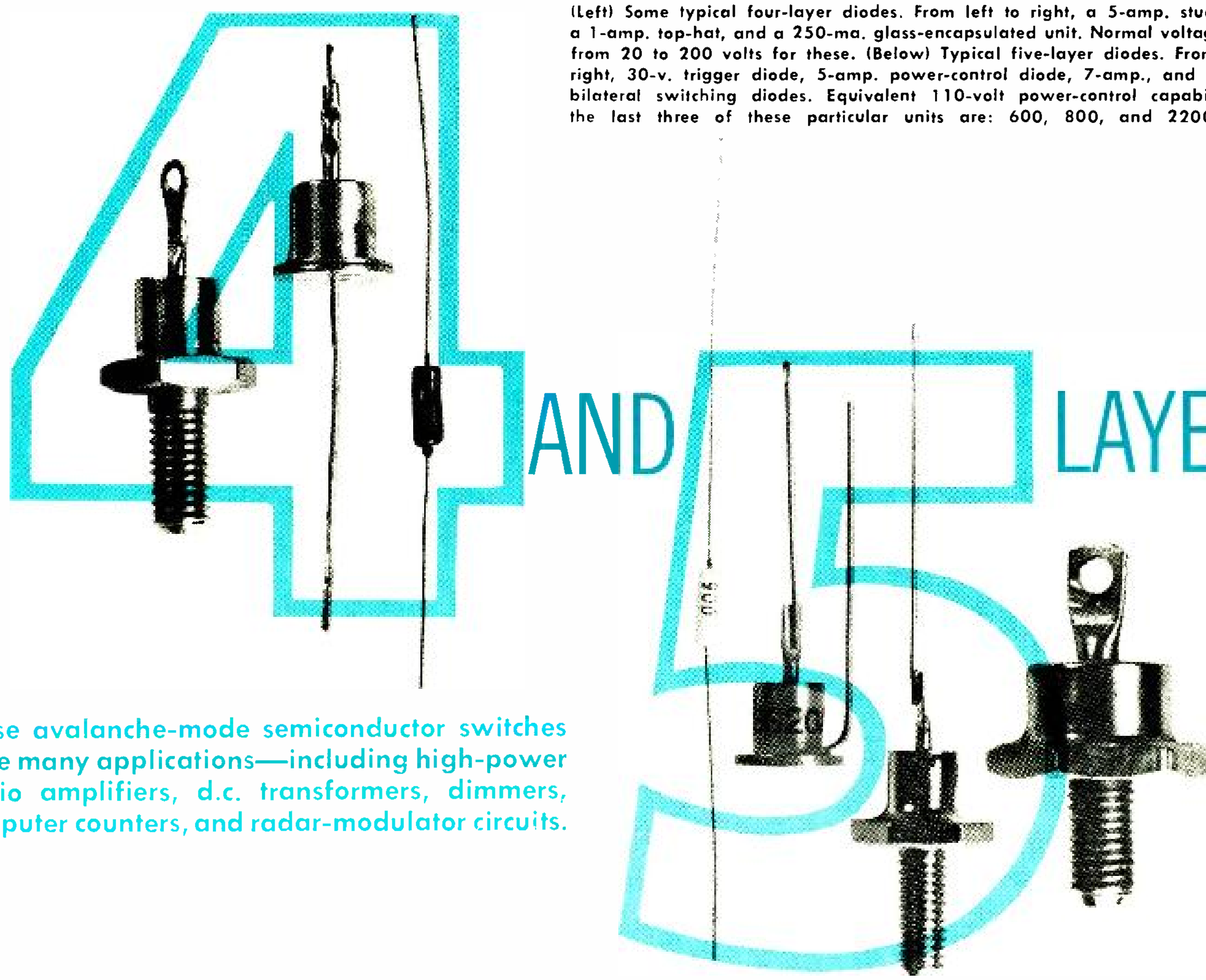


(Left) Some typical four-layer diodes. From left to right, a 5-amp. stud-mount, a 1-amp. top-hat, and a 250-ma. glass-encapsulated unit. Normal voltage range from 20 to 200 volts for these. (Below) Typical five-layer diodes. From left to right, 30-v. trigger diode, 5-amp. power-control diode, 7-amp., and 20-amp. bilateral switching diodes. Equivalent 110-volt power-control capabilities of the last three of these particular units are: 600, 800, and 2200 watts.

4 AND 5 LAYER SEMICONDUCTOR DIODES

These avalanche-mode semiconductor switches have many applications—including high-power audio amplifiers, d.c. transformers, dimmers, computer counters, and radar-modulator circuits.

By DONALD E. LANCASTER

HIGH-powered audio amplifiers using nothing but diodes, d.c. transformers that can step high voltage down, and 5-kw. light dimmers with only five low-cost parts are just a few of the more noteworthy functions that the four- and five-layer semiconductor diodes can perform. These currently available, economical devices can also be used in a wide range of other applications, such as in memories, multivibrators, counters, oscillators, frequency dividers, function generators, switches and triggers, and radar modulators—to name just a scant few.

Basic Operation

These diodes are avalanche-mode semiconductor switches, identical to a gateless silicon controlled rectifier. In the "off" state, the diode impedance is very high, into the tens of megohms. Pulsing the diode while in the "off" state will cause avalanche-mode turn-on, usually in times much less than a microsecond. The "on" state is the very low impedance of a forward-biased diode, so low that the load current must be limited to a safe value, lest the diode destroy itself. The turn-on method is basically different from the conventional SCR gate turn-on and has the advantage of being many times faster. This fast turn-on allows four- and five-layer diodes to operate into the hundreds of kilocycles as power-control devices. This is well in excess of conventional SCR capability.

The four-layer diode is unilateral and will only operate in one current direction. The five-layer diode is bilateral and operates equally well in either current direction. These diodes have ratings varying from milliwatt to kilowatt power-control capability, currents from a few milliamperes to tens of amps., and breakdown (trigger) voltages varying from 20 to 400 volts. Higher ratings are entirely practical. Cost is about the same as an equivalent power SCR.

There are many manufacturers of these diodes. *Clevite* offers a complete line of four-layer devices, while *Transitron* offers a broad line of five-layer devices. Other manufacturers are *Texas Instruments*, *Hunt Electronics*, *General Electric*, and *Western Electric*, to name only a few. Specific device information is available from each manufacturer in the form of data sheets and application notes.

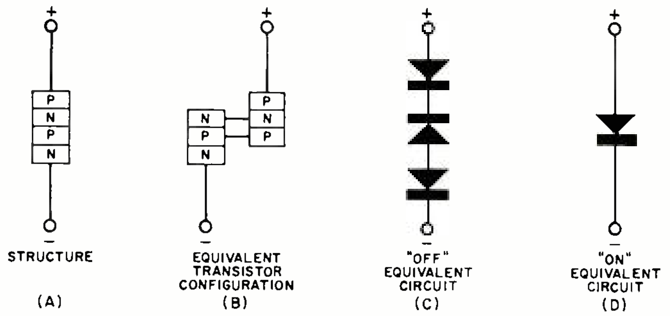


Fig. 1. Four-layer diode structure and equivalent circuits.

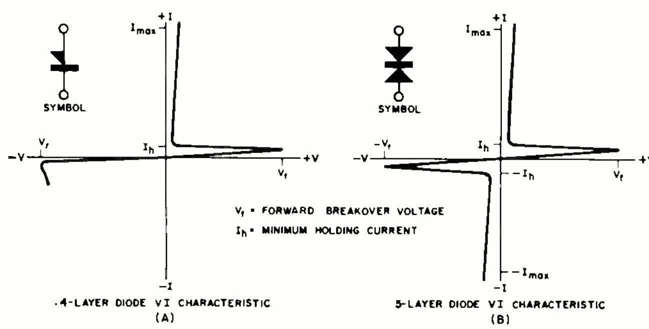
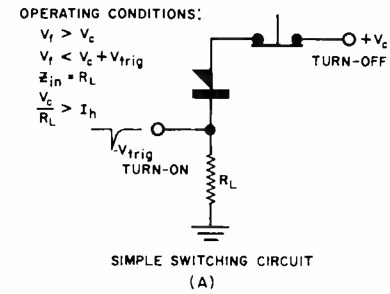


Fig. 2. Both diode types remain "off" until V_f is exceeded, then they rapidly switch "on." Diodes remain "on" as long as current exceeds I_h. If current falls below this value or reverses, then the diode will quickly switch to the "off" state.



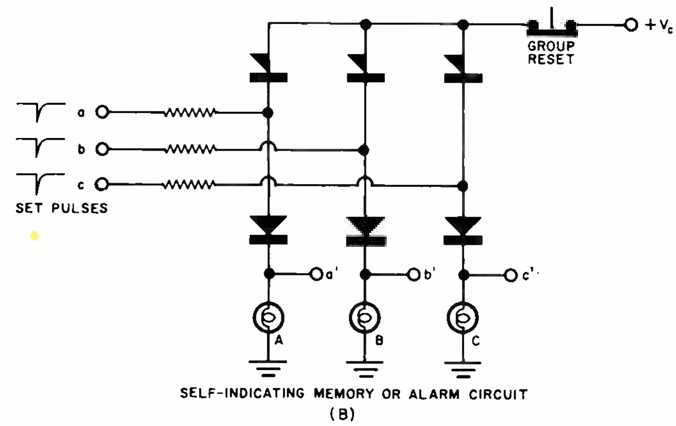


Fig. 3. Diode may be switched "on" by pulsing it in such a way that V_f is exceeded. Diode remains on after pulse ends. Turn-off occurs when the load current is interrupted briefly.

In avalanche-mode turn-on, most of the turn-on energy is provided by the load itself and not by the triggering signal. This trigger merely initiates the turn-on activity. Perhaps this is somewhat like removing a bottom can of a grocery store display. Very little energy is needed to knock one can loose, compared to the total energy produced during this "avalanche" breakdown. Because of this trigger sensitivity, the four-layer diode is inherently a high-gain device. Trigger signals work into what is virtually an open circuit while directly controlling low-impedance, high-power loads.

Turn-off is usually accomplished by letting the main load current drop to a very low or negative value. This is usually relatively easy to do. When discharging a capacitor, the diodes simply stop conducting when the capacitor is discharged. The a.c. line zeros may be used for resetting. A commutating or "speed-up" (a misnomer) capacitor can turn a second diode off as a first one turns on. Many circuits require the inherent locking quality of the turn-on. Here turn-off is accomplished by mechanically or electrically interrupting the load current.

Fig. 1A shows graphically the structure of a four-layer diode. This is seen to consist of four alternate layers of *n*- and *p*-type semiconductor material, normally silicon. An equivalent transistor configuration, shown in Fig. 1B, is useful in understanding the turn-on mechanism. Here an *n-p-n* and *p-n-p* transistor form a locked-pair configuration. If the current gain of each transistor was much less than unity, any current passing through the pair would be rapidly "de-amplified" and the pair would then assume an open circuit, or "off" state. Suppose the current gain were greater than unity. This is possible due to actual device internal feedback. Now, any current flowing through the device will be amplified, and the locked pair will assume a saturated or "on" state. Current is then load-limited only.

By suitably controlling parameters during diode fabrication, the current gain of the four-layer diode is made highly dependent upon the current itself. At low (leakage) currents, the current gain is much less than unity, and the diode stays off. As long as the forward bias on the diode is below the reverse breakdown rating of the middle *n-p* junction, the current gain stays low and the diode stays off. If the reverse breakdown is exceeded, quite a large current will flow. This large current causes a large current gain, and the diode rapidly saturates and assumes the "on" state. This results in the "off" equivalent circuit of Fig. 1C and the "on" equivalent circuit of Fig. 1D.

To turn an "off" diode on, it must be pulsed in the forward voltage direction with a voltage high enough to avalanche the structure. To turn an "on" diode off, the load current must be reduced to a low or negative value.

The turn-on and turn-off mechanisms result in the volt-ampere (*VI*) characteristics shown in Fig. 2. The forward-avalanche (turn-on) voltage is indicated by V_f, the maximum permissible current by I_{max}, and the minimum holding current by I_h. A four-layer diode is never operated in the reverse current direction and care must be taken to observe diode polarity and to limit any circuit reverse voltage to a value that is small compared to V_f. A five-layer diode may be thought of as two four-layer diodes in inverse parallel, and thus operates equally well in either current direction.

Generally, the steady-state I_{max} will be much lower than the pulse I_{max} rating for a low duty cycle. This current rating is based on thermal considerations. For very low duty cycles, pulses that are in the order of a hundred amperes and higher peak currents may be readily handled.

Switching Circuit

A simple switching circuit is shown in Fig. 3A. The diode is chosen to have a V_f higher than the supply voltage V_c, and thus will not turn on of its own accord. If a negative turn-on pulse is applied to the load side of the diode, the diode voltage will be equal to the sum of V_c and the negative trigger voltage V_{trig}. If this voltage exceeds V_f, the diode will turn on. Load current will then flow through R_L. If the load current exceeds I_h, the diode holding current, the diode will stay on. The diode may be turned off by interrupting the load current. This basic circuit may be used as a memory circuit to "remember" the passing of a trigger pulse.

The input impedance of this circuit is R_L when the diode is off and zero when the diode is on. Two modifications allow the input impedance to become very high in either state. By adding a conventional diode in series with the load such that the turn-on trigger will back-bias it, the off impedance becomes very high. As soon as the four-layer diode starts to turn on, the conventional diode becomes forward-biased and does not interfere with load turn-on. Since the turn-on input impedance is now virtually an open circuit, an arbitrarily large resistance may be placed in the trigger line without effect. This allows a high input impedance should a trigger pulse arrive after a diode has already turned on due to a previous pulse.

This results in the more practical circuit of Fig. 3B, a circuit which serves as an annunciator or paging device, or as a self-indicating computer memory. Electrical outputs at a', b' and c' are zero when the diodes are off and V_c when the diodes are on. An electronic gate may replace the group reset button that is shown in the diagram, and individual resets could be provided in each diode line.

Sawtooth Oscillator

The sawtooth oscillator of Fig. 4A uses a four-layer diode. The circuit is identical to the conventional neon-lamp or glow-tube relaxation oscillator, with the exception of the load resistor R_L which must be used to limit the capacitor discharge current to a safe value (usually 10 amperes or more peak current).

The performance is markedly different. The ratio of scan time to retrace time is much higher than a gas tube can provide. Output is referenced to ground instead of the usual 50-volt dropout level of neons. The circuit is temperature-, radiation-, and light-stable. Considerable oscillator power can be produced by such a circuit. For oscillation, V_f must be lower than V_c. For a good sawtooth waveform (a linear ramp instead of an exponential charging curve), V_c should be much higher than V_f. The higher V_c, the better the circuit linearity.

The circuit operation is based upon R charging C until the voltage across C equals V_f. At this point, the diode turns on, discharging C, and turns off. The cycle then repeats. R must be chosen large enough that the charging current will be less than the holding current of the diode. Otherwise, the diode will lock on after one cycle and remain on until V_c is removed. When operated in this mode, the circuit becomes a time-delay generator instead of an oscillator.

The sawtooth oscillator may be synchronized to any frequency *higher* than its free-running frequency by supplying negative trigger pulses to the four-layer diode (Fig. 4B). The diode will now turn on at the instant the sync pulse and the capacitor voltage, when added together, exceed V_f. By controlling sync pulse amplitude, the oscillator may be made to lock on any submultiple of the input frequency, giving frequency division by two, three, four, or five. Division higher than five requires exact control of circuit voltages, sync amplitude, and pulse jitter, but is entirely reasonable. Placing the load resistor in the diode leg of the circuit will produce positive output pulses, while placing the load resistor in the capacitor leg will produce negative output pulses. These pulses may be used to sync additional stages.

The locked-oscillator frequency divider of Fig. 4C is an application of the sawtooth oscillator as a tone generator for an electronic organ. The input oscillator is synchronized to the input pulses at frequency F_0. Each oscillator is synchronized at one-half the previous oscillator frequency, producing lower and lower notes, each spaced exactly one octave apart. The waveform produced is rich in harmonics and readily distorted to produce the various voices of the organ stops. Twelve such chains are needed to produce all the notes. Tuning is by trimming each R and C to yield a

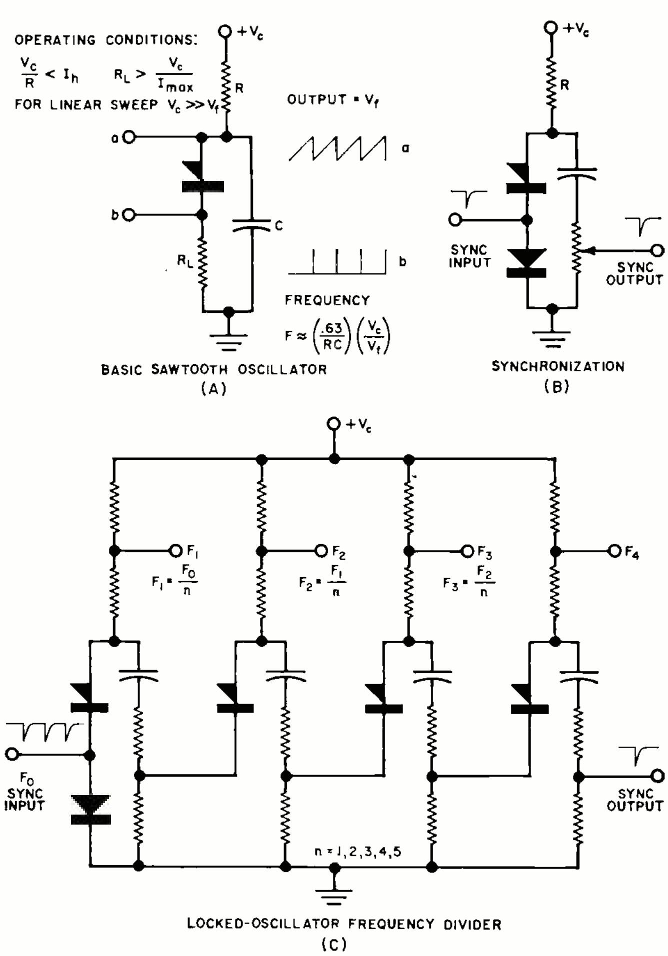


Fig. 4. Four-layer diode sawtooth generators, frequency dividers.

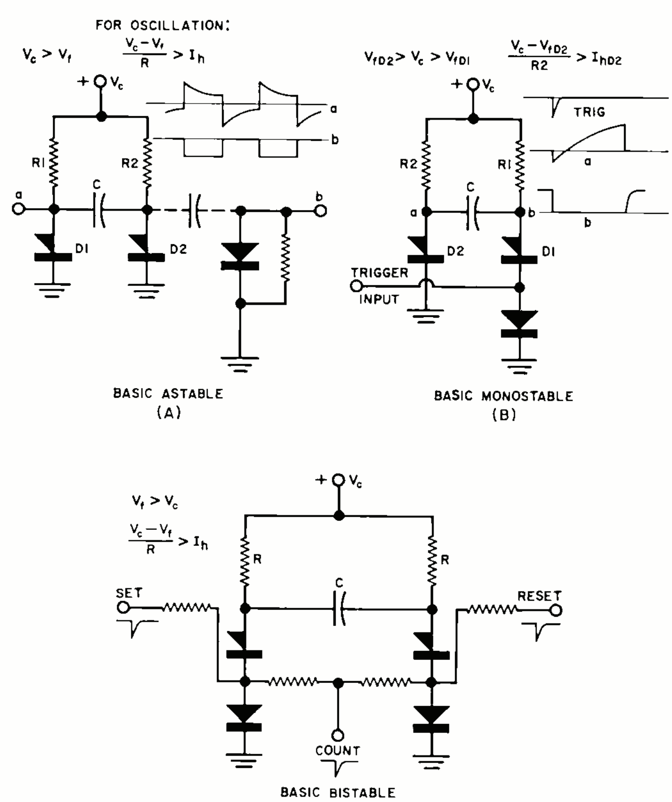


Fig. 5. "P-n-p-n" multivibrators. The astable circuit (A) leads to a family of square- and rectangular-wave generators, pulse generators, and oscillators. The monostable circuit (B) extends into time-delay circuits, ramp generators, delay networks, gated oscillators, sweeps, and pulse shapers. The bistable circuit (C) yields counters, frequency dividers, computer logic, gates, power inverters, shift registers, and memory circuits.

free-running frequency a bit below half the sync frequency.

By alternately dividing by five and then two, the same circuit can provide decade division with only two stages per decade. This is useful for clock and counting chains.

Multivibrators

Where the ultimate in speed is not a requirement, four-layer diodes make excellent astable, monostable, or bistable multivibrators. The present upper switching speed is around two megacycles. These circuits are all based upon the use of a commutating capacitor. The capacitor assumes a charge during one state of the multivibrator, and then uses this charge to turn off one diode as the other one is pulsed on.

Fig. 5 shows some multibrator possibilities. Fig. 5A is an astable (free-running) circuit. Assume the left diode ($D1$) has just turned on. This clamps the left end of commutating capacitor C at ground. C now starts charging toward V_c through $R2$. When the right end of C exceeds V_f of the right diode ($D2$), the right diode turns on. The charge on C cannot change in the brief turn-on time of the right diode, so the left end of C must swing negative by an amount equal to $-V_f$ as the right diode turns on.

This turns off the left diode. The circuit has just changed state, and now the cycle repeats in the opposite direction. An additional diode, a conventional one, may be used to clamp an output to ground to give a true square-wave output.

Various forms of monostable operation are possible, and generally make use of two diodes with different breakdown voltages, or of a circuit in which one side is provided holding current and the other is not. These circuits are useful for sweep generation, one-shot time delays, and pulse-delay networks. Fig. 5B shows one possible form of such a circuit.

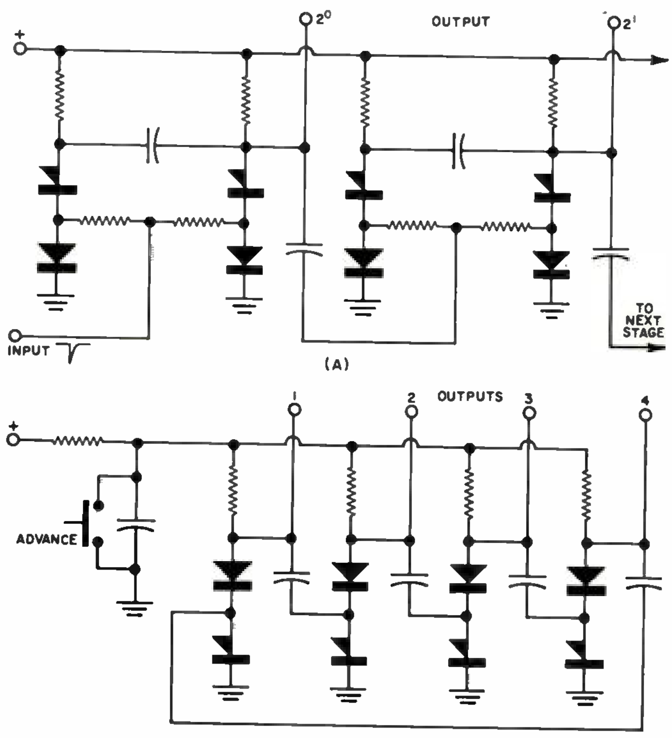


Fig. 6. (A) Binary and (B) ring counter cricuits using diodes.

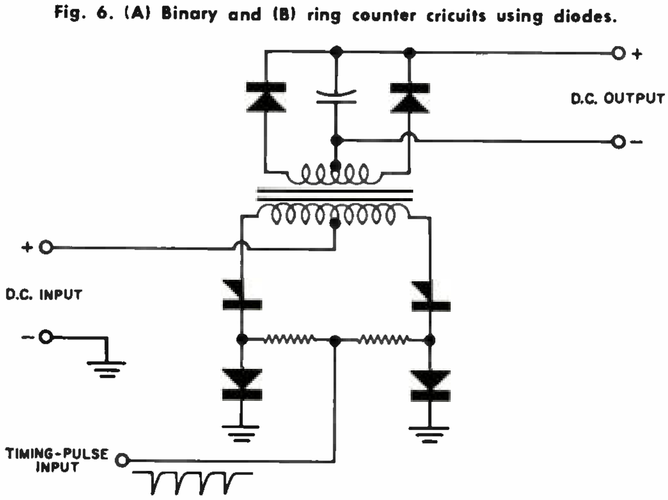


Fig. 7. Unlike circuits with transistors, this circuit can step voltages down as well as up. A 600-v. input could yield a 12-v. d.c. output. Power capability to over 1 kw. may be achieved. Circuit is essentially a power bistable. Transformer senses a.c. primary current and induces secondary voltage of desired step-up or step-down ratio. Rectifiers and filter convert this voltage to d.c. Circuit may be made self-oscillating by deriving trigger pulses from transformer itself. By omitting the rectifiers, circuit becomes a d.c. to a.c. inverter arrangement.

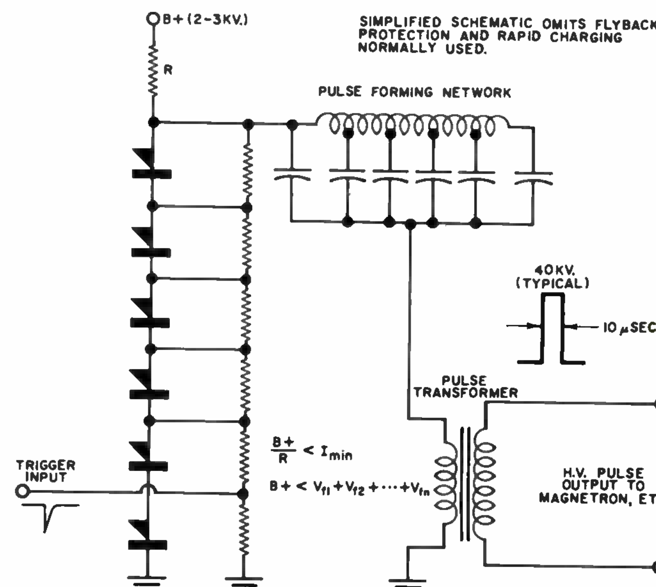


Fig. 8. Radar pulse modulator using string of 4-layer diodes.

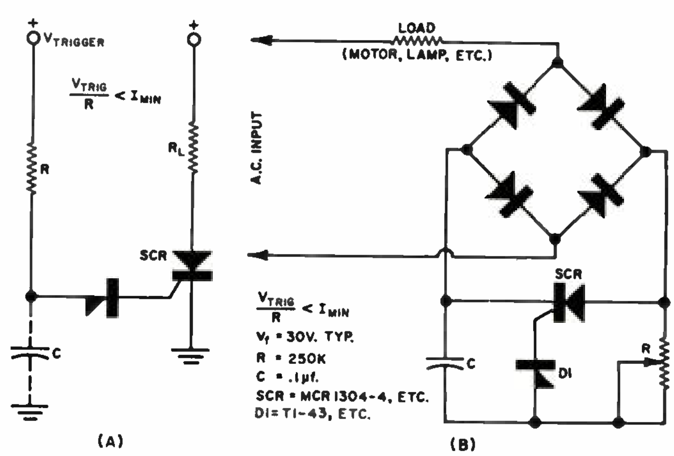


Fig. 9. (A) Addition of 4-layer diode to SCR results in accurate and stable trigger source. Low-power input signal will trigger SCR into conduction if trigger voltage exceeds V_f. As a voltage-level detector or threshold indicator, a very low-power signal can directly control kilowatts of power. An integrator is built by adding C, which is charged by the energy of the input signal. If V_c reaches V_f, the SCR is turned on. (B) A.c. power control used as a light dimmer or motor speed control. At the beginning of an a.c. half-cycle, the charge on C is zero. C then starts to charge through R. When V_c reaches V_f, the SCR turns on, discharges C, and remains on for the remainder of the half-cycle. The SCR then effectively completes the load circuit through the bridge rectifier, providing power for the load. The smaller R is, the faster C will charge, and the earlier the SCR will turn on in each half-cycle. This results in increasing power reaching the load.

The bistable circuit of Fig. 5C consists of two four-layer diodes. Both are supplied sufficient holding current. Both have breakdown voltages in excess of V_c. The circuit is stable. The commutating capacitor (C) turns off the "on" diode whenever the "off" diode is pulsed on by a trigger pulse. In the diagram, "set" pulses will turn the left diode on, while "reset" pulses will turn the right diode on. By pulsing the diodes simultaneously with a short pulse, the bistable will count, alternating states for every successive input pulse. The circuit is self-steering, as long as the trigger pulses are short compared to the RC time constant of the commutating circuit that is employed.

It is possible to cascade binaries to count or divide by 2, 4, 8, 16, etc. or, by the addition of feedback, a binary chain may count to any whole number and then reset. Fig. 6A is such a circuit. The ring counter of Fig. 6B uses a different prin-

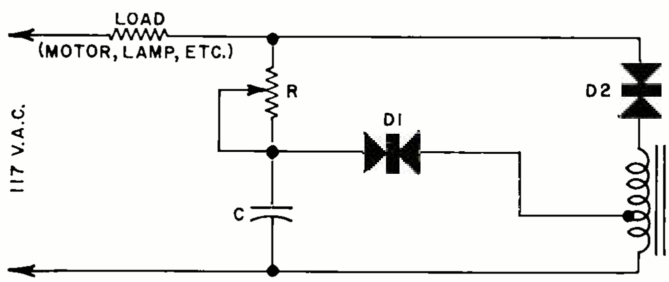


Fig. 10. A light dimmer and power-tool control using 5-layer diodes. No bridge rectifiers or special switching arrangements are needed for single-turn full-wave control. D1, R, and C produce a firing pulse, just as in the SCR circuit. This pulse is stepped up by the pulse transformer to trigger the main 5-layer diode D2. Average load power is determined by how early in each half-cycle D2 turns on. Power control up to around 5 kw. may be achieved using currently available diodes.

ciple for operation; a commutating capacitor routes diode turn-on always to the next sequential stage. Only the capacitor to the right of the "on" stage can charge .

To advance the circuit, the trigger capacitor on the input is momentarily shorted. This removes V_c from all the diodes, and all diodes turn off. The trigger capacitor then starts charging toward V_c, bringing the diodes up with it. The voltage on the diode immediately to the right of the one that was on has a "head start" toward firing due to the charge on the commutating capacitor. This diode then turns on, and the circuit has advanced one stage. Modifications of this technique allow add-subtract counting. Shift-register circuitry is somewhat similar to this arrangement.

Other Applications

Use of a power binary allows a d.c.-to-d.c. transformer circuit. Operation is identical to conventional transistor power converters, except that very high input voltages may be easily accommodated, unlike the 50-60 volt limitation of most transistorized converters. The diode can operate at a high frequency (100 kc.), minimizing the requirements for transformer iron and secondary filtering. Fig. 7 is a circuit of this type. Modifications allow the circuit to become self-oscillating, self-starting, and short-circuit proof. A kilowatt power handling ability may be realized, at efficiencies upwards of 90 percent.

Fig. 8 illustrates the use of four-layer diodes in a radar modulator circuit. This circuit provides the short, high-voltage pulses required by a magnetron or other microwave power tube. The small diodes here replace the less efficient thyratron or pulse tube normally used. Additional circuitry can provide short duty cycles and give flyback protection to the basic design.

An important application of small 30-volt four-layer diodes is as trigger devices for silicon controlled rectifiers in voltage-

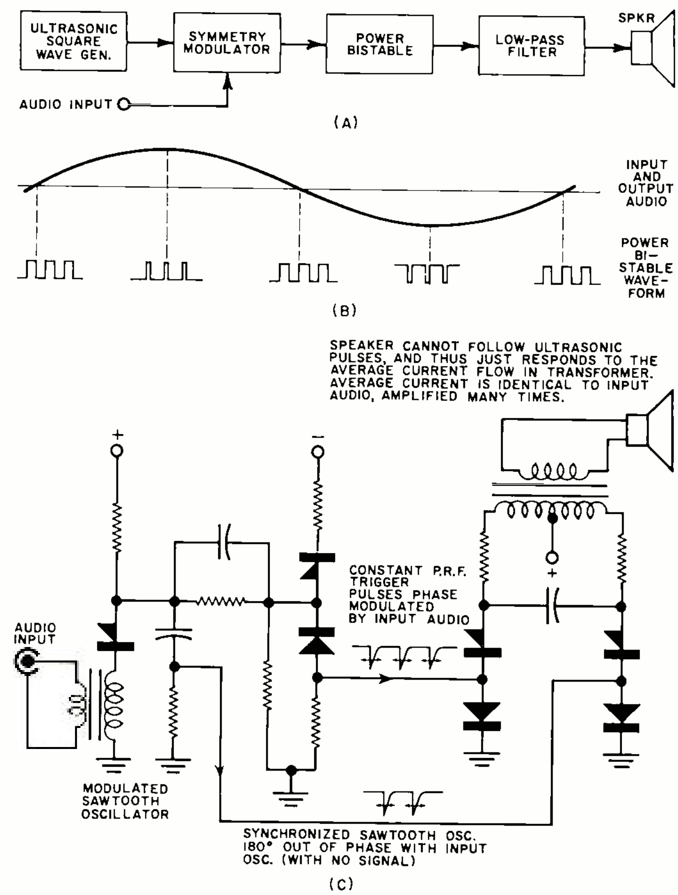


Fig. 11. A transistorless, tubeless audio amplifier which is capable of high gain and power outputs to about 1 kw.

level sensing, integrating, and phase-control applications. Fig. 9 details some of these circuit possibilities.

The SCR light dimmer/power-tool control shown in Fig. 9B requires the use of a bridge rectifier, two SCR's, or a fancy switching arrangement to allow full-range a.c. control. This is due to the unilateral control capability of the SCR. The circuit of Fig. 10 uses a five-layer bilateral diode to trigger a five-layer bilateral power diode. This circuit accomplishes the same function as the circuit of Fig. 9B using only five low cost parts. Dimmers and power-tool controls to 5 kw. of power may make use of this simple circuit.

It is possible to use four-layer diodes as extremely high powered audio amplifiers. Power capability up to 1 kw. of audio at very low distortion may be achieved. This is done by operating a power binary at an ultrasonic frequency, perhaps as high as 60 kc. Input audio is used to symmetry-modulate a 60-kc. oscillator which provides trigger pulses for the power bistable circuit. An output transformer senses the unbalanced current flow in the power bistable due to the asymmetry caused by the input audio. This current unbalance is directly proportional to the input audio, amplified many times.

Since all the diodes operate switching mode, very little heat is generated in any of the semiconductors and the circuit operates very much cooler than any linear amplifier would. A wide-band output transformer is required for this circuit. By direct coupling the input, a frequency response of d.c. to 15 kc. can be achieved using currently available diodes. This circuit is diagrammed in Fig. 11.

In this article we have discussed some of the fairly recent types of four- and five-layer semiconductor diodes. Some of the most important applications of these diodes have been described briefly. As time goes on and as more designers become aware of the uses of these diodes, we can expect to see their use increase considerably in a wide range of electronics equipment. ▲