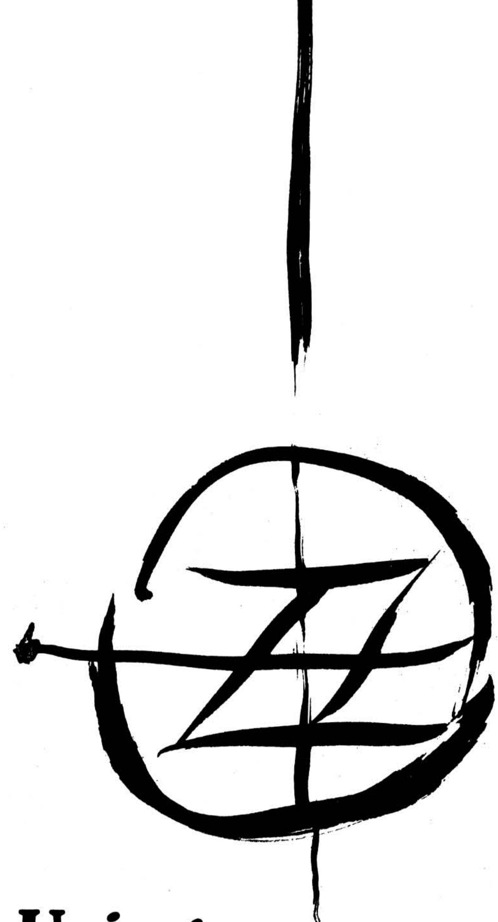
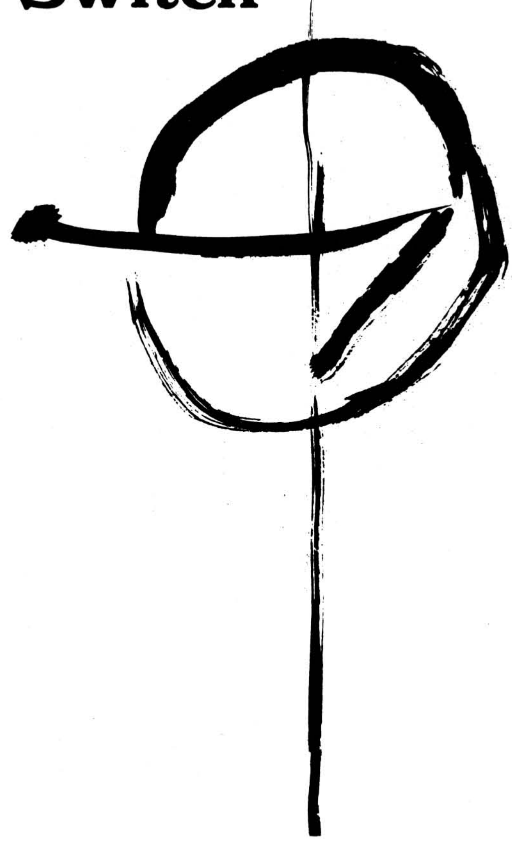


Using The Silicon Bilateral/Unilateral Switch



By Robert Muth

An advanced semiconductor device, fabricated as an integrated circuit, simulates earlier four-layer diodes but provides improved performance.

□ *That there's more than one way to skin a cat is made abundantly clear through the successful development of new solid state devices that do old jobs better and cheaper. The device whose applications are described is the result of a program undertaken by General Electric engineers to build an improved four-layer diode. It actually wound up being an integrated circuit, but one which ultimately will sell for as little as 50 cents. One problem it is intended to solve is that of positively triggering SCRs in the face of circuit component and supply voltage variations. In this application the device is tailored to provide bilateral characteristics. The author decribes circuits that use both unilateral and bilateral versions.* □

AT FIRST GLANCE, the semiconductor switch whose applications will be discussed here may appear to be no more than a rehash of older devices, or at best an improved version of a pnpn diode. This is not the case. The devices are actually simply constructed integrated circuits, containing transistor, diode and resistor elements. Four distinct versions have been fabricated. They comprise both unilateral and bilateral devices having either two or three leads.

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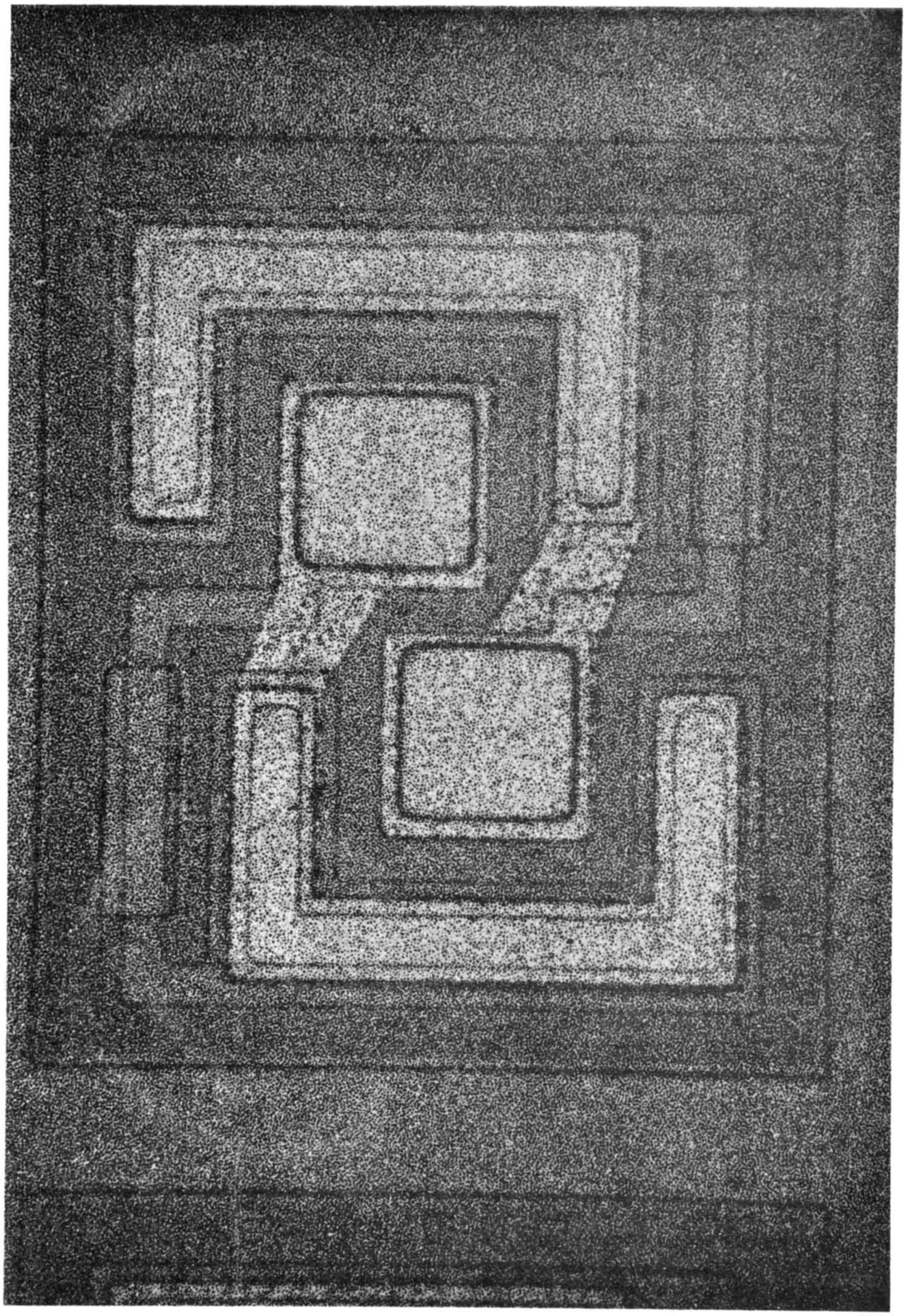
The unilateral devices are called silicon unilateral switches (SUSs) and the bilateral devices are called silicon bilateral switches (SBSs). Symbols for the four types of switches are given in Fig. 1.

Electrical parameters of the devices are straightforward and easily defined as follows (refer to Fig. 2): V_s, the switching voltage, is the maximum voltage that the device can sustain without switching to the conducting state; I_s, the switching current, is the current through the device when V_s is applied; V_F, forward voltage, is the voltage across the device when it's in the conducting state; I_V, valley current, is the current through the device corresponding to the lowest voltage across it while in the conducting state; V_V, valley voltage, is the lowest voltage across it while in the conducting state; V_R, reverse breakdown voltage, is the voltage at which reverse leakage current equals 1 μA.

How SBS and SUS Differ

The unilateral device (SUS) appears as an open circuit when a positive voltage of less than approximately 7.5 volts is applied to the anode with respect to the cathode. If this voltage is exceeded, the device turns on and draws a current that is determined by the applied voltage, the external resistance and the voltage across the device. The device appears as an open circuit for negative anode voltages if the

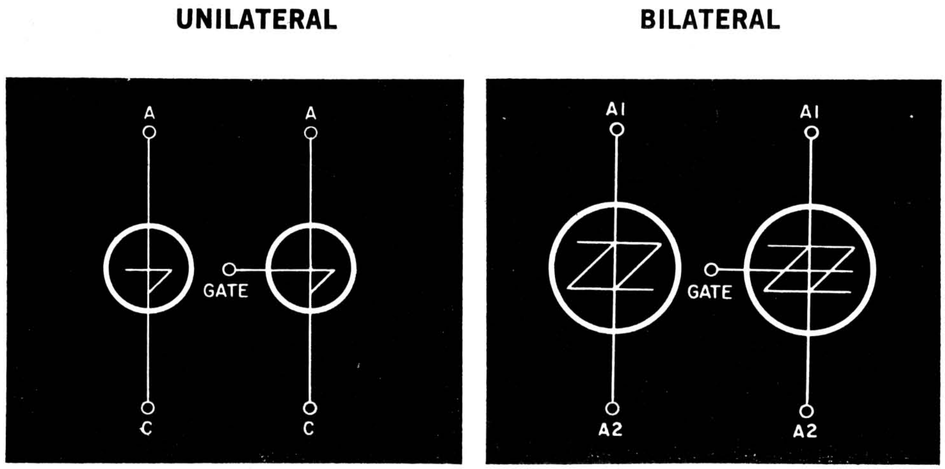


voltage is less than the reverse breakdown voltage (see **Fig. 2a**). On the other hand, the bilateral device (SBS) switches on with a negative anode voltage of the same magnitude and in the same manner that it does with a positive voltage (Fig. 2b). (Devices have also been fabricated that have a third [gate] lead brought out. They can be triggered at even lower voltages by pulling a current from that lead.)

Unilateral Equivalent Circuit

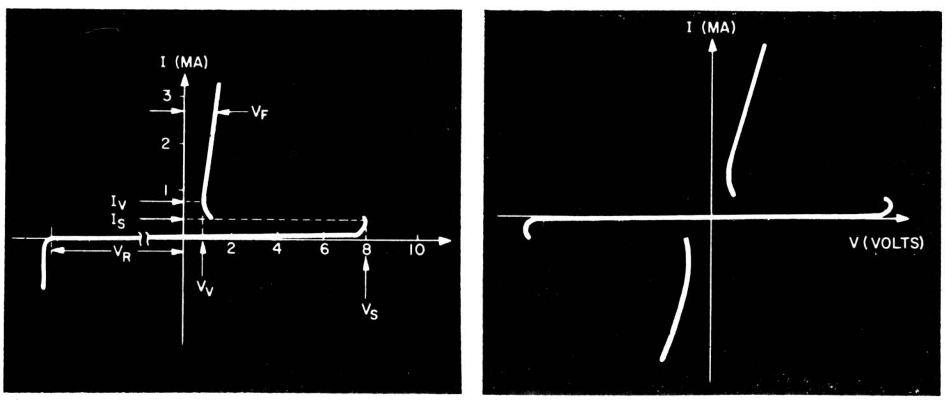
The SUS is best understood by considering the equivalent circuit of **Fig. 3a**. The two transistors are connected so that they provide positive feedback (similar to equivalent circuits for SCRs and silicon controlled switches).

When the switch is in the blocking state both transistors are off. Resistor R_B provides a path for leakage currents and reduces the tendency to trigger due to rapidly rising anode voltages. The breakdown diode does not conduct because the voltage across it is less than its breakdown voltage. If the anode voltage is increased, eventually a voltage will be reached at which the breakdown diode starts to conduct. This causes a base current to flow out of the base of the pnp transistor. When the current becomes adequate, the loop gain of the two transistor feedback loop exceeds unity and both transistors turn on and saturate. The switch is now in the conduction state. It can only be returned to the blocking state by first reversing the anode voltage and then reapplying the positive anode voltage. If the anode is reverse biased,



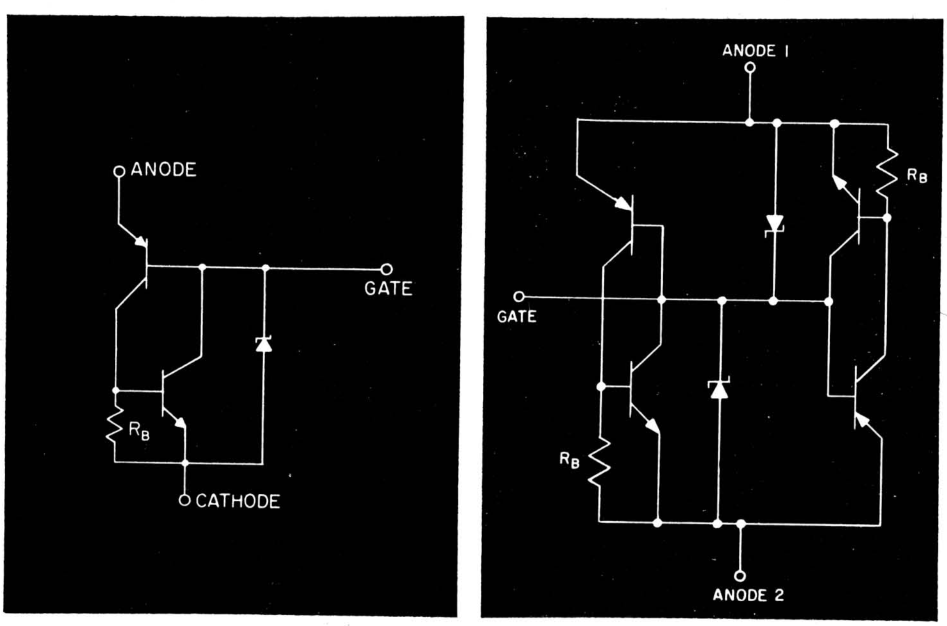
(a) (b)

Fig. 1. Circuit symbols for two and three-terminal unilateral and bilateral switches.



(a) (b)

Fig. 2. Electrical characteristics of (a) the silicon unilateral switch (SUS) and (b) the silicon bilateral switch (SBS).



(a) (b)

Fig. 3. Equivalent circuits for (a) the SUS and (b) the SBS.

the emitter base junction of the pnp transistor becomes reverse biased and blocks current flow. Typically, the junction can block 70 volts.

Bilateral Equivalent Circuit

An equivalent circuit for the SBS is shown in Fig. 3b. It comprises two unilateral switches with the anodes connected to the cathodes of the other switch and with the two gates connected together.

If anode 2 in Fig. 3b is positively biased the equivalent unilateral device on the right looks like an open circuit and allows the device on the left to operate in the same way as the unilateral switch described above. When anode 2 is negatively biased, the device on the right operates as the unilateral switch does.

The device can also be triggered—if the anode voltage is positive but less than the breakdown diode voltage—by pulling current out of the gate lead. The unilateral switch is more sensitive than the bilateral because of the forward biased diode in parallel with the pnp transistors in the bilateral device.

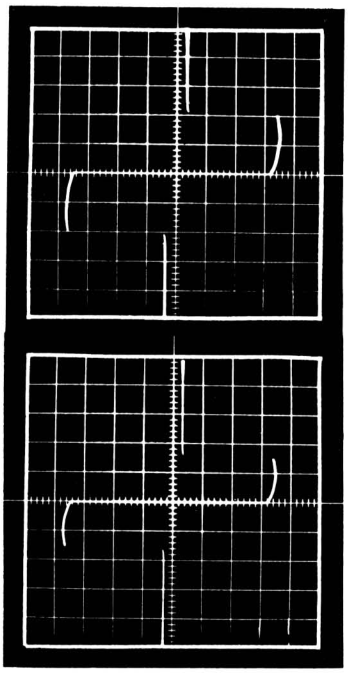
Electrical Characteristics

The V-I characteristics (at 25°C) of the SBS in the low current region are shown in Fig 4a. Here the switching current is somewhat lower than the current at which the device actually switches into full conduction. Also the valley current is quite low. It is just slightly larger than that current at which the device switches into full conduction. Switching voltage is relatively insensitive to change in temperature.

Figure 4b shows the characteristics at 75°C. The good stability is seen more readily from Fig. 5. This stable operation has been achieved by selecting the breakdown voltage of the diode such that it has a positive temperature coefficient which offsets the negative temperature coefficient of the base to emitter drop of the pnp transistor. The switching current and the valley current vary more with changing temperature (Fig. 6). Since the switching current and the valley current are so nearly equal, the device is amenable to use in bistable circuits. But this feature makes it difficult to apply in relaxation oscillators. The characteristics of the device in the higher current regions are shown in Fig. 7 and 8. Because both breakdown diodes are diffused simultaneously, the difference in switching voltages of the bilateral switch for positive and negative anodes is small (less than 0.5 V).

Turn-Off Technique

If the unilateral switch is in the conducting state, and one wishes to return it to the block-



(a)

(b)

Fig. 4. Temperature behavior of the SBS in the low current region at (a) 25°C ambient and (b) 75°C ambient. Horizontal: two volts/div. Vertical: 200 μA per div.

ing state, it is necessary to remove the current to the device. Generally, this is done by reversing the voltage on the anode. The anode voltage must be held at zero volts or negative for a minimum period so that when a positive voltage is reapplied the device will be in the blocking state. This period is called the turn off time. The circuit for measuring turn off time of the unilateral switch is shown in Fig. 9. Initially the relay is open and the switch is blocking. When the relay closes, the anode is reverse biased and the switch turns off. The capaci-

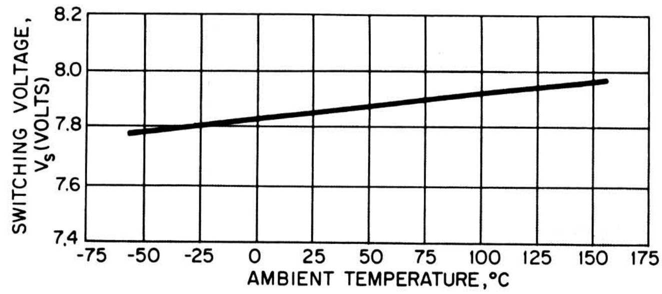


Fig. 5. Switching voltage of the SBS as a function of temperature.

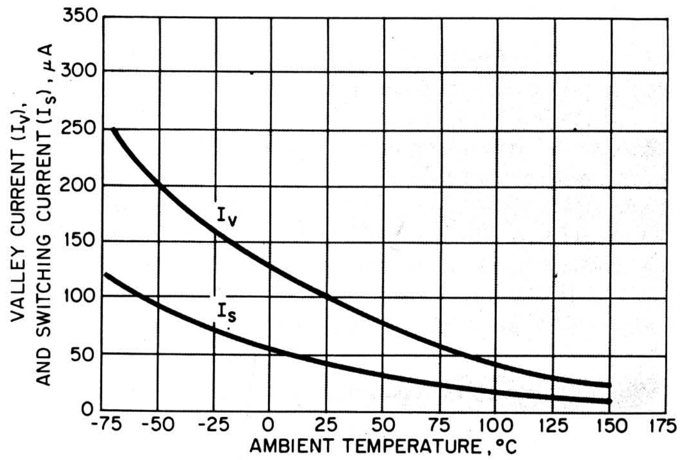


Fig. 6. Valley current and switching current of the SBS are temperature sensitive.

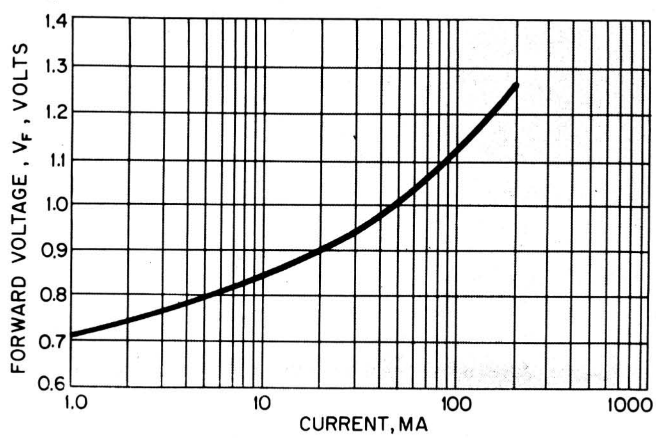


Fig. 7. Forward conductance characteristics of SUS/SBS in the higher current regions.

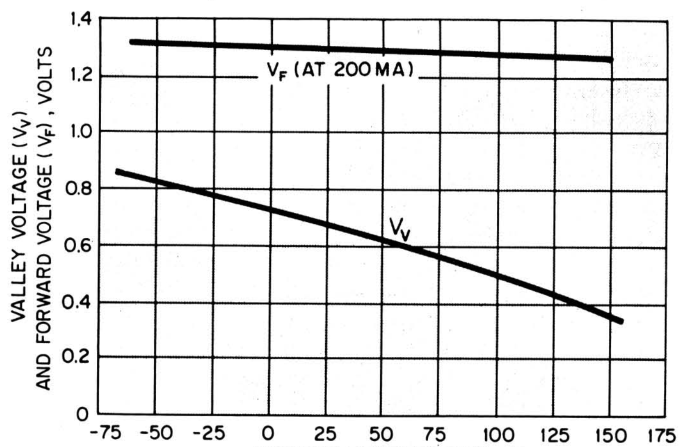


Fig. 8. Forward voltage and valley voltage for the SUS/SBS as a function of ambient temperature (for higher current regions).

tor is adjusted so that when a full five volts is reapplied to the anode the device will not turn back on. When the mercury relay opens, the voltage at the anode of the switch rises above the firing voltage and triggers the device on in preparation for the next cycle. The recovery time, measured at zero volts, is about 6 microseconds at 10 milliamperes and increases to about 9 microseconds at current levels above 50 milliamperes.

Regenerative devices of this type always have a tendency to trigger due to a rapid rate of rise of anode voltage. These switches will block any rise in anode voltage of less than 50 volts per microsecond. This tendency to trigger due to rate effect can be prevented by putting a small current into the gate lead so that the base of the pnp is reverse biased to the breakdown voltage of the diode.

In the case of the bilateral switch in conduction, if the anode voltage is rapidly reversed it is possible that the device will trigger on in the reverse direction due to a rate of rise of anode voltage that is less than that if the device were not initially on. This can usually be prevented by limiting the rate of rise of anode voltagt to less than 0.1 V/µsec.

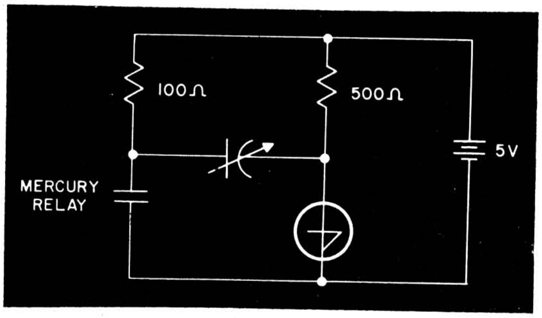


Fig. 9. Circuit for measuring turn-off time of SUS/SBS devices.

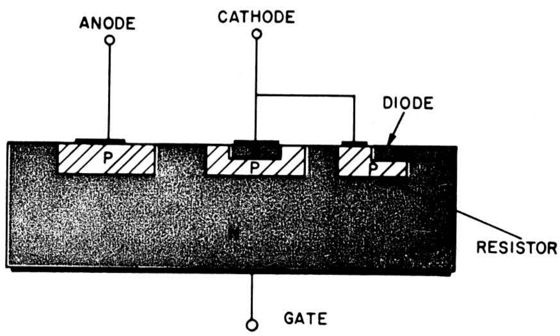
Applying the SUS

At the outset it ought to be made clear that the silicon unilateral switch can do most of the jobs a trigger diode or a four-layer diode can do. But tempera-

Inside the Device

Existing four-layer diodes and most silicon controlled rectifiers use a stacked structure, but the SUS/SBS employs planar techniques in its construction. This results in better stability and control of the electrical parameters.

A cross sectional view of the SUS is shown. An easy way to understand how it operates is to relate the regions in this figure to the parts of the equivalent circuit in Fig. 3a. The emitter of the pnp transistor (anode) corresponds to the P region on the left side of the pellet. The collector region is that P region which is beside and below the N + diffusion in the center of the pellet. This region also corresponds to the base of the npn transistor. Note from Fig. 3a that these two regions are common. The base of the pnp transistor and the collector of the npn transistor consist of the N region in which the device is built and which



comes to the surface between the two P regions mentioned previously. The emitter of the npn transistor (cathode) is the N + region that is diffused into the center P region.

The resistor R_B is P type material. The connection between the cathode and the resistor is made through an aluminum overlay. Although it is not shown here, the P region of the resistor connects into the center P region in a different area of the pellet, thereby connecting the other end of the resistor to the base of the npn transistor. The breakdown diode is formed by the junction between the N material of the substrate and the P region of the resistor. Because the N region is relatively lightly doped, the breakdown voltage of this diode would be normally high. To reduce this breakdown voltage, an N + diffusion is placed on top of the P material of the resistor. Note that only two diffusion steps are used in the construction of this device.

To produce an SBS, two separate unilateral switches are diffused into the wafer and the aluminum overlays connect the anode of one to the cathode of the other. (From the equivalent circuit of the SBS, Fig. 3b, one may observe that all of the lightly doped N regions are common. This includes the bases of both pnp transistors and the collectors of both npn transistors. Thus the device can be made without using isolation techniques normally required in other integrated circuits.)

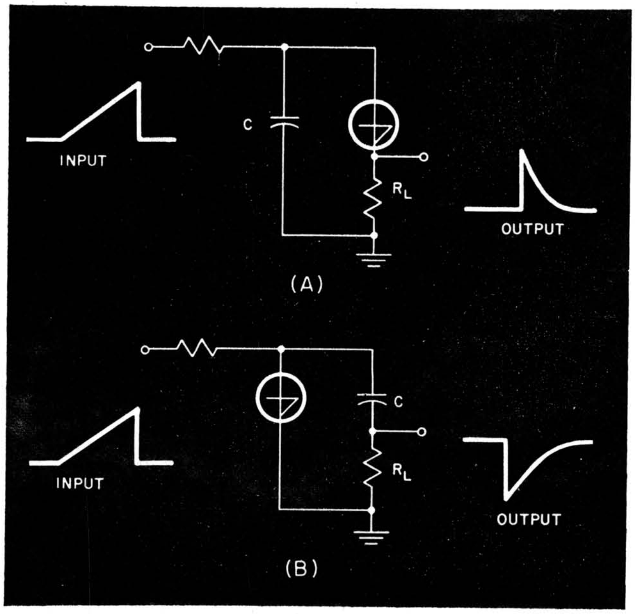


Fig. 10. Using the SUS as a pulse sharpener it's possible to get either a positive or a negative pulse by placing the load in series with (a) the SUS or (b) the capacitor.

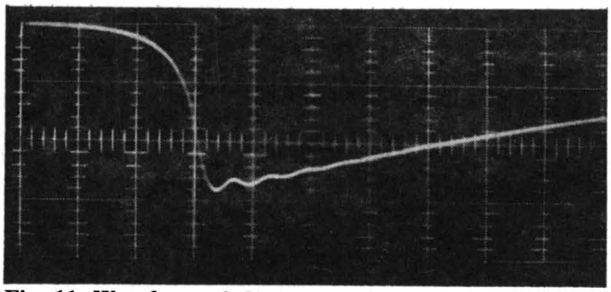


Fig. 11. Waveform of the output pulse shown in Fig. 10b. Vertical: 2 volts/cm. Horizontal: 0.1 μsec/cm. R_L = 100, C = 0.01 μf.

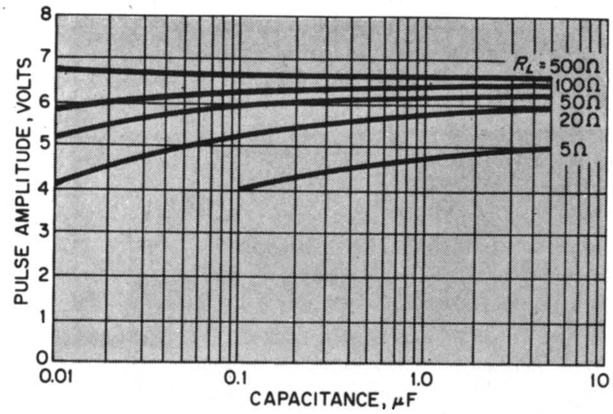


Fig. 12. Pulse amplitude for the circuit of Fig. 10b as a function of R_L and C.

Fig. 13. (Inset below) High duty-cycle monstable multivibrator exploits stability of SUS switching voltage.

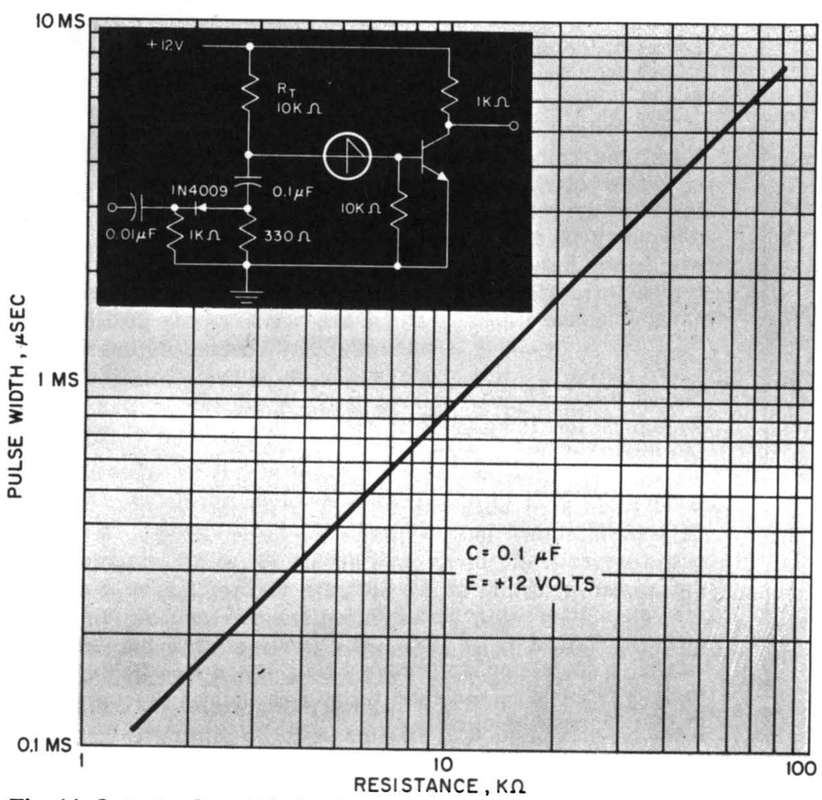


Fig. 14. Output pulse width for the circuit of Fig. 13, as a function of the timing resistor, R_T.

ture stability and the flexibility provided by the third lead provide a potential for new applications dependent largely upon the ingenuity of the circuit designer.

A fundamental use for the unilateral switch is as a pulse sharpener or a capacitor discharge trigger element. Two circuits for doing this are shown in Fig. 10. If a slowly rising input pulse is fed into one of these circuits, the capacitor will slowly charge. No output will be observed during this period. When the firing voltage of the switch is reached, the capacitor will discharge rapidly through the switch and through the load resistor. This results in a high current pulse with a rapid risetime. This is a useful feature for such jobs as triggering SCRs. As shown in Fig. 10, it is possible to get out either a positive or a negative pulse by placing the load in series with the switch or the capacitor.

Fig. 11 shows the output waveform from a circuit like the one in Fig. 10b. Note that the rise time of the output pulse is under 0.1 microsecond. The amplitude of the pulse from such a circuit is a function of the difference between the triggering voltage and the forward voltage of the switch, and the size of the load resistor which determines the peak current through the switch. It is also a function of the capacitor—if the time constant of the capacitor and the load resistor is small in comparison to the turn-on time of the switch. A plot of data taken on the peak output voltage versus the size of the capacitor and the load resistor in the circuit is shown in Fig. 12 (for a circuit of the type shown in Fig. 10b).

Monostable Multi

The monostable multivibrator of Fig. 13 utilizes the stable properties of the SUS switching voltage. The multivibrator gives an output pulse of 0.8 millisecond duration and has a variation in pulse widths between 0°C and 50°C of less than 2 percent. In this circuit, the switch is normally in the conducting mode. The current through the switch turns on the output transistor which is used only as an amplifier. A negative input pulse turns the switch off by coupling through the 0.1 microfarad capacitor to the anode of the switch. The negative-going pulse reverse biases the anode which switches the switch to the blocking condition. The 0.1 microfarad capacitor slowly charges at a rate determined by R_T, the timing resistor.

When the switching voltage of the switch is reached, the device switches into conduction, turning on the transistor and ending the pulse. The timing capacitor recovers rapidly through the 330-ohm resistor, the low impedance of the switch and the base to emitter junction of the transistor. This allows the circuit to be run at an 80-percent duty cycle. The pulse width can be controlled by adjusting R_T. The linearity of this adjustment is quite good (Fig. 14). The pulse width can be reduced by reducing the size of the timing capacitor. The minimum pulse width possible from this circuit is 30 microseconds. This is determined by the recovery time of the switch.

If a higher switching voltage is wanted, the circuit of Fig. 15 is recommended. Here the attenuation across the voltage divider network means a higher input voltage will be required to trigger the switch. The maximum voltage the circuit can block is determined by the collector emitter breakdown voltage of the transistor.

Bistable Memory

The low valley current of the SUS and the stable switching voltage makes the device useful as a bistable memory element. A method in which an array of switches can be connected to give a low-speed scratch pad type of memory is shown in Fig. 16. In this memory, the switch is considered to be in the ONE state when it is conducting. To write a word into the memory, the first step is to turn off the switches for the desired word location by grounding the word-select line.

The next step is to drive the word-select line to +6 volts. Since the cathodes of the devices are grounded through the write digit lines, this voltage is not adequate to switch the devices. If it is desired to write a ONE into a particular digit, the write digit line corresponding to this digit is driven to −3 volts. This puts a voltage across the switch which is adequate to trigger. However, because these anodes are at +3 volts, this voltage is insufficient to trigger digits in those words which have not been selected.

When it is desired to read the content of a particular word in the memory, the word-select line for that word is driven to +6 volts. The diodes associated with every bit in the memory form an OR gate when connected to a resistor in the output circuit. If the device is off, the output of a particular digit line will be at +6 volts. If the switch is on, the output will be at 0 volts. The digits in other words on the output line will be at +3 volts if the switch is in the blocking state. For this reason, the threshold in the output circuit should be set near 4.5 volts. This is halfway between the +6 volts seen when the selected device is blocking and the +3 volts that can be seen at the output when the device is conducting. This type of memory is limited in speed by the recovery time of the switches. It does, however, offer a low cost per bit when compared with flip flops, and requires simple driving and sensing circuitry.

> **The Cost Picture**
>
> Prices of the SBS/SUS could go as low as 50 cents each in quantity. These integrated circuit devices require only eight fabrication steps as opposed to a dozen or more needed in many "conventional" ICs. The new devices can perform functions which would require two to four discrete transistors, a zener diode and several resistors.

Using the SBS

Phase control circuits for SCRs driving AC loads are a natural application for a bilateral switch. Fig. 17 shows such a circuit. This one controls the phase angle with respect to the input sinewave at which the SCR turns on. This is accomplished by adjusting the amount of phase shift and the attenuation of the RC network with the 1.5 megohm variable resistor. When the voltage at the top of the capacitor exceeds the switching voltage of the switch, a current flows out of the 0.1 microfarad capacitor and into the gate of the SCR so that at that instant in the sinewave it is turned on.

An SBS instead of an SUS has been used in this circuit to eliminate the need for a high voltage diode to protect the switch when the sinewave goes negative. The switch turns on when this happens, thus protecting itself. It is necessary, however, to protect the gate of the SCR with a diode. This diode can be a lower-voltage and a lower-cost type than would otherwise be required. The 470-K resistor connected to the gate of the switch eliminates any hysteresis in the circuit by firing the switch every time the sinewave goes negative regardless of

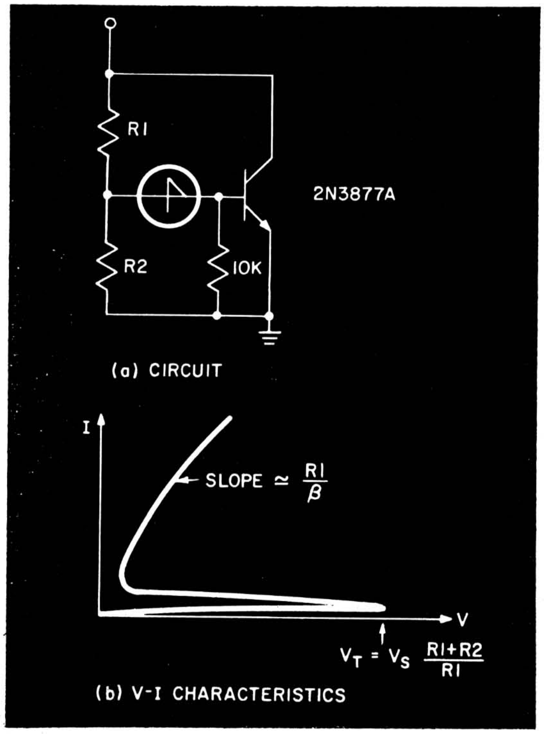


Fig. 15. Adjustable voltage threshold sensor in which attenuation across divider network requires a higher voltage to trigger the SUS.

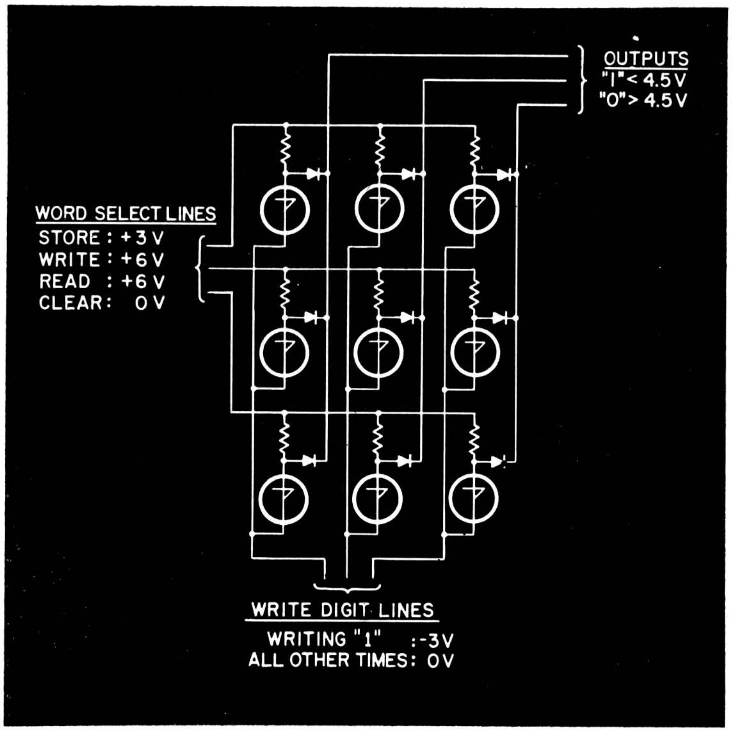


Fig. 16. Low valley current and stable switching voltage of the SUS make it suitable for use in this memory array.

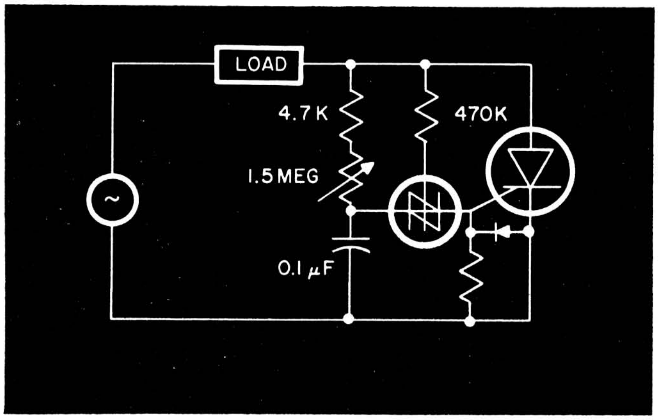


Fig. 17. The SBS used in a practical control circuit in which the phase angle at which an SCR turns on is varied.

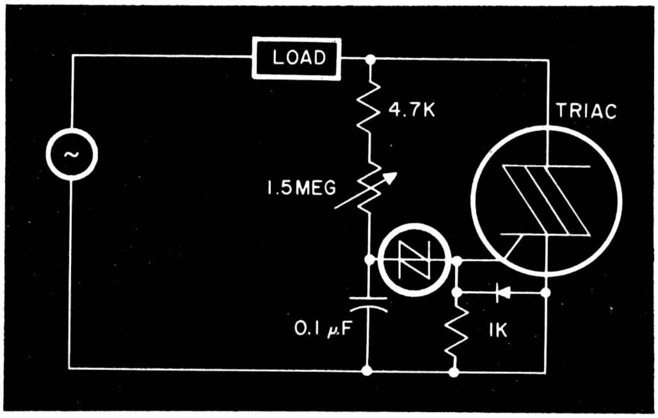


Fig. 18. Full range phase control circuit for a TRIAC uses SBS.

the setting of the variable resistor. With this circuit, the turn-on time of the SCR can be adjusted over the whole positive half cycle of the sinewave and there is no hysteresis.

A phase control for a symmetrical SCR (TRIAC) is shown in Fig. 18. This circuit operates in a similar way to the one in Fig. 17. In this case, the TRIAC, is triggered during both the positive and negative halves of the cycle. Because of the small difference in switching voltage of the SBS for positive anode or negative anode voltage, the difference in phase angle at which the device turns on during the positive half cycle and the phase angle at which it turns on during the negative half cycle is within 5 degrees of 180 degrees. This circuit will also adjust from full to full off.

The hysteresis in the circuit is such that when the device is fully off, if the variable resistor is decreased in value to just barely begin to trigger the TRIAC, the transients in the circuit will cause the trigger point to jump so that the device is on for about 45 percent of a cycle. To get a lower duty factor it is necessary to then increase the size of the variable resistor. **EEE**

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