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Some transient properties of transistors

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The build-up and decay of the collector current of point-contact transistors, in response to a rectangular pulse of emitter current, take place roughly exponentially with time, after a delay of the order of a tenth of a microsecond during which there is negligible response. If the collector current is saturated, or if the collector voltage, instead of being steadily applied, is pulsed on, during or after the pulse of emitter current, effects due to delayed carriers are strikingly noted.

1. INTRODUCTION

The operating time of conventional switching circuits using thermionic valves depends on properties of the valves as well as on other circuit parameters. Thus it will rarely be less than several times the ratio, C/g, of the sum of the input and output capacitances of the valve to its mutual conductance; modern h.f. pentodes have effective values of C/g as small as perhaps 3×10^{-9} sec, enabling multivibrators to switch in about 20×10^{-9} sec, by comparison with which the transit times of the valves of 1×10^{-9} sec or less are small.

The introduction of germanium transistors to electronic switching brings new factors to the determination of operating time and circuit performance. Bardeen and Brattain[1] have shown that transistor action depends on the passage of minority carriers, injected by the emitter, to the collector where they give rise to a collector current, I_c, which, in point contact transistors, usually exceeds the emitter current I_e. The minority carriers (holes if the germanium is *n*-type) travel from the emitter to the collector only slowly, however, and by paths of different lengths so that the resulting collector current lags behind the emitter current, different parts of it by different times. Carriers injected while little or no bias is applied to the collector may remain in the bulk germanium without recombination for long periods (e.g. several microseconds); Meacham and Michaels[2] have already reported some interesting effects so resulting, both in transistors and diodes.

An investigation of some of the transient properties of transistors, suggested by this theory of their action, has accordingly been started—primarily as a step towards the correct prediction of the performance of high-speed switching and pulse circuits.

2. THE TRANSIENT RESPONSE OF TRANSISTORS WITH STEADY COLLECTOR BIAS

Fig. 1 shows the waveform of the collector current of a typical British point-contact transistor, when a rectangular pulse of current is applied to the emitter at time t_o, the collector potential, V_c, being maintained at a steady negative value. After a delay t_d (overlooked apparently by Meacham and Michaels) the collector current rises approximately exponentially with a time constant t_r. Upon cessation of the emitter current, the collector current falls in a similar way after a similar delay. For a small batch of transistors t_d ranged from 0·07 to 0·25 μsec,* and t_l from 0·09 to 0 5 μsec, with a rough correlation between t_d and t_r. The transient behaviour is qualitatively explained by the processes described

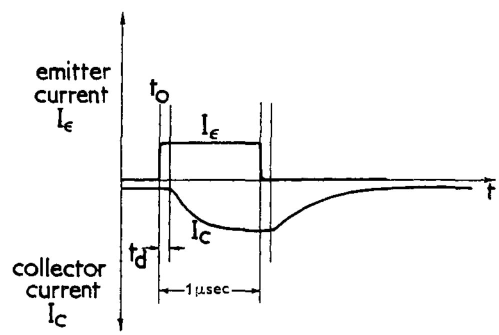

Fig. 1. Showing the transient response of a point-contact transistor

in Section 1 and implies a fall of gain at high frequencies. Measurements of gain-frequency response show good agreement with transient behaviour.

A similar test has been applied to a few *n-p-n* junction transistors. Again there is an initial delay in the onset of significant collector current, but the rise of collector current is no longer as closely exponential. The waveform of the collector current is qualitatively consistent with the theory of Shockley and others[3] that the minority carriers traverse the base layer of a junction transistor primarily under the influence of diffusion, and not of any drift field. Junction transistors made so far have had collector-base and emitter-base capacitances of the order of 10 pF (varying with collector voltage and emitter current) giving the input and output circuits time constants which may set important speed

* t_d is less, however, when there is standing emitter current.

limitations; the circuit conditions will decide whether the capacitances or the transit phenomena set the more important limitation.

3. TRANSIENT EFFECTS DUE TO DELAYED CARRIERS IN POINT CONTACT TRANSISTORS

The operating conditions of a point contact transistor with a resistive load are illustrated in Fig. 2. If the emitter current, I_e, is made zero, the collector is said to be at collector current

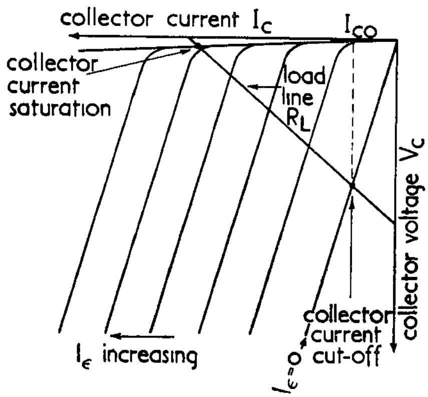

Fig. 2. The operating conditions of a point-contact transistor with a resistive load (R_L)

cutoff (sometimes called collector voltage saturation), though in fact some residual collector current (I_{co}) flows. As I_e is increased, I_c first rises steadily, but later collector current saturation occurs, accompanied by low collector impedance (of the order of a few hundred ohms). The situation is similar to that in a pentode with a resistive anode load when the anode current I_a has been made so large that the anode potential, V_a, has fallen below the knee of the I_a, V_a curves.

At collector current saturation (sometimes termed collector voltage cutoff) very many minority carriers are present in the body of the germanium, so that if I_e is suddenly returned to zero, collector current (in excess of I_{co}) may continue to flow for as long as a few microseconds. Fig. 3 shows

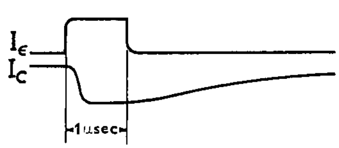

Fig. 3. An effect of collector current saturation in a point-contact transistor

a typical waveform of the collector current under the conditions of Fig. 2, saturation having been reached during the pulse.

The slow recovery (sometimes called turnoff) after collector current saturation may restrict the use of the saturation region in high-speed switching circuits.

An allied effect, thought to be due also to delayed carriers, can be observed if a pulse of current is applied to the emitter while the collector is unbiased. If the collector is later biased by a pulse of voltage, collector current flows immediately; its amplitude is greater than that obtained under steady collector bias, but, as would be expected, decreases as the delay between the emitter and collector pulses is increased. Thus Fig. 4, derived from oscillograms, compares (*a*) a superposition of waveforms observed for a range of delays between emitter and collector pulses with (*b*) the waveform obtained for steady collector bias. The waveforms were derived from the base current and therefore display both emitter and collector currents (only that portion of the collector current in excess of I_{co} is in fact shown). Delayed carriers can be

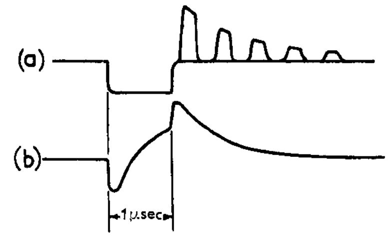

Fig. 4. Base current waveforms

(*a*) For a pulse of emitter current followed by a pulse of collector voltage (composite waveform).
(*b*) For a pulse of emitter current with steady collector bias.

readily observed as long as 4 μsec after the cessation of the emitter current.

Fig. 5 was obtained in the same way as was Fig. 4, except that the collector was pulsed during the emitter pulse. The current available at the collector first rises very rapidly and then approximately exponentially; the envelope of the pulses

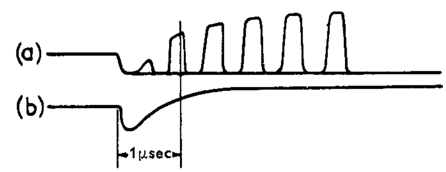

Fig. 5. Base current waveforms

(*a*) For a step of emitter current followed by a pulse of collector voltage (composite waveform).
(*b*) For a step of emitter current with steady collector bias.

of I_c resembles the waveform of the collector current obtained with steady collector bias, particularly during the first 0·5 μsec. The waveforms suggest that diffusion, rather than drift due to a field set up by the collector voltage, dominated the movement of the carriers in the point contact transistors under the test conditions yielding Fig. 5. Ryder and Kircher,(4) however, have found that the frequency response of some of their point contact transistors varies markedly with collector potential, suggesting the predominance of drift. Further work on the variation of t_r (see Section 2) with change of V_c has suggested that diffusion predominates at low potentials and drift at high potentials (e.g. above 10 V) in the units tested.

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