dominated by immediate and continuously increasing reverse-bias leakage. In contrast, the GaAs-collector diode fused at 750^{o}C exhibited a characteristic very similar to that of the as-grown diode, with low reverse-bias leakage current until abrupt breakdown at 16-18V. Since the excessive leakage of the GaN-collector diode does not appear to be inherent to the fusion process (even at as high a temperature as 750^{o}C), it may be due to the GaN material quality. The observed leakage may be similar to the emitter-collector leakage prevalent in (Al)GaN HBTs.[5] However, it remains unclear why the leakage would increase with increasing fusion temperature.

6.6. Transistor Characteristics

Figure 6.5 shows common-emitter I-V characteristics of AlGaAs-GaAs-GaAs HBTs subjected to various thermal processes: as-grown and unannealed, annealed at 750^{o}C for one hour, and formed via fusion for one hour at 600-750^{o}C. I_B step size (ΔI_B) was 0.2mA. β was determined at I_B=0.6mA and V_{CE}=2V. β was highest for the as-grown HBT (β=48). β decreased by an order of magnitude for the sample annealed at 750^{o}C for one hour (β=6.1). β decreased by yet another order of magnitude for the samples fused at 600-750^{o}C for one hour (β=0.68, 0.32). As discussed in Section 6.4, this trend was likely due to diffusion effects. Both annealing and fusion were high-temperature, one-hour processes that ultimately degraded electrical performance. However, as observed with InP-GaAs fused junctions, defect-assisted diffusion was shown to exacerbate degradation in fused samples, as compared to annealed samples.[1]

Figure 6.6 shows the common-emitter I -V characteristics of both AlGaAs-GaAs-GaAs and AlGaAs-GaAs-GaN HBTs, all formed via fusion at 600-750°C for one hour. I_B step size (ΔI_B) was 2mA Given the same I_B (10mA) and the same fusion process conditions (600°C for one hour), the AlGaAs-GaAs-GaN HBT was operable to a high V_{CE} of 40V (Figure 6.6.b.i), while the AlGaAs-GaAs-GaAs HBT exhibited much more leakage when operated to a V_{CE} of only 5V (Figure 6.6.a.i). This suggested that the use of a wider bandgap collector ($E_{g,GaN} > E_{g,GaAs}$) did indeed improve HBT performance at high applied voltages. As discussed in Section 6.5, it is interesting that the GaN-collector HBTs fused at 700-750°C were dominated by base-collector leakage, unlike the GaAs-collector HBT fused at 750°C. Since the excessive leakage of the GaN-collector HBT does not appear to be inherent to the fusion process (even at as high a temperature as 750°C), it may be due to the GaN material quality. The observed leakage may be similar to the emitter-collector leakage prevalent in (Al)GaN HBTs.[5] However, it remains unclear why the leakage would increase with increasing fusion temperature.

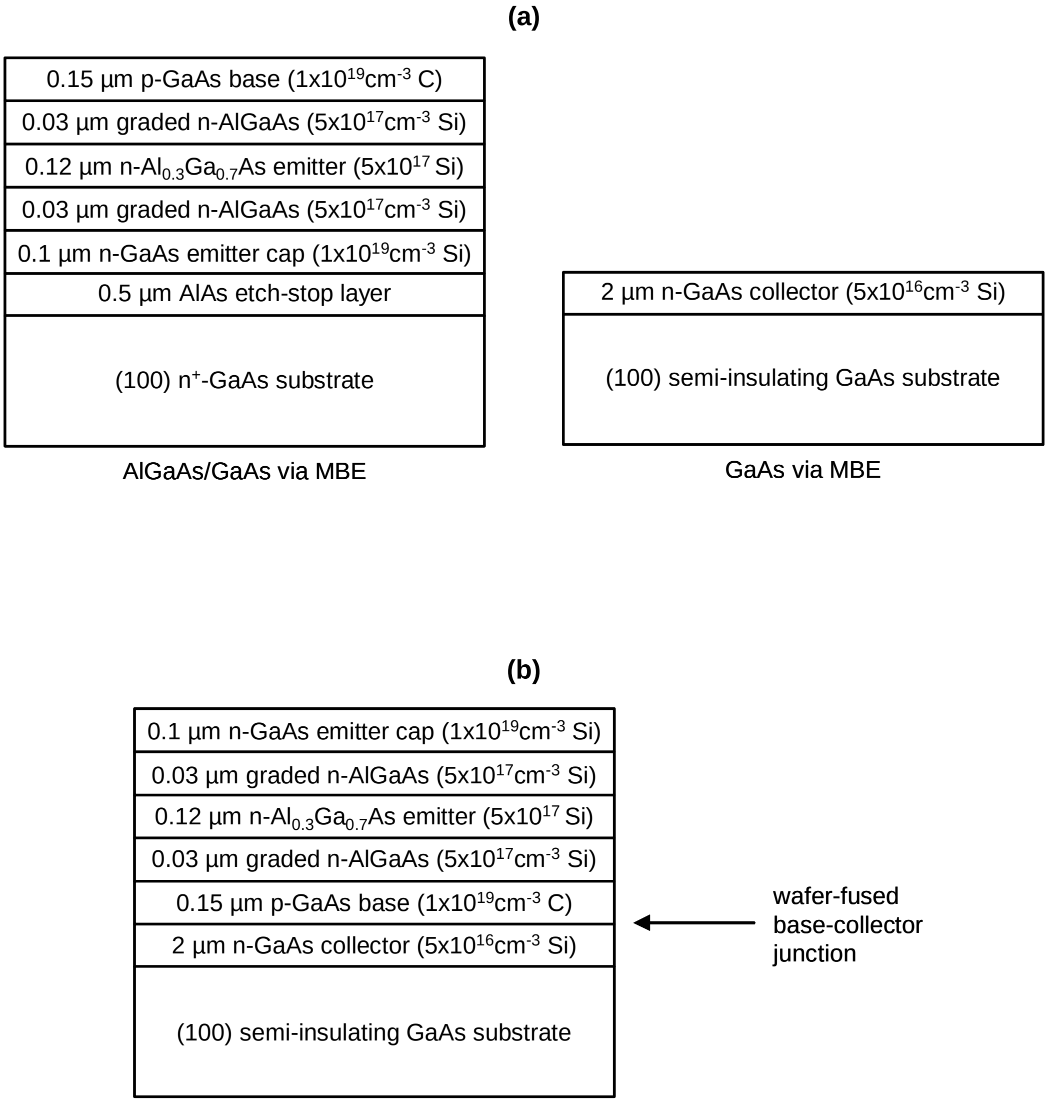

Figure 6.1. (a) Starting materials for the fusion process and (b) the AlGaAs-GaAs-GaAs HBT after fusion and substrate removal. The HBT had the same materials structure, depicted in (b), whether the HBT was as-grown, annealed, or formed via wafer fusion of the starting materials depicted in (a).

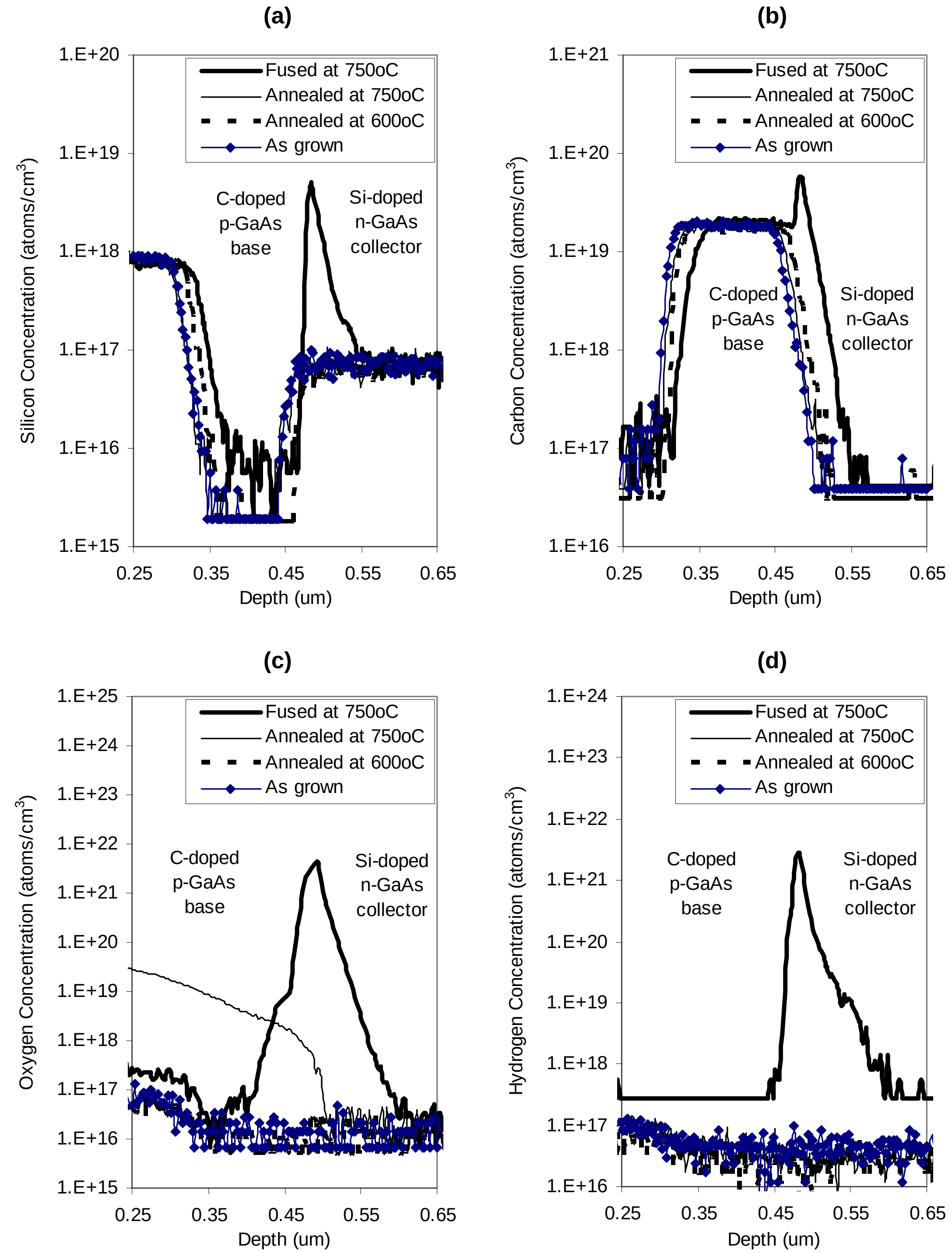

Figure 6.2. SIMS profiles in various samples of the same AlGaAs-GaAs-GaAs HBT structure (Figure 6.1.b), subjected to various thermal processes: as-grown and unannealed, annealed at 600-750^{o}C for one hour, and formed via fusion at 750^{o}C for one hour. Profiles are shown for (a) silicon, (b) carbon, (c) oxygen, and (d) hydrogen. These SIMS data were obtained in collaboration with Yumin Gao at Applied Microanalysis Labs, Inc.

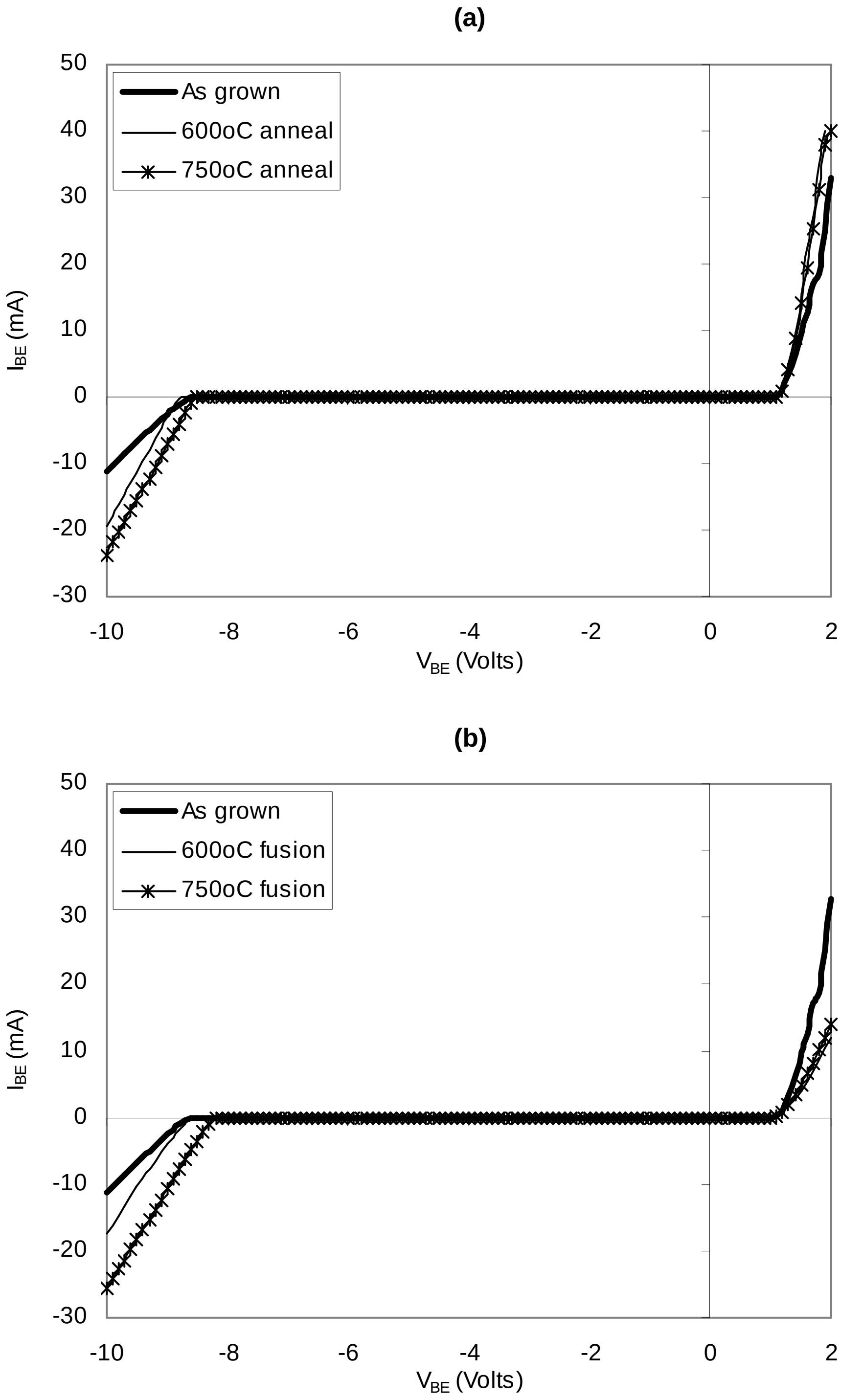

Figure 6.3. I-V characteristics (collector-open) of the emitter-base diodes in AlGaAs-GaAs-GaAs HBTs (Figure 6.1.b) subjected to various thermal processes: as-grown, (b) annealed at 600-750^{o}C for one hour, and (c) formed via fusion at 600-750^{o}C for one hour.

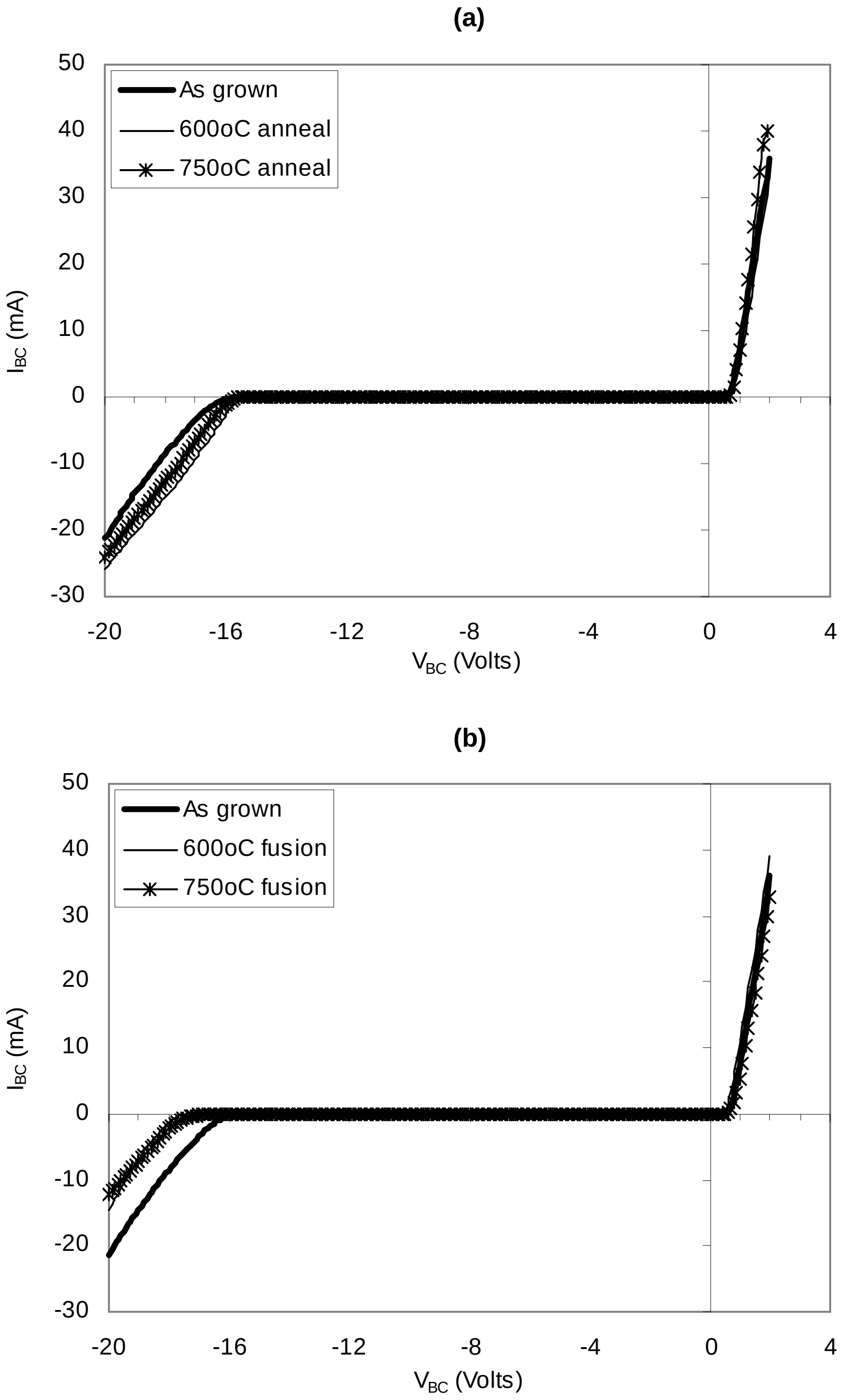

Figure 6.4. I-V characteristics (emitter-open) of the base-collector diodes in AlGaAs-GaAs-GaAs HBTs (Figure 6.1.b) subjected to various thermal processes: as-grown, (b) annealed at 600-750^{o}C for one hour, and (c) formed via fusion at 600-750^{o}C for one hour.

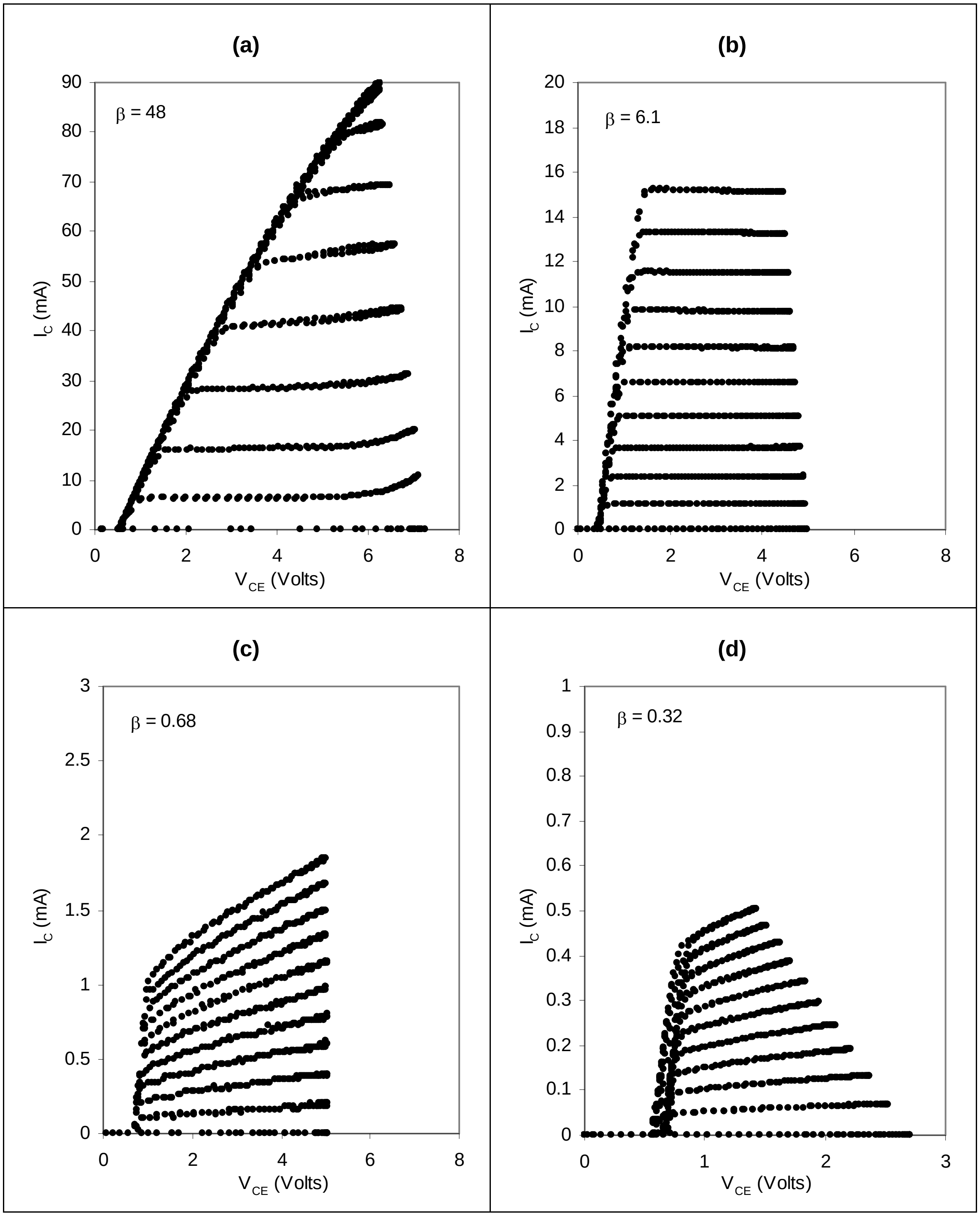

Figure 6.5. Common-emitter I-V characteristics of AlGaAs-GaAs-GaAs HBTs subjected to various thermal processes: (a) as-grown and unannealed, (b) annealed at 750^{o}C for one hour, and formed via fusion for one hour at (c) 600^{o}C and (d) 750^{o}C. Current gains (β) were determined at I_B=0.6mA and V_{CE}=2V. I_B step size (ΔI_B) was 0.2mA.

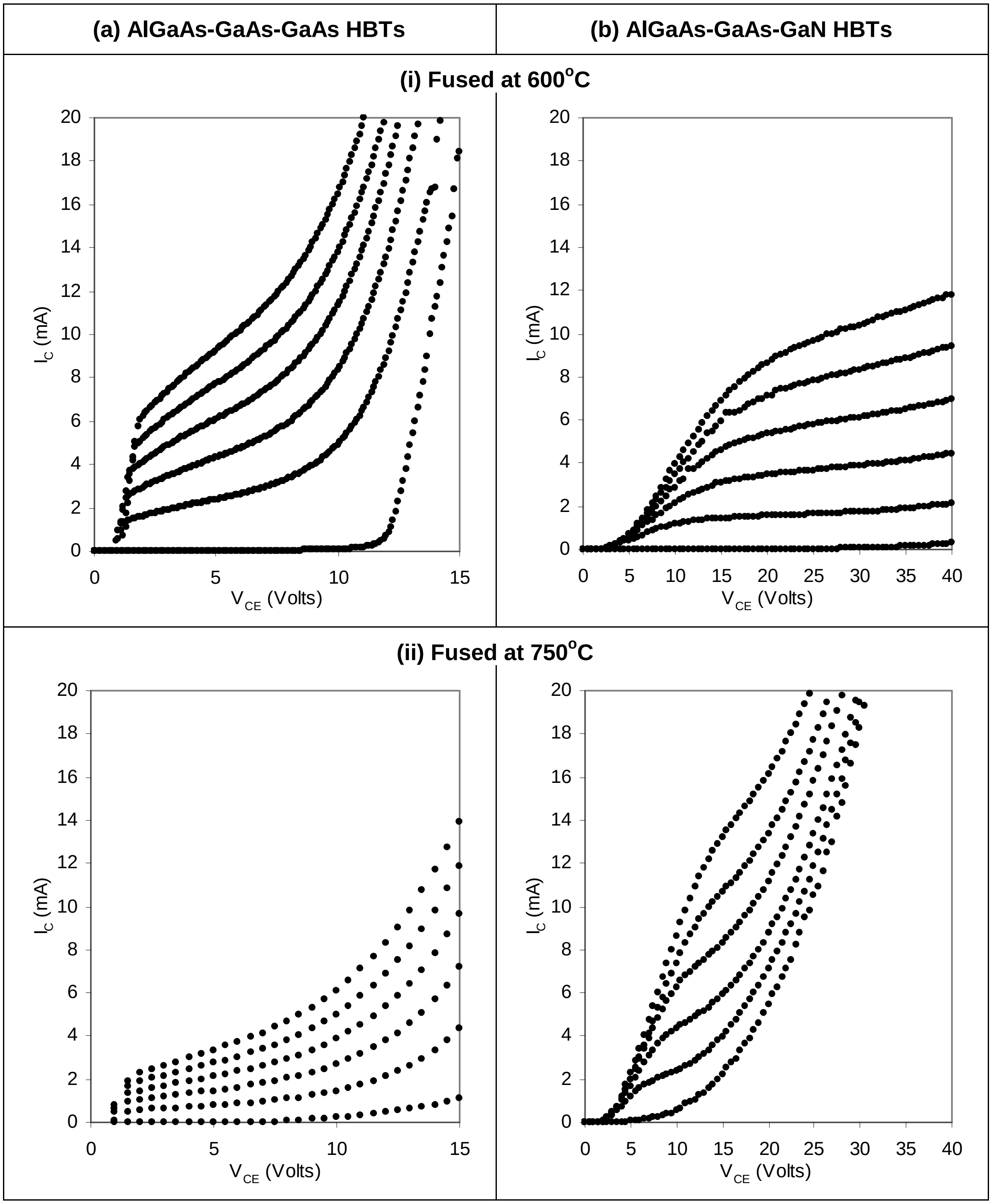

Figure 6.6. Common-emitter I-V characteristics of (a) AlGaAs-GaAs-GaAs HBTs and (b) AlGaAs-GaAs-GaN HBTs, all formed via fusion for one hour at (i) 600°C and (ii) 750°C. I_B step size (ΔI_B) was 2mA.

6.7. References

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