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# Collector Profile Design for High-Performance Dynamic Operation of Bipolar Transistors at Liquid Nitrogen Temperature

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The influence of the collector concentration profile on the dynamic performance of bipolar transistors (BJTs) at liquid nitrogen temperature (LNT) operation has been qualitatively shown for the first time. It has been proved that the high-speed performance for LNT operation comparable to that for room temperature (RT) can be obtained by controlling the collector concentration profile experimentally. Moreover, it has been clarified that the collector profile design is more important in LNT operation than that at RT because of carrier freeze-out in the collector.

## 1. INTRODUCTION

The possibility of high-performance operation of BJTs at LNT had been demonstrated by using advanced device structures[1-3]. However, these works did not consider the collector design, and strict design principle of BJTs for LNT operation has not sufficiently been yet established.

In this study, the importance of the collector concentration profile on dynamic performance has been clarified by the analysis, in which the analytical formulas proposed by Stübing[4] were extended to LNT operation. The estimation has been confirmed from the experimental of the cut-off frequency $f_T$ characteristic at 83 K.

## 2. THEORY AND EXPERIMENTAL

In this study, the analytical formulas for AC operation are proposed, based on a low-temperature BJT DC model, which had been proposed previously[5]. The proposed formulas can be described as Eqs. (1)-(3) summarized in Table 1. These formulas introduce the temperature-dependences of the conductivity modulation effect, base pushout effect, and emitter current-crowding effect into the carrier transit time $\tau_F$ in the previous study at RT[4].

The $\tau_{F1}(T)$ and $\tau_{F2}(T)$ in Eq.(1) are expected to be the carrier transit time in the $I_C$ region in which the conductivity modulation effect occurs but the base width is not modulated, and that in which the base pushout effect occurs in conjunction with the emitter current-crowding effect, respectively. Here the temperature-dependent conductivity modulation factor $f_{CM}(T)$, base pushout factor $f_{PO}(T)$, and emitter current-crowding factor $f_{CR}(T)$ (denoted by bold letters) are newly introduced into this study as shown in Eqs.(2)-(3)[5]. Here, $V_{AF}$, $\mu_n$, $I_{CK}$ are the Early voltage, the electron mobility in the collector, the knee current of the collector current, respectively. $W_B$ and $W_C$ are the base and $n^-$ collector widths in the low injection condition, $\tau_0$ and $I_1(T)$ are constants dependent on the emitter area $A_E$, $\tau_1$ is a con-

Table 1 Proposed analytical formulas. The temperature-dependent conductivity modulation effect ($f_{CM}(T)$), base pushout effect ($f_{PO}(T)$), and emitter current-crowding effect ($f_{CR}(T)$) (denoted by bold letters) are newly introduced.

$$\tau_F(T) = \tau_{F1}(T) + \tau_{F2}(T) \tag{1}$$

$$\tau_{F1}(T) = \tau_0 \left( 1 - \left( \frac{V_{CE}}{V_{AF}} \right)^{.5} + \frac{V_1 \left( \mathbf{f_{CM}(T)} \right)}{V_{CE}} \right) \tag{2}$$

$$\tau_{F2}(T) = \frac{W_B \left( \mathbf{f_{PO}(T)} \right) \cdot W_C \left( \mathbf{f_{PO}(T)} \right)}{4\mu_n V_T} \frac{\tau_1}{2} \left( \left( \frac{I_C - I_1(T)}{I_{CK}(T) - I_1(T)} \right)^2 + \left( \frac{I_C - I_1(T)}{I_{CK}(T) - I_1(T)} \right)^{\alpha \left( \mathbf{f_{CR}(T)} \right)} \right) \quad \cdots (3)$$

stant dependent on $A_E$ and $I_{CK}$, and $V_T$ is defined as kT/q, respectively.

Figure 1 shows the $I_C$ dependence of $\tau_F(T)$ calculated by using the proposed analytical formulas. In the 77 K case, the $I_C$ level in which $\tau_F(T)$ begins to increase was about two-order of magnitude lower than that in the 298 K case. Note that these $I_C$ levels correspond well to the occurrence points of base pushout (indicated by arrows) which were calculated by using the low-temperature DC model[5]. This is because the temperature-dependent base pushout occurs even in the low $I_C$ level ($\fallingdotseq 10^{-4}$A) owing to the carrier freeze-out in the collector. Therefore, device structures which can suppress the occurrence of base pushout at the low $I_C$ region are required to realize high-speed operation at LNT.

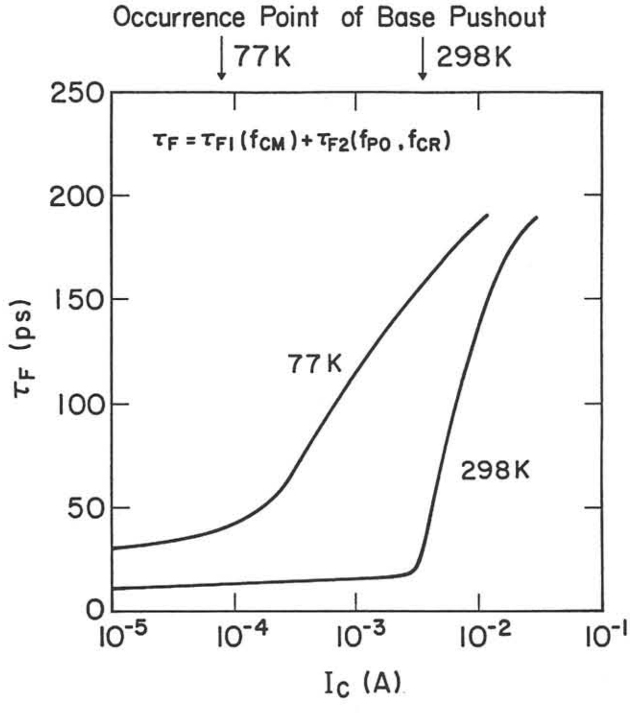

Fig.1 Calculated transit time $\tau_F$ versus collector current $I_C$ at 298 K and 77 K. Temperature-dependent conductivity modulation effect ($f_{CM}(T)$), base pushout effect ($f_{PO}(T)$), and emitter current-crowding effect ($f_{CR}(T)$) have been taken into account. Arrows indicate the occurrence points of base pushout.

In this study, the suppression effect of the base pushout at LNT was examined by devices with an implanted collector. Experimentally, the control of collector concentration was accomplished by selective ion implantation[6] of phosphorus at the acceleration energy $E_a$ ranging from 150 to 300 keV and at the dose $Q_{CI}$ ranging from $5\times10^{11}$ to $3\times10^{12}$ $cm^{-2}$. Rapid thermal annealing for the dopant activation was carried out at 1100 ℃ for 20 sec. The devices used for the measurements were polysilicon emitter BJTs, which have the emitter dimensions of 0.8×4 μm.

## 3. RESULTS AND DISCUSSION

Figure 2 shows the measured $f_T - I_C$ characteristic for the device with the implanted collector and for the conventional device. For the conventional device, maximum $f_T$, $f_{Tmax}$ markedly decreased (8.2 → 2.8 GHz ) at 83 K. For the device with the implanted collector, on the other hand, $f_{Tmax}$ of over 10 GHz was obtained, and this value is higher than that of the conventional device at RT. $f_T$ decreased rapidly as $I_C$ increased beyond the occurrence points of base pushout at RT. At 83 K, on the contrary, $f_T$ continued to increase gradually beyond the corresponding points. This is because that transconductance $g_m$ at 83 K is about four times larger than that at 298 K, in addition to the fact that the temperature-dependent emitter-base junction capacitance $C_{je}(T)$ decreases with decreasing temperature. Furthermore, for the device with the implanted collector, the $I_C$ level at $f_{Tmax}$ shifts to the higher $I_C$ region due to the suppression effect of base pushout. This fact means that the most important point for LNT operation is the reduction of base pushout at the low $I_C$ region by introducing an implanted collector.

Figure 3 shows measured $f_{Tmax}$ as a function of the acceleration energy $E_a$ at the dose of $3\times10^{12}$ $cm^{-2}$. Note that the $f_{Tmax}$ curve for the 83 K case is more sensitive to the $E_a$ change than that for the 298 K case. This is due to the change in the ionized impurity concentration at the base-collector junction because of the temperature-dependent carrier freeze-out in the collector. Figure 4 shows measured $f_{Tmax}$ and phosphorus concentration at the base-collector junction $N_{CI,j}$ at RT as a function of the phosphorus dose $Q_{CI}$. The $f_{Tmax}$ increased with the increase of $Q_{CI}$. This is because the temperature- and

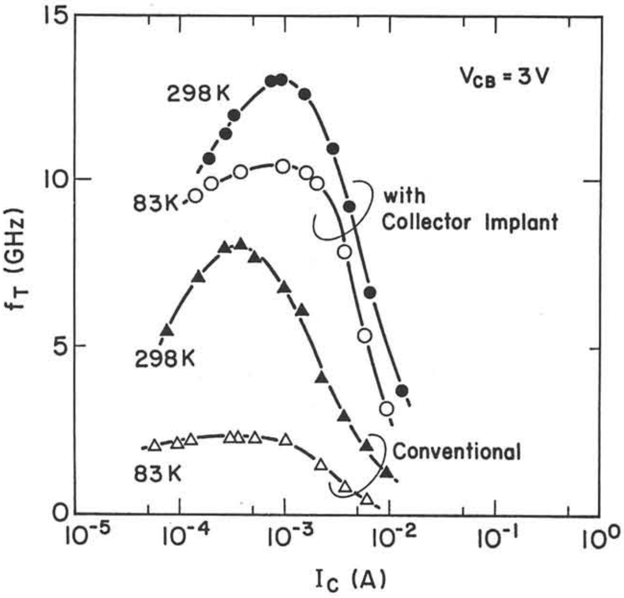

Fig.2 Measured collector current $I_C$ dependence of cut-off frequency $f_T$ for the device with an implanted collector and for the conventional device at 298 K and 83 K.

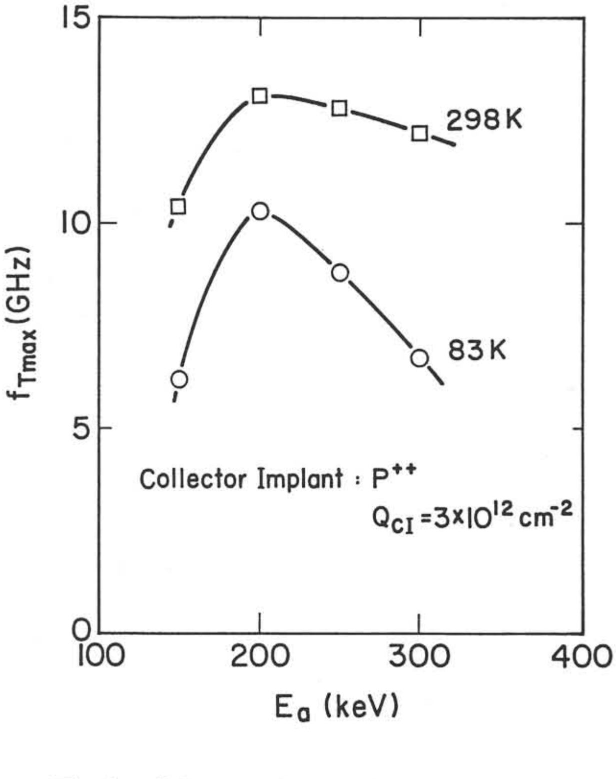

Fig.3 Measured maximum cut-off frequency $f_{Tmax}$ versus acceleration energy $E_a$ at 298 K and 83 K. Collector implantation was performed at the dose of $3\times10^{12}$ $cm^{-2}$.

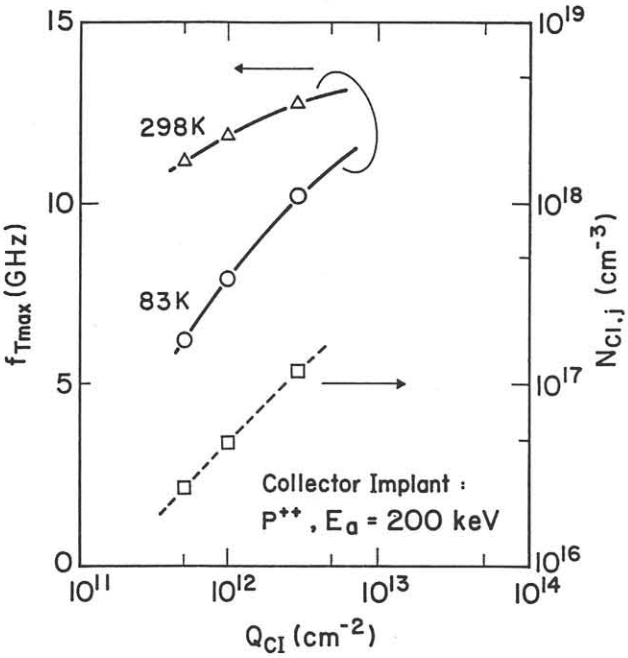

Fig.4 Measured phosphorus dose $Q_{CI}$ dependence of maximum cut-off frequency $f_{Tmax}$ at 298 K and 83 K, and phosphorus concentration at base-collector junction $N_{CI,j}$ obtained from SIMS profile at RT. Collector implantation was performed at the acceleration energy of 200 keV.

concentration-dependences of carrier freeze-out in the collector indicate the results, for instance, $N_{CI,j}(83K) / N_{CI,j}(298K) = 3.8\times10^{-3}$ at $N_{CI,j}(298K) = 2\times10^{16}$ $cm^{-3}$, and $2.7\times10^{-2}$ at $2\times10^{17}$. And again, $f_{Tmax}$ at 83 K was more sensitive to the $Q_{CI}$ change than that at 298 K. Therefore, the control of the collector concentration profile is more important for LNT operation than that for RT.

## 4. CONCLUSION

It has been found by the proposed analytical formulas that $\tau_F$ of the conventional BJTs for LNT operation begins to increase at a low $I_C$ level than that for RT. From the analysis based on the proposed theory, it has been clarified that the gentle slope of $f_T - I_C$ characteristic at LNT is due to the larger $g_m$, though the base pushout occurs even in the low $I_C$ region.

It has been proved that the high-speed performance for LNT comparable to that for RT can be obtained by controlling the collector concentration profile. Moreover, it has been clarified for the first time that the control of the collector concentration profile is essentially important for LNT operation.

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