Carbon-doped GaInP/GaAs heterojunction bipolar transistors grown by metalorganic chemical vapor deposition using nitrogen as the carrier gas

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The use of nitrogen as the carrier gas in metalorganic chemical vapor deposition (MOCVD) for the growth of carbon-doped GaInP/GaAs heterojunction bipolar transistors (HBTs) is reported. The material quality grown using a nitrogen carrier gas is the same as that of using a hydrogen carrier gas. High carbon doping and hole concentrations of 3×10^{20} and 2×10^{20} cm^{-3} in GaAs were obtained. The fabricated HBTs showed very good DC and RF performances indicating that nitrogen can be a promising carrier gas for MOCVD growth. © *1997 American Institute of Physics.* [S0003-6951(97)02348-6]

Great attention to the carbon-doped GaInP/GaAs heterojunction bipolar transistors (HBTs) has been paid, because of their promising performance for microwave applications.[1] In addition, carbon does not form an acceptor state in the GaInP layer, which improves HBT performance.[2] Metalorganic chemical vapor deposition (MOCVD) is one of the most attractive processes for the epitaxial growth of C-doped GaAs-based HBTs, especially for phosphorus containing materials. This is because MOCVD provides high throughput and excellent compositional control. However, safety is an important issue in the MOCVD process for both research and production. In the past, we have demonstrated that toxic group V hydrides, arsine and phosphine, can be replaced with safer alternative group V metalorganics, tertiary-butyl arsine (TBA) and tertiary-butyl phosphine (TBP), in the fabrication of C-doped GaInP/GaAs HBTs with excellent performance.[3] A further improvement in safety would be the replacement of the explosive hydrogen carrier gas by an inert gas. In the last few years, nitrogen has been demonstrated to be an excellent carrier gas in MOCVD for the growth of GaAs- and InP-based materials.[4,5] The material quality of the epitaxial layers grown with nitrogen as the carrier gas is comparable to that of layers grown with hydrogen. In addition, nitrogen is an inexpensive inert gas which reduces the cost of material growth. These factors impel us to consider the use of nitrogen as the carrier gas in the MOCVD growth process.

This letter reports the experimental results of the MOCVD grown C-doped GaAs layer and GaInP/GaAs HBTs using nitrogen as the carrier gas. Very high carbon doping and hole concentrations in GaAs were obtained. Good DC and RF performances of the HBT were achieved.

The MOCVD growth was carried out in a horizontal low pressure reactor. The metalorgnanic precursors used were TMGa, TMIn, TBA and TBP. Nitrogen was used as the carrier gas. Nitrogen bubbled through the metalorganic sources in order to carry the vapor into the reactor. Disilane (100 ppm in hydrogen) was employed as the n-type dopant, and CCl_4 as the p-type dopant. The growth temperature was 600 °C–650 °C. Due to the lower gas phase diffusion coefficients of the metalorganics in nitrogen, the growth rate and therefore the growth efficiency in nitrogen are 60% of that in hydrogen. The nitrogen flow rate and the reactor pressure have to be adjusted accordingly to optimize the growth efficiency and uniformity in the present reactor.

Two types of structure were under study. The first was used to check the carbon doping profiles in GaAs. Two structures with different doping densities were grown. Structure A consists of a 800 Å and a 9000 Å GaAs layer with carbon doped at 3×10^{20} and 7×10^{19} cm^{-3}, respectively. Structure B consists of a 1800 Å and a 8000 Å GaAs layer with carbon doped at 1×10^{19} and 2×10^{16} cm^{-3}, respectively. Carbon concentrations were measured by secondary ion mass spectroscopy (SIMS) analysis. Hole carrier concentrations were measured with a Bio-Rad electrochemical capacitance-voltage (C-V) profiler. The second type was a HBT structure consisting of a 5000 Å GaAs subcollector layer ($n=3\times10^{18}$ cm^{-3}), a 5000 Å GaAs collector layer ($n=3\times10^{16}$ cm^{-3}), a 1000 Å GaAs base layer ($p=1-8\times10^{19}$ cm^{-3}), a 500 Å GaInP emitter layer ($n=3\times10^{17}$ cm^{-3}), a 1500 Å GaAs emitter cap layer ($n=4\times10^{18}$ cm^{3}) and a 600 Å graded $In_xGa_{1-x}As$ (x from 0 to 0.5) contact layer ($n=5\times10^{18}$ cm^{-3}). The HBTs were fabricated with a mesa structure using the conventional method described earlier.[3] The emitter size was 5×5 μm^2.

Figure 1 shows SIMS carbon and hole concentration profiles for structures A and B. A very high doping density of 3×10^{20} cm^{-3} and hole concentrations of 2×10^{20} cm^{-3} were obtained. Relatively constant doping was also achieved. The profile of the hole concentration is very similar to that of the carbon. An abrupt carbon profile was achieved for struc-

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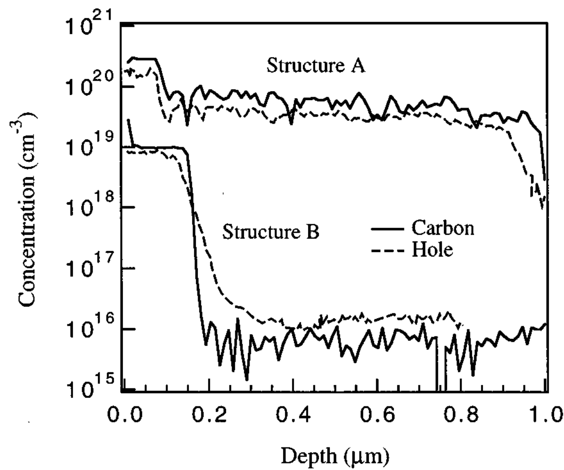

FIG. 1. SIMS depth profile and hole concentration profile for structures A and B grown using N_2 carrier gas. A very high carbon doping, high hole concentration and an abrupt carbon profile were obtained.

ture B, but hole diffusion is observed in the transit region due to the large concentration gradient of the carbon doping. Because of some errors in measuring the low doping concentration, the hole concentration for structure B is higher than the carbon doping density in the low doping region which may not be correct. However, the overall profiles from SIMS and Bio-Rad agree well.

Figure 2 shows the differential current gain versus base sheet resistance for the HBTs. The current gain was measured at a collector current density of 4×10^4 A/cm^2. The data for HBTs grown using a H_2 carrier gas is also shown for comparison. The current gain for the HBTs using a N_2 carrier gas follows a similar slope to that for the HBTs using a H_2 carrier gas indicating that the material quality using N_2 is the same as that using H_2. A low base sheet resistance was obtained using the N_2 carrier gas. However, there is a tradeoff between base sheet resistance and the current gain as well as the maximum oscillation frequency.

The typical Gummel plot for a HBT with a base sheet resistance of 150 Ω/sq is shown in Fig. 3. The ideality factor for the collector current is 1.00 which corresponds to the ideal diffusion current. The base current ideality factors are 2.00 and 1.67 for the low and high base current regimes, which are related to typical surface recombination and base bulk recombination currents, respectively.

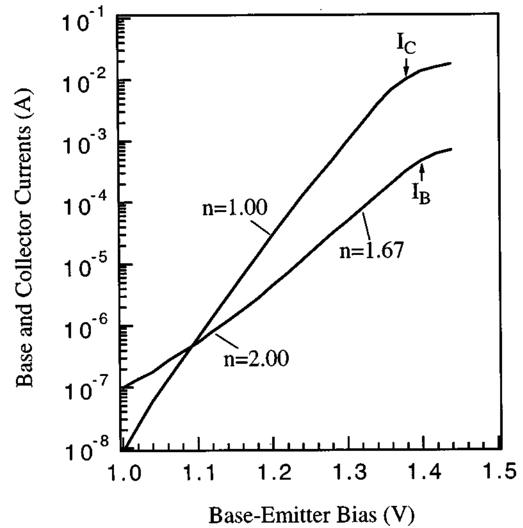

FIG. 3. Gummel plot of a HBT grown using N_2 carrier gas with a base sheet resistance of 150 Ω/sq.

Figure 4 shows the cutoff frequency (f_T) and maximum oscillation frequency (f_{max}) as a function of collector current density for a HBT with a base sheet resistance of 150 Ω/sq. The peak f_T of 45 GHz and peak f_{max} of 120 GHz were obtained for 5×5 μm^2 HBTs. As a comparison with HBTs grown using the H_2 carrier gas, the peak f_T and peak f_{max} are 45 GHz and 110 GHz, respectively, for the HBT with a base sheet resistance of 160 Ω/sq. This further demonstrates the high quality of the HBT material grown using a nitrogen carrier gas.

In summary, we have reported the successful MOCVD growth of C-doped GaAs layers and GaInP/GaAs HBTs us-

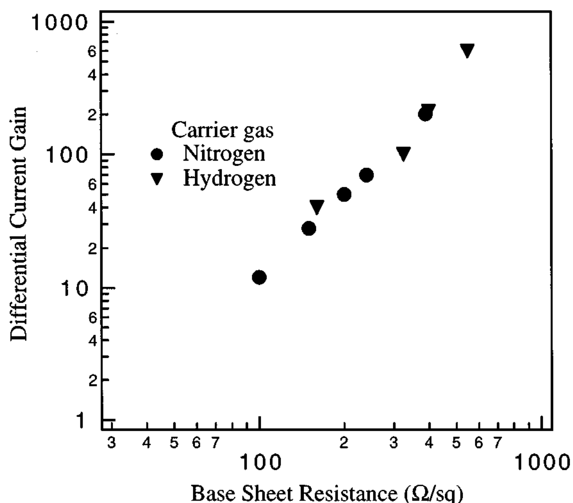

FIG. 2. Differential current gain vs base sheet resistance for HBTs grown using N_2 and H_2 carrier gases. The current gain for HBTs using N_2 carrier gas follows a similar slope to that for HBTs using H_2 carrier gas.

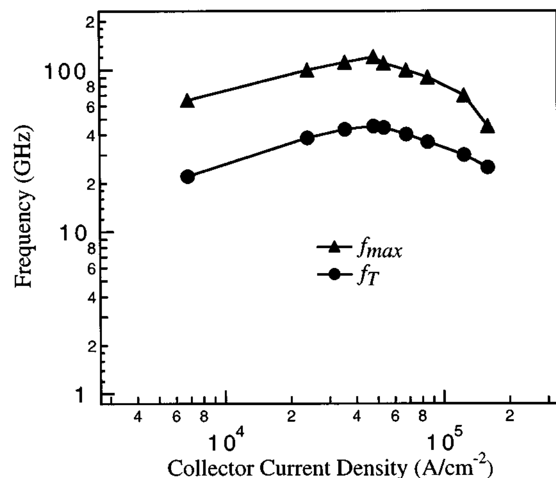

FIG. 4. Cutoff frequency and maximum oscillation frequency as a function of collector current density for a HBT using N_2 carrier gas. The HBT has a base sheet resistance of 150 Ω/sq. Peak f_T of 45 GHz and peak f_{max} of 120 GHz were obtained.

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ing nitrogen as the carrier gas. High hole concentrations and very sharp carbon doping profiles were obtained. The quality of the material grown using the nitrogen carrier gas is the same as that using the hydrogen carrier gas. The good RF performance of the HBTs with a maximum oscillation frequency of 120 GHz and a cutoff frequency of 45 GHz indicates the high quality of the material grown using the nitrogen carrier gas. The above results show that nitrogen can be a promising carrier gas for MOCVD growth.

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