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Current Dependence of Excess Phase in Inhomogeneous Base Transistor

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In general, the excess phase of current amplification factor in inhomogeneous base transistor is defined statically in terms of the so-called built-in field due to the impurity distribution in the base region. In the state of operation, however, the above definition is not available because the resultant base field is affected considerably by the carrier injection level.

In the present paper, the expressions for the excess phase with the carrier injection level, that is, emitter current, are derived theoretically and the validity of them is examind experimentally.

1. Introduction

It is well-known that the excess phase of current amplification factor in inhomogeneous base transistor is defined statically in terms of the so-called built-in field due to the impurity distribution in the base region. This means that the excess phase is determined simply by the manufacturing process. In the experiment and others, however, the results¹⁾ that the excess phase is affected considerably by the carrier injection level have been obtained empirically. This effect need not be taken into account when the transistor is used in the common base configuration and in the frequency range much lower than alpha cut-off frequency, but becomes a serious problem for the circuit design when the transistor is used in the common emitter configuration and in the high injection emitter current.

A number of studies2)3) dealing with the minority carrier distribution in the base region in accordance with the carrier injection level have been made, but the studies dealing with the effect of injection level to the excess phase have apparently not been reported to date.

Consequently, in the present paper we will treat the relations between the excess phase and the minority carrier injection level, that is, emitter current, as the following.

1) The carrier injection is classiffied into relatively high and low levels and then the expressions for the field in the base region are derived according to those levels, respectively.

2) Considering the effect of the field obtained above and the well-known relation between the excess phase and the so-called built-in field due to the impurity distribution,

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the expressions for the excess phase with the carrier injection level or emitter current are derived.

3) The expressions stated above are discussed theoretically with respect to the various conditions and are examined experimentally. The expressions for the excess phase thus obtained are shown to be valid.

2. Derivation of Theoretical Expressions

In order to obtain the expressions for the base field with the carrier injection level, the impurity distribution $N_a(x)$ is assumed to be exponential, since this closely describes the impurity distribution in the inhomogeneous base region. That is,

$$N_a(x) = N_{a0} \exp(-x/L'), \tag{1}$$

where N_{a0} ; impurity concentration at the emitter extreme of the base region,
L' ; $1/e$ length of exponentially graded base region,
x ; distance from the emitter extreme of the base region.

For convenience NPN transistors are considered. The electron and hole current densities J_n and J_p due to the electron and hole distributions $n(x)$ and $p(x)$ in the base region are given as the following equations:

$$J_n = n(x)q\mu_e E(x) - qD_n \frac{\mathrm{d}n(x)}{\mathrm{d}x}, \tag{2}$$

$$J_p = p(x)q\mu_p E(x) + qD_p \frac{\mathrm{d}p(x)}{\mathrm{d}x}, \tag{3}$$

where q ; electron charge,
μ_e ; mobility of electron,
μ_p ; mobility of hole,
E ; electric field in the base region,
D_n ; diffusion constant of electron,
D_p ; diffusion constant of hole.

On the other hand, the charge neutrality requires that

$$n + N_a = p + N_d,$$

where N_a and N_d are accepter and donor densities in the base region. Since the condition of $N_d \ll p$ is satisfied for the NPN transistor, the above expression is simplified as

$$n + N_a = p. \tag{4}$$

Owing to the closeness of the emitter efficiency to unity and the smallness of recombination effects, the hole current J_p in the base region may be considered, in the steady-state, to be negligible, so that

$$J_p \doteqdot 0. \tag{5}$$

From Eqs. (1), (3), (4) and (5), we obtain

$$qD_p\frac{\mathrm{d}n(x)}{\mathrm{d}x}+q\mu_p E(x)n(x) = qD_p\frac{1}{L'}N_a(x)-q\mu_p N_a(x)E(x)\,.$$

Applying the Einstein's relation

$$\mu_p KT = qD_p\,,$$

to the above equation, we have

$$\frac{\mathrm{d}n(x)}{\mathrm{d}x}+\frac{q}{KT}E(x)n(x) = N_a(x)\left\{\frac{1}{L'}-\frac{q}{KT}E(x)\right\}, \tag{6}$$

where K ; Bolzman's constant,
T ; absolute temperature.

In the same way, application of Einstein's relation to Eq. (2) yields

$$\frac{\mathrm{d}n(x)}{\mathrm{d}x}-\frac{q}{KT}E(x)n(x) = -\frac{J_n}{qD_n} = -\frac{I_e}{qD_nA_e}, \tag{7}$$

where A_e is emitter area. In this derivation the various types of recombination have been neglected and J_n has been assumed to be constant thoughout the base region.

Subtracting Eq. (7) from Eq. (6), we obtain the base field $E(x)$ with the electron distribution $n(x)$ and carrier injection level J_n or emitter current I_e as follows.

$$E(x) = \frac{KT}{q}\frac{\frac{1}{L'}N_{a0}\exp(-x/L')+\frac{I_e}{qD_nA_e}}{2n(x)+N_{a0}\exp(-x/L')}\quad, \tag{8}$$

The electron distribution $n(x)$ in Eq. (8) is given as following[3], corresponding to the high and low carrier injection levels respectively.

For high carrier injection level;

$$n(x) = \frac{WI_e}{2qD_nA_e}\left(1-\frac{x}{W}\right)+\frac{N_{a0}}{2}\left\{\exp\left(-\frac{W}{L'}\right)-\exp\left(-\frac{x}{L'}\right)\right\}. \tag{9}$$

For low carrier injection level;

$$n(x) = \frac{L'I_e}{qD_nA_e}\left[1-\exp\left\{-\frac{W}{L'}\left(1-\frac{x}{W}\right)\right\}\right], \tag{10}$$

where W in Eqs. (9) and (10) is base width. We thus obtain the following expressions for the base field $E(x)$ with the emitter current I_e.

For high carrier injection level;

$$E(x) = \frac{KT}{q}\frac{\frac{1}{L'}\exp(-x/L')+\delta/W}{\delta(1-x/W)+\exp(-W/L')}, \tag{11}$$

For low carrier injection level;

$$E(x)=\frac{KT}{q}\,\frac{\frac{1}{L'}\exp(-x/L')+\delta/W}{\frac{2\delta L'}{W}\left[1-\exp\left\{\frac{W}{L'}(1-x/W)\right\}\right]+\exp(-x/L')}\,, \tag{12}$$

where

$$\delta=\frac{WI_e}{qD_nN_{a0}A_e}\,.$$

Then, the mean value of E is

$$\bar{E}=\frac{1}{W}\int_0^W E(x)\mathrm{d}x\,. \tag{13}$$

Here, let us define the base field parameter which expresses conveniently the magnitude of the field in the base region as

$$\eta'=\frac{\bar{E}W}{2(KT/q)}\,. \tag{14}$$

Consequently, the excess phase m of current amplification factor α is expressed in terms of η' as the following well-known relations[4],

$$m=\frac{1}{\sqrt{1-(2C_2/C_1^2)}}-1\,, \tag{15}$$

where

$$\left.\begin{aligned} C_1&=\frac{2\eta'+e^{-2\eta'}-1}{2^{\eta'2}}\,,\\ C_2&=\frac{(2\eta'^2-4\eta'+3)-(2\eta'+3)e^{-2\eta'}}{2!\cdot 2\eta'^4}\,. \end{aligned}\right\} \tag{16}$$

As the results, from Eqs. (12) to (16) we can calculate the excess phase with the emitter current.

3. Considerations

3.1 Numerical Calculations

In order to calculate the base field E and the excess phase m, corresponding to the carrier injection level, derived in previous chapter, let us take the typical physical data as follows;

$$D_n=31\ \mathrm{cm^2/sec}\,,\quad N_{a0}==0.5\times10^{17}/\mathrm{cm^3}\,,\quad W=5\mu$$
$$W/L'=1\sim8\,,\quad T=300\mathrm{K}^\circ\,,$$

provided that the inhomogeneous base NPN transistors for high frequency such as 2SC374 and 2SC68 are considered.

Figs. 1 and 2 show the relations between the base field $E(x)$ and the normalized

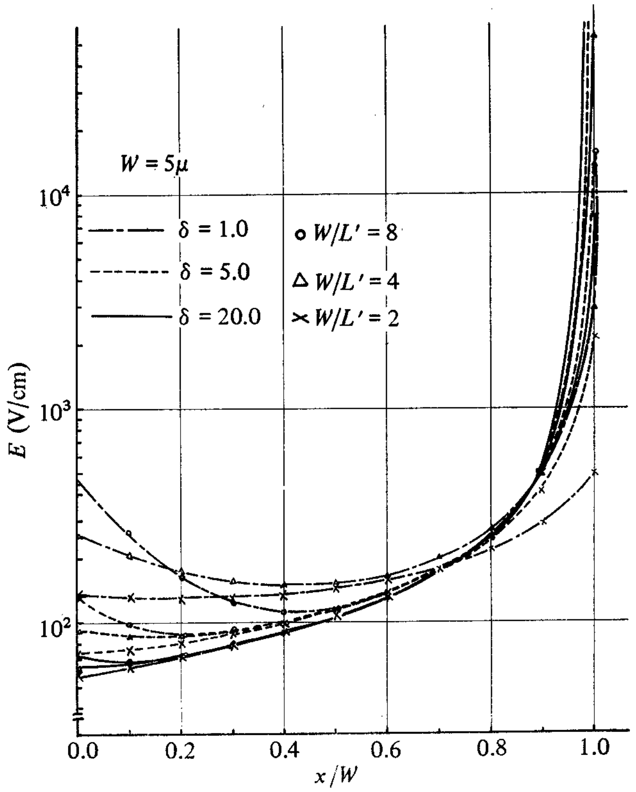

Fig. 1. Relation between E and x/W for high carrier injection level.

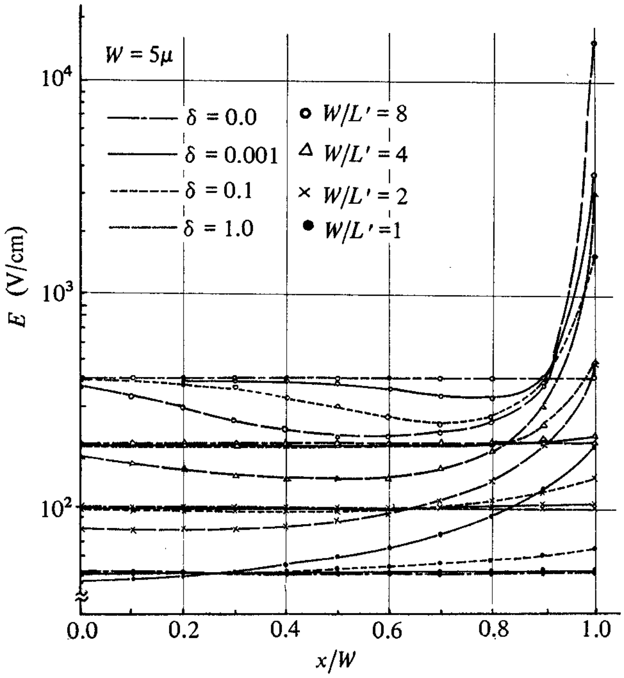

Fig. 2. Relation between E and x/W for low carrier injection level.

distance x/W in the base region for the high and low carrier injection levels respectively, by taking W/L' and δ as parameters, where W/L' is the impurity gradient and δ is the normalized injection current. It can be seen in both figures that the base field becomes higher in the neighborhood of collector.

Figs. 3 and 4 show the excess phase m plotted against the normalized injection current δ for the high and low carrier injection levels. The values of m corresponding to $\delta=1$ in both cases are not equal. Especially, in the vicinty of $\delta=1$ in Fig. 3 the excess phase m decreases with increasing carrier injection, and this tendency is different from that for the higher value of δ. These facts mean that Eqs. (9) and (11) for the high

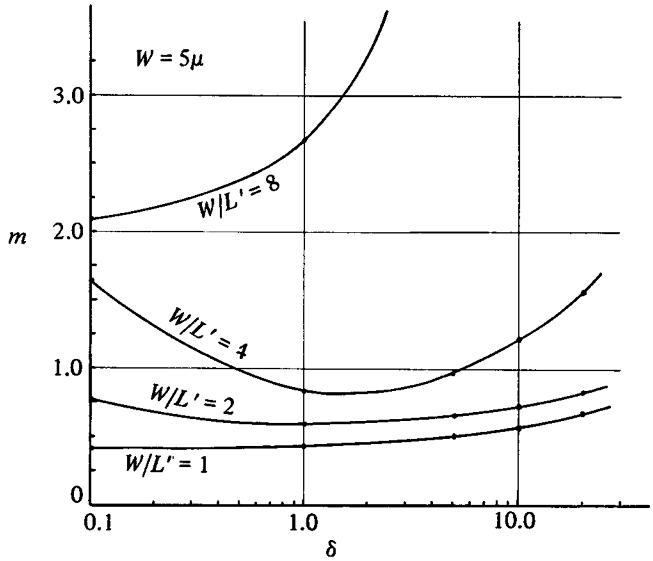

Fig. 3. Relation between m and δ for high carrier injection level.

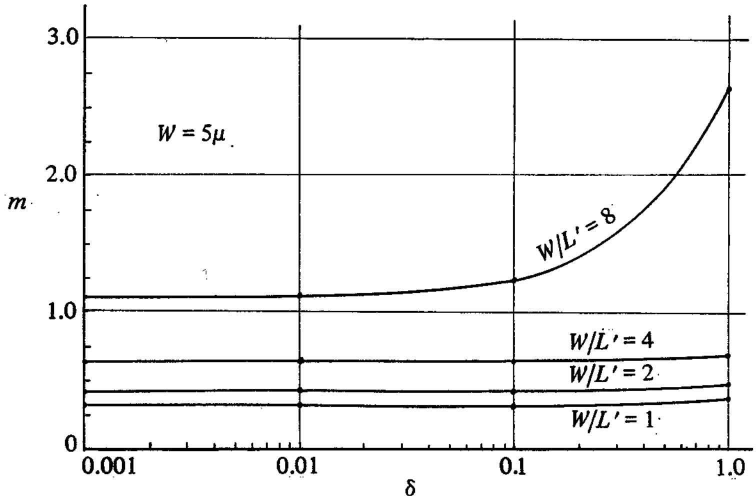

Fig. 4. Relation between m and δ for low carrier injection level.

injection level are valid only for $\delta > 1$, and that Eqs. (10) and (12) for the low injection level are valid only for $\delta < 0.1$.

Fig. 5 shows the graphically synthesized results of Figs. 3 and 4 to fill the deviation for the values and gradients of the characteristic curves in the vicinity of high and low injection boundaries, and illustrates well the following items.

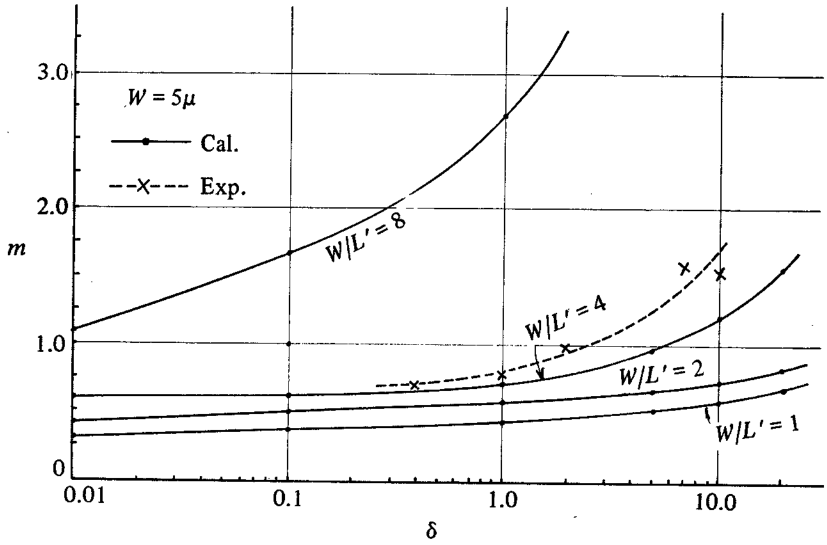

Fig. 5. Resultant relation between m and δ.

1) The base field increases with increasing injection emitter current. Consequently, the excess phase increases with increasing injection emitter current.

2) The tendency described in 1) is emphasized with the increase of the impurity gradient W/L'.

3.2 Measurements

The dotted line at W/L' above 4 in Fig. 5 represents the results measured by using the transistor 2SC374, where $\delta = 1,2,3, \cdots 10$ correspond to $I_e = 1,2,3, \cdots 10\text{mA}$, because we may assume $A_e \doteqdot 2 \times 10^{-6}\text{cm}^2$. The measurements were made by the following experimental equation[5];

$$m = \frac{-(K'+A)}{(1-\alpha_0-2\pi f_{ce} C_0 r_s)(A-K'A^2)+(K'+A)}, \qquad (17)$$

where

$$K' = \tan\theta ,$$
$$C_0 = C_{c'b'} + C_{c'b} ,$$
$$r_s = Z_e + r_{cc'} ,$$

α_0 ; current amplification factor at low frequency,

f_{ce} ; cut-off frequency in common emitter configuration,
A ; arbitrary number such as 2∼5,
θ ; phase angle of current amplification factor of common emitter configuration at Af_{ce}.
Z_e ; total impedance between emitter terminal e and internal base terminal b',
$r_{cc'}$; collector series resistance between external collector terminal c and interminal collector terminal c',
$C_{c'b'}$; collector capacitance between c' and b',
$C_{c'b}$; collector capacitance between c' and b.

The quantitative comparison of the experimental results for a specific transistor with the calculated results based on the typical physical data, as shown in Fig. 5, involves some problems. The quantitative tendency of m in both cases, however, seems to agree well, because the values of $W/L'=4\sim8$ are suitable for general inhomogeneous base transistor.

4. Conclusion

In the present paper we have derived the expressions for the excess phase in terms of the carrier injection levels or emitter current in the inhomogeneous base transistors, which hasn't been so far made clear quantitatively. The results obtained are summarized as the following.

First, by extending the general concept that the so-called built-in field is determined simply by the impurity distribution in the base region, the expressions for the excess phase with the emitter current are derived theoretically. Then, the validity of the expressions thus obtained are examined by the numerical calculation and measurements, and the characteristics that the excess phase increases with increasing emitter current is proved theoretically.

Therefore, this theory is very effective for the analysis and design of the transistor behavior6)7), where the influence of excess phase becomes dominant, such as the common emitter amplifier operating under relatively high emitter current.

Since the several physical parameters of a given transistor, however, are not evident generally, the insufficient points at measurements still remain and there are very much left to do for more exact analysis.

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