Intrinsic stability of an HBT based on a small signal equivalent circuit model

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Abstract: Intrinsic stability of the heterojunction bipolar transistor (HBT) was analyzed and discussed based on a small signal equivalent circuit model. The stability factor of the HBT device was derived based on a compact T-type small signal equivalent circuit model of the HBT. The effect of the mainly small signal model parameters of the HBT on the stability of the HBT was thoroughly examined. The discipline of parameter optimum to improve the intrinsic stability of the HBT was achieved. The theoretic analysis results of the stability were also used to explain the experimental results of the stability of the HBT and they were verified by the experimental results.

Key words: HBT; intrinsic stability; stability factor; small signal equivalent circuit model
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1. Introduction

In recent years, the HBT device has been widely used to develop RF and microwave linear and power amplifiers due to its advantages of high gain, high linearity and high power density. The technology of device fabrication and modeling has gradually come to maturity[1, 2]. The circuit designer can select the GaAs HBT, InP HBT or SiGe HBT and implement a high performance amplifier chip in the appropriate field of application[2, 3]. However, for the designer, the precondition to obtain high performance RF and microwave amplifiers is that the device is in a state of frequency stability and without self-oscillation. So how to improve the frequency stability and suppress self-oscillation is basic and important for HBT devices and amplifiers.

In general, the design of frequency stability is a task of the circuit designer. The designer often inserts some loss impedance network into the periphery of the HBT and makes the HBT unconditional stability in the interesting frequency band[4]. The method may bring some problems. First, the loss network occupies some extra chip area. Second, the structure and the component value of the network should be carefully designed to trade off the total performance of the amplifier. And also the scatter of the component value due to the fabrication process may degenerate the function of the stability network. However, the problems mentioned above could be reduced if the intrinsic stability of HBT were improved by optimizing the inner parameters and characteristics of the HBT. The device design task of the HBT is usually mainly focused on the aspects of high frequency gain, high breakdown voltage and high thermal stability, and these aspects have been well studied. But the aspect of device design to improve the intrinsic frequency stability of the HBT is not carefully investigated. Su *et al.*[5] discussed the RF CMOS stability related to bias and scaling. But the HBT is a different device from CMOS. Jiang *et al.*[6] discussed the impact of base doping profile on stability characteristics of SiGe HBTs. But only one parameter of the base is involved and the small signal model parameters which are related to the stability characteristic and the device deign of the HBT are not discussed. Grebennikov[7] analyzed the frequency stability of the BJT with a compact small signal model. But the small signal model is too simple and only a few parameters are involved. And also the experimental results of the HBT stability are not provided.

In this paper, from the angle of device design, the intrinsic frequency stability of HBTs is thoroughly discussed based on a T-type small signal equivalent circuit model. Firstly, a theoretical formula of the stability factor (i.e. K factor or Rollet factor) to evaluate the frequency stability of the HBT was derived. Then the effect of multiple small signal model parameters on the stability of the HBT is carefully examined with the formula of the stability factor. Some intuitive discipline to improve the intrinsic stability of the HBT was concluded. Subsequently, the stability factors of the HBT with different physical parameters were calculated based on experimental data. The conclusion of the theoretical discussion was used to explain the different experimental results and was verified by the experimental results.

2. Theoretical modeling and discussion

2.1. Theory of stability factor

The stability factor K (i.e. Rollet factor) is commonly used to evaluate the stability of both RF devices and circuits. It is calculated from the small signal S parameter data of the device which can be measured with a network analyzer. The calculating formula is[8]

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2\,|S_{12}S_{21}|}, \quad \Delta = S_{11}S_{22} - S_{12}S_{21}. \tag{1}$$

When the device is unconditionally stable, the K is larger than 1. In general, the stability factor K decreases with decreasing frequency and becomes less than 1 in the lower frequency regime (i.e., in the state of potential instability)[5]. The work

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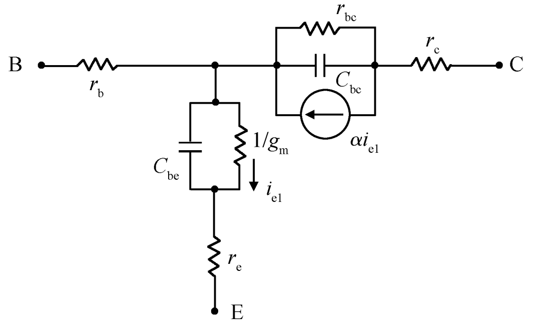

Fig. 1. Small signal equivalent circuit model of the HBT.

Table 1. Element value of small signal equivalent circuit InGaP/GaAs HBT: 2 × 30 μm^2 emitter area; bias: V_{ce}, I_c = 14 mA.

Parameter	Value	Parameter	Value
r_b	1.7 Ω	g_m	0.24 S
r_c	9.3 Ω	α_{T0}	0.989
r_e	2.9 Ω	τ_B	0.3 ps
C_{be}	0.6 pF	τ_C	3.9 ps
C_{bc}	54 fF		

of stability design for the device is to make the K larger than 1 in a wide frequency band. Though the K can be calculated by S parameters expediently, the S parameter is only the description of the outer characteristic of the device. It is difficult to discuss the relationship between intrinsic stability and inner parameters of the device with Eq. (1). So the following formula of K is used in Ref. [8],

$$K = \frac{2\mathrm{Re}(\gamma_{11})\mathrm{Re}(\gamma_{22}) - \mathrm{Re}(\gamma_{12}\gamma_{21})}{|\gamma_{12}\gamma_{21}|}, \tag{2}$$

where γ is the Z, Y or H parameter of the device which can be derived from the small signal equivalent circuit model. Then the relationship between intrinsic stability and inner parameters of the device is easy to analyze and discuss.

3. Modeling of small signal equivalent circuit

A T type of small signal equivalent circuit model was used in this paper and is illustrated in Fig. 1[9]. In order to gain an insight into the effect of inner parameters and characteristics of the HBT on the intrinsic stability performance, the active section of the HBT is emphasized in the model and the parasitic parameters of the interconnect wire of the three electrode poles are not shown. α is the CB current gain in Fig. 1.

$$\alpha = \alpha_{T0}\exp(-\mathrm{j}\omega\tau_C)/(1+\mathrm{j}\omega\tau_B). \tag{3}$$

α_{T0} is the base transport factor for the HBT. τ_B and τ_C are the carrier transit times across the neutral base region and collector depletion layer, respectively. g_m is the transconductance of the HBT. Since the base of the HBT is often heavily doped, the early effect is weak. So the r_{bc} of the BC junction resistor is large enough and is ignored in the following discussion. In order to perform the following derivation and discussion conveniently, an example of circuit element values for an InGaP/GaAs HBT is shown in Table 1. The circuit elements were extracted by curve-fitting to the S parameters measured.

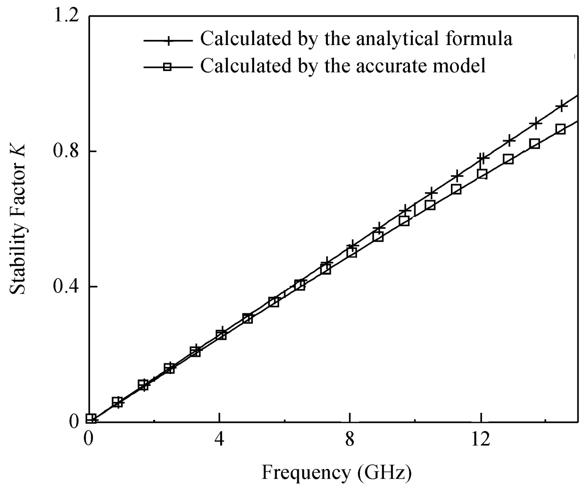

Fig. 2. Stability factor calculated by Eq. (5) and the accurate model of Eq. (2).

3.1. Modeling and discussion of stability factor *K*

Based on the T type circuit model of Fig. 1, the CE Z-parameter of the HBT is expressed as

$$\begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} = \begin{pmatrix} r_e + r_b + z_1 & z_1 + r_e \\ r_e + z_1 - \alpha z_1 z_2 g_m & r_e + r_c + z_1 + (1-\alpha z_1 g_m) z_2 \end{pmatrix}, \tag{4}$$

where $z_1 = 1/(g_m + \mathrm{j}\omega C_{be})$, $z_2 = 1/(\mathrm{j}\omega C_{bc})$. Then the Z parameter is substituted into Eq. (2) of the stability factor K. With appropriate approximation, the stability factor can be derived as

$$K \approx \left[\left(r_e + r_m + 2r_c + 2r_b + \frac{2r_b r_c}{r_e + r_m}\right)\frac{C_{bc}}{\alpha_{T0}} + \left(r_m + \frac{2r_b r_m - r_m^2}{r_e + r_m}\right)C_{be} + \left(1 + \frac{2r_b}{r_e + r_m}\right)\tau_F\right]\omega, \tag{5}$$

where $r_m = 1/g_m$, $\tau_F = \tau_b + \tau_c$.The curves of the stability factor K with frequency were calculated by using analytical expression of Eq. (5) and the accurate model of Eq. (2) based on the values of Table 1. The results are shown in Fig. 2. Despite the discrepancies at high frequencies, which result from ignoring higher orders of frequency, the analytical expressions give reasonable representations of the device characteristics without resorting to more complicated forms of analysis.

It can be seen from Eq. (5) as follows. (1) The base resistance r_b and collector resistance r_c can increase the stability factor K and improve the intrinsic stability of HBT. In fact they are equivalent to the loss element of an external stability impendence network. (2) As the emitter resistance r_e increases from zero to a critical value (about 100 Ω with the element values of Table 1), the K is decreasing. After the critical value, the K is increasing as the r_e increases. This conclusion does not agree

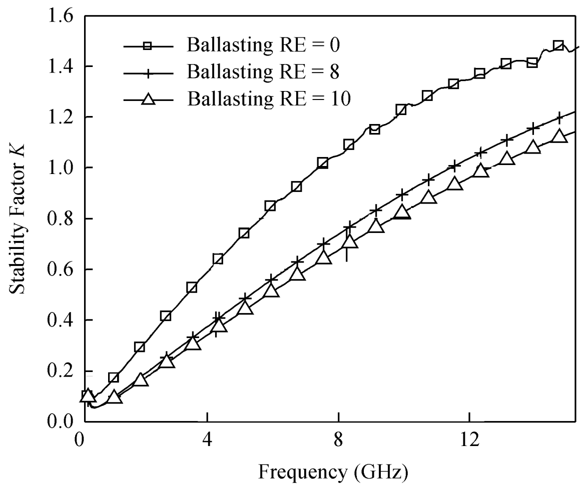

Fig. 3. Stability factors with different emitter ballasting resistors. HBT: 4 × 2 μm × 30 μm emitter size; bias: V_{ce} = 4 V, I_c = 65 mA.

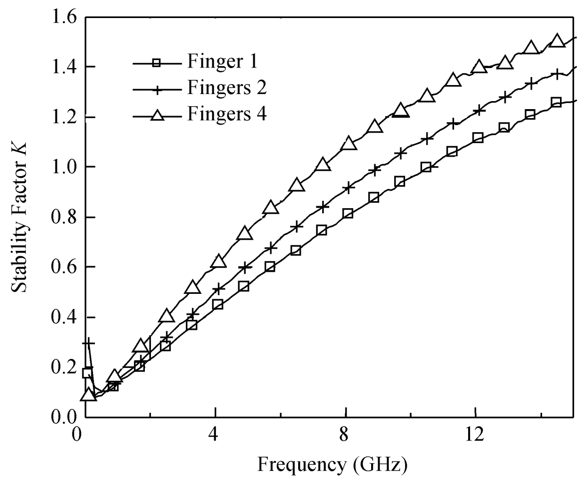

Fig. 4. Stability factors with different emitter fingers. HBT: 1 × 2 μm × 40 μm, 2 × 2 μm × 40 μm, 4 × 2 μm × 40 μm; bias: V_{ce} = 4 V, $J_c = 1 \times 10^4$ A/cm^2.

with the analysis in Ref. [6] that for the RFCMOS the source resistance is always helpful to increase the K and improve the device stability. And the stability effect of the transconductance g_m is similar to the emitter resistance. (3) As the C_{be} and C_{bc} increase, the K also increases. More energy of the RF signal is coupled to the ground by the increase in junction capacitance and the stability of the device is improved. (4) As the transit time τ_F is increased, the K is increased. The high frequency gain of the device is decreased and instead improves the stability of the device. (5) From the formula it can also be seen that the larger DC gain β_{DC} of the HBT leads to a larger α_{TO} and the K-factor is instead decreased. The appropriate DC gain of the HBT is helpful to the intrinsic stability of the device.

4. Experimental results of HBT stability and discussion

In this section the K of the InGaP/GaAs HBT with different physical parameters was calculated based on the experimental data of the S parameters. The conclusion of the theoretic discussion above was used to explain the difference in the calculated results.

In general, a small ballasting resistor is inserted into the emitter finger of the HBT in order to improve the thermal stability of the multi-finger HBT. This resistor is often small (< 10 Ω) to avoid large loss of power gain and efficient for the HBT. The stability factor K of the HBT with different emitter ballasting resistors is shown in Fig. 3. The HBTs were the same structure and tested under the same conditions except that the ballasting resistors were zero, eight and ten ohms. From Fig. 3 the stability of the HBT declines as the ballasting resistors increase. The result is consistent with the theoretical analysis of Section 2. So an emitter ballasting resistor with generally several ohm to improve the thermal stability would also degenerate the electro stability.

The multi-finger structure of the HBT is often used in the amplifier design. Figure 4 shows the stability factor K of the HBTS which is one, two, four emitter fingers. The stability of the HBT is improved with increasing emitter fingers. Normally, due to the parallel of emitter fingers, the junction capacitance is raised and then improves the stability of the HBT like the analysis results of Section 2.

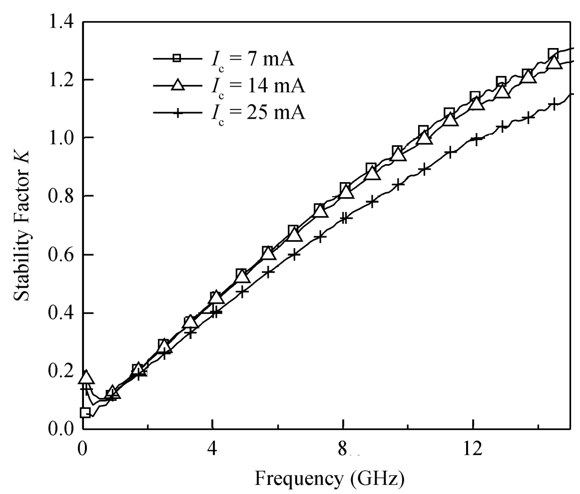

Fig. 5. Stability factor with different bias currents. HBT: 2 × 40 μm^2 emitter size; bias: V_{ce} = 4 V, I_c = 7, 14, 25 mA.

Figure 5 shows the stability factor K of the HBT under different bias currents. As the bias current is increased, the stability of the HBT is reduced. Because of the larger bias current, the junction capacity C_{bc} becomes smaller and the transconductance g_m becomes larger. From the results of Section 2, these factors make the stability factor K decline and degenerate the stability of the device.

5. Conclusion

In this paper the intrinsic stability of the HBT was insight studied based on a small signal equivalent circuit model. The impact of the mainly model parameters on the intrinsic stability of the device was discussed with an analysis formula of the stability factor K. The results of theoretic analysis were also verified by the experimental data of multiple HBTs. So for the circuit designer optimum selection of the device structure and bias condition can be helpful in the improvement of the intrinsic stability of the device. Also, the present analysis method and conclusion can guide the device designer to improve the intrinsic stability by trade-off design with other performance of the device.

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