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LB-1080

TRANSISTOR SWITCHING PERFORMANCE FROM CHARACTERISTIC CURVES

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Approved

Stuart Wm. Seeley

This bulletin describes a simple graphical method for determining the non-linear switching performance of transistors. Characteristic curves are used to determine the base current step to achieve a specified collector response time. The information required is taken directly from the curves. The calculation involves, at most, simple ratios.

The technique has been checked out for a range of collector voltage and current excursions and rise times with the RCA 2N109 and RCA 2N269 transistors. The errors range less than 10 percent for the example chosen.

The procedures are readily extended to the case of a capacitively-coupled voltage drive.

Collector Response Time From Characteristic Curves

A method has been evolved to determine transistor switching performance from two sets of characteristic curves. One set of curves (Fig. 1a) is the collector current response to steps of base current at constant collector voltage. The other (Fig. 1b) is the collector-emitter voltage response to a step of base current at constant emitter current. From these two sets of curves the base current drive needed to achieve a specified output and response time can be determined.

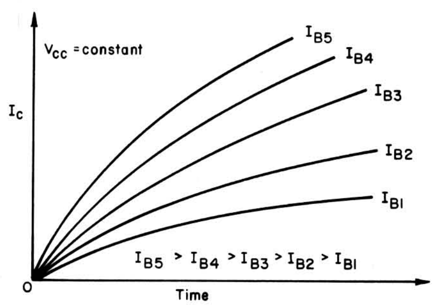


Fig. 1(a) - Collector-current response to steps of base current.

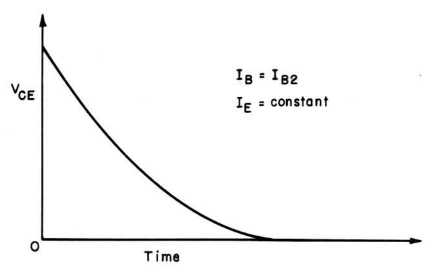


Fig. 1(b) - Collector-emitter voltage response to a step of base current at constant emitter current.

Discussion of Characteristic Curves

The principles involved are set forth by reference to the simplified equivalent circuit of Fig. 2. Strictly speaking, such a representation is intended for small-signal operation at a fixed operating point. Its use for non-linear large-signal operation of this sort provides simply an accessible starting point.

To achieve a specified collector current and voltage change and response time a certain base current drive is required. In terms of the equivalent circuit of Fig. 2 this input base current is delivered partly to the emitter diffusion capacitance, $C_{b'e}$, and partly to the collector junction capacitance, $C_{b'c}$. The scheme advocated here is to determine these two currents separately and to presume that the principle of superposition applies; that is, that the results can be added to give the base current drive required for both collector current and voltage swing.

The base current delivered to the emitter diffusion capacitance, $C_{b'e}$, can be considered as that required to provide drive for the equivalent generator, $g_m V_{b'e}$, which is to supply the specified current change at the collector. The collector current response to steps of base current is determined by using the circuit of Fig. 3. Collector current response is proportional to the voltage change across

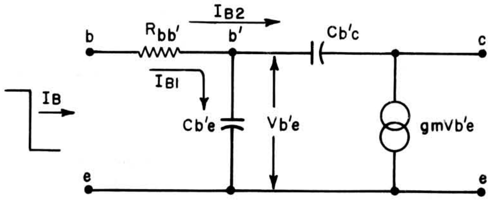


Fig. 2 - Simplified equivalent circuit for high frequency operation.

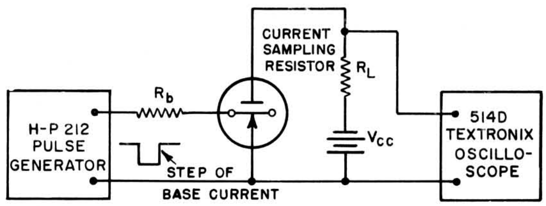


Fig. 3 - Circuit for determining collector current response to steps of base current at constant collector voltage.

the small sampling resistor, r_L. A number of base current steps of different magnitudes provide the family of current response curves shown in Fig. 1.

The current delivered to the collector junction capacitance, $C_{b'c}$, is that required to supply the charge needed for the specified collector junction voltage change. The collector-emitter voltage response to a step of base current at constant emitter current is obtained by using the circuit of Fig. 4. Holding emitter current constant insures that the step of base current will be delivered to charge the collector junction capacitance. In practice it is convenient to measure the resulting voltage change at the emitter rather than the base. This is valid since the one follows the other by approximately one tenth volt. Furthermore this reduces in a simple way the shunting effect of the probe capacitance by a factor of (β + 1) where β is the common emitter current gain of the transistor. Then the effect of the 14-$\mu\mu$f oscilloscope probe capacitance upon the measurement is negligible in most cases.

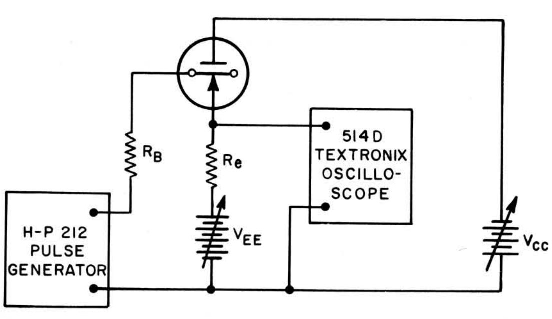


Fig. 4 - Circuit for determining collector voltage response to steps of base current at constant emitter current.

Because the voltage change across the collector junction capacitance for constant emitter current is closely a single-valued function of the charge delivered at the base only one curve for one base current is required. Then the time required for a given voltage excursion across $C_{b'c}$ is inversely proportional to the step of current supplied to this capacitor. This is the case even though $C_{b'c}$ is quite nonlinear.

Illustrative Example

An example will demonstrate the use of the characteristic curves. Let the required current swing be from cutoff to 5 ma; the required voltage excursion from 12 volts to 3 volts and the specified rise time, 0.5 μsec.

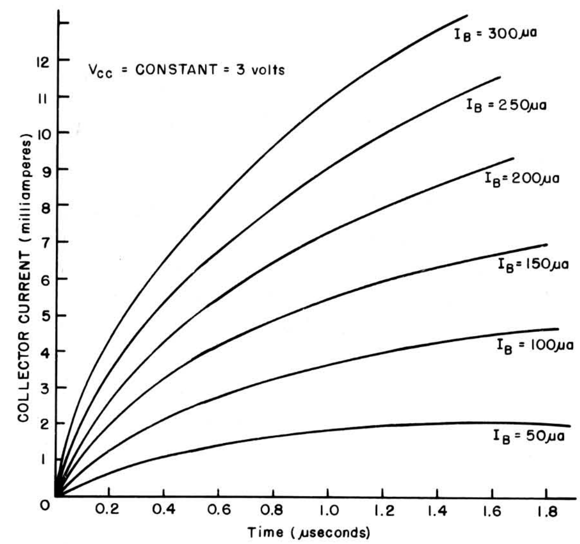


Fig. 5 - Current response to steps of base current.

From Fig. 5, the current response curve for this example, a base step current of 200 μa provides a collector current of 5 ma in the specified 0.5 μsec.

From Fig. 6, the voltage response curve for this example, a base step current of 100 μa charges the collector junction capacitance through the voltage excursion from 12 volts to 3 volts in approximately 1.4 μsec. To accomplish this voltage excursion in the specified 0.5 μsec. then requires

$$\frac{100 \times 1.4}{0.5} = 280\ \mu a$$

since the time is inversely proportional to the current drive used.

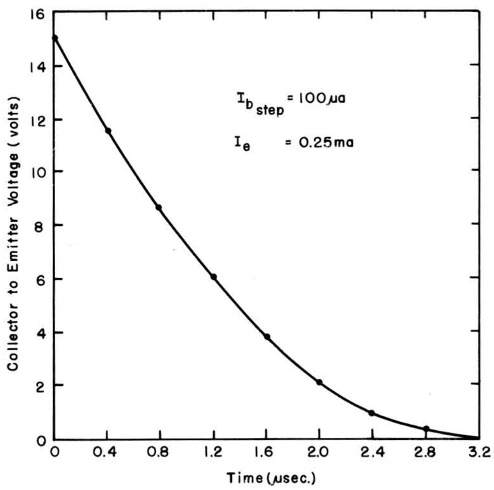


Fig. 6 - Voltage response to steps of base current.

The conclusion is that a base step current drive of 480 μa will achieve a collector current of 5 ma, and a collector voltage excursion from 12 volts to 3 volts in 0.5 μsec.

Experimental Results

The current and voltage response curves described above have been obtained for transistors of the RCA 2N109 and RCA 2N269 (computer) types. These characteristic curves for the 2N269 are shown in Fig. 7; those for the 2N109 in Fig. 8.

By the use of these curves the base current drives required to achieve a variety of collector voltage and current excursions rise times were determined. These data for the transistor of the 2N269 type are listed in Table I together with the figures representing the results achieved. Similar data for a 2N109 transistor is listed in Table II.

The test circuit used to obtain these results is shown in Fig. 11.

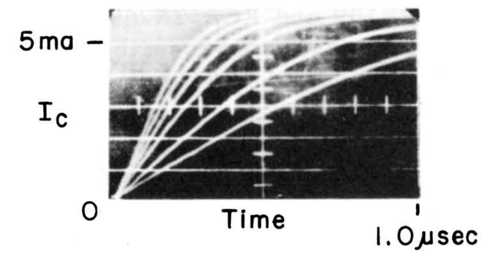
Discussion of Results

Implicit in the procedure described above are a number of important assumptions. The principle of superposition has been mentioned. The use of the collector voltage response curve in the manner described presumes that: (1) the collector junction capacitance is independent of emitter current for the range considered, and (2) the RC time constant of the collector junction capacitance and the collector feedback conductance, $g_{b'c}$, is long as contrasted to the time excursion of the voltage response curve

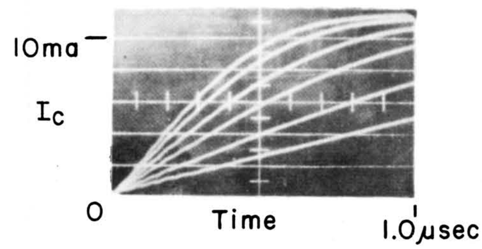
Table I. Experimental Values Used in Designing for Response Times with 2N269 Transistor

ΔV_c volts	ΔI_c ma	Δt μsec.	V_{cc} volts	R_L	I_I (μa)	I_v (μa)	I_β (μa)	Fig.	Δt(Obs.) μsec.
6	3	0.3	-12	2K	350	220	570	9A	0.27
6	6	0.4	-12	1K	500	165	665	9B	0.37
6	12	0.8	-12	0.5K	380	83	463	9C	0.85
8	4	0.5	-10	2K	320	200	520	9D	0.50
6	12	1.0	-12	0.5K	320	66	386	9E	1.00
8	4	0.5	-12	2K	320	180	500	9F	0.50

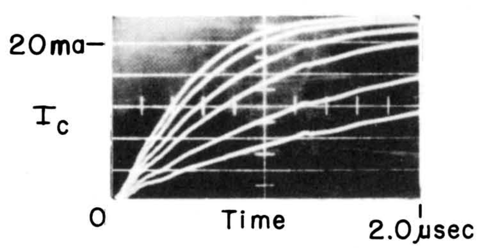
ΔV_c = Collector voltage excursion to be obtained.
ΔI_c = Collector current excursion to be obtained.
Δt = Collector response time to be obtained.
V_{cc} = Collector supply voltage.
R_L = Collector load resistance.
I_I = Base current drive calculated for collector current response.
I_v = Base current drive calculated for collector voltage response.
I_β = $I_I + I_v$.
Δt(Obs.) = Observed time elapsed during excursion.



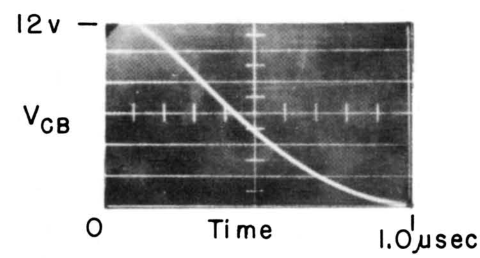
(a) Current responses to steps of 200, 300, 400, 500, 600 and 700 μa, base drive V_{cc} = -2v



(b) Current response to identical conditions to (a); Large current values considered



(c) Current response to conditions identical to (a); Longer time interval considered



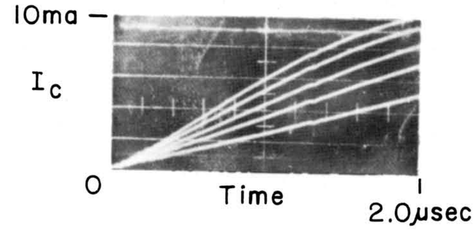
(d) Voltage response to 200 μa step of base current

Fig. 7 - Response curves of 2N269 type transistor.

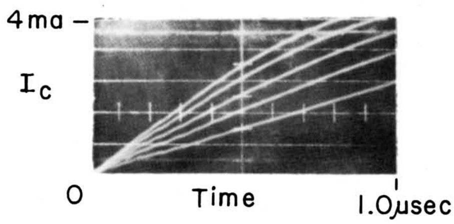
Table II. Experimental Values Used in Designing for Response Times with 2N109 Transistor

ΔV_c volts	ΔI_c ma	Δt μsec.	V_{cc} volts	R_L	I_I (μa)	I_v (μa)	I_β (μa)	Fig.	Δt(Obs.) μsec.
6	4	1.0	-10	1.5K	460	170	630	10A	1.05
6	4	1.5	-12	1.5K	310	110	420	10B	1.60
4	2	0.5	-12	2K	500	200	700	10C	0.53
8	4	1.0	-12	2K	500	210	710	10D	0.90
6	6	1.4	-12	1K	500	110	610	10E	1.45
8	8	2.0	-12	1K	480	105	585	10F	2.10

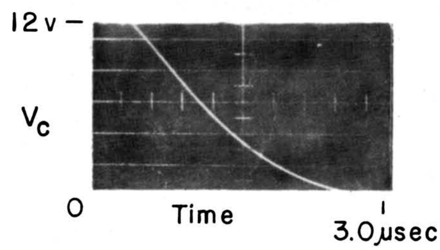
ΔV_c = Collector voltage excursion to be obtained.
ΔI_c = Collector current excursion to be obtained.
Δt = Collector response time to be obtained.
V_{cc} = Collector supply voltage.
R_L = Collector load resistance.
I_I = Base current drive calculated for collector current response.
I_v = Base current drive calculated for collector voltage response.
I_β = $I_I + I_v$.
Δt(Obs.) = Observed time elapsed during excursion.



(a) Current response to steps of 300, 400, 500, 600 and 700 μa base drive V_{CC} = -2v



(b) Current response to conditions identical to (a); Shorter time interval considered



(c) Voltage response to 200 μa step of base current

Fig. 8- Response curves of 2N109 type transistor.

or any rise time to be achieved. This latter requirement is to be satisfied if one curve for one base current is to provide the needed information.

It is felt that these two conditions are well met for the examples considered. Detailed analyses[1] show that the contribution to collector junction capacitance due to collector current is small and decreases with base width. Also, the collector feedback conductance, $g_{b'c}$, ranges less than a micromho, so that the associated time constant would be at least ten μsec. for a collector junction capacitance as low as 10 μμf. The time excursions for the collector-emitter voltage response curves are much less than this for the examples considered.

The use of current response curves in the manner described presumes that the collector current response to a step of base current drive is independent of collector voltage. That this assumption is not valid is demonstrated all too well by current response curves obtained at different collector voltages. Variations of current rise-time for a stepped base current range as high as 50 percent for collector voltages from 1.5 volts to 12 volts. A plot of such variation as a function of collector voltage is shown in Fig. 12. Nonetheless, the results obtained prove to be substantially better than this, the relative error being 10 percent or less for the examples chosen.

The apparent anomaly here can perhaps be justified on two counts. In the examples considered that portion of base current required to charge the collector junction capacitance is a substantial fraction of the total. Presuming that this current has been determined correctly, the relative error contributed by the voltage variation of the current transfer characteristic would be appreciably reduced.

Also, the fact that the examples considered involve a considerable voltage excursion means that the very large errors which would obtain for high voltages are not actually incurred. Indeed, it can be demonstrated that current response curves obtained at or near the lowest voltage of an excursion provide very nearly the correct base drive information. Thus a set of current response curves obtained at a collector voltage of one to three volts would be adequate for many applications.

Clearly, however, there are conditions of operation for which collector current response curves obtained at a single voltage can result in gross errors using the procedure as described. This problem of voltage variation of the collector current response is treated below.

Voltage Variation of Collector Current Response.

Procedure

It is possible to take into account the voltage variation of the collector current response to a step of base current. Shown in Fig. 13 are collector current response curves which can serve this purpose. Fig. 13a shows the collector current response to steps of base current at a fixed collector voltage, as before. Fig. 13b shows the collector current response to one step of base current at different collector voltages.

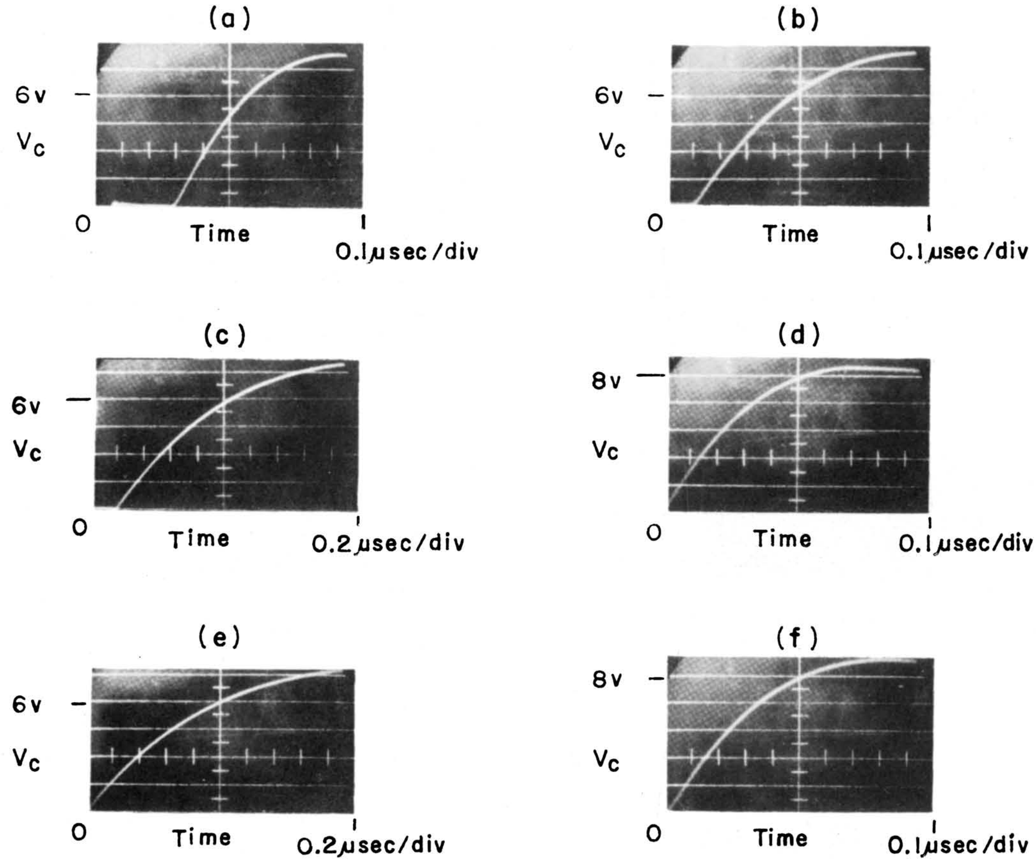


Fig. 9 - Voltage waveforms produced with base drivers calculated from response curves. Type 2N269 transistor.

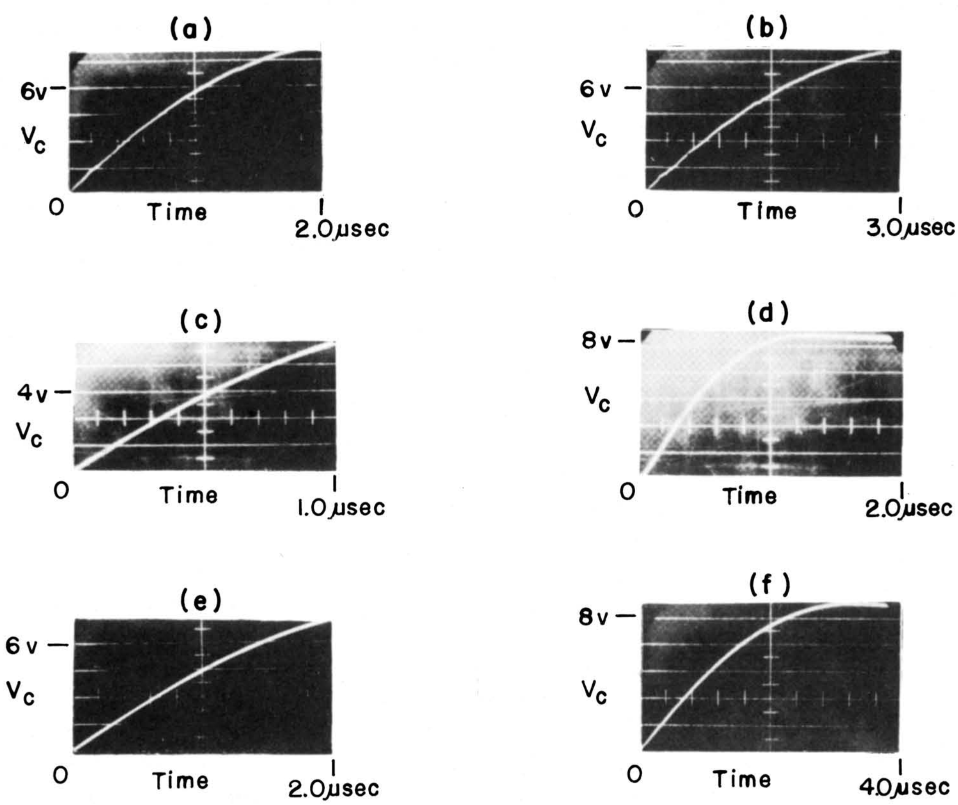


Fig. 10 - Voltage waveforms produced with base drives calculated from response curves. Type 2N109 transistor.

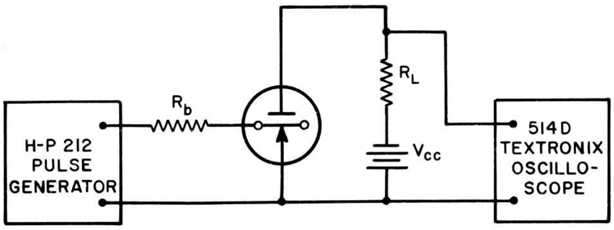


Fig. 11 - Circuit for measuring rise time with calculated value of base current as input steps.

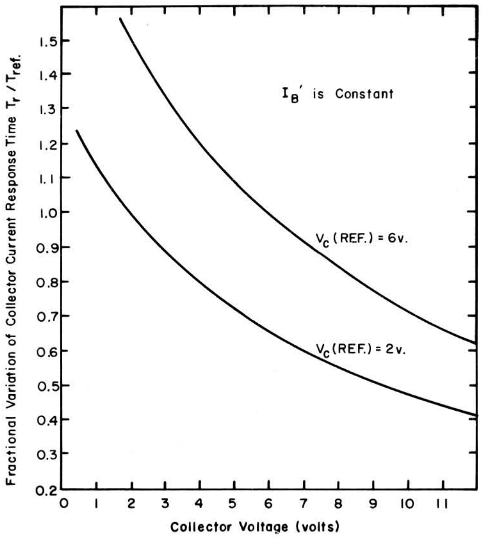


Fig. 12 - The fractional variation of collector current response time plotted as a function of collector voltage.

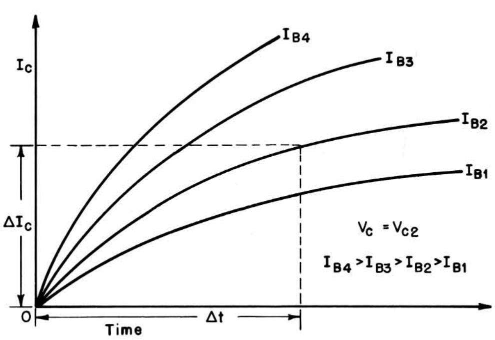


Fig. 13(a) - Variation of collector current with time for various stepped values of base current.

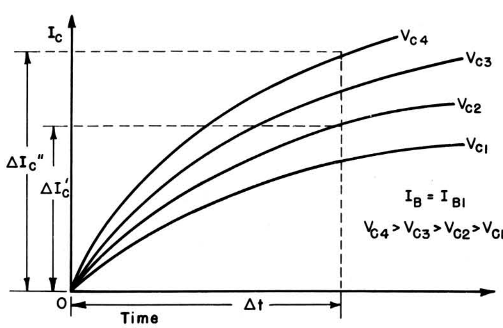


Fig. 13(b) - Variation of collector current with time for various collector voltages.

These curves can be used in two ways to determine the step of base current that provides a specified collector current and rise time at an arbitrary collector voltage. Again the procedure is illustrated by an example.

Let the specified parameters be ΔI_c, Δt, and V_{c4} as shown in Fig. 13. Then from Fig. 13a the step of base current, I_{b2}, provides the specified collector current excursion, ΔI_c, in the time, Δt, but at the collector voltage V_{c2}, rather than at the specified value, V_{c4}. And from Fig. 13b the step of base current, I_{b1}, provides in the time, Δt, collector current, $\Delta I_c'$, at the collector voltage, V_{c2}. At the specified collector voltage, V_{c4}, the corresponding collector current is $\Delta I_c''$. This establishes the ratio

$$\text{(a)} \qquad \frac{I_{bo}}{I_{b2}} = \frac{\Delta I_c'}{\Delta I_c''}$$

where:

I_{bo} is the sought-for step of base current associated with the specified parameters ΔI_c, V_{c4} and Δt.

I_{b2} is the step of base current associated with ΔI_c, V_{c2} and Δt.

$\Delta I_c'$ is the collector current excursion associated with I_{b1}, V_{c2} and Δt.

$\Delta I_c''$ is the collector current excursion associated with I_{b1}, V_{c4} and Δt.

The effect of the increase of the collector voltage from V_{c2} to V_{c4} has been to lower the base current drive requirement in the ratio $\Delta I_c'/\Delta I_c''$.

An alternative procedure is to use just the curves of Fig. 13 (b). These show that the step of base current, $I_{\beta 1}$, yields collector current, $\Delta I_c''$, in the time, Δt, at the collector voltage, V_{c4}. Using the ratio:

$$\text{(b)} \qquad \frac{I_{bo}}{I_{b1}} = \frac{\Delta I_c}{\Delta I_c''}$$

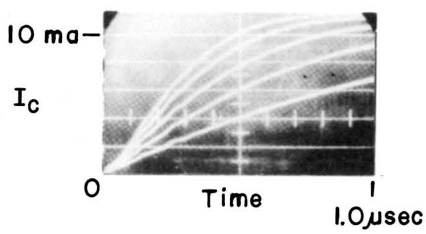
the sought-for base current is obtained.

These procedures have been checked using the examples listed in Table III. The current response curves are shown in Fig. 14a and 14b. The input base currents obtained by the two approaches are in close agreement. The resulting current response curves for these examples are shown in Fig. 14c. The relative error range is less than 5% for these examples

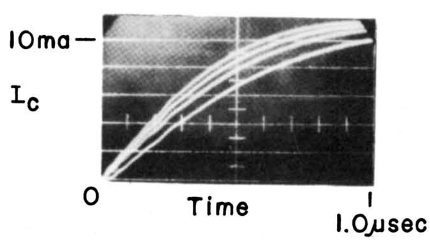
Table III. Examples Used in Verifying the Procedure for Compensating for Voltage Variations

ΔI_c	Δt	$\Delta I_{c'}$	$\Delta I_{c''}$	$I_{\beta 1}$	$I_{\beta 2}$	$I_{\beta o}^{(a)}$	$I_{\beta o}^{(b)}$	$I_{\beta o}(Obs.)$
ma	μsec	ma	ma	μa	μa	μa	μa	μa
6	0.50	8.0	9.0	400	300	270	270	270
6	0.30	5.0	6.1	400	500	390	410	400
8	0.60	8.8	10.0	400	370	320	330	330
8	0.45	7.0	8.5	400	450	380	370	380

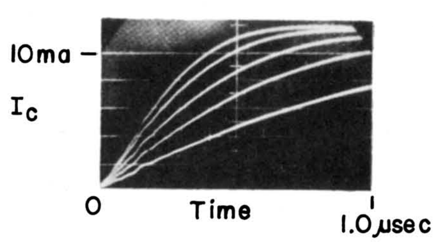
ΔI_c, Δt, $\Delta I_c'$, $\Delta I_c''$, $I_{\beta 1}$ and $I_{\beta 2}$ are all defined in the previous section where ratios (a) and (b) are developed.
$I_{\beta O}$ (a) is a value of $I_{\beta O}$ computed from ratio (a) $I_{\beta O}$ (a) is value of $I_{\beta O}$ computed from ratio (b)
The curves used to obtain the above values and the experimental verification are shown in Fig. 14.



(a) V_{CC} = 3v Steps of base current drive are 200, 300, 400, 500, and 600 μa.



(b) I_B = 400 μa V_{CC} is stepped at -1½, -3, -4½, -6v



(c) V_{CC} = -6v. Steps of base current drive are 200, 300, 400, 500 and 600 μa. Used to check computed values from Table III

Fig. 14 - Current response curves of 2N269 type transistor.

Collector Current Response with Collector Voltage Excursion

Curves of the type shown in Fig. 14 yield the base input drive to achieve a specified collector current response at an arbitrary collector voltage. The more general problem of obtaining a desired current response with a collector voltage excursion yet remains. Detailed discussion is left to an appendix, but the conclusion is a simple one; current response curves obtained at or near the lowest voltage of an excursion provide very nearly the correct base drive information.

Switching Characteristics With Capacitance-Coupled Voltage Drive

Many switching applications do not involve a constant-current base drive. Rather, the situation may be similar to that of Fig. 15, where a voltage input is capacitively coupled to the base of the transistor. In such a case the change delivered to the base is the significant parameter in effecting the desired collector response.

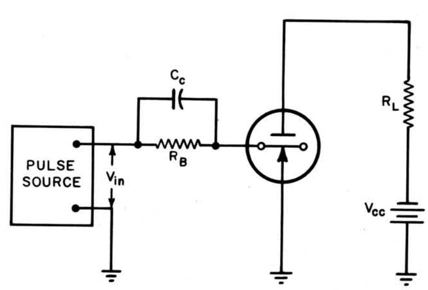


Fig. 15 - Switching transistor driven by an R-C coupled voltage source.

It follows that this charge is simply:

$$\Delta Q = I_b \, \Delta t = C_c V_{in}$$

where Δt is the desired time increment and I_b is the base current drive as determined by the procedures outlined in this report. Then, if the coupling capacitor, C_c, is known the required input voltage drive can be determined.

J. E. Lindsay

J. E. Palmer

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Appendix

Voltage Variation of the Collector-Current Response

The problem of the voltage variation of the collector current response curves is now treated in greater detail. Subject to certain simplifying assumptions these response time variations prove to be a fairly simple function of the voltages involved and the punch-through voltage of the transistor. Also the procedures used to determine collector current response at an arbitrary voltage and for a voltage excursion are justified.

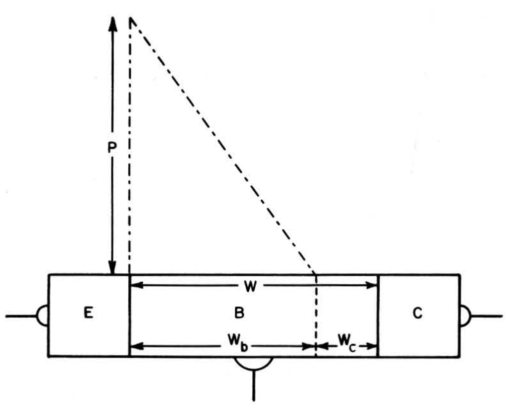

Fig. 16 - A schematic diagram of charge distribution in the base of an active transistor.

With respect to a transistor shown schematically in Fig. 16, the following terms are defined:

V_c = Collector junction voltage

I_c = Collector current

I_b = Input base current

β = Common emitter current gain, presumed constant

Q = Charge in the base region

P = Hole density at the base side of the emitter junction

W = Geometric base width

W_c = Width of depletion layer due to the applied collector voltage

W_b = Electrical base width

A = Equivalent area of base region

q = Electron charge

D_p = Diffusion coefficient for minority carriers in the base region

In terms of this schematic the charge of either sign in the base region is given by:

$$Q = \frac{APW_b q}{2} \qquad (1)$$

Charge storage in the base region is thus proportional to the electrical base width, W_b, presuming some uniformity of geometry.

Collector current is directly proportional to the charge gradient in the base region so that:

$$I_c = \frac{qD_p PA}{W_b} \qquad (2)$$

from which

$$W_b = k\,(\sqrt{V_{cP}} - \sqrt{V_c}) \tag{3}$$

Also the base current drive supplies charge to the base region and furnishes drive for collector current according to:

$$I_{bo} = \frac{dQ}{dt} + \frac{I_c}{\beta} \tag{4}$$

from which

$$d\left[\frac{W_b^2\, I_c}{2D_p}\right] = \left[I_{bo} - \frac{I_c}{\beta}\right] dt \tag{5}$$

In the above expression the electrical base width, W_b can be related to the applied collector voltage and the punch through voltage of the transistor in the following way. The electrical base width is equal to the geometric base width minus the depletion layer; thus

$$W_b = W - W_c \tag{6}$$

also the depletion layer is proportional to the square root of the applied collector voltage (presuming uniform resistivity base material) while the geometric base width is related to the punch-through voltage in the same way

$$W_c = k\sqrt{V_c}\,, \qquad W = k\sqrt{V_{cp}} \tag{7}$$

Then

$$W_b = k\,(\sqrt{V_{cp}}\quad \sqrt{V_c}) \tag{8}$$

and it is possible to write

$$\frac{d\,I_c}{\left[I_{bo} - \frac{I_c}{\beta}\right]} = \frac{2\,D_p}{k^2\,(\sqrt{V_{cp}} - \sqrt{V_c})^2}\, dt \tag{9}$$

A solution of this Eq. (9) for which the collector voltage varies according to:

$$V_c = V_{cc} - I_c R_L \tag{10}$$

is possible but detailed,

However, for a constant collector voltage, the condition for the current response curves, the result is:

$$ln\left[\frac{I_{bo}}{I_{bo} - \frac{I_c}{\beta}}\right] = \frac{2\,D_p t}{\beta\, k^2\,(\sqrt{V_{cp}} - \sqrt{V_c})^2} \tag{11}$$

Using this expression the variation of current rise time with collector voltage for a specified base current drive and collector current can be written as:

$$\frac{t_1}{t_2} = \frac{(\sqrt{V_{cp}} - \sqrt{V_{c1}})^2}{(\sqrt{V_{cp}} - \sqrt{V_{c2}})^2} \tag{12}$$

where t_1 and t_2 are times associated with operation at collector voltages V_{c1}, and V_{c2} and V_{cp} is the punch-through voltage, a measure of the base width.

This ratio has been plotted in Fig. 12 as a function of collector voltage, V_C, for an assumed punch-through of fifty volts and reference collector voltage of two and six volts. These curves show that rise-time variations of 50 percent and more obtain for a reasonable range of collector voltage. Oscillograms of collector current response to a step of base current drive at different collector voltage show changes of this magnitude (see oscillogram in Fig. 14b).

The solution of Eq. (9) can also be written in the form

$$I_c = \beta I_{bo}\left[1 - exp\left(\frac{-K}{(\sqrt{V_{cp}} - \sqrt{V_c})^2}\right) t\right] \tag{13}$$

where the quantity K absorbs the previous constants which have been introduced. This is a general ex-

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For some purposes these relationships are not really very precise. Accurately, the expression for the depletion layer thickness should take into account a contact voltage, V_0, in addition to the applied collector voltage. Also the punch-through voltage is often not a sufficiently good indication of equivalent or average base width because of irregularities in the junction interfaces. However, the purpose here is to illustrate in a qualitative way that response time varies considerably with collector voltage.

pression for the collector current response to a step of base current at constant collector voltage. It is introduced at this point to explain the procedures used to take account of the voltage variation of collector current response.

For the case of a fixed rise time and collector voltage it follows that:

$$\frac{I_{c1}}{I_{c2}} = \frac{I_{b1}}{I_{b2}} \tag{14}$$

This is the relationship used with the curves of Fig. 13b.

For the alternate procedures using both sets of curves the pertinent relations are:

$$\Delta I_c = \beta I_{b2}\left[1 - \exp\left(\frac{-K}{(\sqrt{V_{cp}} - \sqrt{V_{c2}})^2}\right)\Delta t\right]$$

$$\Delta I_c' = \beta I_{b1}\left[1 - \exp\left(\frac{-K}{(\sqrt{V_{cp}} - \sqrt{V_{c2}})^2}\right)\Delta t\right]$$

$$\Delta I_c'' = \beta I_{b1}\left[1 - \exp\left(\frac{-K}{(\sqrt{V_{cp}} - \sqrt{V_{c4}})^2}\right)\Delta t\right] \tag{15}$$

$$\Delta I_c = \beta I_{bo}\left[1 - \exp\left(\frac{-K}{(\sqrt{V_{cp}} - \sqrt{V_{c4}})^2}\right)\Delta t\right]$$

from which

$$I_{bo} = I_{b2}\left(\frac{\Delta I_c'}{\Delta I_c''}\right) \tag{16}$$

yields the base drive information desired.

Collector Current Response With Collector Voltage Excursion

There remains the general problem of determining base current drive to achieve specified collector current response accompanied by collector voltage excursion. A detailed solution of Eq. (9) for an assumed collector voltage variation is fairly cumbersome and is not consistent with the simplicity of these graphical methods. Also the accuracy obtainable does not justify such a degree of precision. So another attack is presented.

The two situations illustrated in Fig. 17 are considered. These are collector current response curves obtained for a transistor driven by steps of base current under two conditions. One curve is obtained with the transistor at constant collector voltage, V_{cc}. The other is the collector current response accompanied by a collector voltage excursion. In both cases the same value of collector current, ΔI_c, is obtained at the time, Δt, at the voltage, V_c.

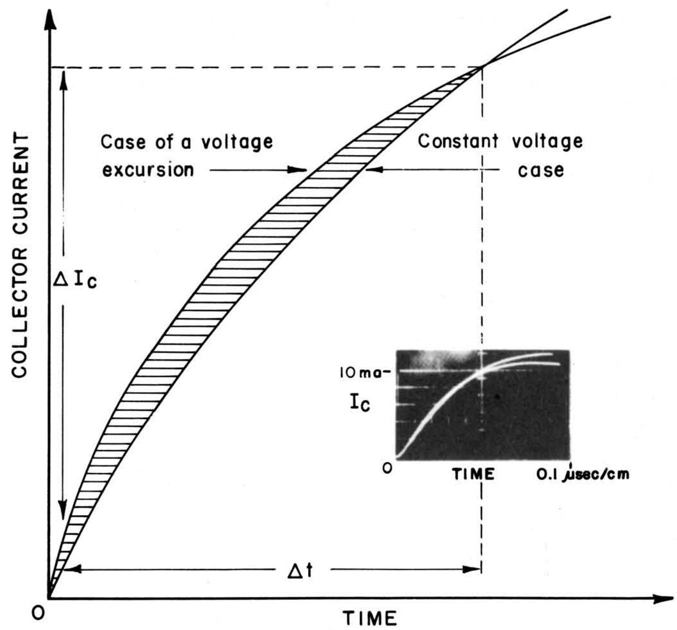

Fig. 17 - The transient collector current waveforms appearing when:
(a) The collector undergoes a change in voltage
(b) Current switching alone is involved
The insert shows an oscillograph of this phenomena.

The contention is that the base current drive requirements for this current excursion, ΔI_c, in time, Δt, are nearly the same for the two cases regardless of the voltage excursion.

The relationship shown in Eq. 4:

$$I_b = \frac{dQ}{dt} + \frac{I_c}{B}$$

shows that the step of base current, I_b, supplies charge to the base region at the rate, dQ/dt and also furnishes the collector current drive, I_c/β. The total charge, delivered to the base of the transistor in the time, Δt, is:

$$\int_o^{\Delta t} I_b \, dt = \int_o^{\Delta t} \frac{dQ}{dt} \, dt + \int_o^{\Delta t} \frac{I_c}{\beta} \, dt \qquad (17)$$

$$I_b \, \Delta t = Q_b = Q + \int_o^{\Delta t} \frac{I_c}{\beta} \, dt \qquad (18)$$

Now since at time, Δt, the transistor is at the same state in each case the charges, Q, in the base region are identical. Therefore the total charge delivered to the base in each case, Q_b, can differ only in the term

$$\int_o^{\Delta t} \frac{I_c}{\beta} \, dt$$

There is some small difference in this term for the two cases. As shown in Fig. 17 the current excursion which starts at the higher voltage rises faster initially. The charge difference involved is proportional to the shaded area between the two curves. This small difference is negligible compared to the total charge delivered to the base.

An oscillogram of current response curves of this sort is shown with Fig. 17. In this case the fixed collector voltage is six volts, while the voltage excursion is from 12 volts to 6 volts. The difference between the two curves is small.

The conclusion is that current response curves obtained at the lowest voltage of the excursion give very nearly the correct base drive information.

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