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Stability of carbon and beryllium-doped base GaAs/AlGaAs heterojunction bipolar transistors

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GaAs/AlGaAs heterojunction bipolar transitors (HBTs) utilizing highly Be-doped base layers display a rapid degradation of dc current gain and junction ideality factors during bias application at elevated temperature. For example, the gain of a $2\times10\ \mu m^2$ device with a $4\times10^{19}\ cm^{-3}$ Be-doped base layer operated at 200 °C with a collector current of 2.5×10^4 A cm^{-2} falls from 16 to 1.5 within 2 h. Both the base emitter and base collector junction ideality factors also rise rapidly during device operation, and this current-induced degradation is consistent with recombination-enhanced diffusion of Be interstitials producing graded junctions. By sharp contrast, devices with highly C-doped ($p = 7\times10^{19}$ cm^{-3}) base layers operated under the same conditions show no measurable degradation over much longer periods (12 h). This high degree of stability is most likely a result of the fact that C occupies the As sublattice, rather than the Ga sublattice as in the case of Be, and also has a higher solubility than Be. The effect of nearby implant isolated regions in promoting Be diffusion is also reported.

There is currently great interest in the performance and application of high speed GaAs/AlGaAs heterojunction bipolar transistor (HBT) devices and circuits.[1] To this point most of the layer structures have utilized either Be or Zn as the p-type dopants for the base layer. However, it has recently been reported that HBTs containing these dopants show a current-induced degradation of their dc characteristics during operation of the devices.[2,3] To simulate this effect, Uematsu and Wada[4] used Be-doped GaAs tunnel diodes to show that the Be diffusion under forward bias conditions was enhanced by a factor of $\sim 10^{15}$ at 300 K, and that the enhancement mechanism was most likely recombination-enhanced diffusion of Be interstitials. In HBTs the current densities are typically in the range 10^4–10^5 A cm^{-2}, somewhat larger than those used in the tunnel diodes,[4] and one might expect substantial problems with the stability of such devices. In this letter, we show that in contrast to the problems encountered with Be-doped HBTs, devices utilizing carbon as the base dopant are not subject to significant degradation during operation. We also examine the effect of implant damage isolation in promoting Be diffusion within the HBT structure.

The HBT layer structures consisting of a 6000 Å GaAs subcollector ($n = 3\times10^{18}\ cm^{-3}$), 4000 Å GaAs collector ($n = 2\times10^{16}\ cm^{-3}$), 800 Å GaAs base ($p = 4$–$7\times10^{19}$ cm^{-3}), 800 Å $Al_{0.3}Ga_{0.7}As$ emitter ($n = 5\times10^{17}\ cm^{-3}$), 200 Å graded $Al_xGa_{1-x}As$ layer ($x = 0.3\rightarrow0$, $n = 1.5\times10^{19}\ cm^{-3}$), 2000 Å GaAs contact layer ($n = 1.5\times10^{19}\ cm^{-3}$), and 300 Å graded $In_xGa_{1-x}As$ cap layer ($x = 0\rightarrow0.5$, $n = 5\times10^{19}\ cm^{-3}$) were grown by conventional solid source (Be and Si dopants) molecular beam epitaxy (MBE) or by all gas-source metalorganic MBE (MOMBE) at $\sim$500 °C growth temperature. In this latter case carbon (from the trimethylgalluim source chemical) and tin (from tetraethyltin) were used as the p and n dopants, respectively. The samples were fabricated into either large diameter (100 μm), mesa-HBTs using wet chemical etching, or into small ($2\times10\ \mu m^2$) devices using the dry-etch, self-aligned process reported previously.[5] These latter devices are isolated using multiple energy implants, followed by annealing at $\geqslant$500 °C.[6] The finished devices were held at 200 °C on a temperature controlled probe stage and biased to give a collector current of 2.5×10^4 A cm^{-2} for both Be- and C-doped structures. For the measurement of the effects of implant isolation damage, structures consisting of 1000 Å GaAs ($n = 3\times10^{18}\ cm^{-3}$), 3000 Å GaAs ($n = 5\times10^{16}\ cm^{-3}$), and 2000 Å GaAs ($p = 3\times10^{19}\ cm^{-3}$) were grown by MBE on n^+ substrates and sections implanted with either F^+ ($7\times10^{13}\ cm^{-2}$, 40 keV + $7\times10^{13}\ cm^{-2}$, 100 keV + $7\times10^{12}\ cm^{-2}$, 200 keV + $7\times10^{12}\ cm^{-2}$, 250 keV) or H^+ ($3\times10^{15}\ cm^{-2}$, 40 and 60 keV) ions, followed by annealing at 525 °C for 60 s. These simulate the multiple energy $F^+ + O^+$ implant scheme needed to isolate our HBT structures. The junction current-voltage (I-V) characteristics were recorded before and after the implant and anneal steps, and the Be profiles measured by resonance ionization mass spectrometry (RIMS), a technique which has advantages over the more conventional secondary ion mass spectrometry with regard to reducing matrix effects and mass interferences.[7]

Table I shows the result of the bias-aging study of the Be- and C-doped HBTs biased at 200 °C for 2 h (Be doped) or 12 h (C doped). The Be-doped device shows a remarkable decrease in current gain from 16 to 1.5 in just 2 h, and both the base–emitter and base–collector junction ideality factors increase markedly. After bias application these ideality factors are in excess of 2 and it is not clear what this means physically other than that the junction transport characteristics are severely compromised. By contrast, the C-doped device shows no significant change in its dc characteristics even after 12 h of bias application

TABLE I. Degradation of HBTs with carbon ($p = 7\times10^{19}$ cm^{-3}) or beryllium ($p = 4\times10^{19}$ cm^{-3}) doped base layers. The device size was 2×10 μm^2, the operating temperature 200 °C and the collector current density 2.5×10^4 A cm^{-2} for both types of material. We show current gains and junction ideality factors n before and after device operation at 200 °C for various periods.

	Be doped		C doped	
	Initial	After 2 h	Initial	After 12 h
Current gain	16	1.5	17	16
Base–emitter	1.3	2.4	1.4	1.4
Base collector	2.0	4.5	1.3	1.3

at 200°C. The decrease in gain from 17 to 16 is within our measurement error. An important point to note is that the Be-doped HBT only showed degradation when bias was applied—simply heating to 200 °C for extended periods did not alter the device characteristics.

The current-induced degradation of the Be-doped devices is consistent with movement of Be out of the base layer and into the adjoining emitter and collector regions. This will produce graded junctions and most likely the higher ideality factors shown in Table I. To attempt to confirm this hypothesis, large area (100 μm diameter) devices were biased for 12 h at 200 °C, the contact metallization was removed, and the Be profile measured by RIMS. Figure 1 shows that a small amount ($\sim$80 Å) of Be redistribution into the collector layer was observed although no significant diffusion into the emitter could be detected. Although the Be spillover into the collector as a result of biasing was small, it was well above the resolution of the RIMS technique ($\sim$30 Å). A direct measurement of the Be motion is difficult in these structures which are similar in size to the RIMS analysis area, and in which Be need only penetrate the emitter–base and base–collector regions in a few areas in order to degrade the device characteristics. Because of the need to average the RIMS signal over essentially the whole area of the device, it is difficult to detect such punch-through effects. Nonetheless, this is the first direct unambiguous measurement of the motion of Be due to bias application in an HBT structure.

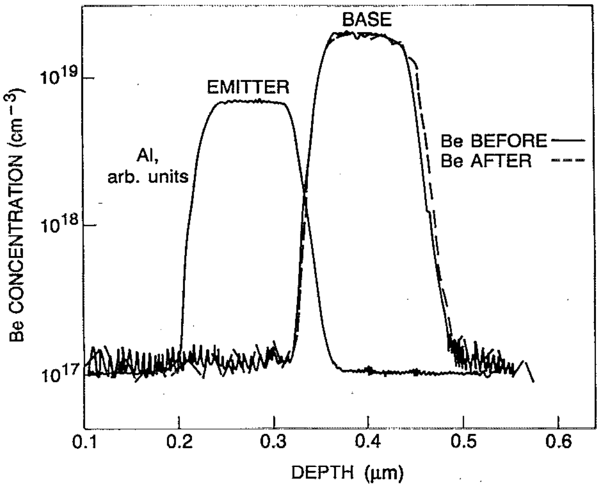

FIG. 1. RIMS profiles of Be in the base of an HBT structure before and after 12 h of bias application (collector current 2.5×10^4 A cm^{-2}) at 200 °C.

Our results are consistent with the hypothesis of Uematsu and Wada[4] with respect to the recombination-enhanced motion of Be interstitials. They suggest that electron-hole recombination at a particular site in the lattice liberates Ga interstitials, which migrate to a substitutional Be_{Ga} site and interchange, leaving a Be interstitial which is free to move through the crystal. There are clearly an ample supply of minority carriers in HBTs operating at high current densities. In the case of our C-doped devices, the carbon occupies the As sublattice and should be insensitive to the injection of interstitial Ga atoms. A further point to consider is that the doping efficiency of carbon during MOMBE growth is essentially unity, and hence there are few, if any, interstitial carbon atoms available to migrate. In contrast, we generally find an activation efficiency progressively less than unity for Be incorporated into GaAs by MBE above $\sim3\times10^{19}$ cm^{-3}, so there are most likely a substantial number of Be interstitials present even before the current-induced degradation begins. It would be interesting to monitor the stability of C-doped devices in which the layer structure was grown by metal organic chemical vapor deposition, in which interstitial carbon atoms have been detected.[8]

A further important point to note is that the current-induced degradation of Be-doped devices occurred in both mesa-isolated and implant-isolated HBTs, indicating that the presence of lattice damage is not the cause of the device degradation. It is however, necessary to understand the effect of implant isolation on the junction characteristics and on any enhanced Be diffusion during the anneal required for maximum resistivity.[6] Figure 2 shows RIMS profiles of Be in the p-n junction samples before and after either F^+ (top) or H^+ (bottom) implantation and 525 °C, 60 s annealing. In both cases there is a small amount of Be diffusion even for this low temperature anneal, and the greater degree of lattice damage created by the F^+ implants, necessary because these isolate the most highly doped layer in an HBT structure (the base), leads to marginally more diffusion. A transport of ions in matter (TRIM)[9] calculation of the damage profiles in the two cases are shown in Fig. 3. The important feature of these results is that while the implant isolation damage is not the primary cause of the enhanced Be diffusion during device operation it may assist the rate of initial degradation by providing a source of defects and interstitial Be atoms. Further work is being performed on this point.

Consistent with the greater degree of damage in the form of deep level, recombination centers created by the F^+ implants, Fig. 4 shows that there is an increase in low-bias, base–collector current in the p-n junctions. Less increase in this current is observed for the annealed H^+ implants. This type of junction degradation represents the downside of using implantation for either base–collector capacitance reduction or device isolation of HBTs. The alternative of mesa isolation is not attractive however for circuit fabrication where the maintenance of surface pla-

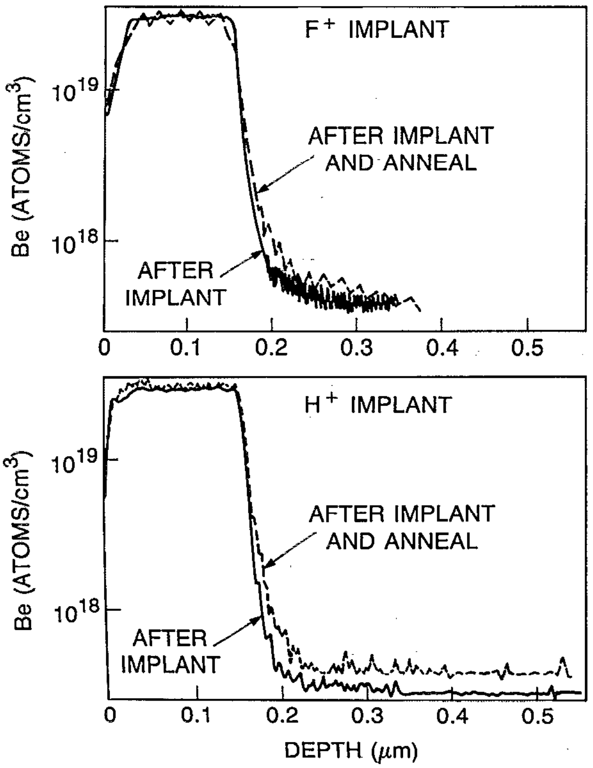

FIG. 2. RIMS profiles of Be in a *p-n* junction after implantation with F^+ (7×10^{13} cm^{-2}, 40 + 100 keV; 7×10^{12} cm^{-2}, 200 + 250 keV) ions (top) or H^+ (3×10^{15} cm^{-2}, 40 + 60 keV) ions (at bottom) and after a subsequent anneal at 525 °C for 60 s.

narity is key. Eventually however, III–V technology may be forced to adopt some of the dielectric isolation techniques in use for Si curcuits or selective-area growth.

In conclusion, we have shown that the current-induced

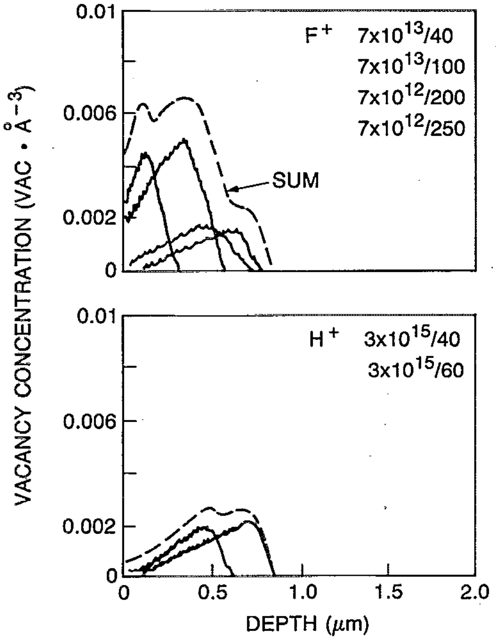

FIG. 3. Calculation of the relative damage profiles in GaAs caused by the implant isolation schemes of Fig. 2.

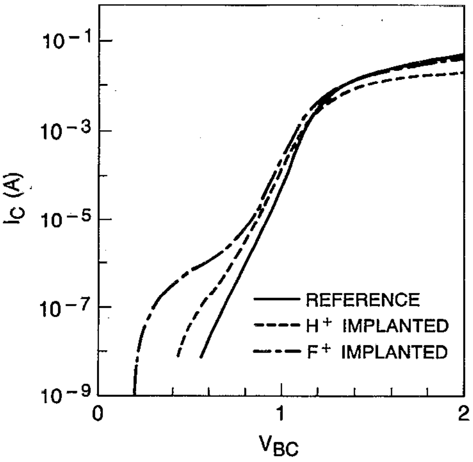

FIG. 4. Base–collector junction current–voltage characteristics from *p–n* junction before and after the implant isolation (F^+ or H^+ implant plus anneal) schemes of Fig. 2.

degradation of Be-doped HBTs, presumably as a result of recombination-enhanced Be diffusion, is absent in C-doped structures. Combined with the already well-documented dependence of Be diffusion during epitaxial growth on both Be concentration and the concentration of *n*-type dopants in the layers adjoining the base region,[10,11] there appear to be few reasons to continue the use of very high concentrations of Ga-site acceptors in structures intended for high-speed HBT circuit applications. In devices requiring lower doping, the Ga-site acceptors may still be acceptable.

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