New method for determining parasitic access inductances of high frequency on-wafer coplanar Heterojunction Bipolar Transistors

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Abstract: New analytical extraction procedure is developed for determining independently the parasitic inductances of high frequency on-wafer coplanar Heterojunction Bipolar Transistor. It takes into account the influence of inductive effect due to other device parameters which can not be neglected for these transistors and it does not require any numerical optimizations or special test structures. In particular the analytical expressions demonstrate that base resistance and intrinsic and extrinsic base-collector capacitances have a significant effect on the accurate determination of the HBT parasitic inductances. Our theoretical investigations are validated using two types of transistors: A on-wafer coplanar GaInP/GaAs HBT and a microstrip mounted GaInP/GaAs which have a unity current gain cutoff frequency of 80 GHz respectively.

Introduction: the significant progress in the development of HBT technology in recent years has lead to increased HBT performances and potentialities which allow immense applications of HBTs in microwave, optical and high speed digital communications. This leads to the increasing needs in the development of accurate characterization procedures allowing us to obtain the linear equivalent circuit of the transistor which is crucial to optimize the device and circuit performances. To determine the intrinsic device elements the accurate extraction of extrinsic parameters is a good tool which allows to reduce the number of unknown device parameters and then ensures a unique solution. Special test structures and/or numerical optimization techniques have been used to extract the HBT parasitic inductances, Dacosta et al (1) and Cai et al (2). Currently methods determine the parasitic access inductances from imaginary parts of Z parameter in high frequency range. This assumes that the device inductance values are large enough to neglect the influence of the inductive terms due to other device parameters. For very high frequency performance transistors and using on-wafer coplanar measurements the parasitic access inductance values are very weak and their effect is only significant at very high frequency range (up to 40 GHz for the used transistor). On the other hand the influence of other device parameters such base resistance and intrinsic and extrinsic base-collector capacitances can not be ignored because it contributes largely to increase the global inductive effect and leads to mask the effect related to parasitic inductances only. We propse in this paper an extraction procedure to determine analytically the parasitic access inductances of high frequency on-wafer coplanar HBTs. It uses S prameter measurements of the transistor biased in non conducting state (I_b=0uA, V_{CE}=0V) and differs from previous methods in the following points: - it takes into account the influence of other device parameters which contribute to increase largely the global inductive effect of the transistor, - it uses the lower part of the frequency range (0.3-25 GHz for the used transistor) to determine global inductive effect which is used to calculate the inductance values. This is not the case of currently methods which use the high part of frequency range and thereby need very high frequency S parameter measurements (up to 40 GHz for the used transistor) due in particular to the very weak inductance values of high frequency performance HBTs. On the other hand the analytical expressions allow to calculate separately the inductive effect due to other elements and the inductive effect relating to each parasitic inductance. Thereby they lead to know the device parameters which are contained in each inductive term expression.

Procedure and results: Fig. 1 shows a small signal equivalent circuit of HBT biased in cutoff mode as described by Lee and Gopinath (3) and its elements determined using the proposed procedure. HBT S parameter measurements are performed using HP automatic network analyser and high frequency on-wafer probes over a frequency range of (0.3 to 40) GHz and then converted to Z parameters. The effect of pad contact in particular parasitic pad capacitances (not shown in Fig. 1) is removed from measurements. The principal steps of the procedure can be summarized as follows:
Step 1- Z parameter expressions are obtained without any approximations using Fig. 1:

$$Z_{11} = R_E + \frac{R_1}{1 + j\omega R_1 C_1} + \frac{1}{j\omega C_\pi} + \frac{R_b}{1 + j\omega R_b C} + j\omega(L_e + L_b) \qquad (1)$$

$$Z_{12} = Z_{21} = R_E + \frac{1}{j\omega C_\pi} + \frac{\dfrac{R_b C}{C_c}}{1 + j\omega R_b C} + j\omega L_e \qquad (2)$$

$$Z_{22} = R_c + R_E + \frac{1}{j\omega C_\pi} + \frac{1 + j\omega R_b C_{bc}}{j\omega (C_{bc} + C_c)(1 + j\omega R_b C)} + j\omega(L_e + L_c) \qquad (3)$$

$$\text{with } C = \frac{C_{bc} C_c}{C_{bc} + C_c}$$

Step 2- Suitable combinations of real and imaginary Z parameter parts (Eq.4-6) are obtained from (1-3):

$$-\omega \mathrm{Imag}(Z_{12}) = \frac{1}{C\pi} + \frac{1}{Cc}\frac{(RbC\omega)^2}{\left[1+(RbC\omega)^2\right]} - Le\omega^2 \tag{4}$$

$$-\omega \mathrm{Imag}(Z_{22}-Z_{12}) = \frac{1}{(C_{bc}+C_c)}\frac{1}{\left[1+(R_bC\omega)^2\right]} - L_c\omega^2 \tag{5}$$

$$-\omega \mathrm{Imag}(Z_{11}-Z_{12}) = \frac{1}{C_1}\frac{(R_1C_1\omega)^2}{\left[1+(R_1C_1\omega)^2\right]} + \frac{1}{C_{bc}}\frac{(R_bC\omega)^2}{\left[1+(R_bC\omega)^2\right]} - L_b\omega^2 \tag{6}$$

$$\mathrm{Real}(Z_{11}\text{ - }Z_{12}) = \frac{R_1}{1+(R_1C_1\omega)^2} + \frac{\frac{R_bC}{C_{bc}}}{1+(R_bC\omega)^2} \tag{7}$$

$$\mathrm{Real}(Z_{11}) = R_E + \frac{R_b}{1+(R_bC\omega)^2} + \frac{R_1}{1+(R_1C_1\omega)^2} \tag{8}$$

Step 3- Simplified equations are obtained from (4-6): for f<< $f_1 = \dfrac{1}{2\pi R_bC}$ = 77.5 GHz, Eq. (4-6) can be rewriten as follows:

$$\text{-}\omega.\mathrm{Imag}(Z_{12}) \approx \frac{1}{C_\pi} + (\frac{(R_bC)^2}{C_c} - L_e)\omega^2 \tag{9}$$

$$\text{-}\omega \mathrm{Imag}(Z_{22}-Z_{12}) \approx \frac{1}{(C_{bc}+C_c)} - (\frac{(R_bC)^2}{C_{bc}+C_c} + L_c)\omega^2 \tag{10}$$

$$\text{-}\omega \mathrm{Imag}(Z_{11}\text{ - }Z_{12}) \approx \frac{1}{C_1}\frac{(R_1C_1\omega)^2}{\left[1+(R_1C_1\omega)^2\right]} + (\frac{(R_bC)^2}{C_{bc}} - L_b)\omega^2 \tag{11}$$

The second terms of the right expressions in (9-11) show clearly the effect of global inductive terms. The base resistance and intrinsic and extrinsic base-collector capacitances have an influence on the determination of parasitic inductances. Thereby to determine the inductances Lb, Lc, and Le correctly, we have to take into account the corrective terms $\dfrac{(R_bC)^2}{C_c}$, $\dfrac{(R_bC)^2}{C_{bc}+C_c}$ and $\dfrac{(R_bC)^2}{C_{bc}}$ respectively.

Step 4- global inductive effect are independently calculated: Curves 1 (Fig.2 a-c) show a slope visible over a large frequency range of f≤27GHz. This result confirms the effect of the global inductive terms described in (9-11). Up to 27 GHz, we note a slight change of the slope due to condition f<<f1 which is no verified and then to $(RbC\omega)^2$ which is no negligible in (4-6). For f>>$f_2 = \dfrac{1}{2\pi R_1C_1}$, Eq. 11 can be rewriten as follows:

$$\text{-}\omega \mathrm{Imag}(Z_{11}\text{ - }Z_{12}) = \frac{1}{C_1} + (\frac{(R_bC)^2}{C_{bc}} - L_b)\omega^2 \tag{12}$$

Inductive terms $\dfrac{(R_bC)^2}{C_c}$-L_e and $\dfrac{(R_bC)^2}{C_{bc}+C_c}$+$L_C$ in (9,10) and the inductive term $\dfrac{(R_bC)^2}{C_{bc}} - L_b$ in (12) can be easily determined using linear regression over frequencies f≤27GHz and f_2<<f<<f_1 respectively (curves 1, Fig. 2a-c). For the studied transistor, f_1 and f_2 are 77.5GHz and 1.6GHz respectively. We can note a slope visible over a frequency range of (15-27) GHz (Fig. 2b). Inder f=15GHz, the result shows the effect of $(R_1C_1\omega)^2$ whose influence can no more be neglected.

Step 5- calculation of Cbc, Cc and Rb in order to determine the corrective terms: To calculate C_{bc}, C_c and R_b, we determine R_bC/C_{bc} and R_b+R_E using respectively (7) and (8) and $C_{bc}+C_c$ using eq. (13) derived from (10):

$$\frac{-1}{\mathrm{Imag}(Z_{22}-Z_{12})}=\frac{(C_{bc}+C_c)\omega}{1-(L_c+\frac{(R_bC)^2}{C_{bc}+C_c})(C_{bc}+C_c)\omega^2} \qquad (13)$$

Eq. 13 shows that $C_{bc}+C_c$ can be obtained from experimental result shown in Fig.3a using linear regression over all frequencies $f<<f_3=\frac{1}{2\pi}\sqrt{\frac{1}{L_c(C_{bc}+C_c)+(R_bC)^2}}$. For $f_2<<f<<f_1$, Eqs. (7) and (8) give $\frac{R_bC}{C_{bc}}$ and R_E+R_b respectively. Thereby $\frac{R_bC}{C_{bc}}$ and R_b+R_E can be determined from frequency dependance of $\mathrm{Real}(Z_{11}-Z_{12})$ and $\mathrm{Real}(Z_{11})$ respectively using linear regression over a frequency range of (20-25) GHz which satisfy $f_2<<f<<f_1$ (Fig.3b-c). The resistance R_E which is bias independent is determined using the method prposed by Maas and Tait (4). the above results allow us to calculate R_b, C_c and C_{bc} and then the corrective terms: $\frac{(R_bC)^2}{C_{bc}+C_c}$, $\frac{(R_bC)^2}{C_{bc}}$ and $\frac{(R_bC)^2}{C_c}$.

Step 6- Parasitic inductance values are calculated substuting corrective terms in global inductive effect expressions described above:

$$L_e=\frac{(R_bC)^2}{C_c}-(\frac{(R_bC)^2}{C_c}-L_e),\ L_b=\frac{(R_bC)^2}{C_{bc}}-(\frac{(R_bC)^2}{C_{bc}}-L_b) \text{ and } L_c=(\frac{(R_bC)^2}{C_{bc}+C_c}+L_c)-\frac{(R_bC)^2}{C_{bc}+C_c}$$

Fig. 4 presents the result obtained for a microstrip mounted HBT. The measurements show a very visible slope over a wide frequency range due principally to inductive effect of wires bonding. The parasitic inductance values are in this case large enough compared to other inductive terms and the currently methods can be used.

Conclusion: Original procedure for determining parasitic access inductances of high performance on-wafer coplanar HBTs is developed. The approach takes into account the influence of inductive terms due to other device elements and does not need very high frequency S parameter measurements. The procedure is applied on two types of HBTs: an on-wafer coplanar GAlnP/GaAs HBT and a microstrip mounted GaInP/GaAs HBT. The results show that the base resistance and base-collector capacitances have a significant effect on the accurate determination of high frequency HBT parasitic inductances. This is not the case of the microstrip mounted HBT where the effect of wires bonding is more important and then masks the influence of other inductive terms.

References:

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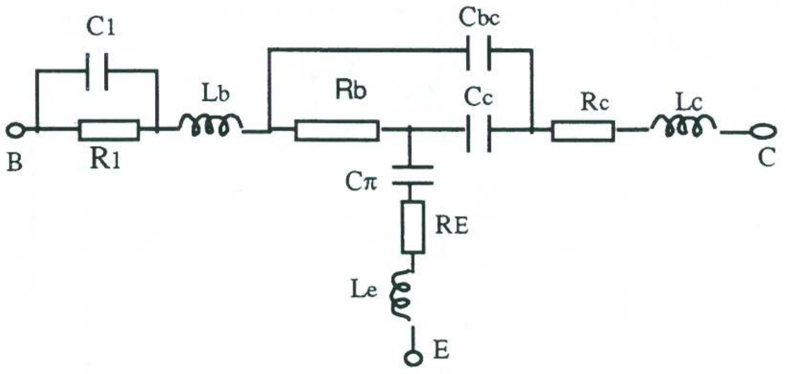

Le= 10 pH
Lb= 55 pH
Lc= 3 pH
Rb= 77 Ω
Rc= 15 Ω
RE= 15 Ω
Cbc= 60 fF
Cc= 47 fF
Cπ= 40 fF
C1= 200 fF
R1= 500 Ω

Fig. 1: cutoff-mode small signal equivalent circuit of HBT with VCE=0 condition and parameter values determined using the proposed procedure.

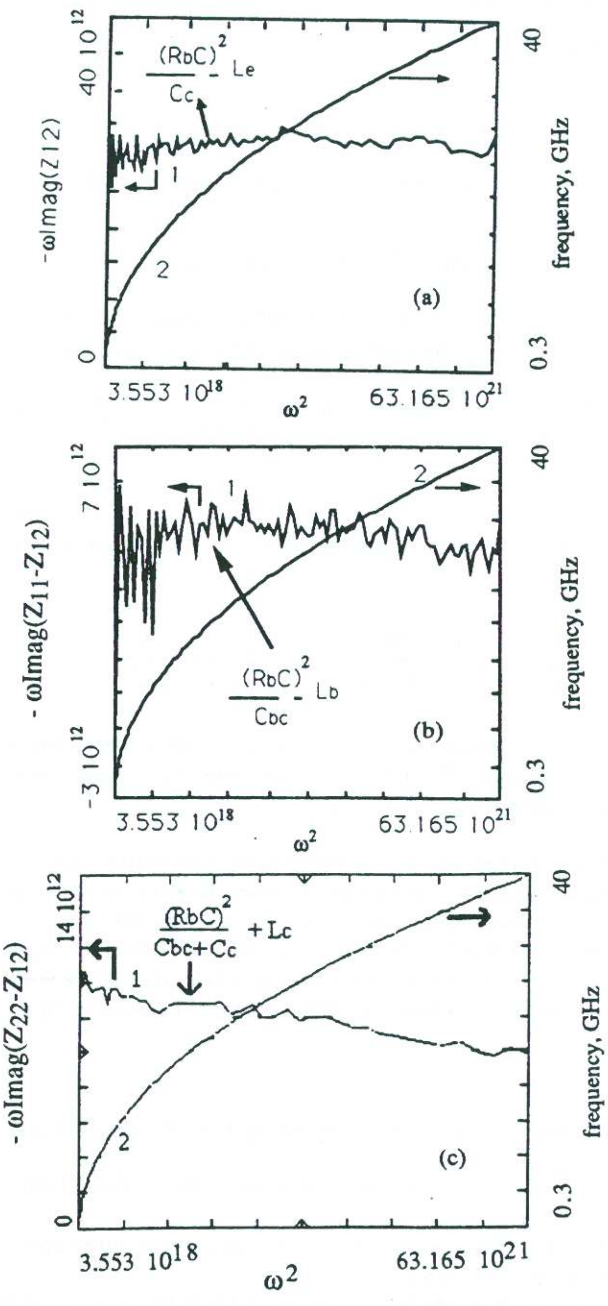

Fig.2: determination of the global inductive effect

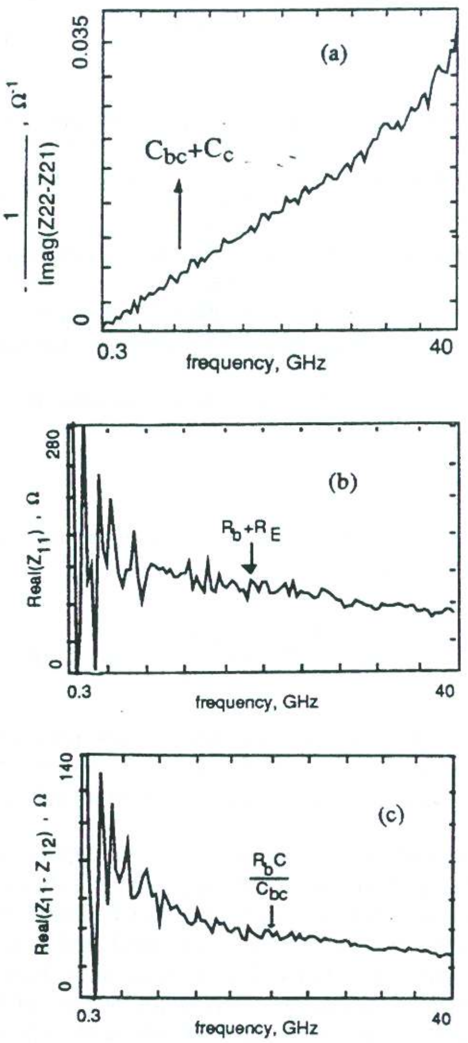

Fig.3: determination of $C_{bc}+C_c$, R_b+R_E, and R_bC/C_{bc} from real and imaginary parts of combined Z parameters

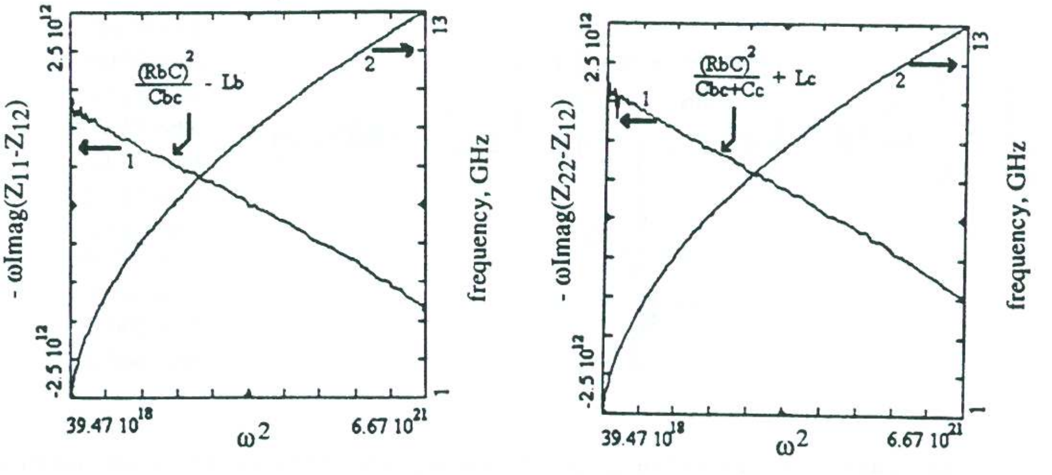

Fig.4 : combined Z parameter imaginary parts as function on ω^2 of a microstrip mounted HBT. Curves 1 show a visible slope over a wide frequency range due to important influence of inductances effect related to wire bonding.