RCA Application Note

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Operation of Memory-Core-Driver Transistors in the Primary-Voltage-Breakdown Region

by

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The design of transistor circuits for use in memory-core-driver applications requires a knowledge of the inherent voltage-breakdown characteristics of the transistor being used, and the limitations these characteristics impose upon the circuit designer. Voltage-breakdown characteristics are of primary importance in circuits having inductive loads because the extremely high peak powers that are generated influence both the transistor mode of operation and the system reliability.

State-of-the-art conditions are such that increases in both switching speed and high-voltage breakdown cannot be achieved simultaneously; in the design of a switching transistor one parameter must be sacrificed for the enhancement of the other.

This note shows that, without sacrifice in switching speed, transistors can be safely operated in the primary-voltage-breakdown mode effectively extending the operating-voltage range.

Reverse-Voltage-Breakdown Characteristics

The reverse-breakdown characteristics of a typical transistor, normally referred to as avalanche breakdown characteristics, are shown in Fig.1. The breakdown action can be initiated from energy supplied by either a heat source or an electric field, E. In this note only the latter is considered.

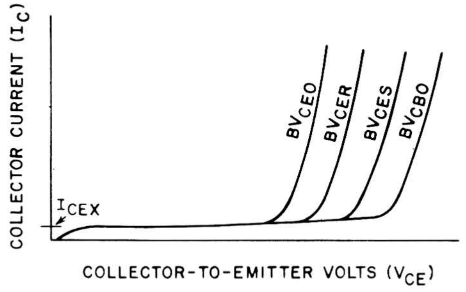

Fig.1 - Reverse-Voltage-Breakdown Characteristics of a Typical Transistor

Breakdown Characteristic with Base Open

With the base open, the collector-to-emitter current, I_{CEO}, flowing before breakdown can be shown to be:

$$I_{CEO} = \frac{I_{CBO}}{1 - \alpha} \approx I_{CBO} \cdot h_{FE} \tag{1}$$

In the test circuit shown in Fig.2, the application of a reverse-bias voltage to the collector-emitter junction simultaneously forward-biases the emitter-base junction. As the reverse bias is increased (the base-to-emitter forward bias also increases), I_{CEO} will increase; because I_{CBO} changes very little in the low-voltage region, the α of the transistor must increase if Eq. (1) is to be satisfied. This increase factor, M, is empirically determined from:

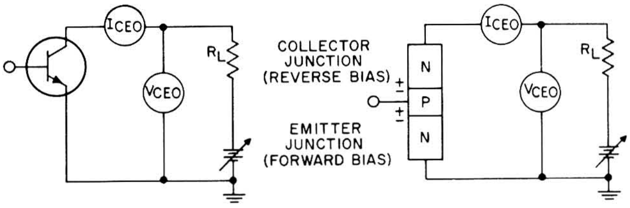

Fig.2 - Test Circuit for Determining the Collector-to-Emitter Breakdown Voltage with Base Open (BV_{CEO})

$$M = \frac{1}{1 - (V/BV_{CBO})^n} \tag{2}$$

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Eq. (2), when applied to Eq. (1), results in

$$I_{CEO} = \frac{I_{CBO}}{1 - \alpha M} \qquad (3)$$

From Eq. (2), when $\alpha M = 1$, I_{CEO} goes to infinity. In this condition, known as avalanche breakdown, the voltage V is defined as BV_{CEO}.

Therefore,

$$\alpha M = 1 = \frac{\alpha}{1 - (BV_{CEO}/BV_{CBO})^n} \qquad (4)$$

The solution of Eq. (4) for BV_{CEO} is

$$BV_{CEO} = (1-\alpha)^{1/n} BV_{CBO} \approx \left(\frac{1}{h_{FE}}\right)^{1/n} BV_{CBO} \qquad (5)$$

The integer n ranges from 2 to 6; the value depends on the transistor material and type dopant used. For n-type silicon, n = 4; for p-type silicon, n = 2. This avalanche or multiplication effect can be damaging to the transistor, but it can be used to advantage if operation is confined within certain limitations. Because this note is concerned primarily with core-driver applications (in which high currents are switched through inductive loads), the dangerous or damaging aspects of voltage breakdown are considered. If operation in the primary-voltage-breakdown mode is permitted to continue for too long a period, a thermal-runaway condition occurs resulting in a unit entering second breakdown.

Second Breakdown

Second breakdown in transistors is characterized by a sudden drop in the collector voltage and a sudden increase in the collector current. Because this current is very high (greater than 1 ampere), the power level is also very high and transistors subjected to this condition will almost always be permanently damaged. The phenomenon of second breakdown is not completely understood and various theories have been presented as to why it occurs. However, the damaging effects of this phenomenon are clearly evident and are manifested as small "burn" or "hot" spots in areas of minute crystallographic defects or non-uniform impurity regions in the base and active collector regions. At these burn spots, the silicon material actually melts and forms a collector-to-emitter short circuit. The high temperatures that produce these burn spots are caused by thermal runaway. To determine the second-breakdown threshold, the circuit designer should have a method of measuring the energy-dissipating capability of the transistor.

Breakdown Characteristics with Inductive Load

The reverse-breakdown characteristics of a transistor that switches inductive loads depend, to some extent, on the external circuit between the base and emitter. Fig.3 shows the reverse-breakdown characteristics (BV_{CER}) as a function of the base-to-emitter resistance, R_{BE}.

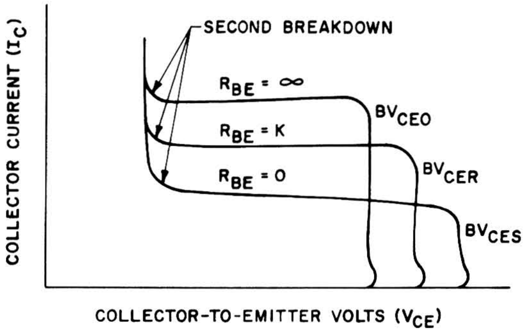

Fig.3 - Reverse Voltage Breakdown as a Function of Base-to-Emitter Resistance (R_{BE})

The reverse-breakdown characteristics are also a function of the base-to-emitter bias. Fig.4 shows the reverse-breakdown characteristics (BV_{CEX}) as a function of reverse base-to-emitter bias. As the reverse bias is increased, primary breakdown occurs at a higher voltage; however, the current level at which second breakdown occurs is lower. Thus, an increase in bias has the same effect as a decrease in base-to-emitter resistance. In the design of core-driver circuits, these various reverse-breakdown characteristics are very important and must be considered.

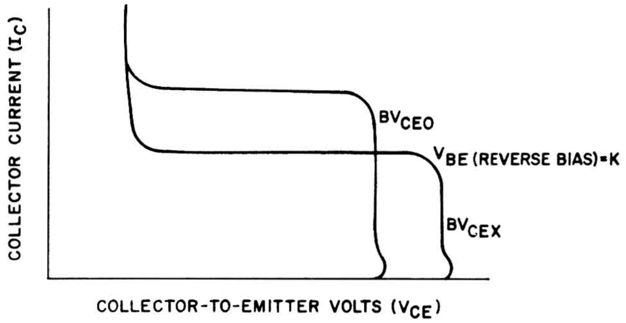

Fig.4 - Reverse Voltage Breakdown as a Function of Reverse Base-to-Emitter Bias

The equivalent circuit for a core driver, as shown in Fig.5, is a series inductance L, which represents the total inductance of the memory plane, and a current-limiting resistor, R_L, whose value is determined by the current required to switch, or partially switch, a memory core from its original state. The characteristic load line for an inductive load is elliptical, as shown in Fig.6. The value of the inductance affects the size and shape of this ellipse.

When the transistor in Fig.5 is turned on (by the application of a base current, I_{B1}), the inductance tends to maintain the collector current at the low value, I_{CEX}, even though the collector voltage falls rapidly. The collector current reaches its saturation value, I_S, over a period determined by the time constant L/R_L.

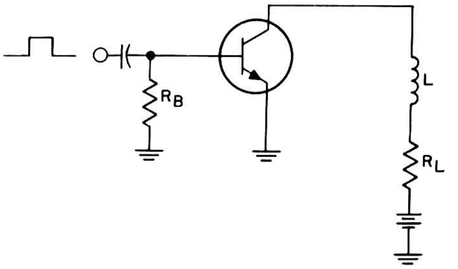

Fig.5 - Equivalent Circuit of Core Driver

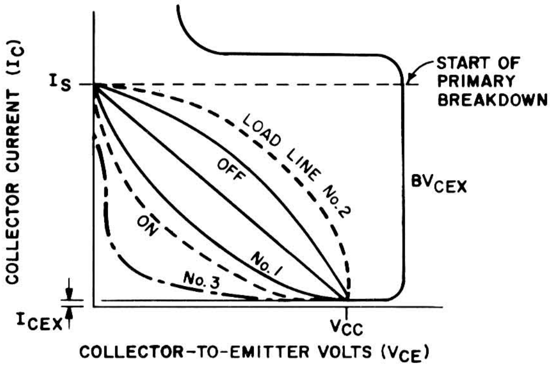

Fig.6 - Load Lines for Three Different Inductive Loads

When the transistor is turned off (I_{B1} is removed), the inductance again tends to resist any change in the collector current, I_S, and in addition, the inductance returns stored energy to the circuit (in accordance with $J = \frac{1}{2} LI^2$) in the direction that tends to keep the collector current flowing. Not until this energy is almost completely expended can the collector voltage return to its normal "off"-state value, V_{CC}.

The induced voltage, or "kickback voltage" $e = L(di/dt)$, generated in the inductive load adds to the supply voltage so that the collector voltage at turnoff e_T is given by

$$e_T = L\frac{di}{dt} + V_{CC} - iR_L \qquad (6)$$

If this induced voltage [$L(di/dt)$] is large enough, primary voltage breakdown, BV_{CEX}, occurs in the transistor.

Fig.6 shows typical load lines for three different inductive loads. The narrowest ellipse (No.1) represents the load containing the least inductance. The reverse-breakdown characteristic is shown as BV_{CEX}, where X denotes the external base-input circuit. The inductance represented by load line No.3 is large enough that $e + V_{CC} - iR_L$ is greater than BV_{CEX}, and primary voltage breakdown occurs when the transistor is turned off.

If the load resistance is decreased to meet a high current requirement, the load line may be above the second-breakdown $I_{S/b}$ level, as shown in Fig.7.

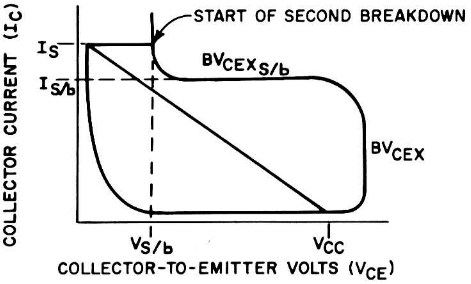

Fig.7 - Inductive Load Line Entering Second-Breakdown Region

Under these conditions turn-on presents no problem. However, when the unit is turned off, the induced voltage "e" causes primary voltage breakdown and if the current is high enough and if this condition persists, second breakdown will occur and the transistor will probably be damaged. This type of failure can be avoided if the saturated collector current I_S is kept below the second-breakdown $I_{S/b}$ level.

Of primary importance is the fact that the transistor will not remain in primary breakdown indefinitely. The transistor will only be "temporarily latched" because the latch power is being supplied by the charged inductor. This condition is unlike a "sustained" latch condition which results with a resistive load.

One method for the prevention of primary voltage breakdown is to limit the inductance to as low a value as possible. However, present-day and future computers require larger memories which means more memory planes and therefore more inductance. In addition, memory cycle times are continually being reduced and, because the trend in present-day memories is toward the Linear Select mode, the transistor currents are almost twice as high as in the coincident-current type of memory. Hence, all three factors—inductance, current, and switching speed—tend to increase the induced voltages, and thereby increase the possibility of breakdown when a transistor is turned off.

Operation in the Primary-Voltage-Breakdown Mode

In Fig.8, the resistive load and V_{CC} have been chosen so that the load line crosses the BV_{CEX} characteristic. When the transistor is turned off, the collector current decreases from saturation level, I_S, along the load line and the collector voltage increases so as to approach V_{CC}. Before the collector voltage reaches V_{CC}, however, primary breakdown occurs and the collector current cannot drop below the "latch" value, I_A. The collector will conduct a current of I_A at a voltage V_A indefinitely or until the transistor is turned on again. In this stage (point A), the power ($P_A = I_A V_A$) dissipated in the transistor heats the collector junction. This heating during the time it operates at point A can damage the transistor, or it can result in second breakdown which accelerates the failure of the transistor. This example illustrates the danger of operation in this region and why it is usually avoided in circuit design work.

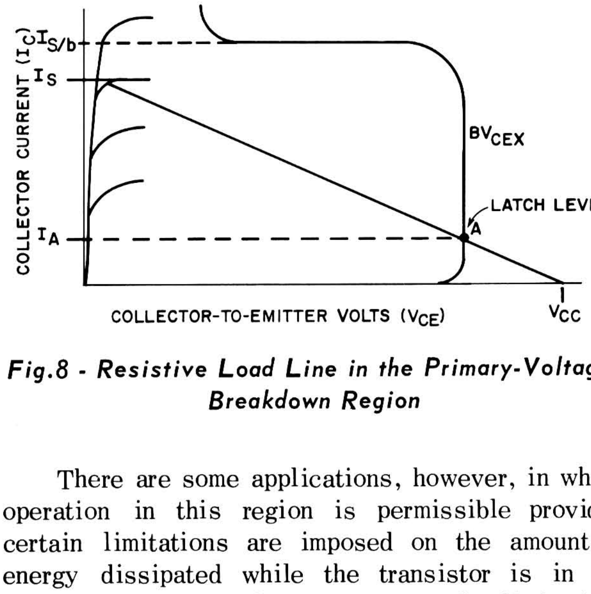

Fig.8 - Resistive Load Line in the Primary-Voltage-Breakdown Region

There are some applications, however, in which operation in this region is permissible provided certain limitations are imposed on the amount of energy dissipated while the transistor is in the primary-voltage-breakdown mode. The limitations are the power level and the length of time that such dissipation is permitted. With inductive loads, although the peak power is greater than with resistive loads, the time involved is much less because the latch condition is temporary.

The power and time permissible before the transistor is damaged or enters the more destructive second-breakdown region are determined as follows. If the energy ($J = \frac{1}{2} L I_S^2$) stored in an inductance is suddenly made to discharge through a transistor, the instantaneous current, i, is a function of the transistor breakdown voltage, the time constant L/R, and the dc current I_S flowing before the inductance began discharging. A circuit simulating these conditions is shown in Fig.9. When the switch is in position 1 (the equivalent of a saturated transistor), the initial current I_S is proportional to V_{CC}/R_L and the energy stored in L is $\frac{1}{2} L I_S^2$. When the switch is in position 2 (the equivalent of turning off the transistor), the instantaneous current is expressed by:

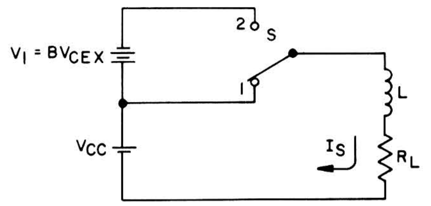

Fig.9 - Circuit Simulating Effects of Primary Breakdown

$$i = \frac{V_{CC} - V_1}{R_L} + \left[I_S - \left(\frac{V_{CC} - V_1}{R_L} \right) \right] e^{-t_1 R_L / L} \qquad (7)$$

By setting Eq. (7) equal to zero, the time t_1 for the completion of turn-off is obtained as

$$t_1 = \frac{L}{R} \ln \left(1 + \frac{R_L I_S}{V_1 - V_{CC}} \right) \qquad (8)$$

From the energy expression $J = \int_0^{t_1} V_1 \, i \, dt$, the energy absorbed by the transistor during turnoff is given by

$$J = \int_0^{t_1} V_1 \left[\frac{V_{CC} - V_1}{R_L} + \left[I_S - \left(\frac{V_{CC} - V_1}{R_L} \right) \right] e^{-t_1 R_L / L} \right] dt \qquad (9)$$

Evaluation of this expression, with the assumption that $I_S R_L$ is greater than $V_1 - V_{CC}$, gives the following approximation for the energy absorbed by the transistor

$$J \approx \frac{V_1 L I_S}{R_L} = \frac{(BV_{CEX}) L I_S}{R_L} \qquad (10)$$

Not only does this equation show that the amount of energy that must be absorbed by the transistor is a constant but it also shows that primary reverse breakdown $BV_{CEXP/b}$ will affect the energy-absorption capabilities of the transistor. The higher the voltage breakdown the greater the amount of energy the transistor can absorb. This energy expression assumes that the junction-temperature increase is negligible. However, in switching high inductances, the peak powers can be extremely high, and the junction-temperature increase can be significant. As a result, thermal runaway can take place despite the fact that the BV_{CEX} is sufficiently high to absorb the stored energy, J. Therefore, to safeguard a transistor against damage when operated in the primary-voltage-breakdown mode, the thermal properties of the transistor must be considered as well as the maximum energy it can absorb.

Power-Dissipation-Capability Measurements

One method for measuring the dissipation capability of a transistor that operates in the primary-breakdown mode is to measure the time required for second breakdown to occur at various power levels and for different load inductances. The disadvantage of this type of test, because of its repetitive nature, is that it is very time consuming.

In a more practical method, the circuit shown in Fig.10 can be used to measure the energy-dissipating capabilities of transistors which operate in the primary-voltage-breakdown region under various base-input conditions. A pulse, variable in both width and magnitude, is supplied by a pulse generator which is terminated in its characteristic impedance by resistor Ro. At the beginning of the test, the pulse width is set to approximately 50 nanoseconds and the pulse magnitude is increased gradually until primary voltage breakdown occurs. Until primary breakdown is reached, the collector-to-emitter voltage V_o will follow the input voltage V_{in}. When primary breakdown is reached, the collector-to-emitter voltage V_o will remain at $BV_{CEXP/b}$. Any further increase in V_{in} will result in an increase in I_C as shown in Fig.11c. Before $BV_{CEXP/b}$ is reached, the I_C flowing is leakage current only. After breakdown, the current I_C is a function of V_{in} (Fig.11c). When V_{in} is increased far enough, the unit will enter $V_{S/b}$ as shown in Fig. 11d. As mentioned earlier, $V_{S/b}$ is characterized by a sudden drop in collector-to-emitter voltage and a sudden rise in collector current. During second breakdown, extreme caution should be exercised so as not to damage the unit. The pulse width or the time in second breakdown should be kept at a minimum. Once the second-breakdown condition is established, the transistor is brought back into the safe operating area by reduction of the input voltage. The shaded areas in Fig. 11d represent the energy dissipation in the transistor while it is in the primary-voltage-breakdown mode. This energy is evaluated as the product of $V_{P/b}$, I_S, and t_1. From data obtained through the repetition of the above test at various pulse widths, energy-dissipation curves can be plotted.

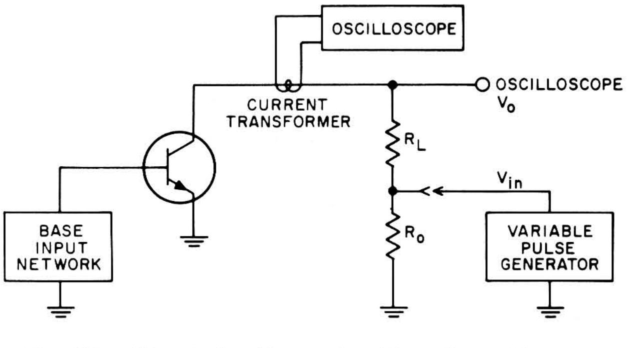

Fig.10 - Circuit for Measuring Transistor Energy-Dissipation Capabilities when Operated in Primary-Voltage Breakdown Region

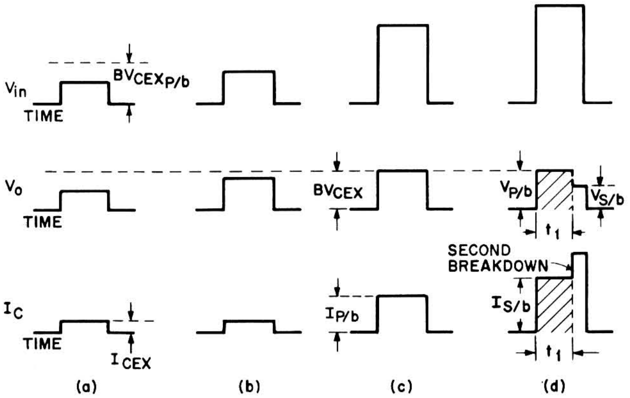

Fig.11 - Voltage and Current Waveforms Depicting Primary-Voltage Breakdown and Second Breakdown

Data for Core-Driver Transistors

Fig.12 shows the power dissipation as a function of time allowed in primary breakdown for a number of transistors. The 2N3261 transistor is a low-current, low-voltage-breakdown device; the 2N3512 transistor has higher current and voltage-breakdown ratings; the Dev. No. TA2626 transistor has even higher current and voltage-breakdown ratings.

A comparison of these curves indicates that in the lower-voltage-breakdown units second breakdown occurs more readily. This observation is in agreement with Eq. (10), which states that the maximum energy a transistor can dissipate safely is proportional to its primary-voltage-breakdown rating.

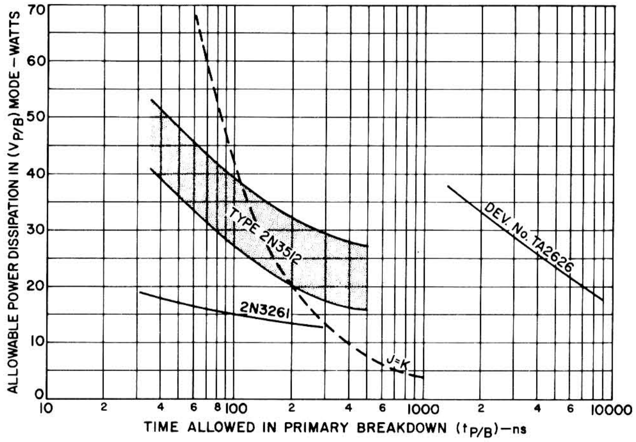

Fig.12 - Power Dissipation as a Function of Time in Primary-Voltage-Breakdown Region for Various Transistors

For an allowable time in the primary-voltage-breakdown region of 50 nanoseconds, the 2N3261 can dissipate only about 17 watts before second breakdown occurs. The type 2N3512 transistor can dissipate 36 watts before second breakdown. The type TA2626 transistor can operate safely at this same power (36 watts) level for even a longer period of time. A constant-energy plot J = K is also included. In comparing this constant-energy plot with those of the various transistors tested, it is evident that the actual transistor energy curves are not a constant, but will vary depending not only on the breakdown characteristics but on the thermal properties of the particular transistor. The curves for Fig.12 were for the $I_B = 0$ condition. The same procedure can be used for various base-input configurations.

Primary-Voltage-Breakdown-Mode Life Test

A 1000-hour life test was performed on the type 2N3512 transistor to evaluate the effect that operation in the primary-voltage-breakdown mode would have on such parameters as the dc beta and BV_{CEO}. The circuit, the associated waveforms, and the elliptical load line are shown in Fig.13.

The test units were turned on with a forward base current of 10 milliamperes; at saturation, the current flowing was 250 milliamperes. The units were turned off each cycle by the interruption of base current. Rated BV_{CEO} for this transistor is 45 volts.

The test circuit is designed so that L_L (di/dt) + V_{CC} is greater than BV_{CEO} and therefore the transistor operates in the primary-voltage-breakdown region following turn-off in each cycle. Operation in the primary-voltage-breakdown mode is for approximately 700 nanoseconds, after which the collector returns to V_{CC}. The peak power dissipated is $I_S BV_{CEO}$ = (0.25)(45) = 11 watts. At the completion of a 1000-hour pulsed life test, there were no catastrophic failures and the degradation of various parameters was insignificant. The BV_{CEO} breakdowns held up very well.

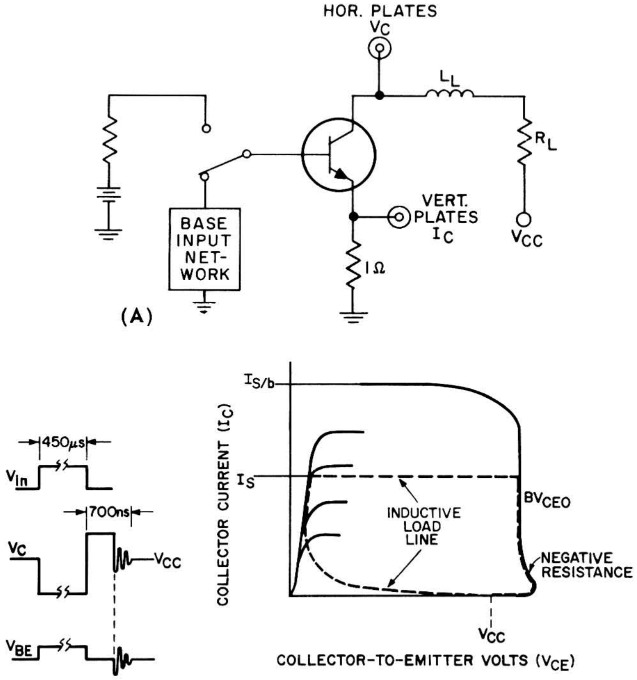

Fig.13 - Circuit for Testing Operating Life in the Primary-Voltage Breakdown Region and Associated Waveforms

Summary

A transistor that drives an inductive load can be operated in its primary-voltage-breakdown region provided the following boundary conditions are imposed:

a) The power level, for the time during which the transistor is operated in the $V_{P/b}$ region, should not exceed the maximum peak-power level determined in the "Power-Dissipation-Capability Measurements" portion of this note. A 15- to 20-per-cent safety factor should also be provided.

b) The collector supply voltage, V_{CC}, is less than the BV_{CEX} of the transistor.

This mode of operation, when the above conditions are met, can result in lower transistor costs since the V_{CEO} specification need not be so stringent as is generally the practice. It makes possible the use of certain types of transistors in applications in which they are not now used because of V_{CEO} limitations. Such an application is a memory-driver circuit where the tendency is to specify $V_{CEO} >> V_{CC} + L(di/dt)$.