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FAST LOW LEVEL PULSE HEIGHT DISCRIMINATOR

by

E. DE BLUST (EURATOM), I. DE LOTTO (CISE)
and V. MANDL (EURATOM)

1963

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a) The sweep speed is 50 n sec/div and the vertical sensitivity 100 mV/div.

b) The sweep speed is 10 n sec/div with the same sensitivity as before.

The oscilloscope was a Tektronix 585

FAST LOW LEVEL PULSE HEIGHT DISCRIMINATOR

SUMMARY

The behaviour of the tunnel diode in a fast low level pulse height discriminator is here analyzed. The characteristics of the tunnel diode in fast trigger circuits are studied by plotting the switching waveforms for non linear load and variable input pulse amplitude and shape. The relations between the switching time, the "lambda" pulse and the hysteresis are considered and extended also to the classical trigger circuits. As a result of the analysis a discriminator circuit has been developed after an investigation of the different bias circuits. The lowest threshold level is about 2 mV and the input range is higher than 100. The linearity is satisfactory over the whole range and a good temperature stability can be achieved with a simple and cheap thermostat. The length of the "lambda" signal is about 8 nsec but could be further reduced with faster components and more care in the circuit lay-out.

1 - I N T R O D U C T I O N

The tunnel diode has been widely used in nuclear electronics as a basic component of fast pulse height discriminators (1, 7). This is due to the simplicity of most circuits, because the tunnel diode can be operated with less components than a transistor, due to its small size, to the stability of its characteristics and to the fast response associated with a high loop gain and short delay. Many authors have described discriminator circuits which are linear and stable with minimum threshold levels from 50 to 100 mV and with an input signal range of about 100. However no circuits were developed, as far as we know, for signals of the order of millivolts with linearity and stability comparable to those of discriminators with higher input levels.

The usefulness of such circuits may be quite large because in this way it is possible to avoid all the problems of development of a fast linear amplifier with rise time of the same order of magnitude of the pulse lenght "lambda"[x] in a tunnel diode discriminator.

In the present paper after an initial brief description of the tunnel diode characteristics, its application to trigger circuits is discussed. The influence of the bias on the sensibility and stability of the threshold is considered and the factors affecting the switching speed, the delay and the settling time are analyzed. Finally the circuit which has been developed is described and the experimental results are reported.

(x) The "lambda" pulse is the duration of the input signal for which the threshold level is twice the value which is required for an input signal of infinite lenght. All our measurements have been made at a threshold of 2 mV and the input signal corresponding to the "lambda" pulse was 2 mV above this level.

2 - THE BEHAVIOUR OF THE TUNNEL DIODE AS AN ACTIVE COMPONENT INSIDE A REGENERATIVE LOOP

The steady state voltage vs. current characteristics of a germanium tunnel diode[(x)] are well known (8,9). The transient behaviour is affected in a first order approximation by the junction capacity C of the diode itself, by its negative conductance -G, by the series inductance L_s and the series resistance R_s. Moreover it depends on current and voltage peak to valley ratio (I_P/I_V and V_P/V_V). The typical characteristics are as follow :

$$C \simeq 1 \div 20 \text{ pF}$$

$$L_s \simeq 5 \text{ nH}$$

$$R_s \simeq 2 \text{ ohm}$$

$$I_P - I_V \simeq 1 \div 20 \text{ mA}$$

$$V_P - V_V \simeq 300 \text{ mV}$$

$$-G \simeq 5 \div 20 \times 10^{-3} \text{ Siemens}$$

One of the most interesting properties of the tunnel diode which makes its application attractive in low level discriminator is the temperature behaviour. The stability in temperature of the peak current depends on the doping and of the resistivity of the semiconductor material, that is from the peak voltage. The variations are normally within one part in one thousand per degree centigrade but also smaller in special diodes and in the neighbourhood of 25°C. The stability of the peak voltage is of the same order and the voltage itself is always decreasing with the rise of the temperature while the peak current changes may have both positive and negative directions as the temperature grows higher. Intrinsically less stable are the valley voltage

(x) - Here we do consider only germanium tunnel diodes.

and current. The order of magnitude for voltage variation is of about - 1 mV/°C and for current of about + 1 % /°C. Also the negative conductance is sensitive to the temperature and decreases of about 0.5 % /°C with the increase of temperature.

From this brief survey it can be seen that both the peak voltage and current may be considered as sufficiently stable with temperature and for special applications when an extra stability is required a rough thermostat may be used. It is possible then to design a voltage or current-sensitive discriminator with good stability.

The behaviour of the tunnel diode as a negative resistance device has already been described many times. Here we present an extension to the capacitive and non linear resistive load of a graphical method already published (10) for computing the switching time. In Fig. 1 are represented the voltage vs. current characteristics of a tunnel diode and in Fig. 2 the steady state characteristics of a load composed of a transistor and a parallel resistance. This circuit is indicated in Fig. 3 and its nodal equation is as follows :

$$I = I_D + I_C + I_o \qquad (1)$$

and is plotted in Fig. 4. The current I indicates the supply current, I_D the diode current, I_C the capacitor current and I_o is the current of the load in parallel to the capacitor $(I_R + I_G)$. - Obviously the magnitude of the current I_D, I_C and I_o depend on the a c impedance of the components.

Let us suppose that C is constant during a short time interval Δt. Then

$$\Delta V_C = \Delta I_C \left(\frac{\Delta t}{C} \right) \qquad (2)$$

and by substituting the value of I_C from equation(1) into (2) we can rewrite it as :

$$\Delta V_C = \Delta V_D = -\Delta(I_D + I_o)\left(\frac{\Delta t}{C}\right) \qquad (3)$$

This expression represents a straight line on the V_D I_D plane of the characteristics and V_C vs. time Δt can be easily calculated from it. It is also important to remark that we have supposed that the amplitude of the input signal does not change appreciably during each Δt interval. When these two conditions are satisfied (constant C and switching time much faster than the input signal) equation 3 may be represented as shown in Fig. 5 and the voltage V_D across the diode can be plotted vs. time for both the forward and the backward switching transients. The results obtained will be as accurate as the V_D, I_D and V_o, I_o characteristics could be defined and the smaller time intervals are chosen. It means that $-C/\Delta t$ slope should be as high as possible. When C is not constant it will be necessary to calculate for each step of the plot in Fig. 5 a new value of C from the $C = C(V_C)$ function and the corresponding slope $-C/\Delta t$ of the lines. These slopes are then either increasing or decreasing as C is being reduced or growing higher, because normally $C = C(V_C)$ is a monotonic function. This type of plotting is quite tedious and is normally avoided also because results of sufficient accuracy can be obtained by simply considering a mean value of C, as seen before.

Much more interesting is the influence of the input pulse shape and amplitude on the output pulse because it happens quite often that fast discriminators are used with input signals which have a duration comparable to the switching time of the circuit. The value of the current I (see Fig. 4) then changes with the input signal and $(I_R + I_G)$ lines are shifted parallely to the I axis. The plotting method previously described can be adopted also to this case, but a Δt interval small enough must be taken so that a good precision can be obtained by varying the origin of the $\frac{-C}{\Delta t}$ lines according to the input signal. This procedure is illustrated in Fig. 6.

The switching times are as fast as the I_C current is high with constant C, in particular as high as the I_C/C ratio. This behaviour is quite obvious and well known but the graphical analysis is useful to appreciate visibly the dependence of the switching time from the I_C current. It may be also useful to point out that, all other conditions being equal, the magnitude of I_C is in inverse ratio to I_R and I_o so that it is always convenient to design circuits with high impedance in parallel to the tunnel diode. Referring to Fig. 2 and 3 it may be seen that the transistor junction supplying the I_G current is generally reverse biased up to the point V_v of the characteristic of the tunnel diode ; i.e., that it behaves like a high impedance for almost all the switching time. In this way the resistor R must have a high dynamic value in order not to limit the switching speed.

The jitter during the rise time depends mainly on the loop gain of the circuit in the neighbourhood of the switching points P and Q (see Fig. 5). From the mathematical point of view the jitter magnitude is in inverse ratio to the second derivative of the $I_C = I_C (V_C)$ function in tangent points P and Q. The influence of the intrinsic loop delay will be examined later.

The above analysis, developed for tunnel diodes, applies also to other negative resistance circuits. For these circuits it is necessary to choose the proper point inside the loop for plotting the steady state VI characteristics in order to appreciate in the best possible way the equivalent capacitive and resistive load.

3 - THE BIAS CIRCUIT

The bias circuit is defined by the steady state VI characteristics of the equivalent load of the tunnel diode and by the magnitude of the current I (see Fig.3). The circuit may have two stable positions or one stable and one semistable position which or is independent from the input signal or lasts as long as the input signal remains above the threshold. In these last two circumstances, when one semistable pole does exist, the discriminator must have a memory generally performed by a L R circuit or by a delay line. These three above mentioned conditions of stability are shown in Fig. 7. The steady state load line indicated by the N. 1 cuts three times the characteristics of the diode but only A and B are stable working positions. In this case, an external reset circuit with memory is required in order to switch the circuit from B to A. The load lines 2 and 3 have both a single stable position C, but the load 2 dynamic characteristic cuts the tunnel diode characteristic also at the point D giving the wanted semistable position.

From the previous discussion it is clear that better performances are obtained by biasing the circuit with load lines of the first and the second type. In this way the circuit has a higher dynamic impedance in parallel to the tunnel diode thus giving faster switching with constant output voltage. From this point of view the first two biasing circuits are equivalent.

Let us now examine the other properties which distinguish these two circuits. The regenerative action takes place when the working point meets the point P of tangency between the steady state VI tunnel diode characteristic and the dynamic load characteristic. Sometimes the steady state and dynamic characteristics of the load are not equal as it happens for the load line 2 of Fig. 7, then the bias circuit and the diode show two different impedances. This is illustrated in Fig. 8. Let us consider that the diode is biased at the point T of the characteristics. The segment TR gives then the magnitude of the bias current and the segment TS the input signal current which is necessary in order to bring the diode from the point T to P in which starts the regeneration. (This procedure is valid only when the input signal variations are fast as compared to the time constant of the tunnel diode equivalent load). It is very interesting then to make a plot of TR (the bias current I_b) vs. TS (the signal current I_s) beginning from the point T superimposed over the point P (the minimum threshold) and going with the point T to the left of the characteristics. For simplicity we have approximated the tunnel diode characteristic with three straight lines as in Fig. 9. Referring to notations indicated in the figure :

$$\frac{TR}{TS} = \frac{a - c}{b - c}$$

and for $a > b > c$

$$\mathrm{tg}\,\beta > \mathrm{tg}\,\alpha > \mathrm{tg}\,\gamma$$

The TR vs. TS is plotted in the same figure and it can be observed that the threshold and the bias current are non linear for the low voltage levels. This non linearity has been also experimentally controlled by measuring the bias voltage V_b vs. the signal voltage V_s (instead of the currents) in the circuit of Fig. 10 which has a load line of the second type and is triggered by a low impedance generator. The results are given in Fig. 11. This non linearity is emphasized as the difference between the terms a and b of Fig. 9 becomes bigger and it does exist, as said before, only when the steady state and dynamic load lines are different. When the load has an unique characteristic at rest and during the switching, the terms a and b are equal and $\mathrm{tg}\,\beta = \mathrm{tg}\,\alpha = \mathrm{tg}\,\gamma$, so that the threshold is always linear with the bias.

Another property which distinguishes the circuits with the dynamic load line different from the steady state load is the long settling time(x). This is due to the delay lines or inductances which are used as already mentioned. In the first case, it may be difficult to make a good impedance matching because the tunnel diode undergoes a big change of impedance during switching from its low to high voltage state and back and this mismatch always negatively affects the settling time of the circuit. Moreover the spikes of the mismatched line may trigger the circuit at the end of the pulse, so that the discriminator behaves as having a higher hysteresis. When an inductance is used, the voltage swing on its terminals during the semistable state is generally from five to eight times higher than the corresponding voltage during the settling time which is in this way increased by a factor of five to eight in respect to the output pulse duration. This is illustrated in Fig. 12.

From this analysis it may be seen that the circuit with a dynamic load characteristic which differs from the steady state has two main disadvantages: the non linearity of the threshold at low voltage levels and the long settling time. For these reasons these circuits, which are very attractive because of their simplicity, were not used in our discriminator and we have preferred a bistable circuit which needs a separate reset and input circuit.

The reset circuit makes the discriminator itself more complex and limits the minimum duration of the semistable state and the maximum

(x) - The settling time is defined here as the interval of time required by the circuit threshold to reach its quiescent value after the arrival of an input pulse.

repetition frequency. The input circuit was required because it was necessary to transform a voltage signal across a low value resistance of the order of 50 Ohms into a current to be supplied to the tunnel diode from a high output resistance. This circuit introduces a supplementary delay and also a small integration of the input signal.

4 - THE DELAY TIME, THE "LAMBDA" PULSE AND THE HYSTERESIS

It has been seen in chapter 2 and from the plots made that a certain interval of time which we have defined as delay time is introduced between the time in which any switching circuit is driven into the negative resistance region and the time in which the regenerative action is fully developed. This delay is a characteristic of each regenerative circuit and depends on the loop gain. When the input signal is larger than strictly necessary to drive the circuit up to the point P, the delay becomes smaller as the overdrive becomes higher.

From the mathematical point of view as seen in chapter 2 the delay is dependent on the rate of rise of the divergent terms of the function $V_C = V_C(t)$. For the tunnel diode circuits it is possible to obtain mathematical expressions from a theoretical analysis of the tunnel effect in the highly doped junctions or from the experimental investigations. These expressions are somewhat incomplete for the part of the tunnel diode characteristic near the valley point and cannot be easily related to the physical parameters of the tunnel diode. Much simpler are the mathematical expressions for conventional trigger circuits without tunnel diodes, calculated with the mutual conductance gm and the load resistances as parameters ; but it is more difficult in this case to specify the exact values of the shunt capacitances and of the delay introduced by the regenerative loop, (distributed capacitances effect on the loop gain). The following formula calculated for the circuit of Fig. 13 and interpreted in the same figure gives a fair approximation :

$$di = dv \left[\frac{1}{R_1} - \frac{gm_1\ gm_2}{gm_1 + gm_2} \right] = dv \left[\frac{1}{R_1} - i_1 \left(1 - \frac{i_1}{I}\right) \frac{1}{\theta} \right]$$

where i_1 indicates the current through T_1 , I the emitter supply current and θ may be considered 25 mV at 20°C ambient temperature. When the two transistors of the circuit are equal the maximum negative conductance is obtained for $i_1 = I/2$ and equals $i = -I/4 \cdot 1/\theta$. The calculations were made by opening the loop and substituting the load resistance with a voltage generator v and by computing the current i through this generator. The switching time and the delay introduced can be valued by considering the collector of T_1 shunted with an equivalent capacitance C which represents the transistor and the load capacitances as well as the stray capacitances.

In this way a regenerative loop is not considered as a constant gain amplifier associated with a delay circuit, as usually (11, 12). This approximation can be used for computing the threshold level vs. pulse length in conventional switching circuits only, when the input pulse has a length comparable to the "lambda" pulse. The fact that the gain variations during the switching time are neglected does not allow any prediction on the circuit behaviour during the first part of the switching nor of the delay for signals just above the threshold. Moreover with tunnel diodes it is even more difficult to use this equivalent circuit because the diode itself is too small a component and the delay cannot be considered as affected only by the integration effect of its capacitance.

The graphical method introduced in Fig. 13 is very simple and can give qualitative and quantitative indications on the loop gain in any switching circuit. It allows also to determine the "lambda" pulse and and shows how an input pulse which disappears too quickly may stop the already initiated regeneration(xx). This method suffers however of disadvantages which are typical of all experimental investigations and result obtained with one circuit cannot be extended to other circuits even if a similar but rough estimation of their performance is generally possible.

The switching time and the "lambda" pulse depend on the slope of the load line as said before but they can also be related to the circuit hysteresis. Circuits with big hysteresis are faster. This is clearly shown in Fig. 13 and can be explained by the fact that a lower slope of the load line makes available a higher current for charging the equivalent parallel capacitors. This behaviour is well known specially in conventional trigger circuits. The hysteresis should be measured immediately after the end of the switching transient.In this way this method can be extended to other circuits and also to those having hysteresis variable in function of time, as for example a.c. coupled Schmitt triggers and tunnel diode discriminators with inductive load.

From the plots presented it may be seen how a compromise can be found between circuit hysteresis and stability of the steady state condition.

5 - DESCRIPTION OF THE CIRCUIT AND ITS PERFORMANCES

The discriminator developed has two stable positions and a separate circuit provides a reset signal after each input pulse that triggers the

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(xx) A regenerative circuit is considered to be switched when the output voltage reaches a predetermined threshold v, which equals the voltage level of the next circuit to be triggered. In fact the regeneration is a continuous phenomena and it does not give by itself any information about the circuit switching.

tunnel diode. Efforts have been made to reduce the integrating effect in the regenerative loop in order to achieve a small "lambda" pulse length. Therefore high equivalent load resistances and small parallel capacitances were used and the wiring inductances were kept as small as possible.

The complete schematic is shown in Fig. 14. The circuit is sensitive to negative signals and the input is made on the emitter junction of the transistor T_1 which is biased at 1 mA. The input resistance is of about 25 ohm at ambient temperature but higher values could be obtained with series resistors. The collector has a high output resistance as required for fast switching of the tunnel diode and this transistor also isolates the input from transients of the discriminator. In this way other circuits can be operated from the same signal generator without interferences.

The threshold level is adjustable by means of a ten turns helicoidal potentiometer that supplies the bias current to the tunnel diode through the transistor T_2 which behaves also as a high impedance source. The difference amplifier (transistors T_3 and T_4) has a fixed threshold. A rectangular output pulse independent of the input pulse shape is obtained. A second difference amplifier (transistors T_5 and T_6) is used to restore the d c levels and to reset the tunnel diode through the delay line D and transistor T_7. Care must be taken in order to have a reset signal free of spurious transients which may trigger once more the discriminator. For this purpose the diode S 555 G connected to the base of transistor T_7 prevents the charge stored in the base to flow through the tunnel diode. The double difference amplifier introduces a delay of about 30 n sec. A negative output signal is taken from the collector of T_5 and the load resistance is matched to the characteristic impedance of the output cable. The output pulse is shown in Fig. 15. The small positive signal is due to the capacitive coupling through the transistors of the difference amplifiers.

The smallest input signal of 1 mV across a 50 ohm resistance produces a current of 20 μA that should trigger the tunnel diode. To achieve such a low threshold level it is necessary to have both a long term and temperature stability of the peak and the bias currents better than 10 μA at least ; this means of an order of about two and a half parts in one thousand with a diode peak current of 5 mA. This degree of stability is normally compatible with the intrinsic stability of the peak current of the tunnel diode but the bias current still depends on the power supply stability, on the thermal coefficient and tolerance of resistances in the voltage divider, on the base to emitter voltage drop and on the base currents of the transistors T_1 and T_2 as well as on the reverse current of T_3 which is a germanium transistor. The resistances of the divider and the threshold potentiometer can be made as stable as required by a proper choice of components, the -10 Volt power supply shall be superstabilized, but the variations due to the thermal sensitivity of the transistor can be reduced only with a thermostat. This device can be very simple owing to the small size of the components which will be placed inside, their high thermal conductivity and little thermal capacity. Moreover the circuit can be thermally isolated from the ambient outside so that no special fast response thermostat is needed.

There were two possible solutions : a box with metallic walls internally heated with an iron type resistor(°) and kept at about 40°C constant temperature by means of a control circuit or a plane metallic surface of smaller size also heated and controlled as before with components "plunged" into it in order to achieve a good thermal contact. We have used a thermostat of the first type because the second one requires transistors with collector isolated from the case in order to get a good thermal contact without increasing the circuit stray capacitances. The control circuit of this thermostat is shown in Fig. 16.

(°) - An iron for pressing cloth

The performance of the circuit has been experimentally tested with a mercury switch pulse generator (ELA type GNS-1). The linearity of the threshold vs. the bias setting and its stability with temperature have been measured and are reported in Fig. 17 and 18[(x)]. The frequency response has been valued by measuring the threshold level vs; input signal length (Fig.19) and the delay from the input to the output of the circuit with a constant threshold and for different signal amplitudes (Fig.20). The time resolution has been tested by applying two pulses to the input and measuring the amplitude of the second pulse and its delay from the first one (Fig.21).

6 - C O N C L U S I O N S

The results obtained are satisfacory for our purposes but a better temperature stability, if needed, could be obtained with a more sophysticated thermostat. Also the frequency response may be improved using a tunnel diode with a better switching performance at low level signals and a reset circuit with a smaller settling time.

(x) - A commercially available power supply has been used.

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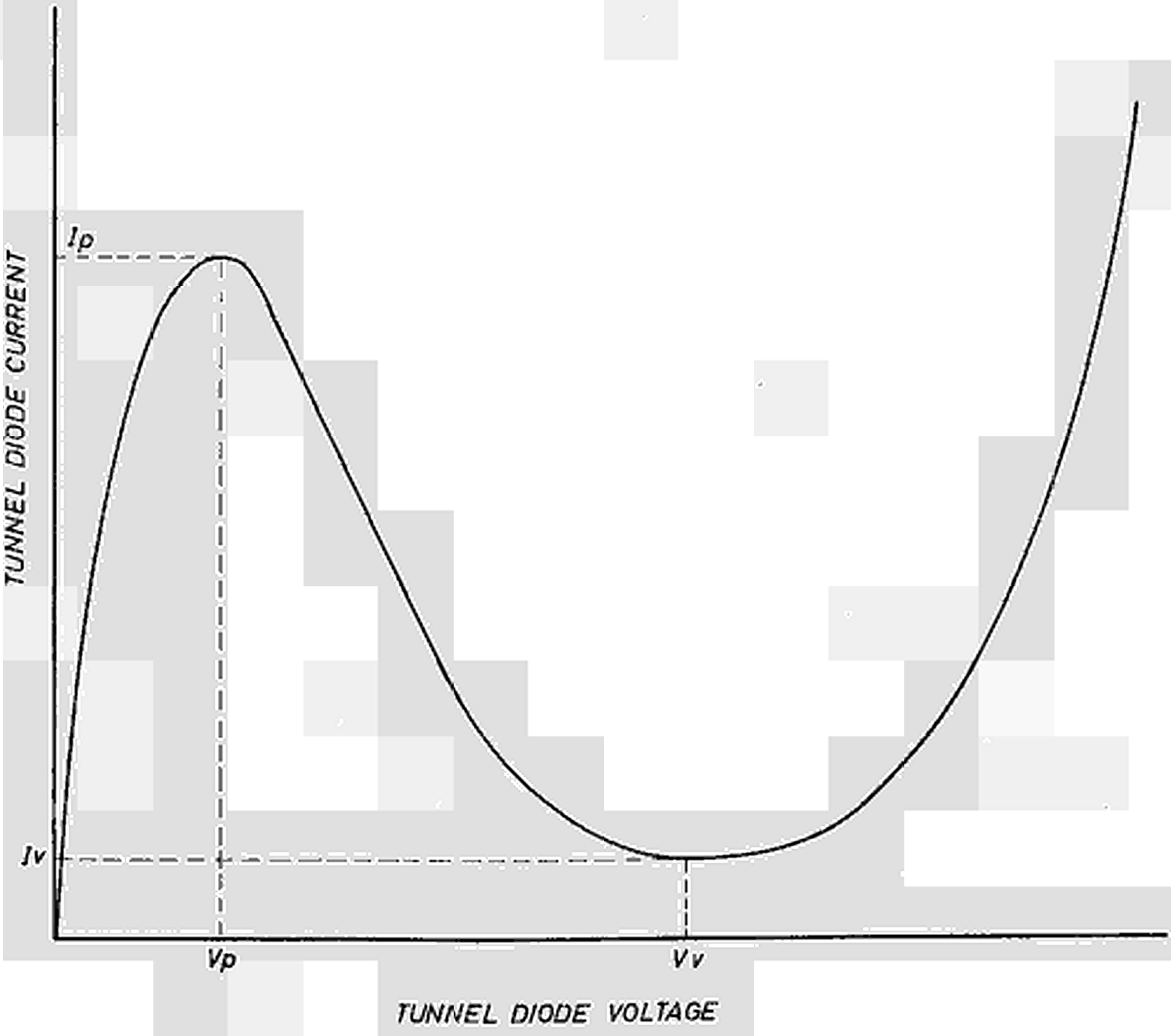


Fig. 1 Typical VI characteristic of a tunnel diode.

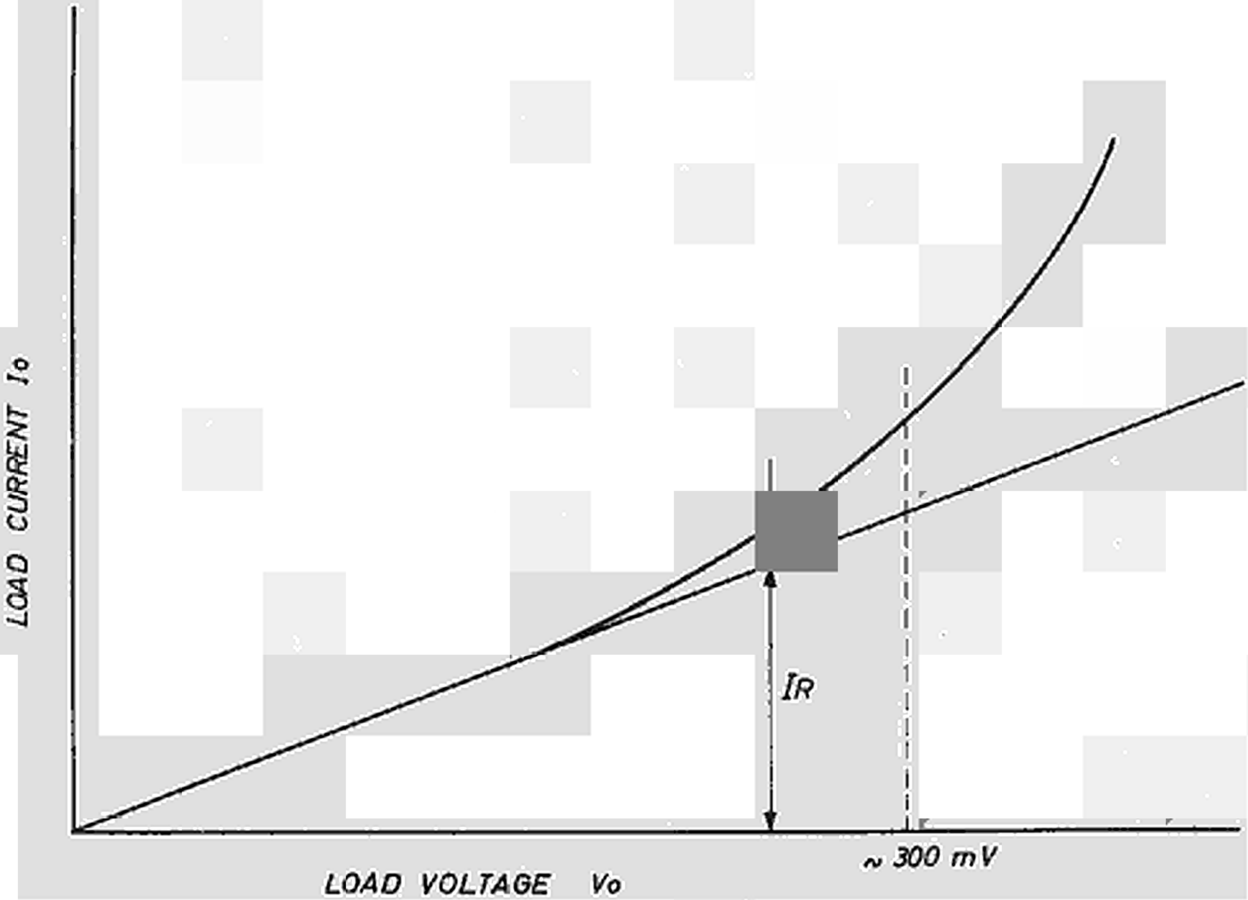


Fig. 2 Steady state characteristic of a load composed of a transistor and a parallel resistance.

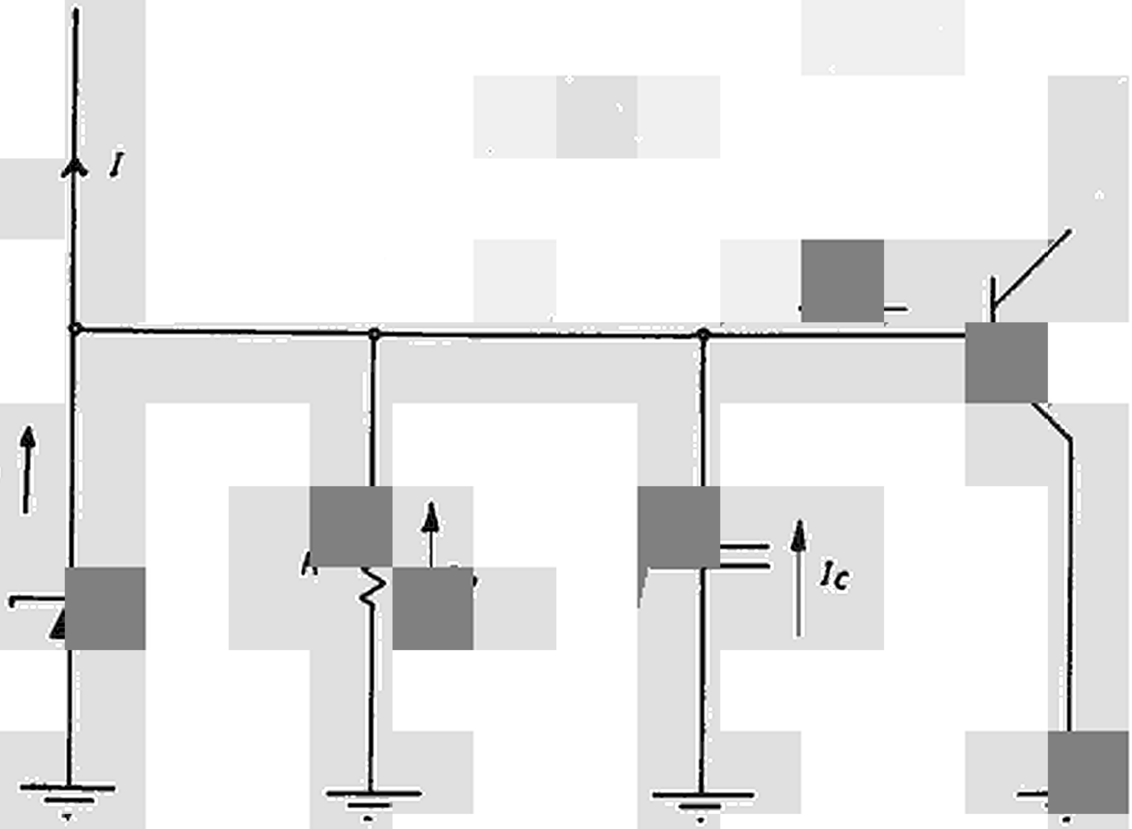


Fig. 3 A typical circuit of a tunnel diode c[redacted]cted to a transistor.

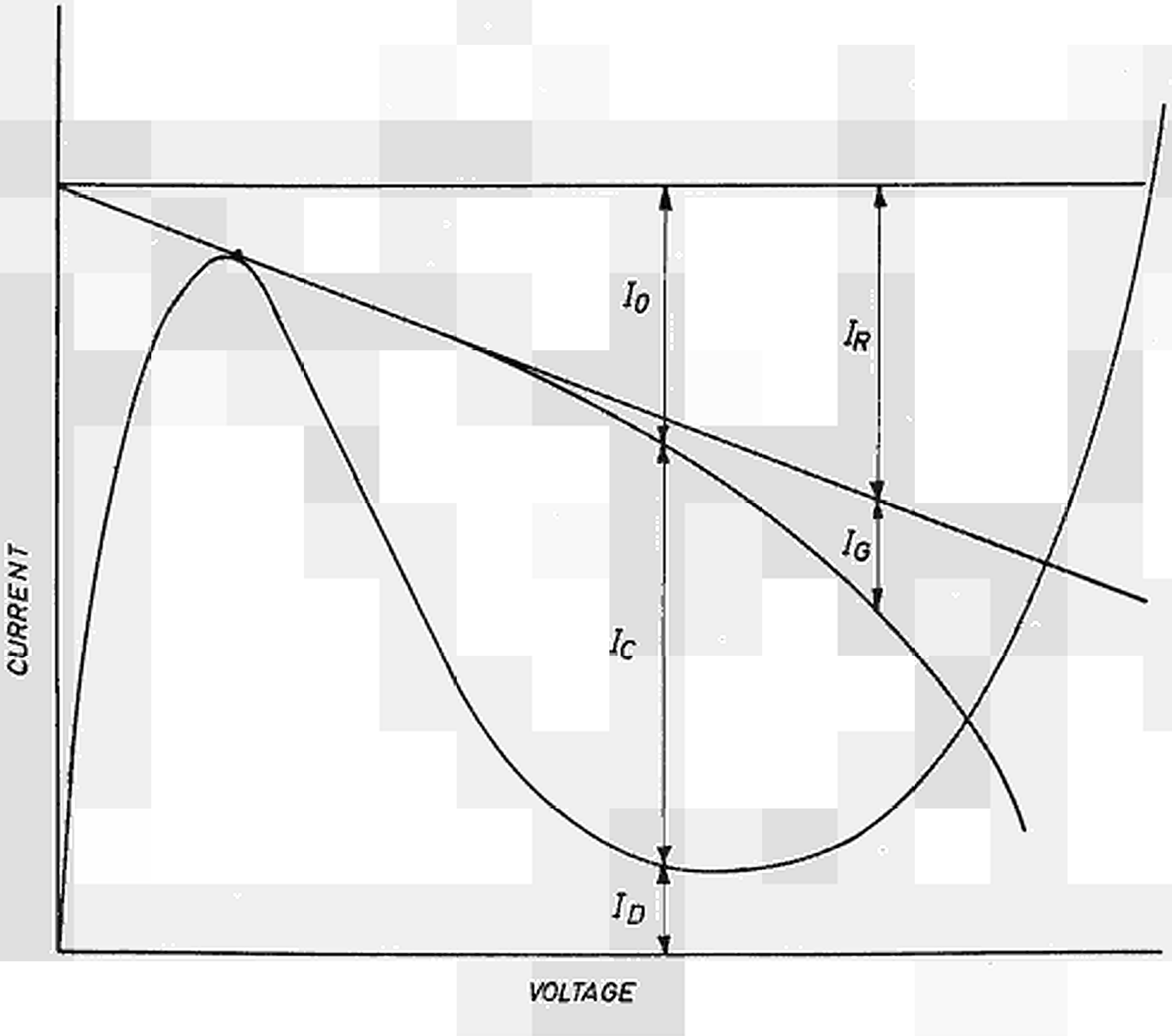
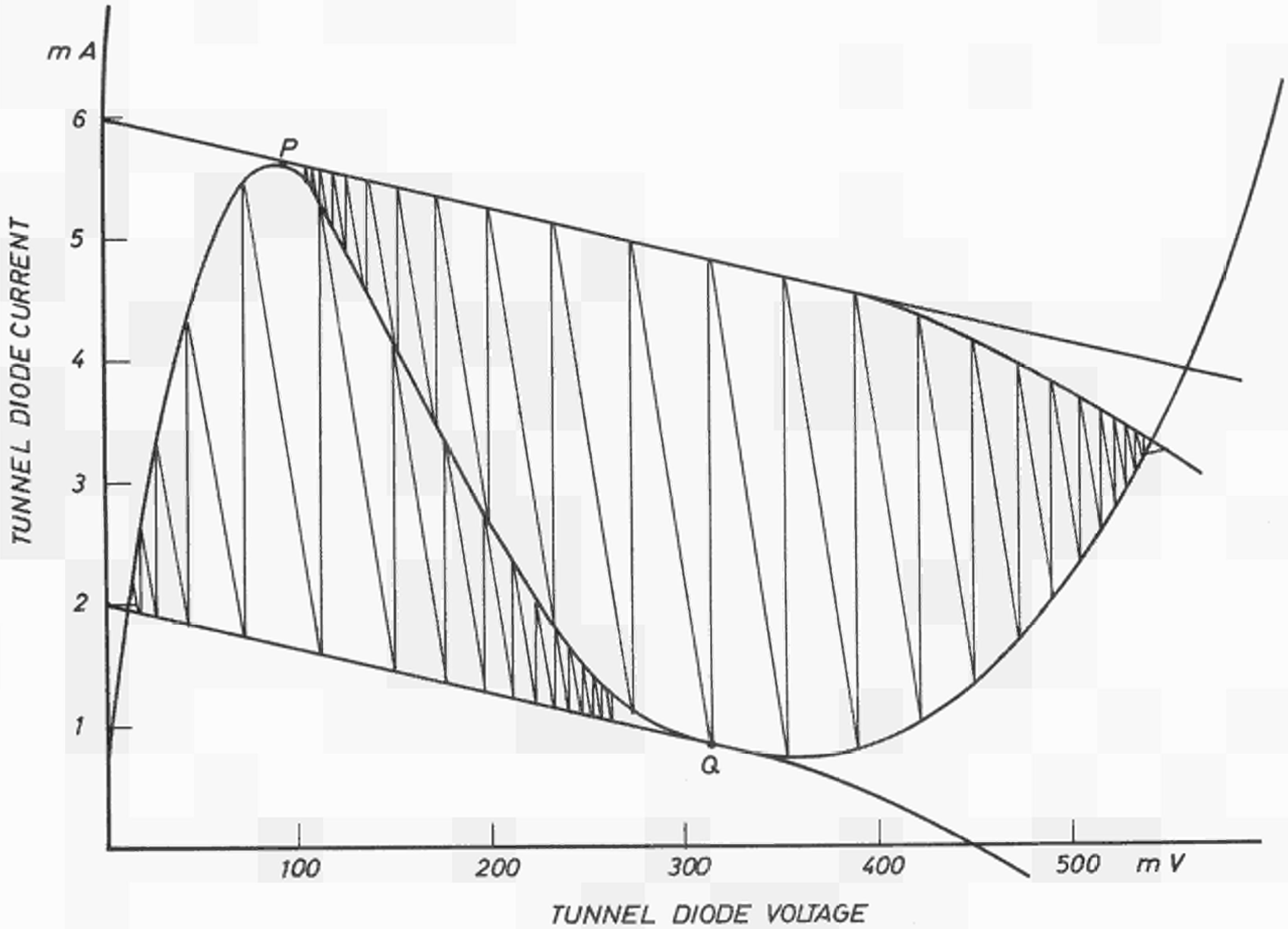


Fig. 4 Graphical plot of the nodal equation of the circuit of Fig. 3.



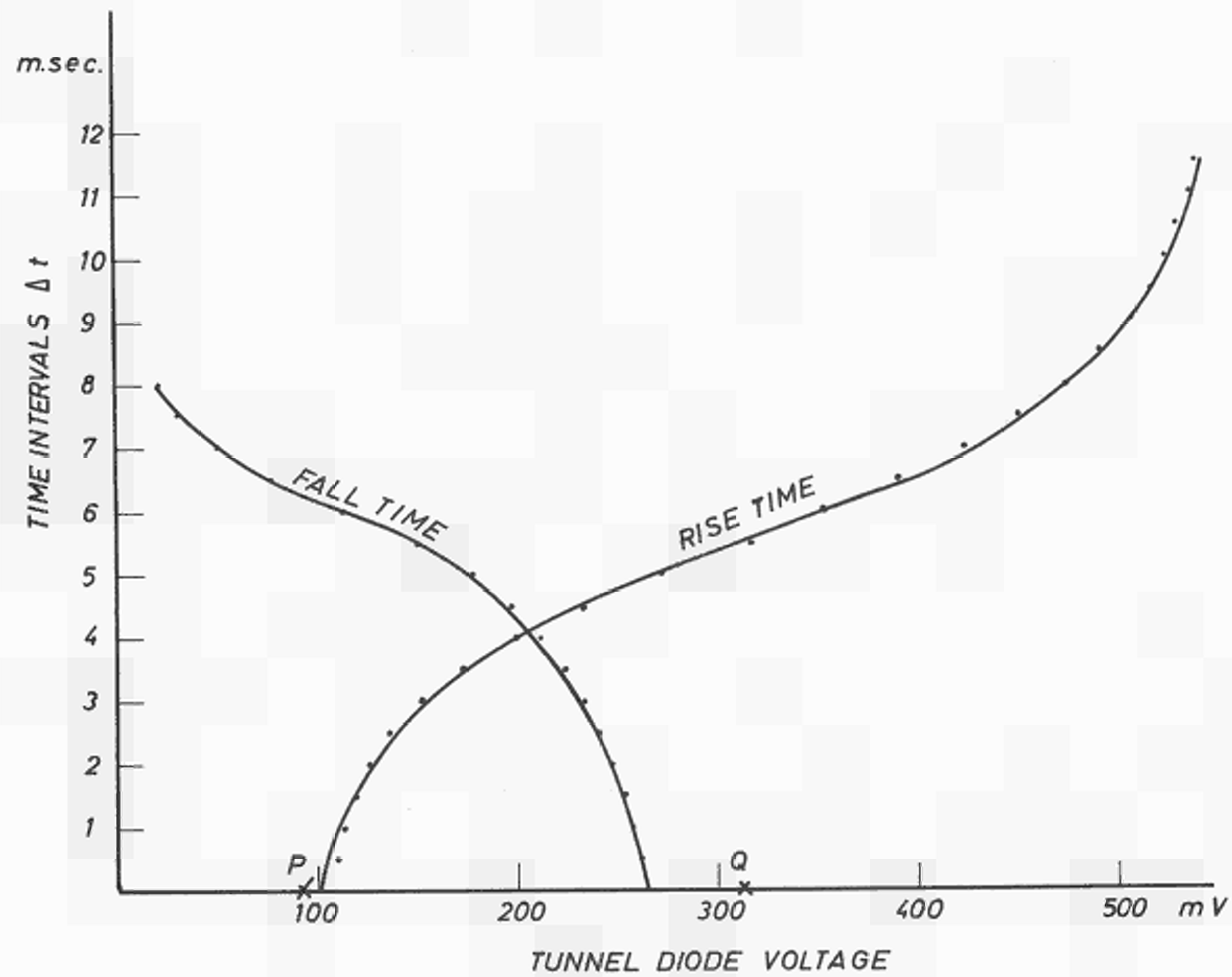


Fig. 5 The rise time and the fall time in a tunnel diode circuit. The capacitance C (50 pF) and the input signal amplitude were supposed constant during each Δ t interval (0.5 n sec).

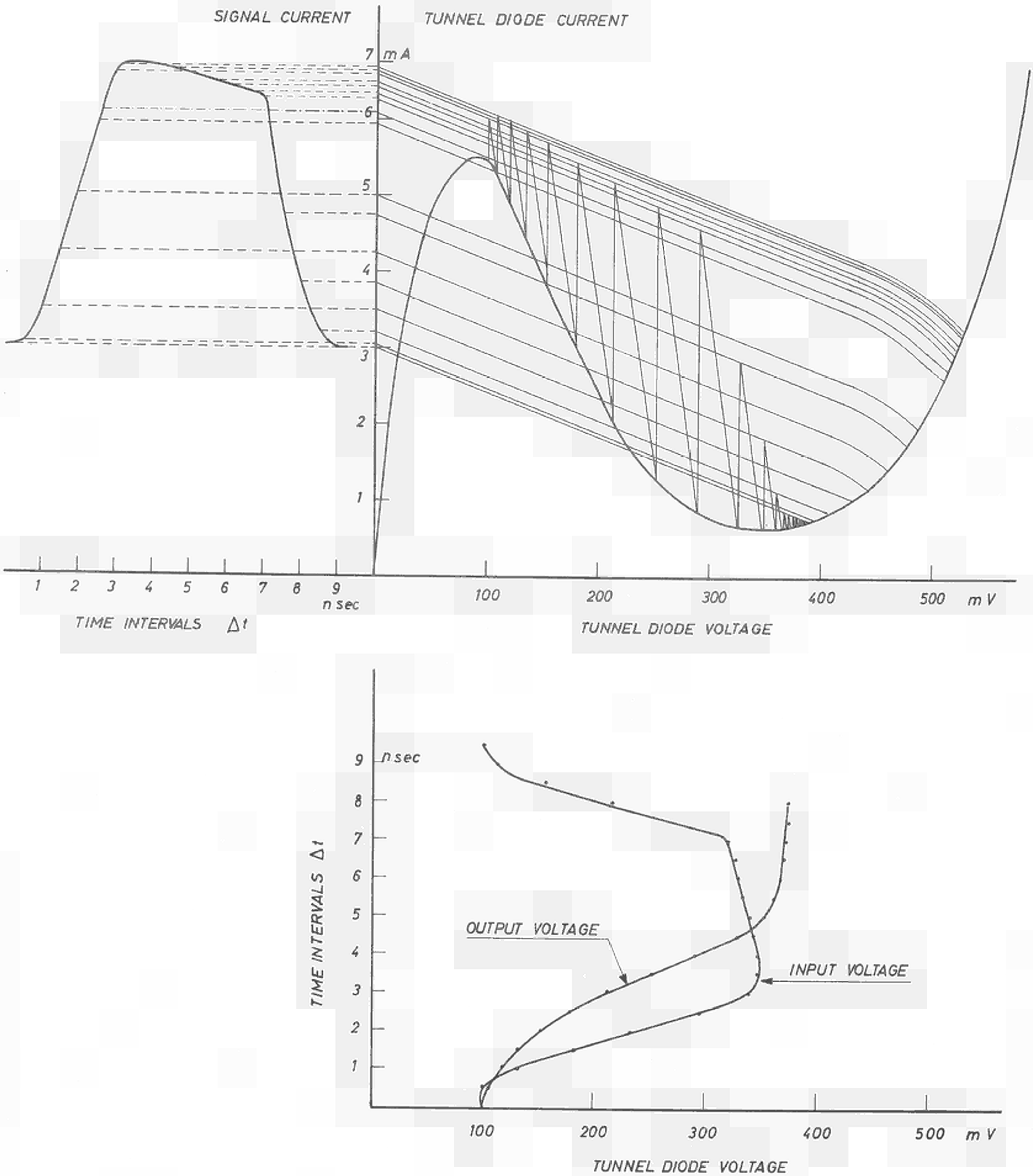


Fig. 6 An example of the rise time determination in a tunnel diode circuit when the switching time is of the same magnitude of the input signal length.

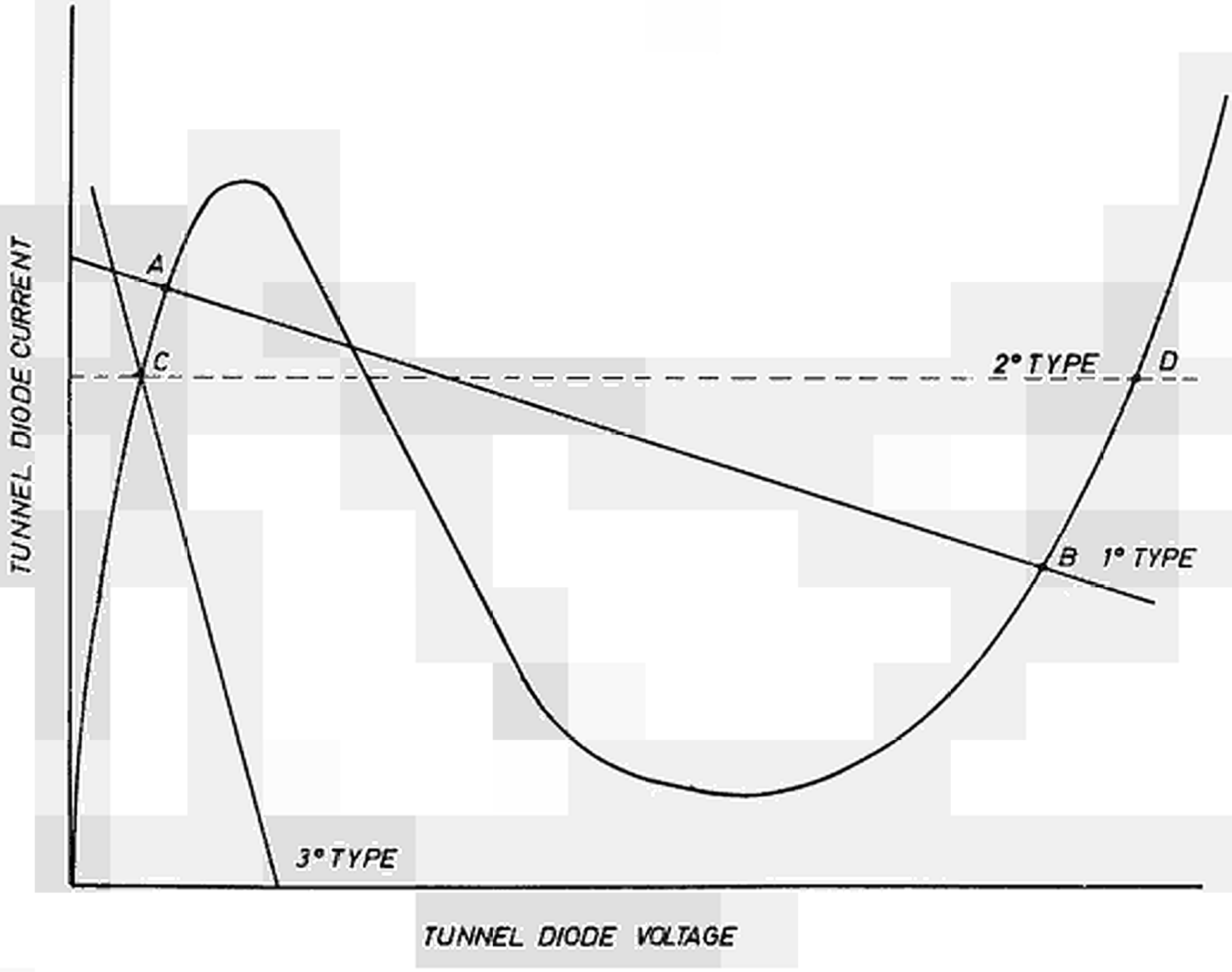


Fig. 7 Examples of the different biasing of a tunnel diode trigger circuit.

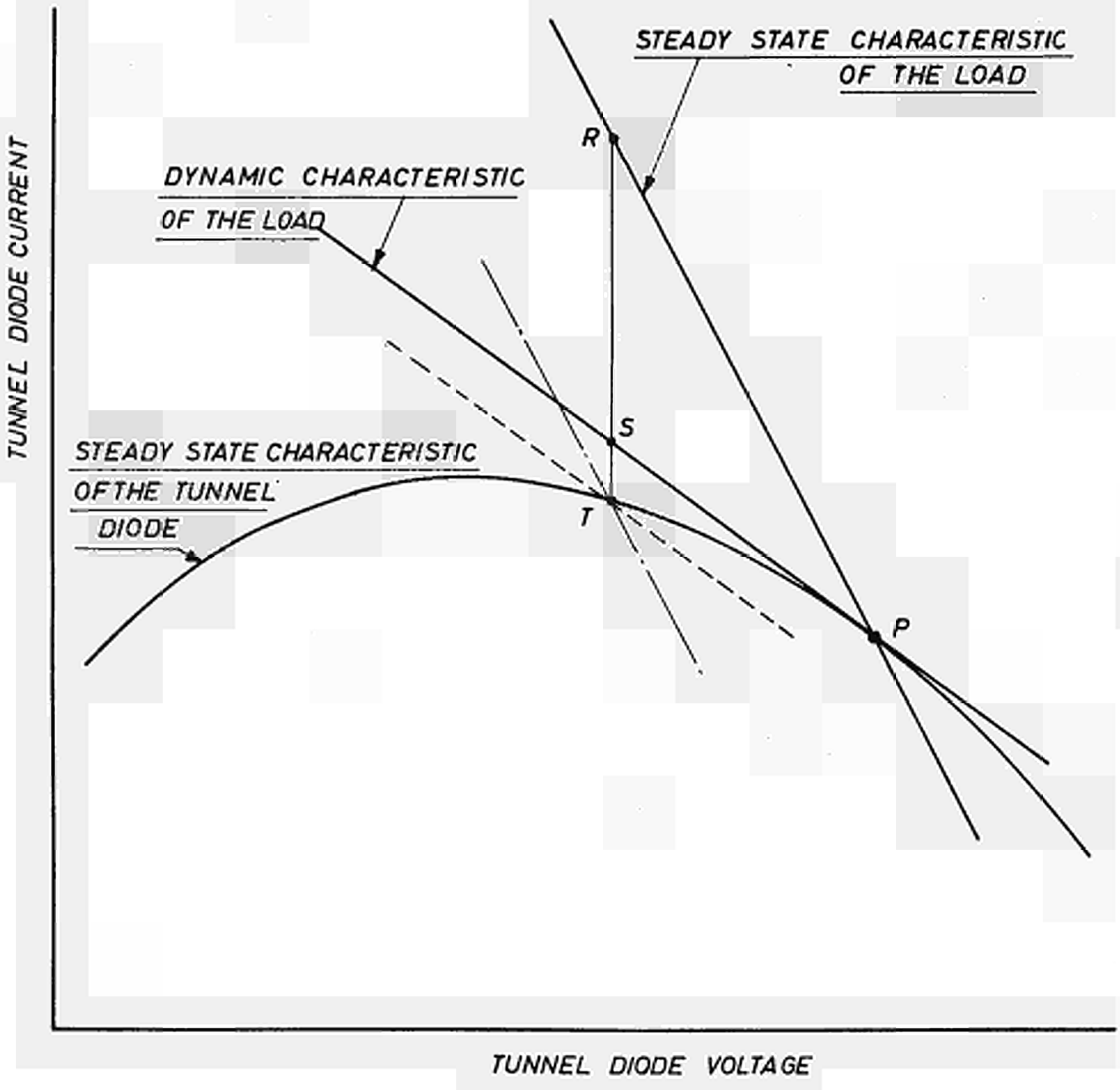
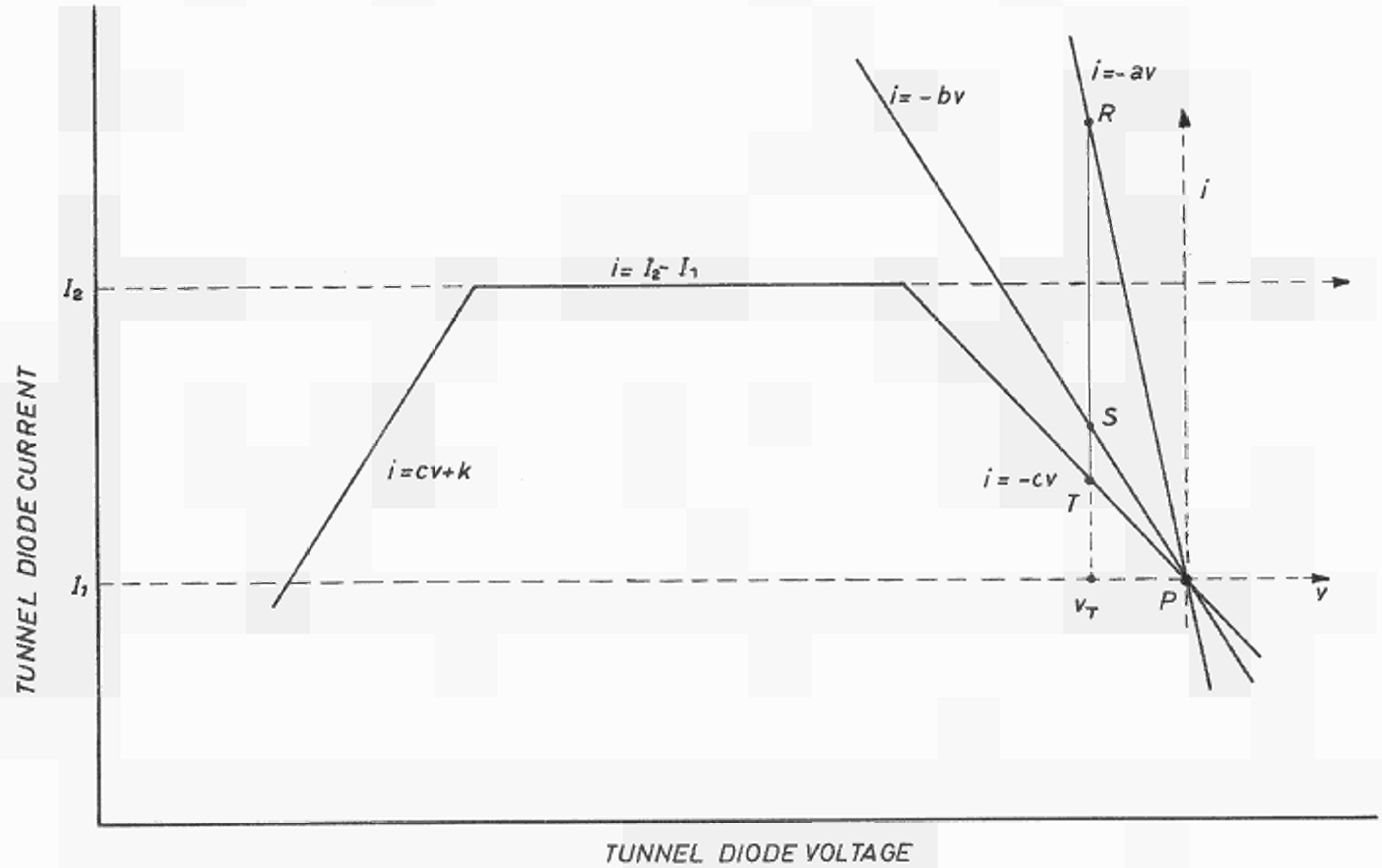
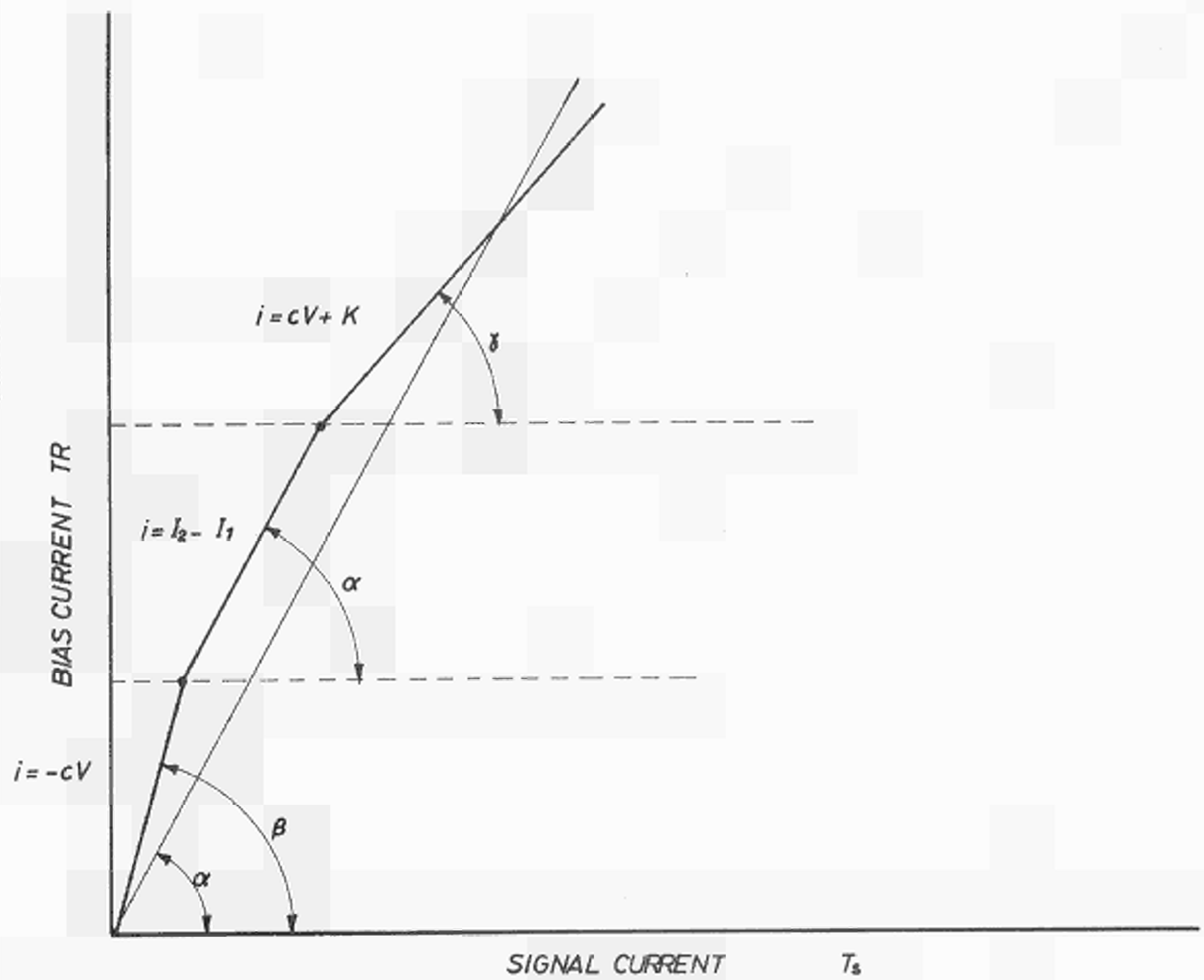


Fig. 8 The tunnel diode characteristic with the steady state and the dynamic load lines.



$TS = i_S - i_T = -bv_T + cv_T = (c-b)\,v_T \qquad TR = i_R - i_T = (c-a)\,v_T \qquad \frac{TR}{TS} = \frac{a-c}{b-c}$



$a > b > c$

$tg\,\alpha = \frac{a}{b} \qquad tg\,\beta = \frac{a-c}{b-c} > tg\,\alpha \qquad tg\,\gamma = \frac{a+c}{b+c} < tg\,\alpha$

Fig. 9 The tunnel diode characteristic approximated with straight lines and the calculated values of the bias and the input signal currents.

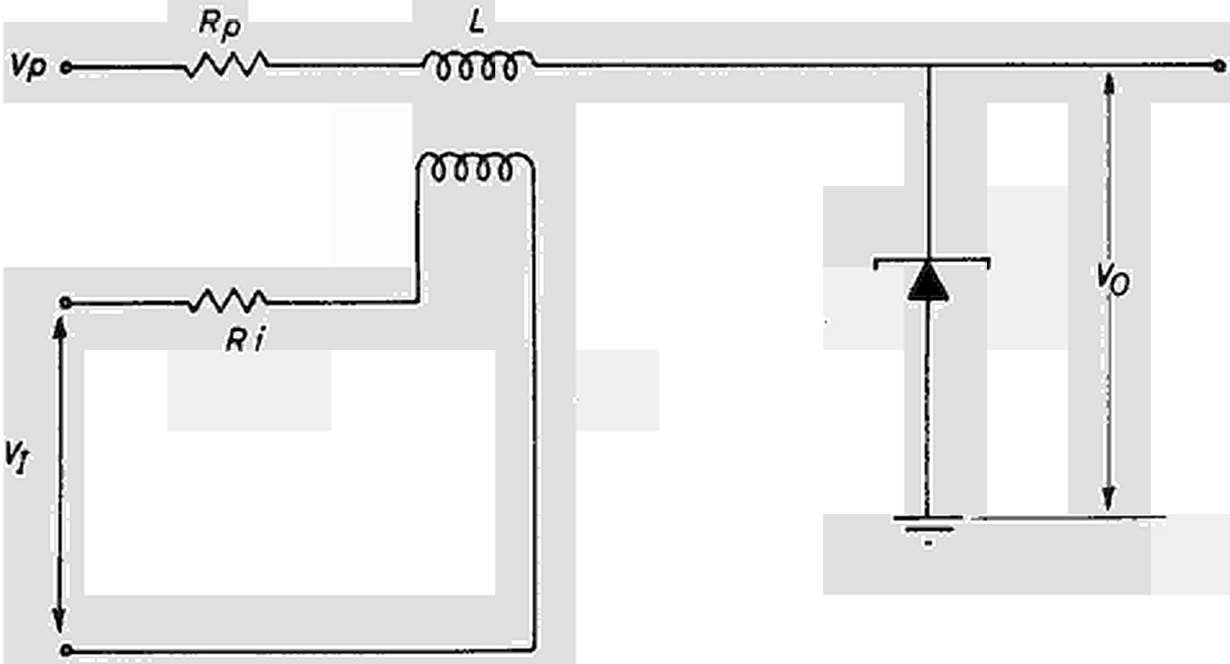


Fig. 10 A tunnel diode sw[illegible]ng ci[illegible] with a load having different steady state and [illegible]mic c[illegible]teristics.

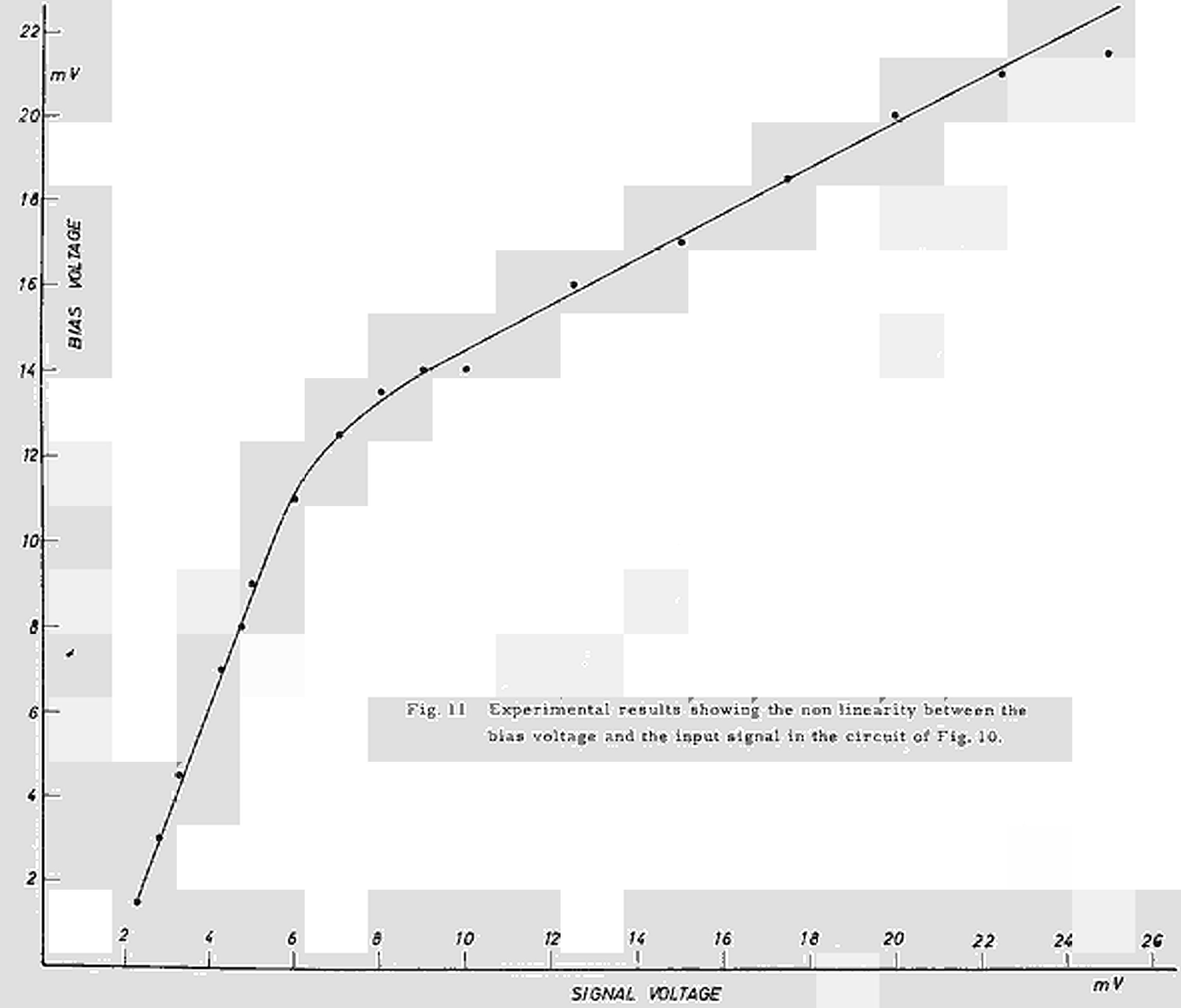


Fig. 11 Experimental results showing the non linearity between the bias voltage and the input signal in the circuit of Fig. 10.

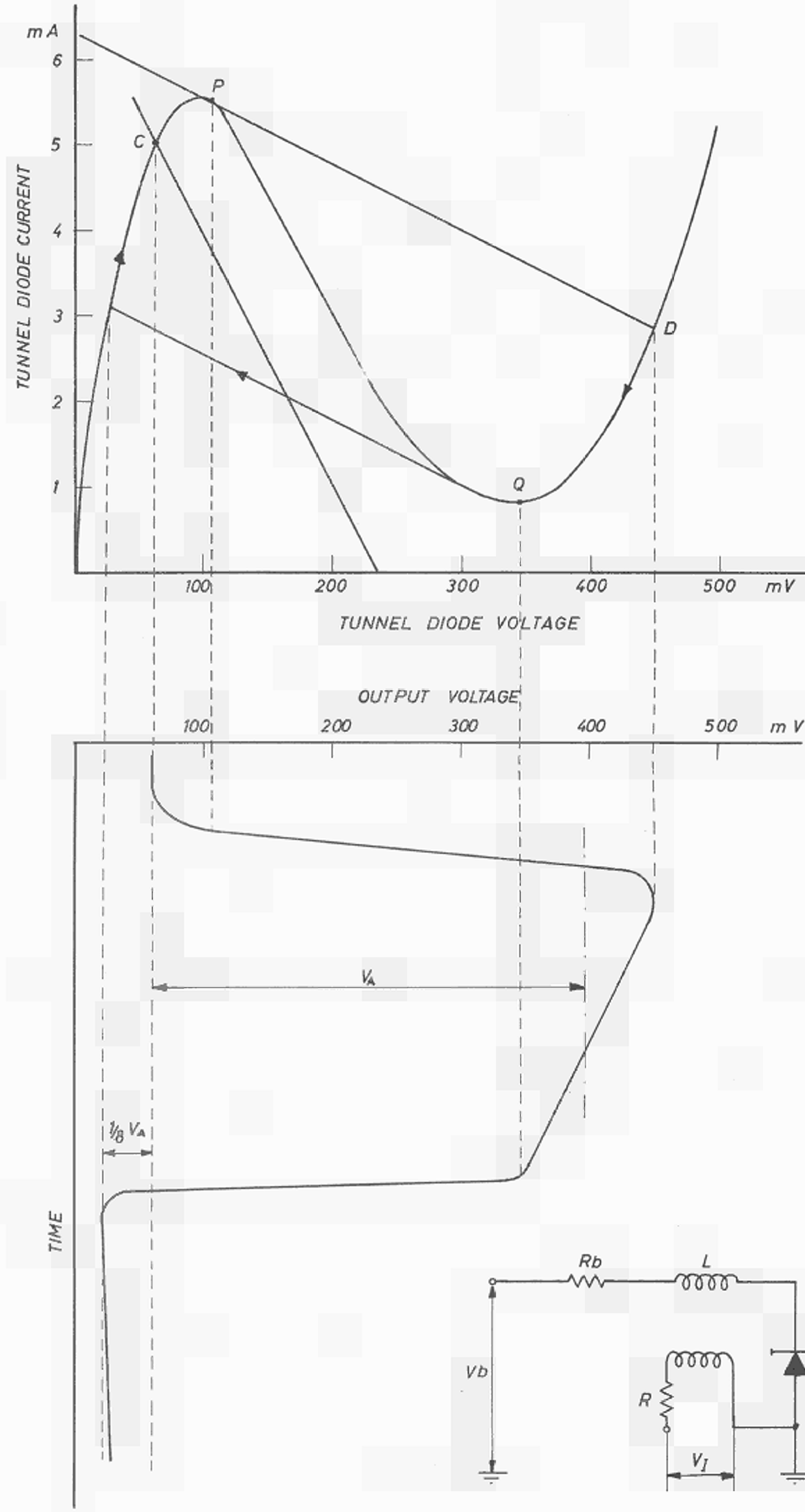


Fig. 12 The settling time of a circuit with inductive load.

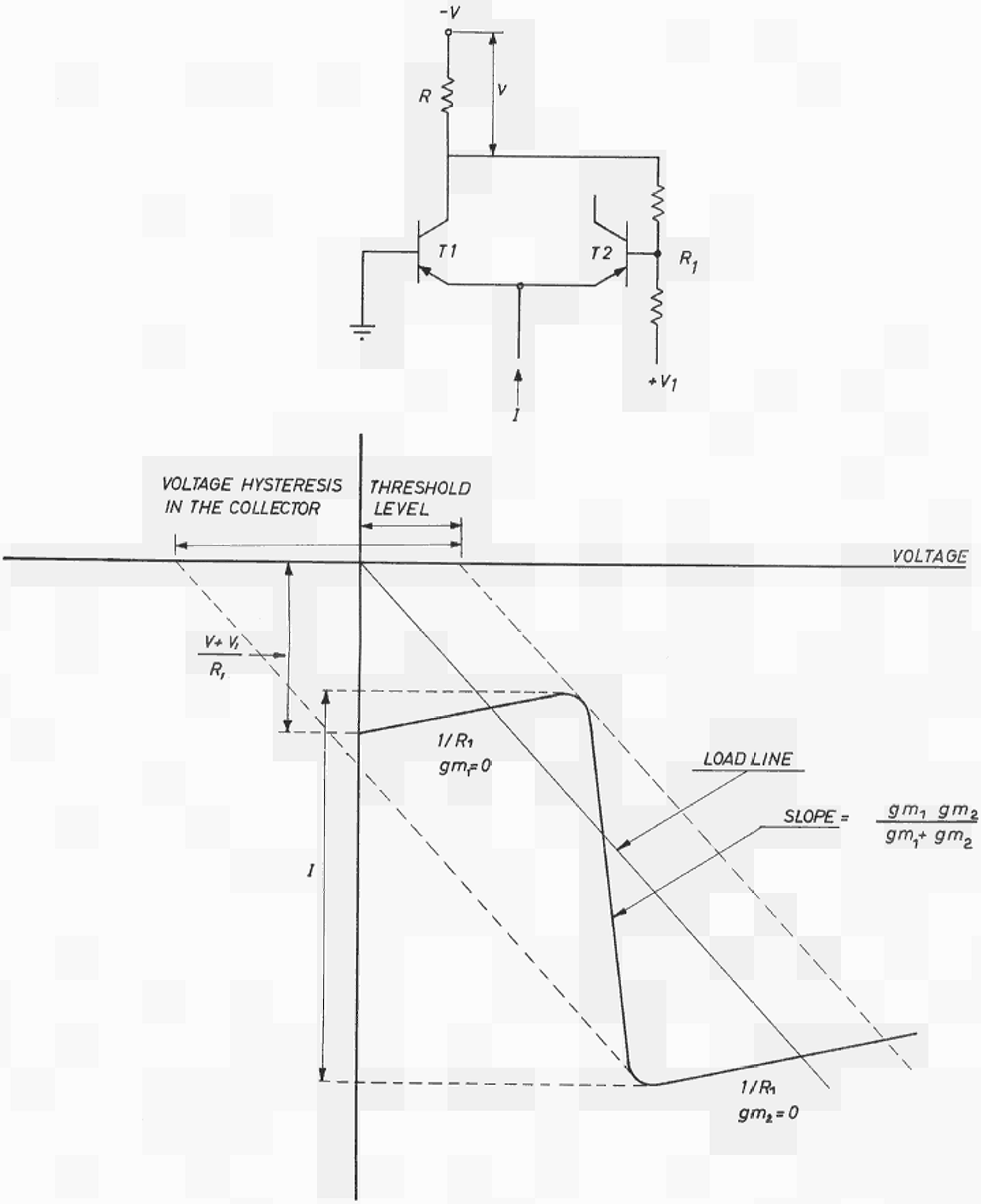
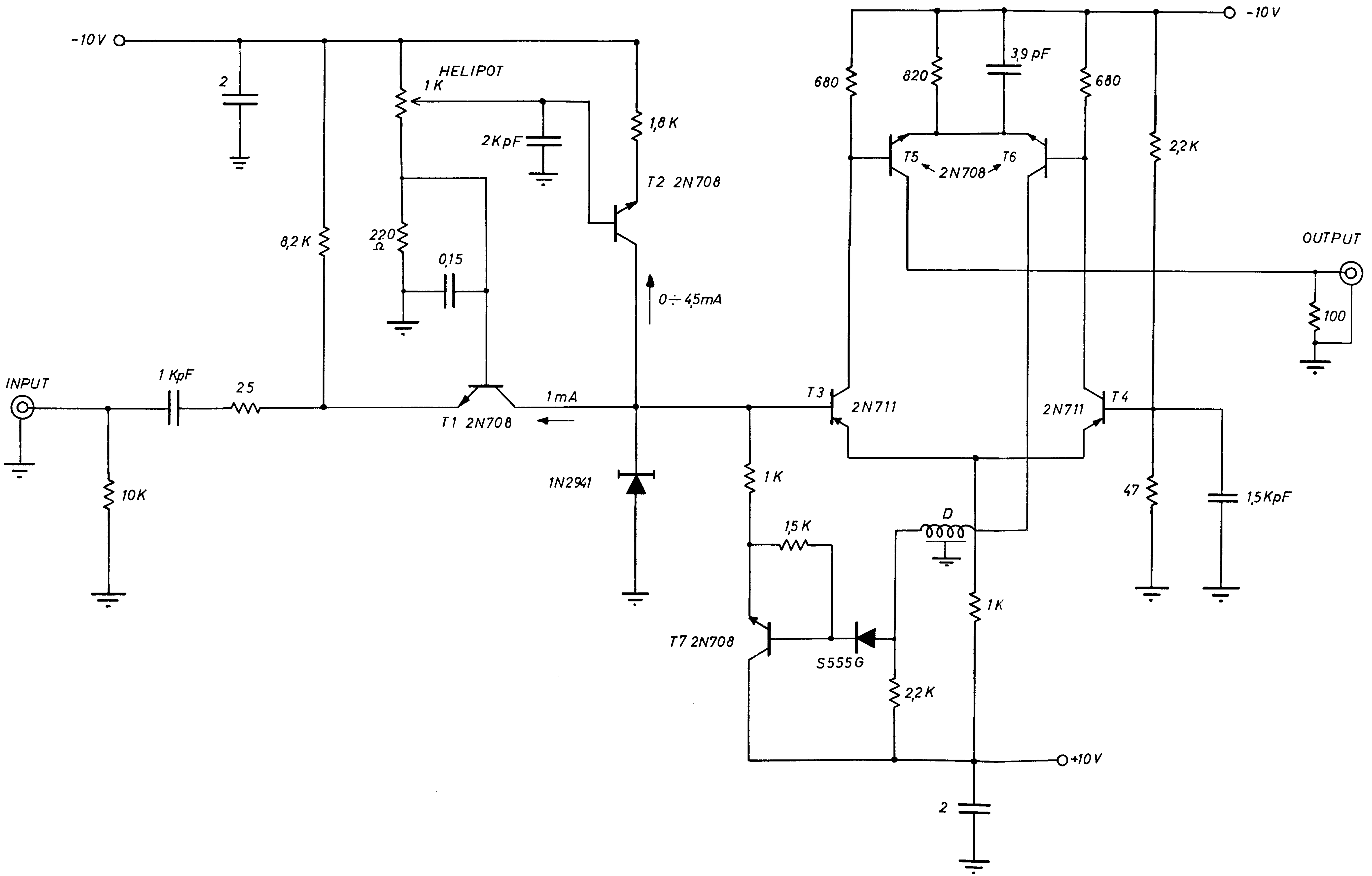


Fig. 13 A conventional trigger circuit with plotted the voltage and the current during the switching.

Fig. 14 The schematic of the discriminator circuit.



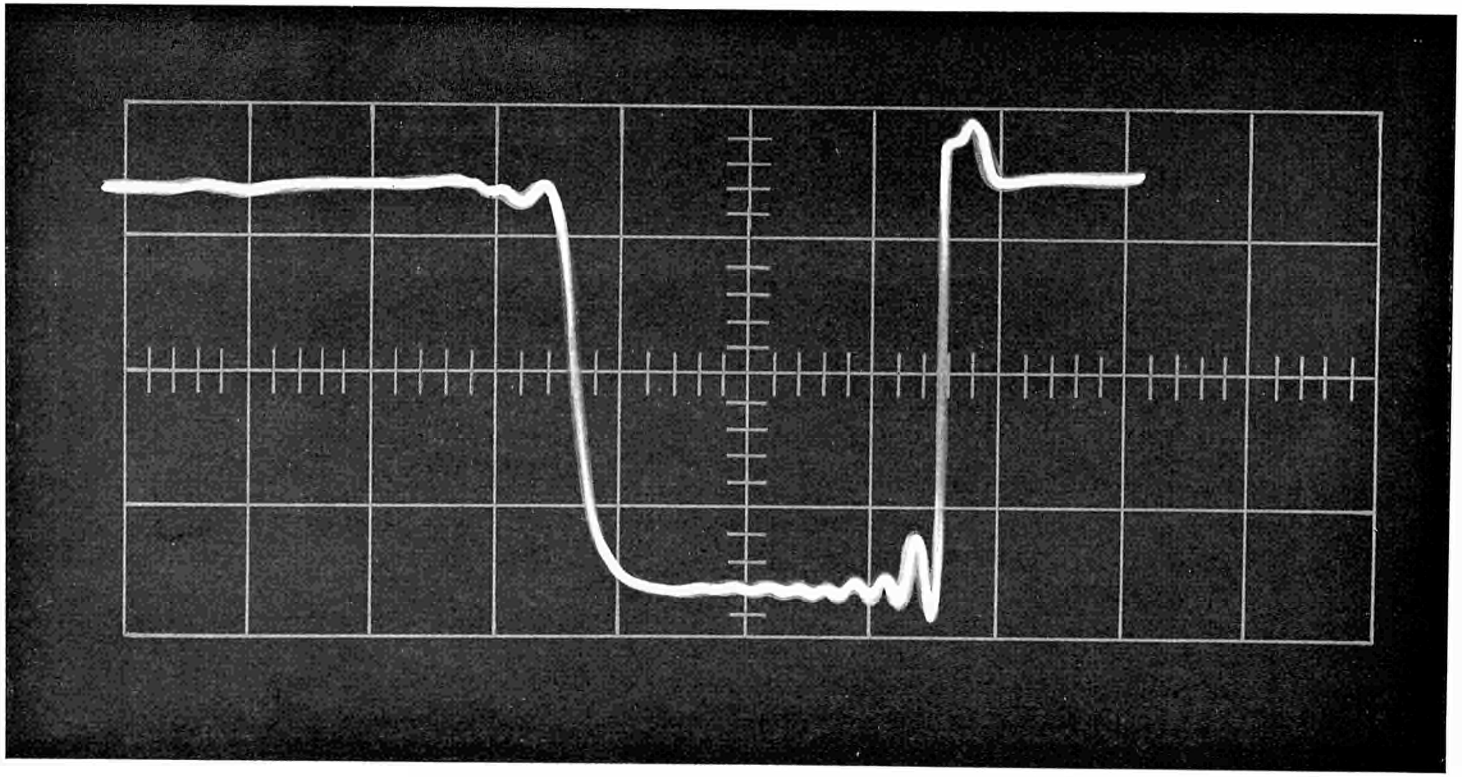


Fig. 15 The output signal from the discriminator circuit.
a) The sweep speed is 50 n sec/div and the vertical sensitivity 100 mV/div.

The oscilloscope was a Tektronix 585

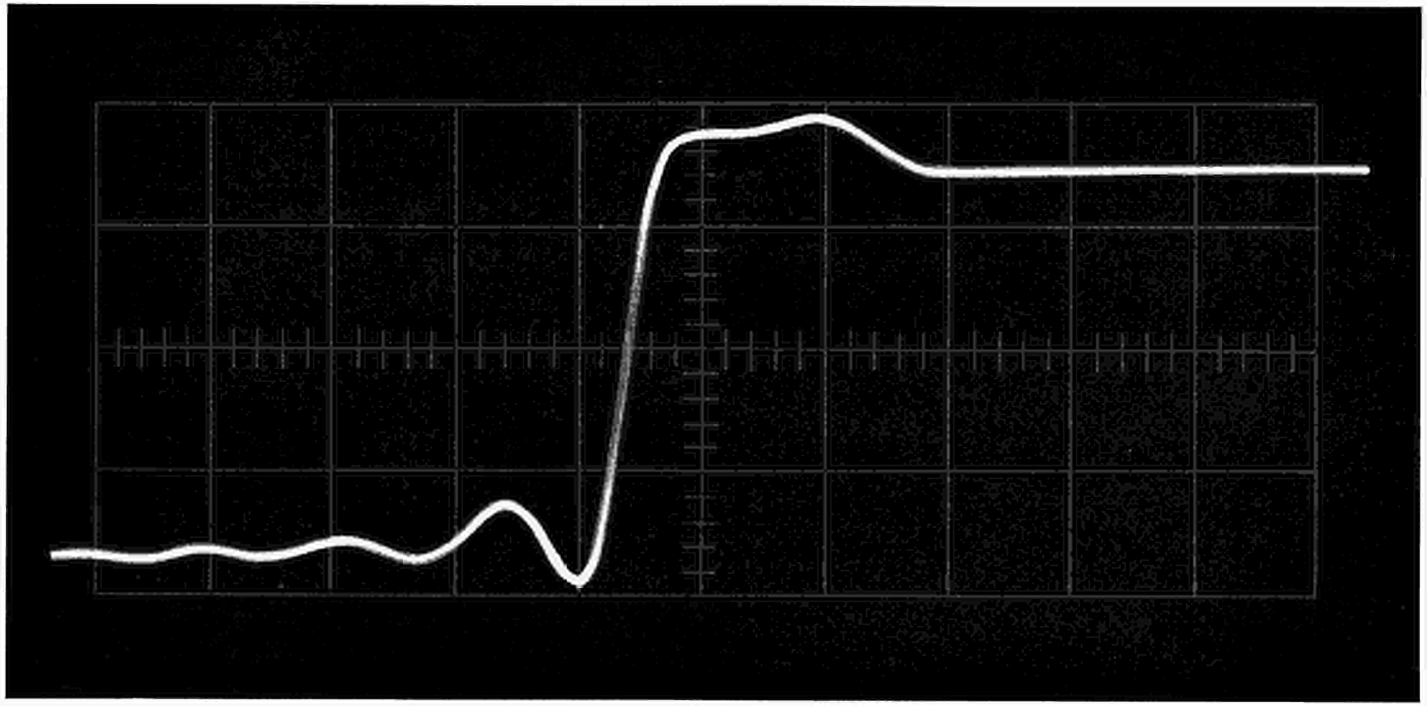


Fig. 15 The output signal from the discriminator circuit.
b) The sweep speed is 10 n sec/div with the same sensitivity as before.

The oscilloscope was a Tektronix 585

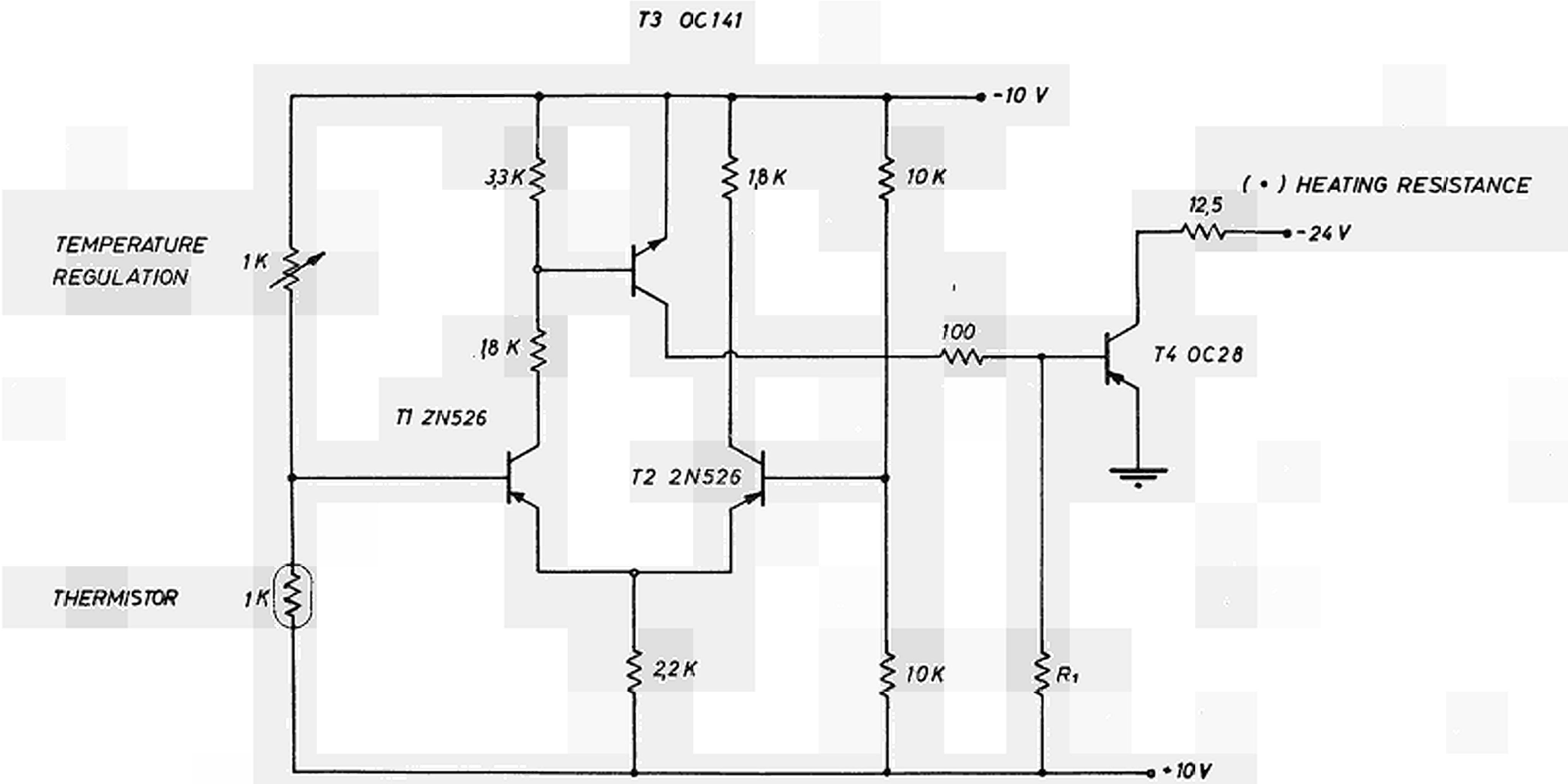


Fig. 16 The schematic of the control circuit of the thermostat.

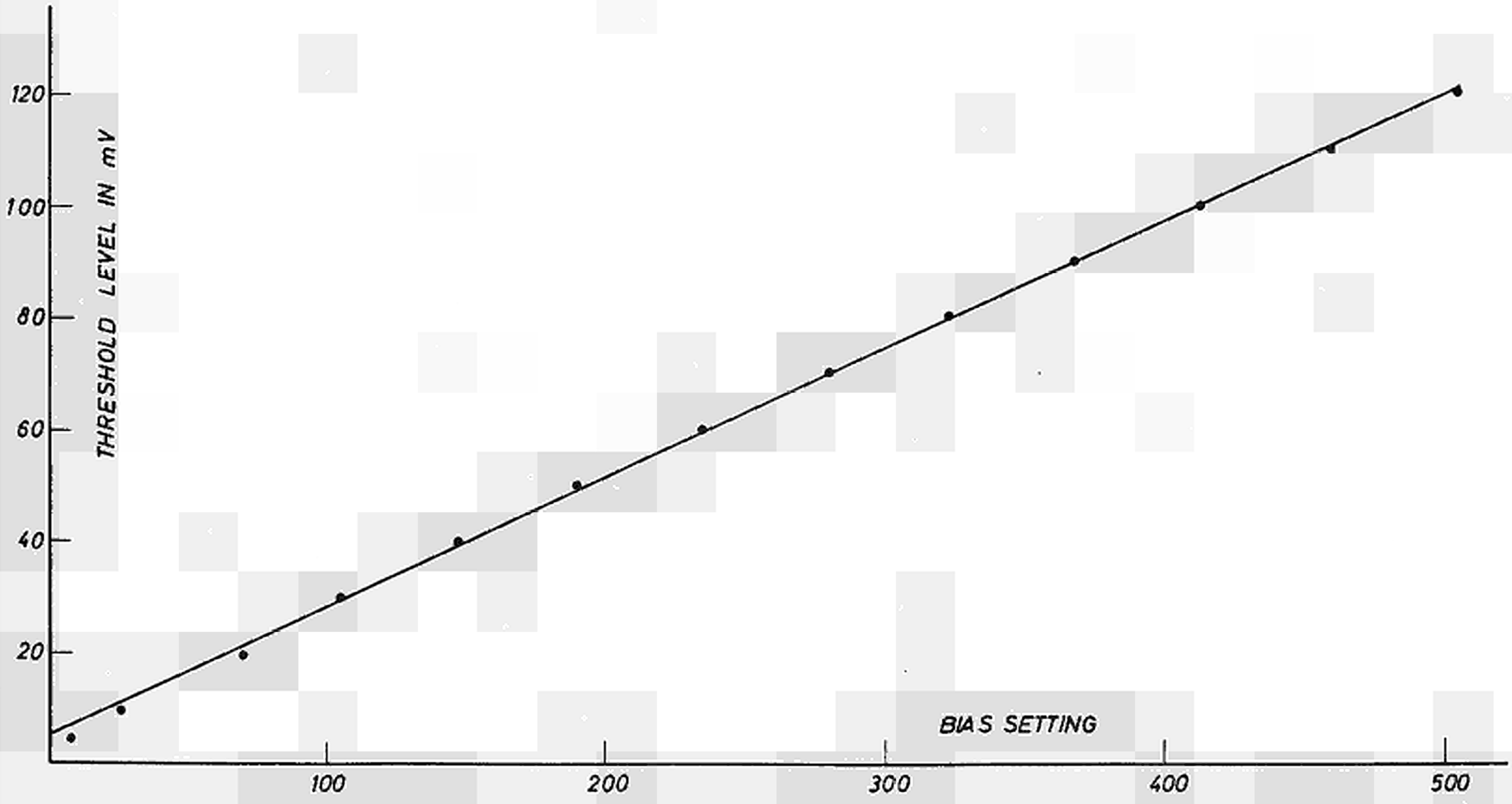


Fig. 17 The linearity of the threshold vs. the bias setting.

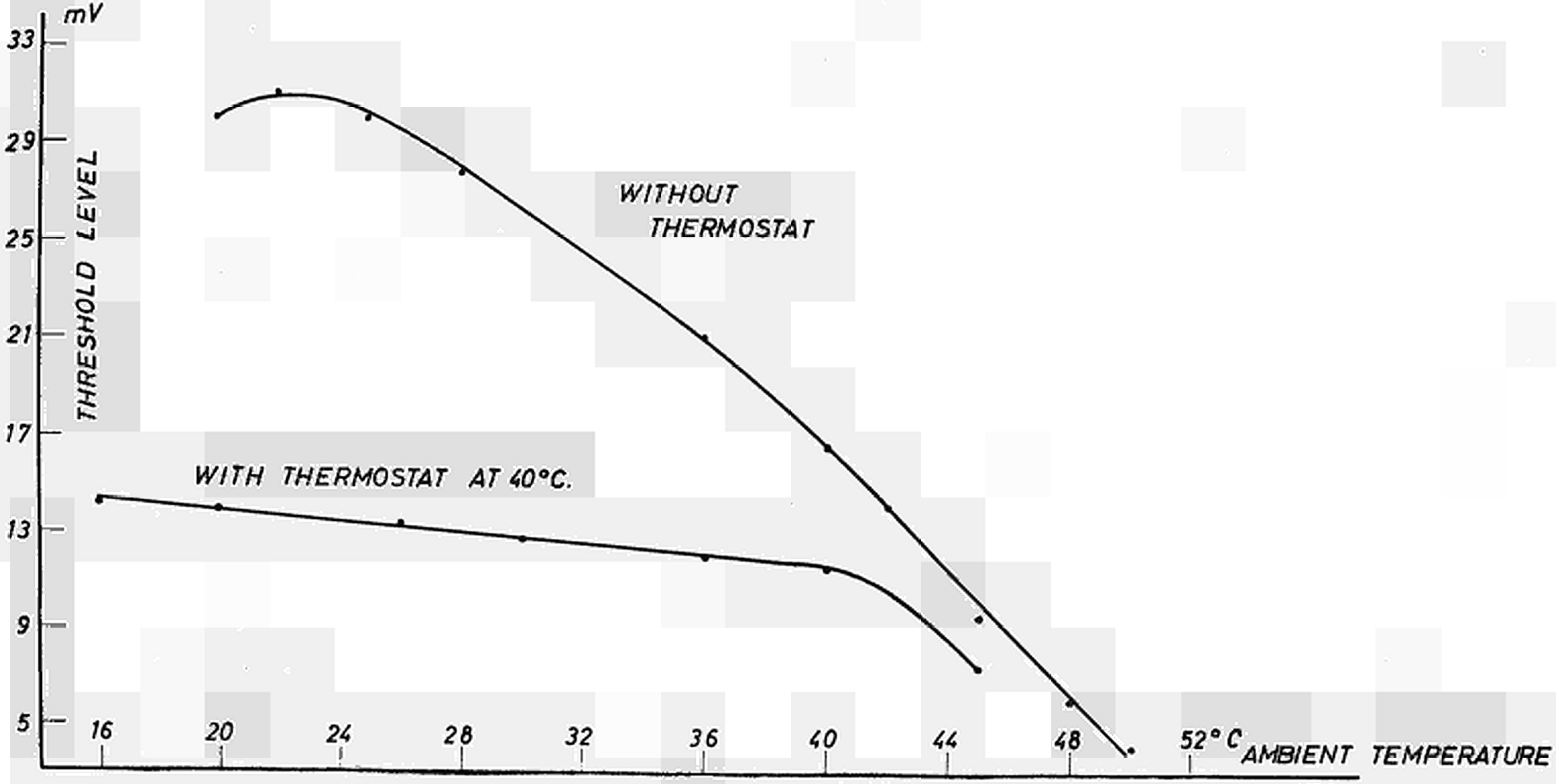
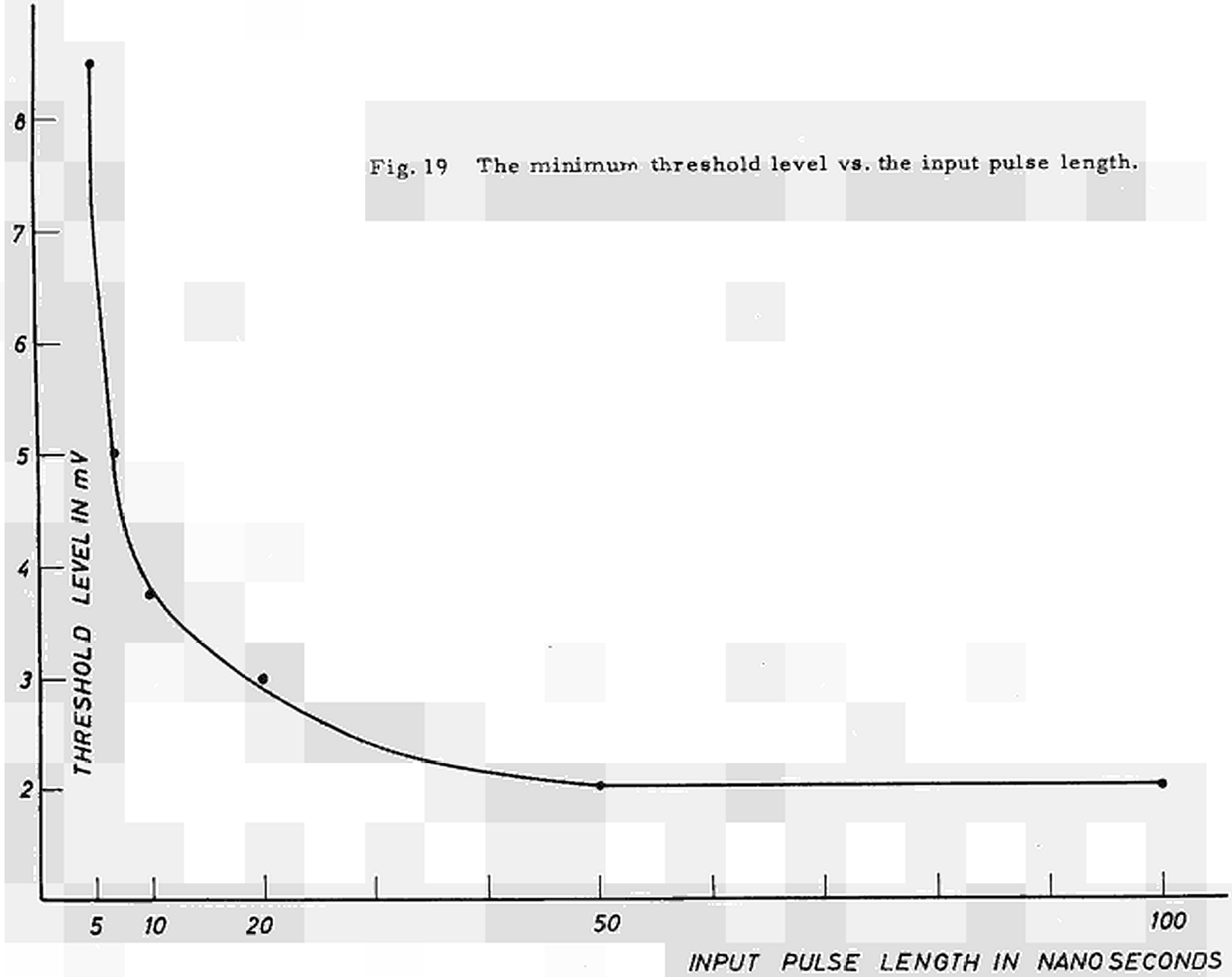


Fig. 18 The stability of the threshold vs. the ambient temperature.

Fig. 19   The minimum threshold level vs. the input pulse length.



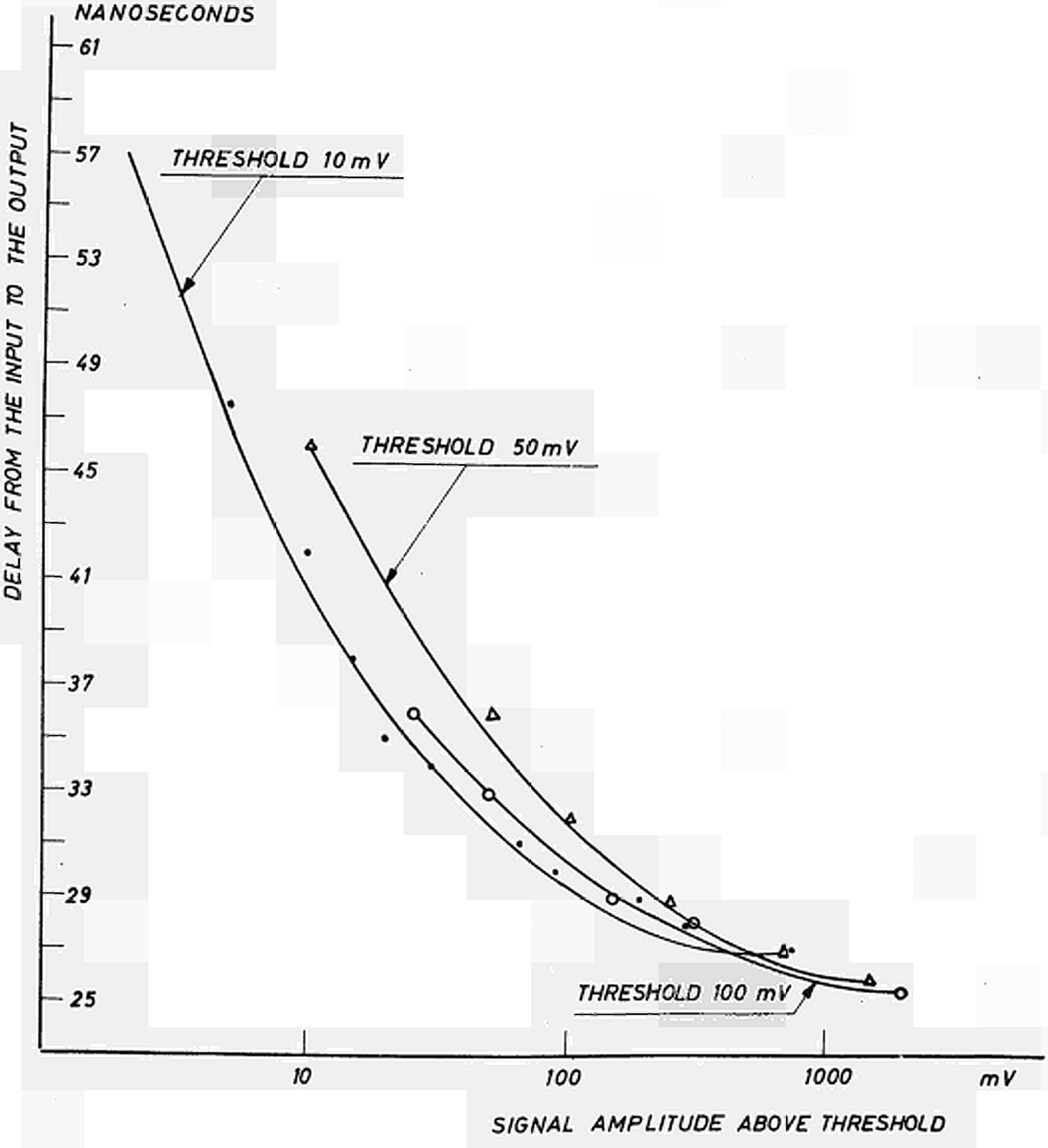


Fig. 20 The delay from the input to the output of the circuit vs. the input pulse amplitude and at the constant threshold.

Fig. 21 The time resolution vs. the input pulse amplitude.