Surface passivation effects of As_2S_3 glass on self-aligned AlGaAs/GaAs heterojunction bipolar transistors

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A recently developed As_2S_3 chemical treatment was used to passivate the perimeters of self-aligned heterojunction bipolar transistors (HBTs). The As_2S_3 chemical treatment significantly lowered the base current resulting in a two order of magnitude reduction in the collector current density at which dc current gain was observed ($\beta = 1$). No degradation with time has been observed in the electrical characteristics of the chemically treated HBTs. This absence of degradation is attributed to the impermeability to oxygen of the As_2S_3 glass which coats the perimeter of the HBT after chemical treatment.

The AlGaAs/GaAs heterojunction bipolar transistor (HBT) is a very promising device for high-speed applications. Both high-speed performance and low power consumption require the reduction of lateral dimensions of an HBT to minimize parasitic capacitances and resistances. However, it has been found that the current gain of an HBT degrades as the emitter size is scaled down.[1] This current gain degradation is caused by the increased importance of base current associated with high surface recombination of minority carriers around the unpassivated emitter-base junction perimeter and at the exposed base surface.[1–3] This surface recombination can be minimized by the use of a graded base to establish a built-in electric field to steer the electrons away from the exposed base surface,[3] or by the use of an AlGaAs layer to passivate the base surface.[4,5]

In the last few years it has been shown that chemical treatments of GaAs surfaces with inorganic sulfides can produce dramatic modifications of the surface electrical properties.[6–12] The gains of non-self-aligned HBTs have been shown to increase by 60-fold with treatment of the emitter base junction with $Na_2S \cdot 9H_2O$.[6,7] Reductions in edge recombination currents have been observed with $Na_2S \cdot 9H_2O$ and ammonium sulfide treatment of GaAs *pn* homojunction solar cells.[8] These reductions in perimeter currents can be attributed to the reduction in surface recombination of the GaAs surface after inorganic sulfide treatment.[11] The chemical nature of one of these inorganic sulfide treatments, ammonium sulfide, has been investigated with x-ray photoelectron spectroscopy (XPS).[13–15] The XPS studies found that the ammonium sulfide treatment removes surface oxides and terminates the GaAs surface with about a monolayer of sulfur. Since the ammonium sulfide chemically modified GaAs surface is terminated with just a monolayer of sulfur, it is not surprising that the surface eventually degrades back to its initial electrical characteristics, due to reoxidation of the underlying GaAs.[14] Recently, Yablonovitch *et al.*[16] have developed a sulfide chemical treatment which leaves the GaAs surface coated with an amorphous As_2S_3 layer. This As_2S_3 chemical treatment resulted in a 100-fold reduction in perimeter current for conventional double-heterostructure lasers with no degradation after four months. This absence of degradation was attributed to the impermeability of the As_2S_3 glass, which prevents oxygen from diffusing to the GaAs surface. The As_2S_3 chemical treatment has also been applied to GaAs *pn* homojunctions resulting in at least a tenfold reduction in the perimeter current.[17] In this letter we report our investigations of the passivation of self-aligned HBTs with the As_2S_3 chemical treatment.

The AlGaAs/GaAs HBT structure used in this experiment is shown in Fig. 1. The epitaxial layers were grown in a Varian GEN II molecular beam epitaxy system on a 2-in.-diam semi-insulating (100)GaAs substrate. The epitaxial layers were grown at a substrate temperature of 600 °C. Si was used as the *n*-type dopant and Be as the *p*-type dopant. The doping densities of the epitaxial layers were determined from the calibrated temperatures of the dopant ovens. The top and bottom of the AlGaAs emitter were parabolically graded to an Al mole fraction of 0.3 over 300 Å. All the HBTs were oriented at 45° to the (110) planes (the natural cleavage planes) so that wet-etched vertical sidewalls were obtained. Alloyed AuGe/Ni/Ti/Au was used for the *n*-type contacts to the emitter and collector, and nonalloyed Ti/Au for contact to the *p*-type base. The emitter contact was used as a mask for both the base etch and the base metallization. A photoresist mask covering the emitter and base contacts was used to define the base and also used as a lift-off mask for the collector metallization. Another photoresist mask was then used to define the collector contact and device isolation. Wet etching of the AlGaAs and GaAs layers was performed using 20:7:1000 $NH_4OH:H_2O_2:H_2O$, which provided well defined vertical sidewalls and an undercut ratio of 1:1. The base and collector contacts were on opposite sides of the emitter as shown in Fig. 1.

After fabrication, the HBTs were electrically characterized. Contacts were made to the HBTs by probing on a micromanipulator model 6000 probe station and electrical data were taken with a Hewlett–Packard model 4145 semiconductor parameter analyzer. Following the electrical

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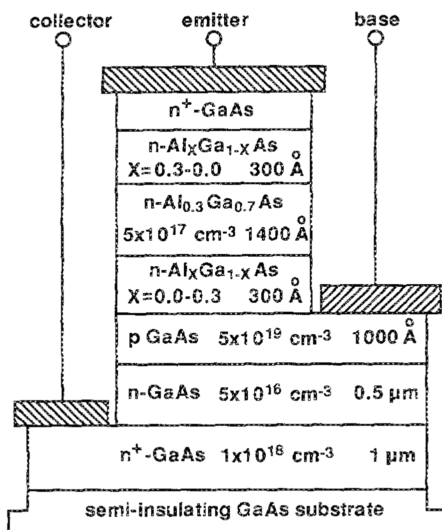

FIG. 1. Cross section of the AlGaAs/GaAs heterojunction bipolar transistor.

characterization, the HBTs underwent As_2S_3 chemical treatment.[16] Briefly, the As_2S_3 chemical treatment consisted of an oxide removal etch in 1:10 NH_4OH:H_2O followed by a 5 min soak in ammonium sulfide. The sample was then rinsed in de-ionized water and placed in a solution of 0.16 M As_2S_3 dissolved in a 1:1 solution of NH_4OH:CH_3OH. The sample was then spun dry under flowing nitrogen. The final step was an anneal at 280 °C on a graphite strip heater in flowing nitrogen for 2 min.

Following As_2S_3 chemical treatment, the HBTs were again electrically characterized. Shown in Fig. 2 is the collector (I_C) and the base (I_B) currents as a function of the base-emitter (V_{BE}) voltage with the base collector junction shorted for an HBT with an emitter size of 14 μm × 14 μm before and after the As_2S_3 chemical treatment. (HBTs with emitter sizes of 14 μm × 14 μm were the smallest HBTs we were able to test after the As_2S_3 treatment without damaging the devices when probing through the As_2S_3 film.) No change was observed in the collector current except for a difference in roll-off at high current levels due to a difference in series resistance. (This difference in series resistance is probably a consequence of the probe contact.) In contrast, there is over an order of magnitude reduction in the base current at biases of $V_{BE} = 0.6$–0.7 V following the As_2S_3 chemical treatment. Also seen in Fig. 2 is that the leakage current initially observed in the base current has been eliminated by the As_2S_3 chemical treatment. Another significant change due to the As_2S_3 chemical treatment was a reduction in the ideality factor of the base current from $n = 1.81$ to 1.54 for biases of $V_{BE} = 0.7$–1.1 V. (The ideality factor of the collector current for biases of $V_{BE} = 0.9$–1.2 V was $n = 1.01$ before and after the chemical treatment). Similar behavior was observed with all the treated HBTs.

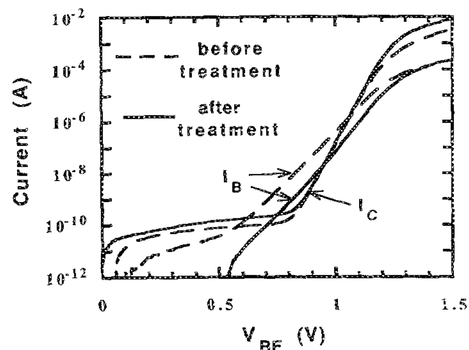

FIG. 2. Collector and base currents as a function of base-emitter voltage with the base collector junction shorted. Characteristics before and after the As_2S_3 chemical treatment of the emitter-base perimeter are shown. The emitter size is 14 μm × 14 μm.

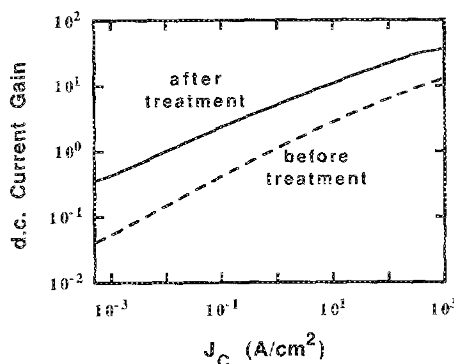

FIG. 3. dc current gain as a function of collector current density determined from Fig. 2 HBT characteristics.

To illustrate the effects of chemical treatment on dc current gain of the HBT, we have plotted the ratios of the collector-to-base currents before and after treatment as a function of the collector current density in Fig. 3. Observed in Fig. 3 is that the collector current density at which gain is first observed ($\beta = 1$) has been lowered by about two orders of magnitude following the As_2S_3 chemical treatment. Also, the dc current gain shows an increase of more than a factor of 10 at the lower current densities. However, the dc current gain after the As_2S_3 chemical treatment still exhibits a strong dependence on current density, which is caused by a continued presence of a base current component due to recombination in the emitter-base depletion region. There is either still some perimeter recombination or the recombination is dominated by the bulk of the junction in the emitter-base depletion region after the As_2S_3 chemical treatment.

In summary, we have investigated the effects of treating the exposed perimeters of self-aligned HBTs with a new As_2S_3 chemical passivation technique. The As_2S_3 chemical treatment significantly lowered the base current, resulting in a two order of magnitude reduction in the collector current density at which dc current gain is observed ($\beta = 1$). Furthermore, no degradation has been observed in the treated HBT characteristics after two months exposure to room temperature and atmospheric conditions.

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[1] O. Nakajima, K. Nagata, H. Ito, T. Ishibashi, and T. Sugeta, Jpn. J. Appl. Phys. **24**, L596 (1985).
[2] S. Tiwari, D. Frank, and S. L. Wright, J. Appl. Phys. **64**, 5009 (1988).
[3] H. Ito, T. Ishibashi, and T. Sugeta, Jpn. J. Appl. Phys. **24**, L241 (1985).
[4] S. Tiwari, *1986 International Electron Devices Meeting Technical Digest* (IEEE, New York, 1986), p. 262.
[5] H. H. Lin and S. C. Lee, Appl. Phys. Lett. **47**, 839 (1985).
[6] C. J. Sandroff, R. N. Nottenburg, J. C. Bischoff, and R. Bhat, Appl. Phys. Lett. **51**, 33 (1987).
[7] R. N. Nottenburg, C. J. Sandroff, D. A. Humphrey, T. H. Hollenbeck, and R. Bhat, Appl. Phys. Lett. **52**, 218 (1988).
[8] M. S. Carpenter, M. R. Melloch, M. S. Lundstrom, and S. P. Tobin, Appl. Phys. Lett. **52**, 2157 (1988).
[9] M. S. Carpenter, M. R. Melloch, and T. E. Dungan, Appl. Phys. Lett. **53**, 66 (1988).
[10] J. F. Fan, H. Oigawa, and Y. Nannichi, Jpn. J. Appl. Phys. **27**, L2125 (1988).
[11] E. Yablonovitch, C. J. Sandroff, R. Bhat, and T. J. Gmitter, Appl. Phys. Lett. **51**, 439 (1987).
[12] E. Yablonovitch, H. M. Cox, and T. J. Gmitter, Appl. Phys. Lett. **52**, 1002 (1988).
[13] C. J. Sandroff, M. S. Hegde, L. A. Farrow, C. C. Chang, and J. P. Harbison, Appl. Phys. Lett. **54**, 362 (1989).
[14] B. A. Cowans, Z. Dardas, W. N. Delgass, M. S. Carpenter, and M. R. Melloch, Appl. Phys. Lett. **54**, 365 (1989).
[15] M. S. Carpenter, M. R. Melloch, B. A. Cowans, Z. Dardas, and W. N. Delgass, J. Vac. Sci. Technol. B 7, 845 (1989).
[16] E. Yablonovitch, T. J. Gmitter, and B. G. Bagley Appl. Phys. Lett. **57**, 19 Nov. (1990).
[17] T. B. Stellwag, P. E. Dodd, M. S. Carpenter, M. S. Lundstrom, R. F. Pierret, M. R. Melloch, E. Yablonovitch, and T. J. Gmitter, Conference Record of the 21st IEEE Photovoltaic Specialists Conference (IEEE, New York, 1990).