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Inductive Transistor and Its Application to Oscillator

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An oscillator is described as an example of utilization of inductance obtained at the output of transistor in the grounded collector configuration. The theoretical analysis of this inductance L_{out} and oscillating frequency f are developed under various conditions for the alloy-junction type transistor of which the avalanche breakdown voltage V_B is lower than the punch-through voltage V_{pt} ($V_B < V_{pt}$), and moderate coincidence with the experimental results is shown to exist. Moreover, the temperature dependences of oscillating frequency and D C biases and their compensations are described.

1. Introduction

A number of studies(1)(2)(3) have been made to obtain an inductive solid-state elements with the development of microminiaturized circuits.

In the previous(4) and other(5)(6)(7) papers, we also reported about the output admittance (inductance and conductance) of the alloy-junction type transistor in the grounded collector configuration. The considerations made hitherto in those papers are summarized, for the sake of reference, as the followings.

1) The inductance mentioned above depends on the circuit conditions, namely, source conductance G_g at the base side, emitter current I_e and collector to base voltage V_{cb}.

2) If the alloy-junction type transistor of which the avalanche breakdown voltage V_B is lower than the punch-through voltage V_{pt} is used and the collector to base is biased close to the avalanche multiplication region, the following inductances are easily obtained;

I. Inductance with small positive conductance,
II. Inductance with negative conductance.

The applications of such inductive transistor to electric circuit are numerous.

The following list shows two examples we have examined.

I. Filter circuit or bandpass amplifier.
II. Coilless sinewave oscillator.

Of the above two, desirable high Q is obtained theoretically in case I, but the sensitivity of the small positive conductance with respect to the collector to base voltage, i.e., the bias sensitivity of effective Q is so high that it is difficult to stabilize the circuit with only a single inductive transistor. Besides, in case of high Q, the frequency characteristics of filter often presents the deformed resonant curve with a jumping phenomena(7). On the other hand, in case II it is possible to construct a stable circuit by a suitable method.

Accordingly, in this paper we will treat the several characteristics of inductive transistor oscillator as described below.

1) The circuit analysis of the oscillating frequency f (or equivalent inductance L_{out}) with respect to the source conductance G_g and the collector to base voltage

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V_{cb} are made under various conditions. These are examined by the experimental results, and the moderate coincidence between them is shown to exist.

2) Fundamental circuit of an oscillator is constructed taking the bias stability into consideration. Further, the temperature dependences of oscillator, that is, the temperature sensitivities of oscillating frequency and of output voltage are shown experimentally and analyzed qualitatively.

3) Finally, satisfactorily temperature-compensated circuit is proposed making good use of the analytical results obtained in 1) and 2).

2. Basic Characteristics of Inductive Transistor

The output admittance ${}_cY_{out}$ of the generally-used high frequency transistor in the grounded collector configuration consists of the inductance and positive conductance, and so behaves like very lossy inductance. However, it is possible to convert this element into the inductance with negative conductance (small loss or lossless inductance) under suitable conditions. Namely, using the alloy-junction type transistor of which the avalanche breakdown voltage V_B is lower than the punch-through voltage V_{pt} ($V_B < V_{pt}$), the collector to base is biased so high as the resultant current amplification factor $\alpha \cdot M$ exceeds unity, where M is the avalanche multiplication factor defined by Miller(8).

Fig. 1 shows the experimental circuit. The source and load conductances, G_g and G_l, are connected respectively to the input and output sides of the transistor in the grounded collector configuration. The collector to base is biased in the range as mentioned above and emitter current I_e is adjusted adequately.

Thus, the properties of both inductance L_{out} and conductance G_{out} obtained at the emitter side are examined with respect to collector to base voltage V_{cb}, emitter current I_e, source conductance G_g and oscillating frequency f.

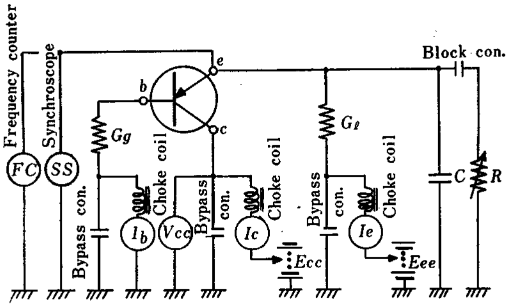

Fig. 1. Experimental circuit

The measurement of inductance L_{out} is carried out by oscillating the circuit with negative conductance G_{out}, inductance L_{out} and inserted capacitor C. This oscillating frequency f is counted by the digital counter and the wave shape is observed by the synchroscope. Since C and f are the known values respectively, L_{out} can be calculated as following,

$$L_{out} = \frac{1}{(2\pi f)^2 C} . \qquad (1)$$

On the other hand, the measurement of negative conductance G_{out} is carried out by decreasing the adjustable resistor R and observing its value at the point where the oscillation just stops (i.e. G_{out} tends to zero).

If the value of R at that point is R_s, G_{out} can be calculated as following,

$$| G_{out} | = G_l + \frac{1}{R_s} . \qquad (2)$$

The experimental results obtained in this way are summarized as following.

1) The inductance L_{out} increases with increasing V_{cb} and $1/G_g$, but decreases with increasing f to the contrary.

2) The negative conductance G_{out} decreases with increasing $1/G_g$ and f. Besides, the negative conductance G_{out}, in the neighborhood of the point where the positive conductance converts into the negative one, increases with increasing V_{cb}.

Moreover, both inductance L_{out} and negative conductance G_{out} increases with increasing emitter current I_e within some limitted range.

3. Theoretical Analysis of Inductive Transistor Oscillator

In order to analyze the oscillating phenomena due to the inductive effect of transistor, it is effective to use the equivalent circuit hybrid π type in high frequency as shown in Fig. 2 in which the circuit is that of the grounded collector. This equivalent circuit is transformed from the grounded emitter equivalent circuit, where

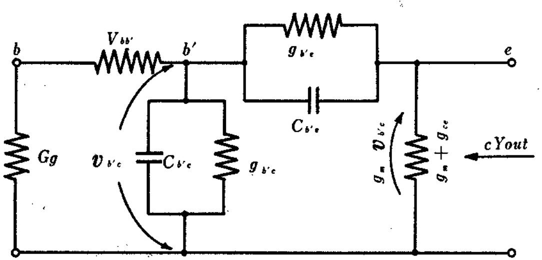

Fig. 2. Equivalent circuit.

$g_{b'e}$: conductance between b' and e,
$g_{b'c}$: conductance between b' and c,
g_{ce} : conductance between c and e,
g_m : mutual conductance,
$C_{b'e}$: capacitance between b' and e,
$C_{b'c}$: capacitance between b' and c,
$r_{bb'}$: spreading resistance between b and b'.

The above elements are examined with respect to emitter current I_e, collector to base voltage V_{cb}, and absolute temperature T. Especially, as V_{cb} is so high the following two effects must be considered.

1) Multiplication of α by the avalanche multiplication.

α is modified by the avalanche multiplication factor M as following.

$$\alpha = \alpha_0 M = \alpha_0/\{1 - (V_{cb}/V_B)^n\} , \tag{3}$$

where $n=3$ for Ge P-N-P transistor and α_0 is the current amplification factor at low V_{cb}.

2) Decreasing of effective base width w.

If it is assumed as

$$V_{ce} = V_{cb},$$

so the expression for w is

$$w = W(1 - \sqrt{V_{cb}/V_{pt}}) , \tag{4}$$

where W is the base width at $V_{cb}=0$, and V_{ce} is the collector to emitter voltage.

As the consequence, each element is represented as following,

$$g_{b'e} = \frac{qI_e}{KT}\left\{1 - \frac{\alpha_0}{1-(V_{cb}/V_B)^3}\right\}, \tag{5}$$

$$g_{b'c} = \sqrt{\frac{\varepsilon\varepsilon_0}{2qN_D}}\,\frac{I_e}{W(1-\sqrt{V_{cb}/V_{pt}})}\left\{1 - \frac{\alpha_0}{1-(V_{cb}/V_B)^3}\right\}\frac{1}{\sqrt{V_{cb}}} , \tag{6}$$

$$g_{ce} = \sqrt{\frac{\varepsilon\varepsilon_0}{2qN_D}}\,\frac{I_e}{W(1-\sqrt{V_{cb}/V_{pt}})\sqrt{V_{cb}}} , \tag{7}$$

$$g_m = \frac{qI_e}{KT} \cdot \frac{\alpha_0}{1-(V_{cb}/V_B)^3}, \tag{8}$$

$$C_{b'e} = \frac{qI_e}{KT} \cdot \frac{W^2}{2D_p}\left(1-\sqrt{V_{cb}/V_{pt}}\right)^2, \tag{9}$$

$$C_{b'c} = \sqrt{\frac{\varepsilon\varepsilon_0 qN_D}{2}} \cdot \frac{1}{\sqrt{V_{cb}}}, \tag{10}$$

$$r_{bb'} = \frac{\rho_B}{8\pi} \cdot \frac{1}{W(1-\sqrt{V_{cb}/V_{pt}})}, \tag{11}$$

where

q : electronic charge, K: Boltzmann constant,
ε : dielectric constant, relative, ε_0 : dielectric constant of free space,
N_D : donor density in base region, ρ_B: resistivity of base region,
D_p : diffusion constant of hole in base region.

The expression for ${}_cY_{out}$ (inductance L_{out} and conductance G_{out}) is simplified by putting $r_{bb'}$ into the side of source conductance G_g.

Namely, we have

$${}_cY_{out} = G_{out} - j\frac{1}{\omega L_{out}} = {}_cY_{22} - \frac{{}_cY_{12} \cdot {}_cY_{21}}{{}_cY_{11}+G_{g'}}, \tag{12}$$

where

$$G_{g'} = 1/(r_{bb'} + 1/G_g) \tag{13}$$

and ${}_cY_{11}$, ${}_cY_{12}$, ${}_cY_{21}$ and ${}_cY_{22}$ are the admittance parameters as shown below (the subscript c denotes the grounded collector configuration),

$$\left.\begin{aligned} {}_cY_{11} &= g_{b'e}+g_{b'c}+j\omega(c_{b'e}+c_{b'c}), \\ {}_cY_{12} &= -(g_{b'e}+j\omega c_{b'e}), \\ {}_cY_{21} &= -(g_m+g_{b'e}+j\omega c_{b'e}), \\ {}_cY_{22} &= g_{b'e}+g_{ce}+g_m+j\omega c_{b'e}. \end{aligned}\right\} \tag{14}$$

Accordingly, the expressions for L_{out} and G_{out} are

$$\begin{aligned} -\frac{1}{\omega L_{out}} = &\frac{\omega^3 c_{b'e}c_{b'c}(c_{b'e}+c_{b'c})}{(G_{g'}+g_{b'e}+g_{b'c})^2+\omega^2(c_{b'e}+c_{b'c})^2} \\ &+\frac{\omega\{C_{b'e}(G_g'+g_{b'c})(G_{g'}+g_{b'c}-g_m)+C_{b'c}g_{b'e}(g_{b'e}+g_m)\}}{(G_g'+g_{b'e}+g_{b'c})^2+\omega^2(C_{b'e}+C_{b'c})^2}, \end{aligned} \tag{15}$$

and

$$\begin{aligned} G_{out} = g_{ce} &+ \frac{(G_g'+g_{b'e}+g_{b'c})(G_g'+g_{b'c})(g_m+g_{b'e})}{(G_g'+g_{b'e}+g_{b'c})^2+\omega^2(C_{b'e}+C_{b'c})^2} \\ &+\frac{\omega^2\{C_{b'e}{}^2(G_g'+g_{b'c})+C_{b'e}C_{b'c}g_m+C_{b'c}{}^2(g_m+g_{b'c})\}}{(G_g'+g_{b'e}+g_{b'c})^2+\omega^2(C_{b'e}+C_{b'c})^2}. \end{aligned} \tag{16}$$

From the frequency condition of oscillation

$$f = 1/2\pi\sqrt{L_{out} \cdot C},$$

the oscillating frequency is expressed as follows,

$$\begin{aligned} f = &\frac{1}{2\pi} \times \\ &\sqrt{\frac{c_{b'e}(G_{g'}+g_{b'c})(g_m-G_g'-g_{b'c})-c_{b'c}g_{b'e}(g_m+g_{b'e})-C(G_g'+g_{b'e}+g_{b'c})^2}{(c_{b'e}+c_{b'c})\{c_{b'e}c_{b'c}+C(c_{b'e}+c_{b'c})\}}}, \end{aligned} \tag{17}$$

if the condition,

$$C < \frac{C_{b'e}(G_g' + g_{b'c})(g_m - G_g' - g_{b'c}) - C_{b'c}g_{b'e}(g_m + g_{b'e})}{(G_g' + g_{b'e} + g_{b'c})^2}, \tag{18}$$

is satisfied.

The examples of numerical calculation of L_{out} and f for Transistor 2SA144 used in our experiment are shown as solid line in Figs. 3 and 4 respectively. These calculation are made by the following procedure.

First, assuming the base resistivity and its width, the avalanche breakdown voltage V_B and punch-through voltage V_{pt} are determined as $90\,V$ and $100\,V$ respectively. Next, using Eqs.(5)~(11), each equivalent circuit element for the required operating voltage V_{cb} is calculated on the basis of ratings (at $V_{cb}=6\,V$, $I_e=1mA$ and $t=25°C$).

Then L_{out}, G_{out} and f are calculated from Eqs. (15), (16) and (17), respectively, where the ratings of given transistor 2SA144 are as following,

at $V_{cb}=6\,V$, $I_e=1mA$ and $t=25°C$

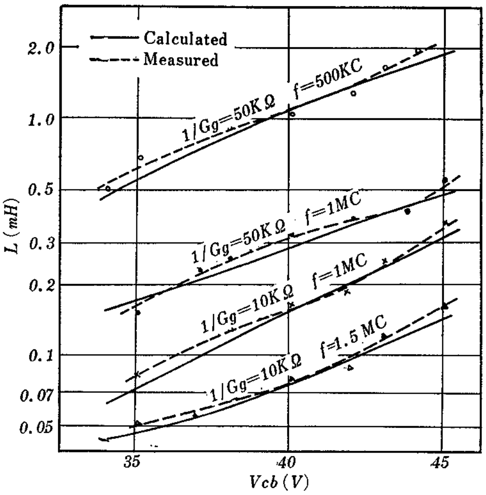

Fig. 3. Relations between L_{out} and V_{cb} for Parameters f and $1/G_g$.

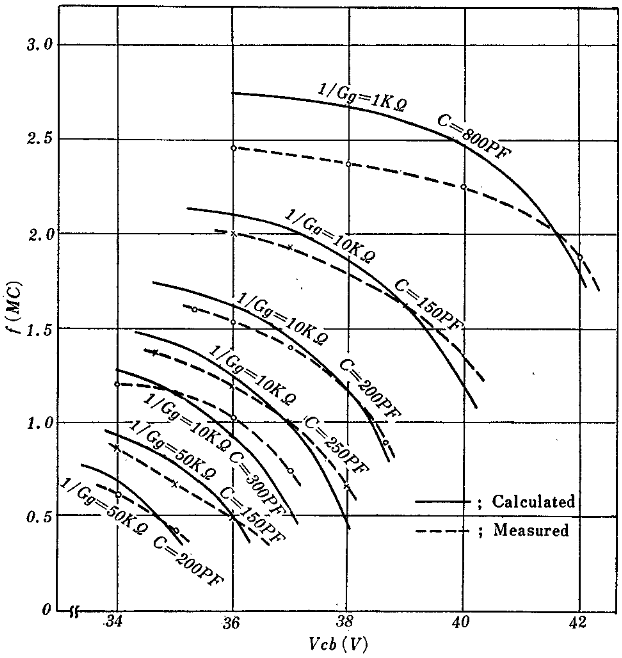

Fig. 4. Relations between f and V_{cb} for Parameters C and $1/G_g$.

$$g_{b'e} = 390\mu\mho, \quad g_{b'c} = 0.5\mu\mho, \quad g_{ce} = 40\mu\mho,$$
$$g_m = 39m\mho, \quad c_{b'e} = 410pF, \quad c_{b'c} = 10.5pF,$$
$$r_{bb'} = 110\Omega.$$

In these calculations, the upper limitation of tunable capacitor C in Eq. (18) and the amplitude condition

$$G_{out} + G_l < 0 \tag{19}$$

are taken into consideration. Therefore, Fig. 4 shows the characteristics of oscillating frequency and its tendency of upper and lower limitations. Besides, these calculated results are examined by the experimental results (dotted line) in Fig. 4, and we see that there is moderate coincidence between them if the operating frequency is somewhat lower than the α cutoff frequency.

4. Application to Oscillator

4-1. Temperature Dependence

Fig. 5 shows the fundamental circuit of inductive transistor oscillator taking D C and A C stability into consideration, R_1 and R_2 are the resistances which satisfy the oscillating and bias conditions. Therefore, the source conductance G_g is determined by

$$G_g = (R_1 + R_2)/R_1 \cdot R_2 \tag{20}$$

R_l means the emitter load resistance and C is the tunable capacitor for the oscillation to be generated. D C bias is provided from a single battery V_{cc}.

This grounded collector circuit is extremely D C stable because it is possible to allow the stabilization factor S to approach unity. In this case, there is no necessity of considering the troubles resulting from the reversal of base current I_b at high temperature range.

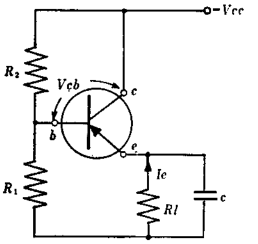

Fig. 5. Fundamental circuit of inductive transistor oscillator.

An example of temperature characteristics of oscillating frequency f and output voltage v_0. under given condition are shown as the solid line in Fig. 6. From these results it is evident that f increases and v_0 decreases with increasing temperature. Moreover, Fig. 7 shows an example of time characteristics of oscillating frequency after starting of operation. As a result, it can be seen that the oscillating frequency becomes stable about 40 minutes later.

In order to consider the temperature characteristics as mentioned above and their methods of compensation, the oscillating conditions in Eqs. (17) and (19) are examined again.

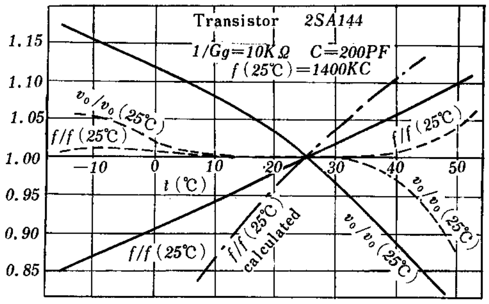

Fig. 6. Temperature characteristics and effects of their compensations.

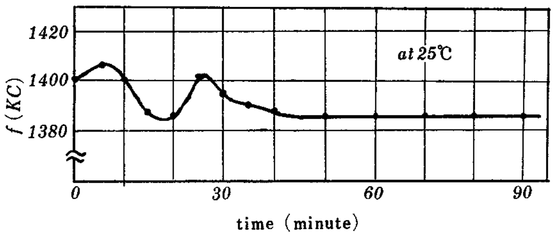

Fig. 7. Oscillating frequency-time characteristics after starting of operation.

The temperature dependence of each equivalent circuit element is calculated from Eqs. (5)~(11), taking the required ambient temperature into consideration in addition to the procedure used in chap. 3. The introduction of temperature dependence into these equations are as following. Namely, the current amplification factor α_0 and the diffusion constant D_p are the decreasing functions of temperature, the base resistivity ρ_B is the increasing function of temperature within the limited range. These quantitative data are derived from W. W. Gärtner's paper(9). Moreover, the temperature dependence of V_B can be obtained(10) from

$$V_B(t) = V_B(25°C)\{1+\beta'(t-25°C)\}, \tag{21}$$

where

$$\beta' = 5.5 \sim 8.8 \times 10^{-4}\ deg^{-1}.$$

Thus, the temperature dependence of oscillating frequency f is obtained by substituting the values of these elements and G_g into Eq. (17), and is represented as a chain line in Fig. 6. In comparison with the experimental results (solid line) in Fig. 6, the tendency of variation is alike. However, the rate of variation is so large as to stop the oscillation at high temperature satisfying no longer the amplitude condition. We think the result is due to the fact that the calculation of the temperature dependence of each element are merely done by guess-work from the general tendency. In this respect we are intending to examine further by the theory and experiment.

4-2. Temperature Compensation

In order to examine the temperature compensation method, the oscillating frequency f vs. V_{cb} and $1/G_g$ characteristics at the constant temperature are calculated once more from Eq. (17). These results are shown in Fig. 8. As the consequence, the oscillating frequency f decreases with increasing V_{cb} and $1/G_g$. Accordingly the compensation of temperature sensitivity is possible by increasing either or both of the two with increasing temperature. In order to attain these condition, following two methods are considered.

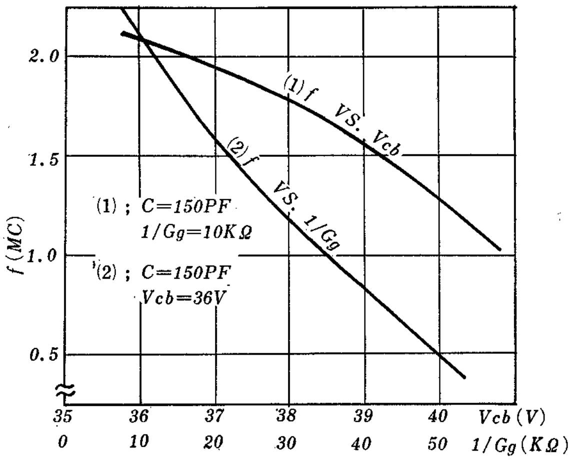

Fig. 8. Relations between f and V_{cb}, $1/G_g$

1) V_{cb} is increased indirectly with increasing temperature by inserting the thermistor in series with V_{cc} in Fig. 5.

2) Both V_{cb} and $1/G_g$ are increased with increasing temperature by inserting the positive thermal sensitive resistor (i.e. posistor) in place of R_2 in Fig. 5.

An example of latter case is shown as dotted line in Fig. 6. As the results, it can be recognized that this modified circuit effectively compensates over the wide operating temperature.

In case of small $1/G_g$, however, R_2/R_1 becomes so large that it is difficult to construct the practical circuit of this oscillator from the standpoint of power consumption. We are considering a method to settle the matter, that is to use terminal resistance of another transistor in stead of resistances R_1 and R_2.

5. Conclusion

In the present paper, the various characteristics of inductive transistor oscillator were described. The results obtained are summarized as following.

1) The output admittance (inductance and conductance) obtained at the emitter side of the transistor in the grounded collector configuration is examined with respect to the collector to base voltage V_{cb} and source conductance G_g. The theoretical analysis of the above inductance L_{out} and oscillating frequency f are developed under various conditions for the alloy-junction type transistor of which the avalanche breakdown voltage V_B is lower than the punch-through voltage V_{pt} ($V_B < V_{pt}$), and moderate coincidence with the experimental results is shown to exist.

2) The practical circuit of oscillator is shown, which was made taking the bias stabilization into consideration, and the temperature dependence of this oscillator is shown experimentally and analyzed qualitatively.

3) Making use of the results given in 1) and 2), fairly good result of temperature compensation can be obtained.

4) From the results as listed above, the guiding principle in practical design of this oscillator can be derived. Besides, the oscillating frequency range of this oscillator is about 0.3~9.0 *MC* under suitable condition.

However, we say with regret that the circuit is inferior to the ordinary amplifier circuit in the power consumption and we hope this problem will be settled by having a transistor of low and stable avalanche breakdown voltage.

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