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Contact resistivity to C-doped (In)GaAsSb with Ti/Pt/Au and Pt/Ti/Pt/Au

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Abstract

We report contact resistivity (ρ_C) of a Ti- or Pt-based electrode to C-doped (In)GaAsSb. For both electrodes, the ρ_C to C-doped InGaAsSb is high due to the lower hole concentration, compared with C-doped GaAsSb. For Ti/Pt/Au electrodes, ρ_C to C-doped InGaAsSb is significantly increased by annealing at 400 °C. On the other hand, ρ_C of Pt/Ti/Pt/Au electrodes is almost constant against annealing temperature. We obtained ρ_C ~ 3 Ωμm^2 to C-doped GaAsSb (hole concentration of 7.9 x 10^{19} cm^{-3}) without annealing. The results indicate that the use of C-doped GaAsSb as a contact layer with Pt-based electrodes in high-speed DHBTs with a graded InGaAsSb base is an appropriate way to obtain a very low ρ_C for boosting f_{max}.

1. Introduction

Double heterojunction bipolar transistors (DHBTs) with an InGaAsSb-quaternary base are attracting a great interest for the applications to ICs operating in the sub-THz region because of their high f_T and reasonably high breakdown voltage[1]. As for f_{max}, reported values for DHBTs with an InGaAsSb base are still smaller than the record for DHBTs with a GaAsSb base (780 GHz)[2] and InGaAs base (> 1.1 THz)[3]. For boosting f_{max}, it is necessary to reduce a base contact resistivity (ρ_C). However, there are very few reports on the contact characteristics for p-type InGaAsSb[4]. In this study, we intensively investigated the contact resistivity of Ti- and Pt-based electrodes, which are widely used in the III-V compound materials, to C-doped GaAsSb and InGaAsSb.

2. Experiments, Results and Discussion

C-doped p-type InGaAsSb films with approximate thickness of 50 to 150 nm were grown on semi-insulating (001)InP substrate by MOCVD. Transmission line measurements (TLM) were performed to estimate ρ_C. Samples with Ti/Pt/Au (20/20/200 nm) or Pt/Ti/Pt/Au (20/20/20/200 nm) electrodes were prepared to investigate the difference in ρ_C with the metal configuration.

In the MOCVD growth of C-doped (In)GaAsSb, the supply of CBr_4 (doping precursor) affects the solid In/Sb contents (i.e. the band gap and energy of valence band minimum) due to the etching effect of CBr_4[5]. Carrier concentration is also an important parameter for ρ_C. Therefore, we first investigated the dependence of ρ_C on the sum of the solid In content (x) and that of Sb (y), or ($x + y$), and hole concentrations (p). The results are shown in Figs. 1 and 2. The data for GaAsSb (open circles) and InGaAsSb (closed circles) without annealing (as deposited) are plotted. As shown in Fig. 1, ρ_C for InGaAsSb decreases as ($x + y$) decreases for both the Ti/Pt/Au and Pt/Ti/Pt/Au electrode configurations. This result essentially depends on the carrier concentration. As shown in Fig. 2, ρ_C tends to decrease with increasing hole concentration similar to other III-V materials[6]. Generally, it is very difficult to obtain a high hole concentration for InGaAsSb with high In- and Sb-content because of the etching effect of doping precursors in MOCVD[5]. That is why the ρ_C to InGaAsSb tends to be high compared with GaAsSb.

Compared with the ρ_C of the Pt/Ti/Pt/Au electrode, that of the Ti/Pt/Au electrode is high for the non-annealed condition. As a next step, in order to evaluate the impact of the thermal process, the samples were annealed in N_2 ambient.

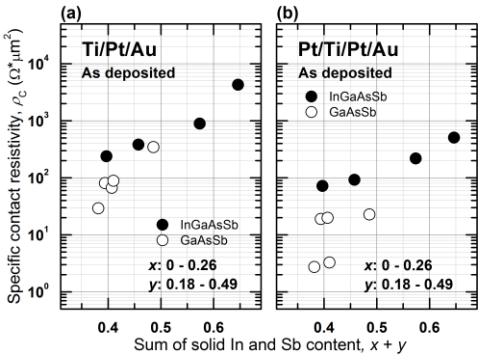

Fig. 1 Contact resistivity vs. the sum of the solid In and Sb contents ($x + y$) for the samples with (a) Ti/Pt/Au and (b) Pt/Ti/Pt/Au electrodes.

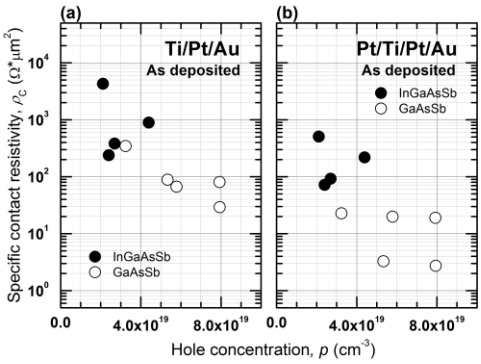

Fig. 2 Contact resistivity vs. hole concentration for the samples with (a) Ti/Pt/Au and (b) Pt/Ti/Pt/Au electrodes.

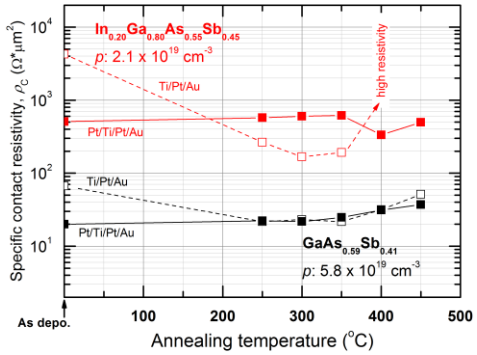

Fig. 3 Dependence of the contact resistivity to C-doped $In_{0.20}Ga_{0.80}As_{0.55}Sb_{0.45}$ and $GaAs_{0.59}Sb_{0.41}$ on annealing temperature.

The ρ_C of C-doped $In_{0.20}Ga_{0.80}As_{0.55}Sb_{0.45}$ and $GaAs_{0.59}Sb_{0.41}$ are plotted as a function of annealing temperature (T_A) in Fig. 3. Note that measurement and annealing were performed alternately for the same samples. (i.e. measurement -> annealing (250 °C, 30 sec) -> measurement -> annealing (300 °C, 30 sec) and so on). For the Pt/Ti/Pt/Au electrode (closed squares), ρ_C is almost constant against T_A for both C-doped $GaAs_{0.59}Sb_{0.41}$ and $In_{0.20}Ga_{0.80}As_{0.55}Sb_{0.45}$. For the Ti/Pt/Au electrode (open squares), ρ_C to C-doped $GaAs_{0.59}Sb_{0.41}$ and $In_{0.20}Ga_{0.80}As_{0.55}Sb_{0.45}$ decreases as T_A increases and becomes minimum at around 300 °C. The minimum value for $GaAs_{0.59}Sb_{0.41}$ is almost same as that of Pt/Ti/Pt/Au electrode. However, ρ_C becomes high when T_A is over 400 °C. In the *I-V* characteristics of the TLM for C-doped $In_{0.20}Ga_{0.80}As_{0.55}Sb_{0.45}$, the dependence of the electric resistance on the distance between electrodes was extinguished after annealing at 400 °C and the current density was significantly low compared with the sample annealed at 300 and 350 °C (indicated as "high resistivity" in Fig. 3).

The degradation of the electric characteristics of Ti/Pt/Au electrodes to C-doped (In)GaAsSb is related to the metal-semiconductor interface reactions. The surface morphology of Ti/Pt/Au electrodes on the C-doped InGaAsSb after annealing at 400 °C is shown in Fig. 4 (a). The sample exhibits very rough surface morphology. This is due to the degradation of interface quality between the Ti-based contact and InGaAsSb caused by high temperature thermal process. On the other hand, as shown in Fig. 4(b) and (c), the surface morphologies of the Pt/Ti/Pt/Au electrode on C-doped GaAsSb and InGaAsSb are very flat even though the sample was annealed at 450 °C. Therefore, the Pt-based electrode is more stable against thermal annealing than the Ti-based ones.

We experimentally obtained the minimum ρ_C of ~ 43 $\Omega\mu m^2$ to InGaAsSb (p ~ 4.4 x 10^{19} cm^{-3}) and ~ 3 $\Omega\mu m^2$ to GaAsSb (p ~ 7.9 x 10^{19} cm^{-3}). The former is an order of magnitude greater than that to GaAsSb. From the viewpoint of contact resistivity and thermal stabilities, using GaAsSb as a contact layer in DHBTs with a graded InGaAsSb base[7] is suitable for boosting f_{max}. Although the values for the GaAsSb in this study are slightly high compared with the record values for p-type GaAsSb with a Pd-based contact (< 1 $\Omega\mu m^2$)[8,9], it is expected that ρ_C of ~ 1 $\Omega\mu m^2$ can be obtained by using highly doped GaAsSb (~10^{20} cm^{-3}) in GaAsSb/InGaAsSb hybrid base DHBTs.

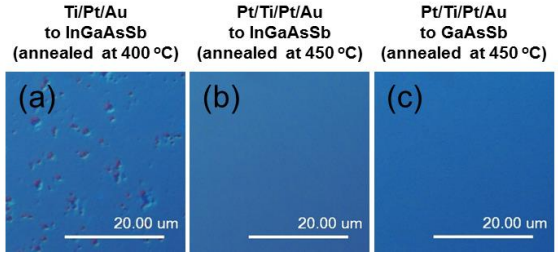

Fig. 4 Surface morphology of (a) Ti/Pt/Au contact to InGaAsSb after annealing at 400 °C, (b) Pt/Ti/Pt/Au contact to InGaAsSb after annealing at 450 °C, and (c) Pt/Ti/Pt/Au contact to GaAsSb after annealing at 450 °C.

3. Conclusions

We investigated the impact of the solid composition, hole concentration, and annealing conditions on the ρ_C of Ti- or Pt-based electrodes to C-doped GaAsSb and InGaAsSb. Since it is difficult to obtain C-doped InGaAsSb with a high hole concentration because of the etching effect of the doping precursors, the ρ_C to C-doped InGaAsSb with both Ti/Pt/Au and Pt/Ti/Pt/Au electrodes is relatively high, compared with that to C-doped GaAsSb. For Ti/Pt/Au electrodes, ρ_C to C-doped InGaAsSb is significantly increased by annealing at 400 °C. For Pt/Ti/Pt/Au, ρ_C is thermally stable and we obtained ρ_C ~ 3 $\Omega\mu m^2$ to C-doped GaAsSb (hole concentration of 7.9 x 10^{19} cm^{-3}). From these results, we conclude that the use of C-doped GaAsSb with a high hole concentration as a contact layer and a Pt-based ohmic contact in the GaAsSb/graded-InGaAsSb hybrid base is best choice for further boosting the f_{max} of antimonide-based high-speed DHBTs without sacrificing the advantage of the graded InGaAsSb base.

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