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

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Abstract — We report effects of annealing on InP/InGaAs heterojunction bipolar transistors (HBTs) having an InGaAs base layer C-doped using CBr₄ or CBrCl₃ as the C source. It was found that ramp thermal annealing (RTA) after growth removes H atoms, which are located in C-doped 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 CBrCl₃, are more stable in terms of thermal stress than those grown using CBr₄.

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 (CBr₄ and CBrCl₃) 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 CBrCl₃ is more stable in terms of thermal stress than that grown using CBr₄.

II. EXPERIMENTAL PROCEDURE

Carbon-doped InGaAs and C-doped base InP/InGaAs HBT epitwafers were grown by low-pressure MOCVD on (100) oriented Fe-doped semi-insulating InP substrates. The epilayer structure is shown in Table 1. Two kinds of halomethane (CBr₄ and CBrCl₃) were the C sources. Triethylgallium and trimethylindium were group-III sources, AsH₃ and PH₃ the group-V sources and H₂-diluted Si₂H₆ the Si (n-type dopant) source. Paradigm-diffused H₂ was the carrier gas.

C-doped InGaAs epitwafers were annealed in N₂ 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 epitwafers 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

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness (nm)</th>
<th>Dopant</th>
<th>Doping (cm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>emitter cap</td>
<td>n⁺ InGaAs</td>
<td>100</td>
<td>Si</td>
<td>3×10¹⁹</td>
</tr>
<tr>
<td></td>
<td>n⁺ InP</td>
<td>20</td>
<td>Si</td>
<td>2×10¹⁹</td>
</tr>
<tr>
<td>emitter</td>
<td>i InP</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>base</td>
<td>p⁺ InGaAs</td>
<td>50</td>
<td>C</td>
<td>4×10¹⁹</td>
</tr>
<tr>
<td>collector</td>
<td>i InGaAs</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>subcollector</td>
<td>n⁺ InP</td>
<td>20</td>
<td>Si</td>
<td>1×10¹⁹</td>
</tr>
<tr>
<td></td>
<td>n⁺ InGaAs</td>
<td>30</td>
<td>Si</td>
<td>1×10¹⁹</td>
</tr>
<tr>
<td></td>
<td>n⁺ InP</td>
<td>340</td>
<td>Si</td>
<td>1×10¹⁹</td>
</tr>
<tr>
<td>etch stopper</td>
<td>i InGaAs</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>buffer</td>
<td>i InP</td>
<td>20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE I
The Layer Structure Of InP/InGaAs HBT
This relation is given by the Bloch-Floquet theorem (also possible in 2D [5] or 3D). 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

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

and plotted in Fig. 2.

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](image)

**Series interdigital capacitor**

2.4 mm

5 mm

8 mm

All spacings = 0.1 mm

Shunt stub inductor

Via to ground

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 matrices are known for the $\Pi$ (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

$$L_R = L_{\text{int}}^s, \quad C_R = 2C_{\text{int}}^p + C_{\text{stub}}, \quad L_L = L_{\text{stub}}^s, \quad C_L = C_{\text{int}}^p,$$

where the series inductance of the stub could be neglected.

![Fig. 4](image)

**Interdigital capacitor**

**Stub inductor**

$Z_{\text{int}} = j[\omega L_{\text{int}} - \sqrt{(\omega C_{\text{int}})(\omega C_p)}]$  

$Y_{\text{int}} = j\omega C_{\text{int}}^{-1}$

$Z_{\text{stub}} = j[\omega L_{\text{stub}} - \sqrt{(\omega C_{\text{stub}})(\omega C_p)}]$  

$Y_{\text{stub}} = j\omega C_{\text{stub}}^{-1}$

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* $\beta d$, 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, \( \tau_B \). In a heavily doped layer like the base in an HBT, minority lifetime is ideally decided by the Auger recombination process. In this case, \( \tau_B \) should be linear to \( (R_S(BE))^2 \), that is, \( \beta \) should show linear dependence on \( (R_S(BE))^2 \). Figure 5 shows the dependence of \( \beta \) on \( R_S(BE) \). For the HBT with the C-doped base grown using CBr\(_4\), the values of \( \beta \) 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 \( \beta \) of the sample with RTA at 650°C for 5 min was lower than that in the case that \( \beta \) 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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REFERENCES


