Influence of carbon sources on thermal stability of C-doped base InP/InGaAs heterojunction bipolar transistors

Noriyuki Watanabe, Masahiro Uchida, Hideo Yokohama, Gako Araki

NTT Advanced Technology Corporation,
3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-0124, Japan, Tel:+81 46 250 3344

Abstract — **We report effects of annealing on InP/InGaAs heterojunction bipolar transistors (HBTs) having an InGaAs base layer C-doped using CBr_4 or $CBrCl_3$ as the C source. It was found that ramp thermal annealing (RTA) after growth removes H atoms, which are located in C-dopedd InGaAs base layer and deactivate C acceptors, resulting in a decrease of base sheet resistance. An RTA simultaneously can deteriorate the C-doped base layer. An evaluation of base sheet resistance and dc current gain indicates that InP/InGaAs HBTs with C-doped InGaAs grown using $CBrCl_3$ are more stable in terms of thermal stress than those grown using CBr_4.**

I. INTRODUCTION

InP/InGaAs heterojunction bipolar transistors (HBTs) are considered to be key-devices for high-speed communications systems operating at over 40 Gb/s. In order to achieve good device characteristics and good reliability, heavy p-type doping with a well-controlled profile is desired for the base layer. Carbon (C) is a promising p-type dopant for III-V compound semiconductors because of its low diffusion coefficient [1-3] and its ability to be doped to extremely high levels [4, 5]. These features make C favorable as a dopant for the base layer of HBTs [6, 7].

When a C-doped InGaAs layer is grown by metalorganic chemical vapor deposition (MOCVD), the hydrogenation of C acceptors is an especially serious problem because it reduces the hole concentration [8]. It has been reported that thermal treatment in inactive gases, such as nitrogen, is effective in removing hydrogen from C-doped InGaAs layers [8-12]. However, thermal treatment for H removal could deteriorate the C-doped InGaAs if it puts too much thermal stress on the C-doped layers, could result in the degradation of device characteristics.

In this report, we investigate the influence of C sources on the thermal stability of C-doped InGaAs base layers. Two C sources (CBr_4 and $CBrCl_3$) were used for growth of C-doped InGaAs layers. From the evaluation of base sheet resistance and dc current gain, it is revealed that a C-doped InGaAs base grown using $CBrCl_3$ is more stable in terms of thermal stress than that grown using CBr_4.

II. EXPERIMENTAL PROCEDURE

Carbon-doped InGaAs and C-doped base InP/InGaAs HBT epiwafers were grown by low-pressure MOCVD on (100) oriented Fe-doped semi-insulating InP substrates. The epilayer structrure is shown in Table 1. Two kinds of halomethane (CBr_4 and $CBrCl_3$) were the C sources. Triethylgarium and trimethylindium were group-III sources, AsH_3 and PH_3 the group-V sources and H_2-diluted Si_2H_6 the Si (n-type dopant) source. Paradium-duffused H_2 was the carrier gas.

C-doped InGaAs epiwafers were annealed in N_2 ambient to remove H atoms that were deactivating C acceptors [11, 12]. Annealing temperature and duration time were 500 °C and 20 minutes, respectively. Hole concentration and mobility were evaluated by the Hall-effect measurement by the Van der Pauw method.

InP/InGaAs HBT epiwafers were annealed after growth in ramp thermal annealing (RTA) equipment. RTA temperatures were 600 and 650 °C, and duration times were 1, 2, and 5 minutes. HBT devices were

Laye	Material	Thickness (nm)	Dopant	Doping (cm^{-3})
emitter cap	n^+ InGaAs	100	Si	3×10^{19}
	n^+ InP	20	Si	2×10^{19}
emitter	i InP	70	-	-
base	p^+ InGaAs	50	C	4×10^{19}
collector	i InGaAs	300	-	-
subcollector	n^+ InP	20	Si	1×10^{19}
	n^+ InGaAs	30	Si	1×10^{19}
	n^+ InP	340	Si	1×10^{19}
etch stopper	i InGaAs	20	-	-
buffer	i InP	20	-	-

TABEL I
The Layer Structure Of InP/InGaAs HBT

electrically small unit cell with inductances/capacitances $L_R / C_L / C_R / L_L$ (H/F) mimicking the incremental cell of Fig. 1a. The corresponding dispersion relation can be computed analytically by using Kirchoff's laws and Bloch-Floquet theorem (also possible in 2D [5] or 3D). This relation is given by

$$\cos\left(\beta a\right) = 1 - \frac{1}{2}\left[\frac{1}{\omega^2 L_L C_L} + \omega^2 L_R C_R - \left(\frac{L_R}{L_L} + \frac{C_R}{C_L}\right)\right] \tag{5}$$

and plotted in Fig. 2.

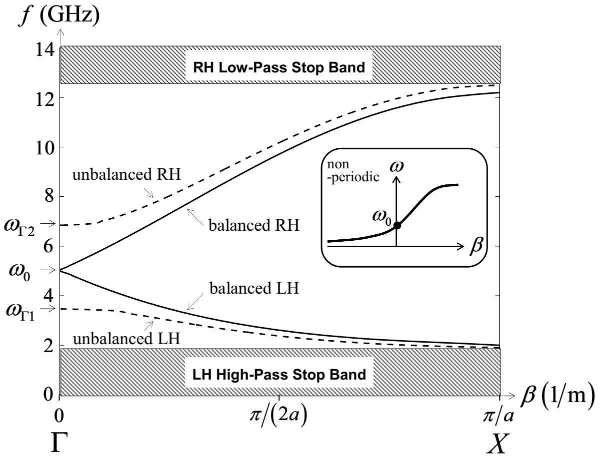


Fig. 2 Dispersion relation computed for the balanced and unbalanced CRLH-TL. Balanced: $L_R = L_L = 1$ nH, $C_R = C_L = 1$ pF; unbalanced: $L_R = 1$ nH, $L_L = 5.5$ nH, $C_R = 1$ pF, $C_L = 2$ pF. The inset shows the dispersion curve of a balanced non periodic CRLH-TL.

III. PARAMETERS EXTRACTION

An accurate parameters extraction of CRLH structures is crucial for efficient design. The first two applications of the next section use a microstrip implementation of the CRLH structure, as shown in Fig. 3. This implementation was also successfully used in a novel backfire-to-endfire leaky-wave antenna presented in [6].

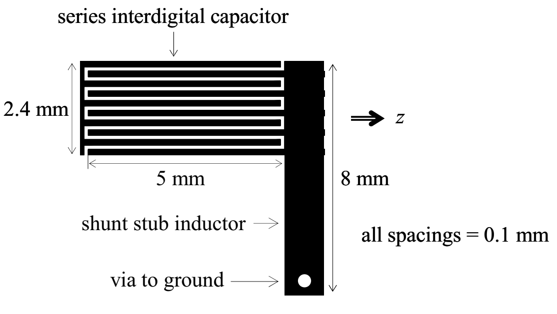
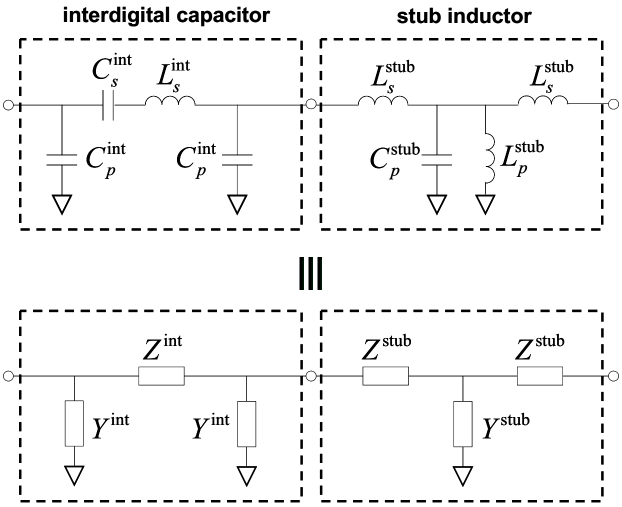


Fig. 3 Layout of the unit cell of the microstrip implementation of the CRLH-TL, including a series interdigital capacitor of value C_L and a shunt stub inductor of value L_L shorted to the ground plane by a via.

The extraction procedure can be performed with the help of Fig. 4. It consists in the following steps: (1) full-wave simulate or measure, separately, the interdigital capacitor and the stub inductor; (2) transform their S-parameters into Y (for C) and Z (for C) parameters, whose matrixes are known for the Π (for C) and T (for C) networks; (3) then all the values in the top circuits of Fig. 5 are known; (4) finally, obtain the CRLH parameters as

$$L_R = L_s^{\text{int}},\ C_R = 2C_p^{\text{int}} + C_p^{\text{stub}},\ L_L = L_p^{\text{stub}},\ C_L = C_s^{\text{int}} \tag{6}$$

where the series inductance of the stub could be neglected.



$$Z^{\text{int}} = j\left[\omega L_s^{\text{int}} - 1/\left(\omega C_s^{\text{int}}\right)\right] \qquad Y^{\text{stub}} = j\left[\omega C_p^{\text{stub}} - 1/\left(\omega L_p^{\text{stub}}\right)\right]$$

$$Y^{\text{int}} = j\omega C_p^{\text{int}} \qquad Z^{\text{stub}} = j\omega L_s^{\text{stub}}$$

Fig. 4 Circuit model for the unit cell shown in Fig. 3.

IV. SELECTED APPLICATIONS

A. *Arbitrarily Tight Coupled-Line Coupler*

A novel broadband tight backward-wave directional coupler with level [7] is obtained by replacing the microstrip lines of the conventional coupled-line coupler by the CRLH line described in Fig. 3. A rigorous even/odd mode analysis revealed that this device exhibits unique properties:

- It can achieve *any arbitrary level of coupling.* In comparison, conventional backward coupled-line couplers are typically limited to less than -10 dB coupling.
- It is based not only of capacitive-electric coupling (conventional), but also on *inductive-magnetic* coupling.
- Its *electrical length βd*, is not 90 degrees (conventional), as in the conventional case, but *zero degrees*.
- The previous point is a consequence of the fact that the *even/odd* equivalent TLs are operating in *a frequency gap*: their characteristic impedances Z_{0e} / Z_{0o} are purely imaginary, and $\gamma_{e,o} = \alpha_{e,o}$, where the

monotonically regardless of the C source, and higher RTA temperature enhanced the reduction rate of dc current gain. The current gain is linear to the minority carrier lifetime in base layer, τ_B. In a heavily doped layer like the base in an HBT, minority lifetime is ideally decided by the Auger recombination process. In this case, τ_B should be linear to $(R_S(BE))^2$, that is, β should show linear dependence on $(R_S(BE))^2$. Figure 5 shows the dependence of β on $R_S(BE)$. For the HBT with the C-doped base grown using CBr_4, the values of β were much less than the expected value when the Auger recombination is dominant. This suggests that RTA could induce some non-radiative recombination centers in the C-doped base layer even if it does not seem to have any adverse influence (an increase in $R_S(B)$, for instance). Similar behavior was observed for the HBT with the C-doped base grown using $CBrCl_3$. As shown in Fig. 5, the value of β of the sample with RTA at 650°C for 5 min was lower than that in the case that β was linear to $(R_S(BE))^2$, although the other gains well fit the $(R_S(BE))^2$ tendency. From results shown in Fig. 3, RTA does not deteriorate $R_S(B)$ of $CBrCl_3$-doped samples. The results in Fig. 5 suggest that RTA might cause some thermal damage to the C-doped InGaAs base even if $R_S(B)$ shows no change. Nevertheless, from Fig. 5, it can be stated that a base C-doped using $CBrCl_3$ shows good thermal stability compared with that doped using CBr_4.

IV. SUMMARY

In this work, we investigated the influence of C sources on the thermal stability of C-doped base InP/InGaAs HBTs. Hydrogen atoms in the C-doped layer, which deactivate C acceptors, can be removed by RTA. However, RTA at higher temperature and for longer durations could deteriorate the crystal quality of the C-doped InGaAs base, resulting in an increase in base sheet resistance and a reduction in dc current gain. The detarioration of the C-doped InGaAs base can be suppressed by using $CBrCl_3$ as the C source.

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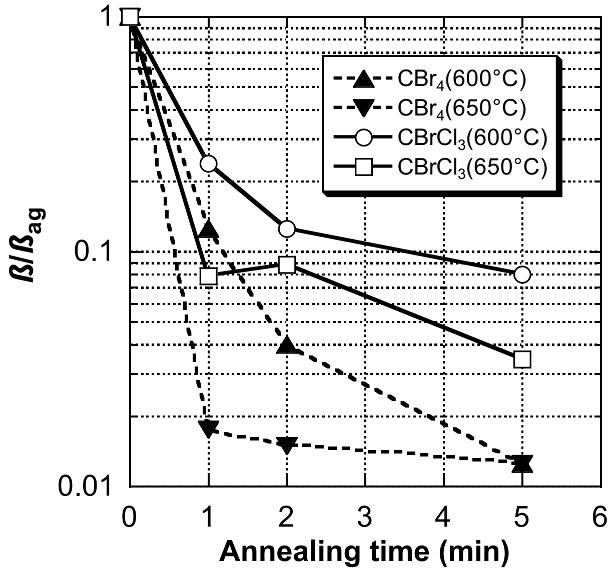

Fig. 4 The dependence of dc current gain on RTA time. The value of β is the dc current gain at collector current density of 1 kA/cm^2.

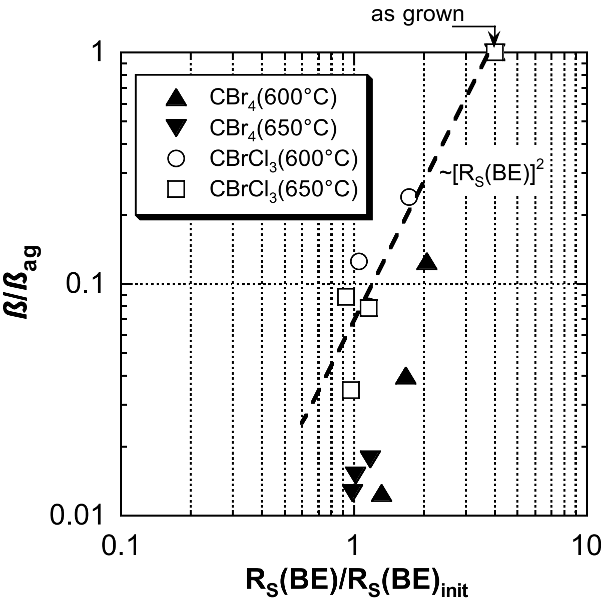

Fig. 5 The relationship between dc current gain and intrinsic base sheet resistance.

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