APPLICATION NOTES

MOTOROLA Semiconductor Products Inc.

SIGNIFICANCE OF Q_T IN SWITCHING CIRCUITS

by

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The charge factor (Q) in a transistorized pulse system is a figure of merit in much the same manner that gain-bandwidth product (f_t) is a figure of merit for an amplifier. Consider briefly a pulse transmission system where the voltage of a line must be changed by V volts. Since a finite capacity C is associated with the line, a charge $Q = CV$ must be moved in order to effect this change. To move this charge in a given time t, a certain current I is required; viz. $Q = It$. Thus with a given current, low Q is synonymous with fast switching.

The concept of total control charge, Q_T, is not only a figure of merit but is a useful tool in the design of transistor circuits particularly where capacitors are used for triggering or R-C networks are used to improve response time.

The concept is most easily understood by examining the familiar linear circuit of Figure 1. It is well known that if the time constant of the speed up network, $\tau_1 = R_1C_1$, equals the time constant, $\tau_2 = R_2C_2$, the waveform at point C will be a perfect reproduction of that at B, but reduced in amplitude according to the ratio of R_1 and R_2. During the time that a constant level is applied at point A, charge Q_1 developed on C_1 will also equal the charge Q_2 developed on C_2.

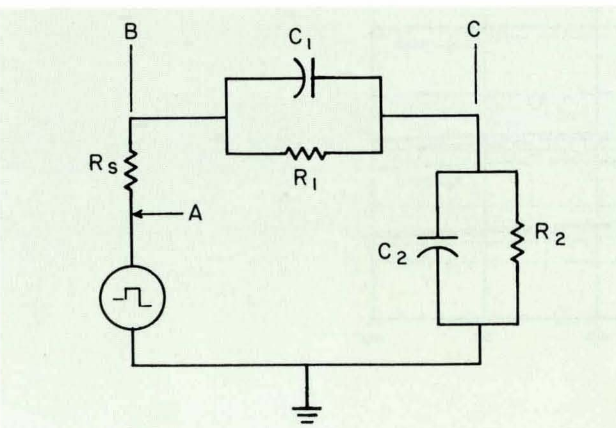


FIGURE 1
Linear Circuit Compensation

The impedance of this network, of course, decreases with frequency so that the signal at B may show rise time deterioration compared to the signal from the source at point A. However, there is no distortion of the signal in passing from B to C.

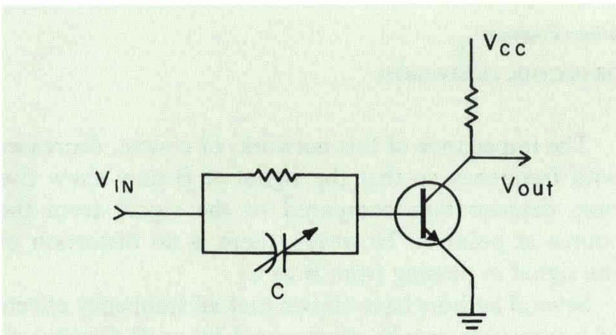
Several authors have shown that all frequency effects of a transistor can be represented by an R-C network from internal base to emitter. Base spreading resistance r'_b can be lumped with R_s. If a transistor were substituted for the network R_2C_2, by adjusting τ_1 for a square wave output, the transistor input impedance could be deduced. If the transistor were driven into saturation, a square wave output would occur during turn-on regardless of the value of τ_1, but information can be gained by observing the waveform during turn-off. Since a transistor in saturation is grossly non-linear, approximating its behavior by a linear network is not satisfactory. But the use of a speedup network to find the charge required to turn off a transistor has proven to be valuable.

When a transistor is held in a conductive state by a base current I_B, a charge Q_s is developed or "stored" in the transistor. If I_B were suddenly removed, the transistor would continue to conduct until Q_s is removed from the active regions through an external path or through internal recombination. Since the internal recombination time is long compared to the ultimate capability of a transistor, for fast switching the designer needs to know the value of the internal charge. Q_s may be written as —

$$Q_s = Q_I + Q_V + Q_X$$

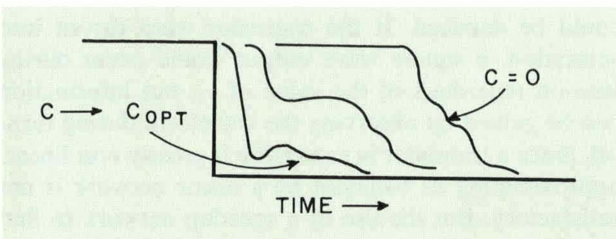
Q_I is the charge required to develop the required collector current. This charge is primarily a function of alpha cutoff frequency. Q_V is the charge required to change the collector-emitter voltage. It is primarily caused by collector-base feedback capacity. Q_X is excess charge resulting from overdrive, i.e., operation in saturation. The carriers which result comprise Q_X and are stored in the base and collector regions.

The charge required to turn a transistor "on" to the edge of saturation is $Q_I + Q_V$ but to turn it off, the full charge Q_s must be removed. Referring to the circuit of Figure 1, if the charge on the speedup capacitor Q_T equals the charge on the transistor Q_s, then when point B is grounded turn-off would be immediate if transistor r'_b were zero. In practice, point A is a more convenient place to ground and R_S and r'_b limits circuit speed.



Q_T TEST CIRCUIT

FIGURE 2



TURN-OFF WAVEFORM

FIGURE 3

A test circuit which measures Q_T is shown in Figure 2. C is adjusted to the minimum value which will produce a waveform similar to the one indicated by the solid trace in Figure 3. This will be where the "bumps" just disappear. It has not been established under this condition of turn-off that the charge Q_T on C actually equals the charge Q_s in the device, but Q_T certainly represents the charge necessary to control the turn-off of the transistor from a circuit designer's point of view. The charge is given by —

$$Q_T = C\ (V_{in} - V_{BE})$$

Using this relation, the designer may optimize C for any input voltage if Q_T at the desired operating point is known.

When making measurements with this circuit it is important that the input pulse be long enough to allow carrier equilibrium to be reached. One μsec is long enough for VHF transistors. For greatest accuracy pulse instrumentation should have capability to at least 15 ns rise time and utmost care must be given to the selection and mounting of the R-C network and transistor socket. A low source impedance also makes the effects of capacitor adjustment easier to discern.

Charge measurements of representative silicon logic transistors are shown in Figure 4. It is evident that the low figures for the 2N834 permit faster switching in any given circuit since low charge means less current is required to switch the transistor in any given time. The curves also permit optimum values of speedup capacitors to be selected.

Using too large a speedup capacitor will cause a slight reduction in response time but a heavy penalty will be paid in circuit recovery time which will limit pulse repetition frequency.

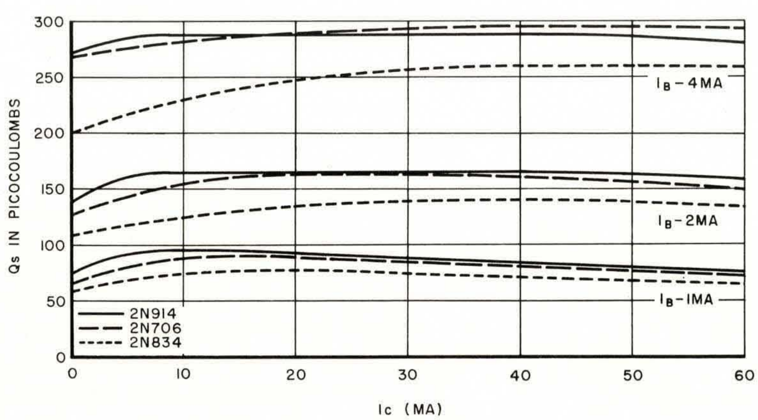


FIGURE 4
COMPARATIVE Q_T

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