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Enhanced Carbon Incorporation in InGaAs Grown at Low Temperature by Metalorganic Molecular Beam Epitaxy (MOMBE)

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Heavily carbon-doped p-type InGaAs is promising for a base layer of InP/InGaAs or GaAs/InGaAs heterojunction bipolar transistors (HBTs) provided carbon can be highly incorporated with a high electrical activation as an acceptor and has low diffusivity in InGaAs. Although there have been a number of reports on successful carbon doping in InGaAs, carbon doping in InGaAs is complicated by an amphoteric nature of carbon in InGaAs. In general carbon becomes an acceptor in GaAs but a donor in InAs. The amphoteric nature of carbon makes it difficult to obtain carbon-doped InGaAs with a high hole concentration, particularly for high indium molar fractions. In this paper we report the MOMBE growth of carbon-doped InGaAs with high hole concentrations. A hole concentration of as high as 5×10^{19} cm^{-3} is obtained for $In_{0.48}Ga_{0.52}As$, which is nearly lattice-matched with InP substrate.

Carbon-doped InGaAs layers with a thickness of 3000 A were grown at low temperatures by metalorganic molecular beam epitaxy(MOMBE). Figure 1 shows a schematic diagram of a MOMBE apparatus with a pressure-control supply of trimethylgallium (TMG). The InGaAs layers were grown on semi-insulating (SI) GaAs (001) substrates by MOMBE using TMG, solid In and As_4. In order to achieve higher hole concentrations, we employed low growth temperature, which was effective to obtain heavily carbon-doped p-type GaAs with a hole concentration of as high as 1.5×10^{21} cm^{-3} by MOMBE using TMG and As_4[1]. The indium molar fraction was varied by adjusting the indium beam flux.

Figure 2 shows the hole concentrations for various indium molar fractions of InGaAs grown at temperatures of 380 and 450 °C. The hole concentration of InGaAs grown at 380 °C is an order of magnitude higher than that grown at 450 °C for each indium molar fraction. In the MOMBE growth of InGaAs, an amount of monomethylgallium ($GaCH_3$) is believed to control the constituent GaAs growth rate and carbon incorporation. Carbon is incorporated with a Ga-C bond and can effectively occupy an arsenic site of the growing layer. Since low growth temperature increases an amount of Ga-C bonds at the growing surface, one can expect a higher hole concentration.

Figure 3 shows a comparison of hole concentrations of carbon-doped p-type InGaAs for various growth methods. Increased hole concentrations were found after annealing GSMBE-grown $In_{0.5}Ga_{0.5}As$[2] and MOCVD-grown $In_{0.53}Ga_{0.47}As$[3], which suggests hydrogen from the carrier gas and/or the cracked AsH_3 passivates carbon.

However, incorporation of less hydrogen is expected during the MOMBE growth using helium as a carrier gas, which results in a higher hole concentration in the as-grown even for high indium molar fractions. The described MOMBE growth of InGaAs with high hole concentrations has an advantage over the GSMBE and MOCVD growth because it does not require an annealing step, which may relax a lattice mismatch and generate misfit dislocations.

References

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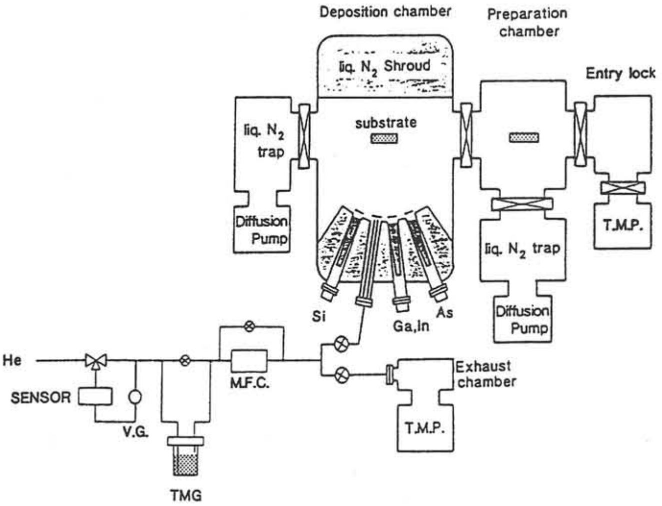

Fig. 1. Schematic diagram of a MOMBE apparatus with a pressure control gas-supply of TMG.

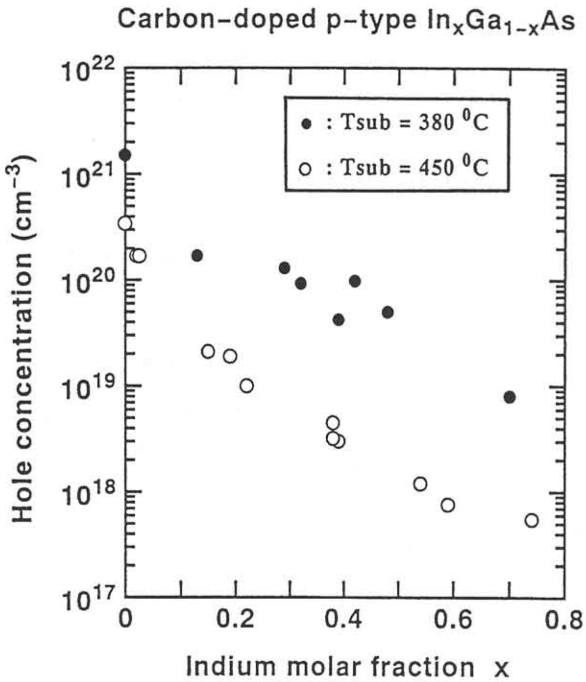

Fig. 2. Dependence of the hole concentrations on the indium molar fractions at growth temperatures of 380 and 450 °C. ● and ○ represent growth temperatures of 380 and 450 °C, respectively.

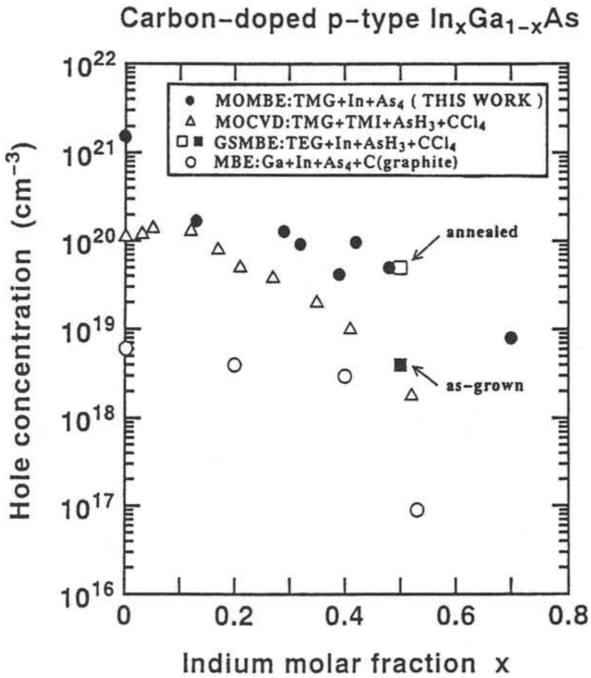

Fig. 3. Comparison of hole concentrations of carbon-doped p-type InGaAs for various growth methods. ■, △ and ○ represent carbon-doped $In_xGa_{1-x}As$ layers grown by GSMBE using CCl_4[2], MOCVD using CCl_4[3] and MBE using graphite[4] as a carbon source, respectively. □ shows the hole concentration of the InGaAs grown by GSMBE after annealing for 5 min at 420 °C.