

M. Klein
A. P. Kordalewski

Germanium PNP Thyatron

This note describes a germanium *PNPN* switching device with thyatron-like characteristics. Unlike other four-layer switching devices described recently in the literature, this device does not rely on alpha-variation for switching. Its alpha is essentially constant and large enough to make the device regenerative. The device is normally biased "off" and it may be switched "on" by a signal which momentarily overcomes the bias.

Many four-layer switching transistors have been developed in the past few years. These include two-terminal and three-terminal devices in silicon and germanium.¹⁻⁵ All these devices have in common a mode of operation by which the total alpha (current gain) is normally less than unity but increases to unity as a function of signal current, causing the switch to turn on regeneratively. In the silicon switches this alpha-variation is due to inherent properties of the semiconductor material;^{2,4} in the germanium Thyristor it is due to the nature of a metal-semiconductor contact;^{1,3} in the germanium *PNPN* switch it has been obtained by using base widths that exceed the carrier diffusion length so that a current-dependent field contribution to alpha is generated.⁵

Device requirements

The germanium *PNPN* Thyatron was developed as a solid-state replacement for thyatrons for functions such as operating relays under the control of signals from transistor logic circuits. Device specifications for this service include:

peak inverse voltage	100 v
load current	100 to 300 ma
signal current	<1 ma
signal voltage	<1 v.

Switching might be accomplished with circuits assembled from complementary transistors, but for requirements like the ones stated here, the individual transistors would have to meet unusual specifications; it will appear from the subsequent discussion that both transistors would be required to have high collector-breakdown voltages and one would need an abnormally low alpha. For these reasons, it becomes economical as well as convenient to use a self-contained device.

Device design considerations

For the realization of the required peak-inverse voltage for the switch, it would be desirable to have a collector-

junction avalanche voltage considerably over the specified 100 volts. In this voltage range, surface effects begin to dominate bulk properties in determining the junction breakdown point. With appropriate etching techniques a junction breakdown voltage of 120 to 150 has been obtainable. The device must therefore be designed to make the most of this value.

For the calculation of the peak inverse voltage the device is represented as two interconnected transistors.⁶ This is shown in Fig. 1. In the "off" condition the *NPN* transistor section is biased "off" at the emitter. The *PNP* section operates in the floating-base condition with the applied voltage across the collector. Miller and Ebers⁷ have shown that, in this situation, avalanche breakdown will occur when

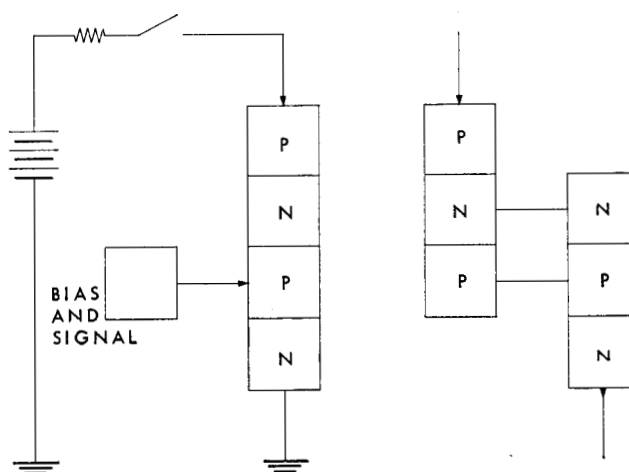
$$\alpha_N M = 1, \quad (1)$$

where α_N is the current gain of the *PNP* transistor section and M is the avalanche multiplication factor. Then

$$M = 1/[1 - (V/V_B)^n], \quad (2)$$

where V is the applied voltage, V_B is the collector-junction avalanche breakdown voltage, and the exponent n is 3 or 6 when the base material is *N* or *P* type, respectively. Figure 2 gives the relation between α_N and (V/V_B) calculated from Eqs. (1) and (2). It can be seen from Fig. 2 that, for a floating-base breakdown voltage of 90% of the collector-junction avalanche voltage, it is necessary

Figure 1 Schematic diagram of *PNPN* Thyatron.



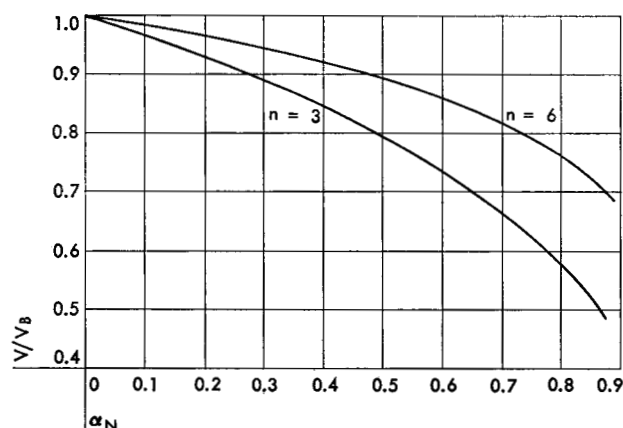


Figure 2 Floating-base avalanche breakdown characteristics.

that α_N be very low, about 0.3. Current gains of this magnitude might be obtained by using an emitter with low injection efficiency or by simulating low injection efficiency with a leaky emitter; the latter was chosen, as described in the section entitled "Device Structure."

For regenerative switching, the sum of the PNP and NPN alpha's must exceed unity. The NPN alpha, therefore, must be over 0.7. This is easily accomplished in spite of the unfavorable ratio of emitter-to-collector area of the NPN section which results from thermal design considerations, as described later.

With the switch in the "off" condition the current across the collector junction is given by:⁸

$$I_c = \frac{I_{c0} + \alpha_P I_B}{1 - \alpha_T}, \quad (3)$$

where I_c = current across collector junction (positive in direction from N to P);

I_{c0} = total saturation current for the central junction (positive in direction from N to P);

I_B = bias current into the control base;

α_T = sum of PNP and NPN alphas;

α_P = current gain of NPN section.

The effect of avalanche multiplication on this equation would be to change I_{c0} and the alphas by an appropriate factor.

In this device the sum of the alphas, α_T , is always greater than unity and the denominator of Eq. (3) is negative. In the absence of current to the control electrode, therefore, Eq. (3) indicates current through the device in a direction opposed to the voltage (see Fig. 1). This is the negative-resistance condition and, with a suitable load resistance, the device will switch "on" and go into saturation. To bias the switch "off," I_B must be sufficiently negative so that I_c in Eq. (3) is positive. The condition is:

$$|I_B| > \frac{I_{c0}}{\alpha_P}. \quad (4)$$

The control current needed to hold the switch "off" is nearly equal to the saturation current of the central junction and it will have the same temperature variation. A specified upper limit on the control current required for operation over some temperature range therefore implies a limit on the saturation current of the collector.

Bias of a few-tenths of a volt is sufficient to cut off the controlled emitter junction, and the device switches on at 0 volt. A swing of only a few-tenths of a volt is thus required from the signal source.

Analysis of the switching speed of the device would be complicated, because the parameters vary over a wide range as the switch goes into saturation and because the configuration to be studied consists of two transistors in a feedback circuit. Fortunately, turn-on speed adequate for the service for which the device was designed is very easily obtained. Only some qualitative remarks, therefore, will be made here about switching speed. Turn-on time depends on the collector capacitance, the cut-off frequency of the NPN transistor section, the alphas, and the load impedance. For faster operation the cross-sectional area of the device would be reduced to decrease collector capacitance, and the P base width would be reduced to increase the cutoff frequency of the NPN section. Increased alpha of the NPN section would increase the total alpha of the device and this also would increase the speed since, because of the feedback, the time constant of the transient is a decreasing function of gain.

Since this device is switched by a bias change rather than by a current-dependent increase of gain, the sustaining current is very low. In fact, as may be seen from Eq. (3), this current will be comparable with the saturation current of the collector junction. It is possible, therefore, to operate the device with small as well as large load currents. On the other hand, it is not practical to switch off any but very small load currents by a signal to the control base, because the turn-off signal would be required to be comparable in magnitude with the load current. In general, external means must be provided for interrupting the load current.

Device structure

The structure of the device is shown schematically in Fig. 3. It is built upon a P-type germanium die 60 mils in diameter and about 5 mils thick, with pre-diffused N skins about 0.5 mil thick on both surfaces. The parent germanium has a resistivity of about 5 ohm-cm. A lead-gallium (0.5 per cent gallium) dot alloyed to the top skin provides a recrystallized P layer. Contact to the interior P region is made by an indium dot which is alloyed through the upper N skin. A large lead-antimony dot (5 per cent antimony) alloyed to the bottom N skin serves as an N contact to this layer and as solder for securing the semiconductor structure to the header.

It was stated in the discussion of design considerations that a leaky emitter was desired to provide a very low alpha for the PNP section. This emitter characteristic is afforded by the lead-gallium alloy junction. An unsatu-

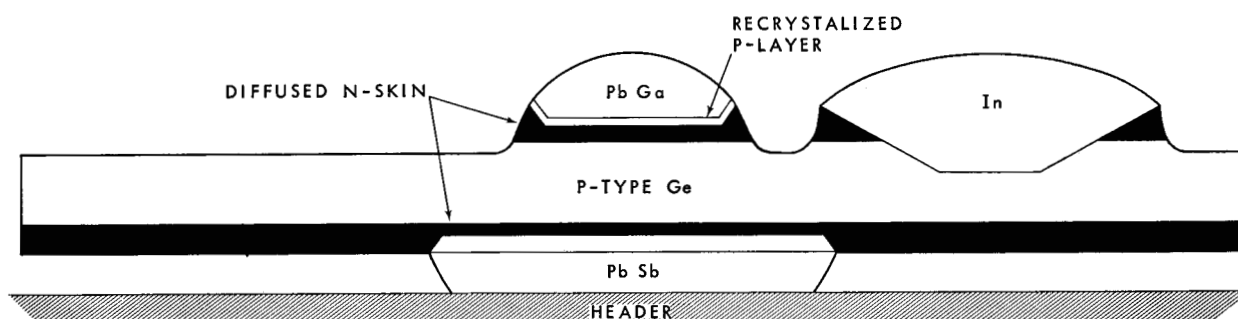


Figure 3 PNP Thyatron device structure.

Figure 4 Switching characteristic of PNP Thyatron. For characteristic "C", $|I_B| > I_{c0}/\alpha_P$. For characteristic "A" and "B", $|I_B| < I_{c0}/\alpha_P$.

rated reverse-characteristic is obtained and the α is about 0.3.

This emitter characteristic is unconventional and some further details are probably of interest. The low emitter efficiency cannot be due to low doping of the emitter side of the junction because a relatively large concentration of gallium is used in the dot.

Surface leakage is not important in determining the emitter leakage, as evidenced by insensitivity to etching treatments and to atmosphere. Metallographic sections of experimental junctions show that the recrystallized region obtained with the lead-gallium alloy is characteristically irregular and discontinuous. This results in a leaky junction and it provides an effective shunt across the emitter, giving a low emitter efficiency.

The bottom emitter is soldered directly to the header to provide a good thermal connection. This construction results in a large emitter-to-collector area ratio for the NPN section of the device. This geometry is not favorable for high α , but there is no difficulty in obtaining a value in excess of 0.7, as required for regeneration.

Characteristics

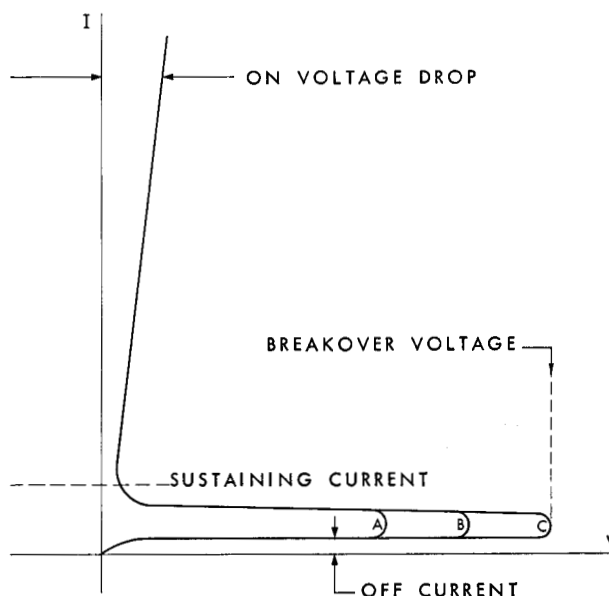
The PNP Thyatron has a breakover voltage of 70 to 100 volts. It is biased "off" by a current of less than $20 \mu\text{a}$ to the control base from a constant current source. The sustaining current is less than $10 \mu\text{a}$. For a load current of 300 ma, the voltage drop is about 0.5 v. The device can deliver about 200 ma in a 20°C ambient without special cooling means. Switching speed is about $0.2 \mu\text{sec}$.

Figure 4 shows the switching characteristic schematically. With bias current I_B equal to or above the magnitude called for by Eq. (4), the maximum breakover voltage is obtained, as shown at (C). For lower values of current, the breakover voltage is dependent on base current. This is to be expected, since the saturation current in Eq. (4) is voltage dependent because of avalanche multiplication.

Acknowledgment

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Footnotes and References

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8. Equation (3) is readily obtained by the methods outlined by J. L. Moll, M. Tanenbaum, J. M. Goldey, N. Holonyak, "PNPN Transistor Switches," *Proceedings of the IRE*, **44**, 1174-1182 (September, 1956).
A result similar to Eq. (3) is given in Reference 4.