Modeling and Experimenting with the Shockley Four-Layer Diode

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My interest in early heart pacemaker technology often leads me into forgotten corners of mid-century electronics. Recently, while analyzing an RF pacemaker circuit, I encountered a part I hadn't seen since my youth in the 1970s: the Shockley four-layer diode.

A Shockley four-layer diode (often described as a PNPN device) is a two-terminal semiconductor switch that behaves less like an ordinary diode and more like a compact, self-contained trigger element. At low applied voltage it remains in a very high-impedance "OFF" state, drawing only leakage current. When the voltage across it reaches a characteristic breakover threshold, internal regenerative feedback causes it to switch abruptly into a low-impedance "ON" state, producing a sharp current surge and a rapid collapse of device voltage. It then latches on and continues to conduct until the current falls below a holding current, at which point it returns to the OFF state and the cycle can repeat. In other words, it provides a clean, repeatable threshold-and-latch function with only two terminals. This property made it very attractive before the integrated circuit era as an elegant building block for relaxation oscillators, pulse generators, and gating circuits.

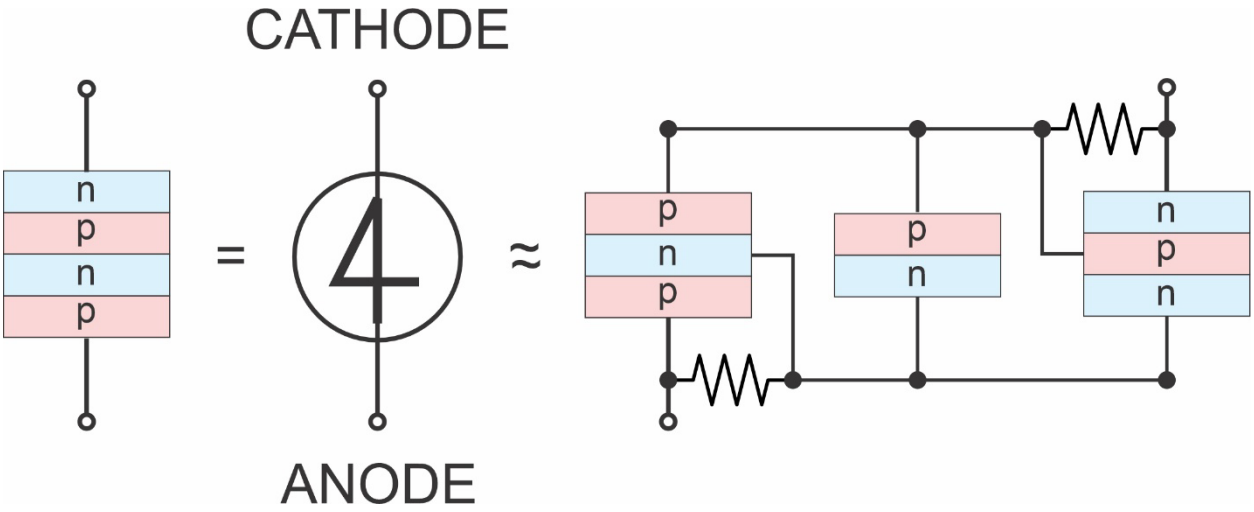


Figure 1 – The four-layer Shockley diode

The Shockley Diode

After co-inventing the transistor at Bell Telephone Laboratories, William Shockley became convinced that the next major step in solid-state electronics would come from silicon devices and from a new class of semiconductor switching elements. In September 1955, Shockley and instrument entrepreneur Arnold O. Beckman agreed to establish the Shockley Semiconductor Laboratory as a division of Beckman Instruments. Shockley leased space in Mountain View, California, and began recruiting a team to develop

and manufacture advanced semiconductor devices. Central to Shockley's commercialization vision was the four-layer (PNPN) "Shockley diode" - a bistable, two-terminal switching device he had conceived at Bell Labs for telephone switching applications, where a compact threshold-and-latch element promised to reduce parts count in large switching networks. If you are interested in the history of the Shockley diode, I refer you to Jack Ward's excellent paper "The first silicon in Silicon Valley – Volume 1 - Shockley 4-Layer Bistable Transistor Diodes."

As shown in Figure 1, the Shockley four-layer diode is a two-terminal, four-layer semiconductor structure arranged as P–N–P–N between an anode and a cathode. The outer P layer is tied to the anode terminal and the outer N layer to the cathode terminal, with two internal junctions in between. In physical terms it is essentially a thyristor-like device without a gate: there is no third terminal to control it directly, only the anode and cathode. Shockley gave it a diode-like symbol, giving its arrow the shape of the number 4 to represent its four-layer structure.

A useful way to visualize the PNPN stack is as two interconnected bipolar transistors formed within the same piece of silicon: a PNP transistor and an NPN transistor whose collector and base regions are coupled. This "two-transistor" view is not just an analogy; it explains the latching behavior. In Shockley's own conceptual equivalent, the four-layer diode replaces a small network (two transistors with resistive shunts and an avalanche PN diode trigger element) that provides regenerative switching.

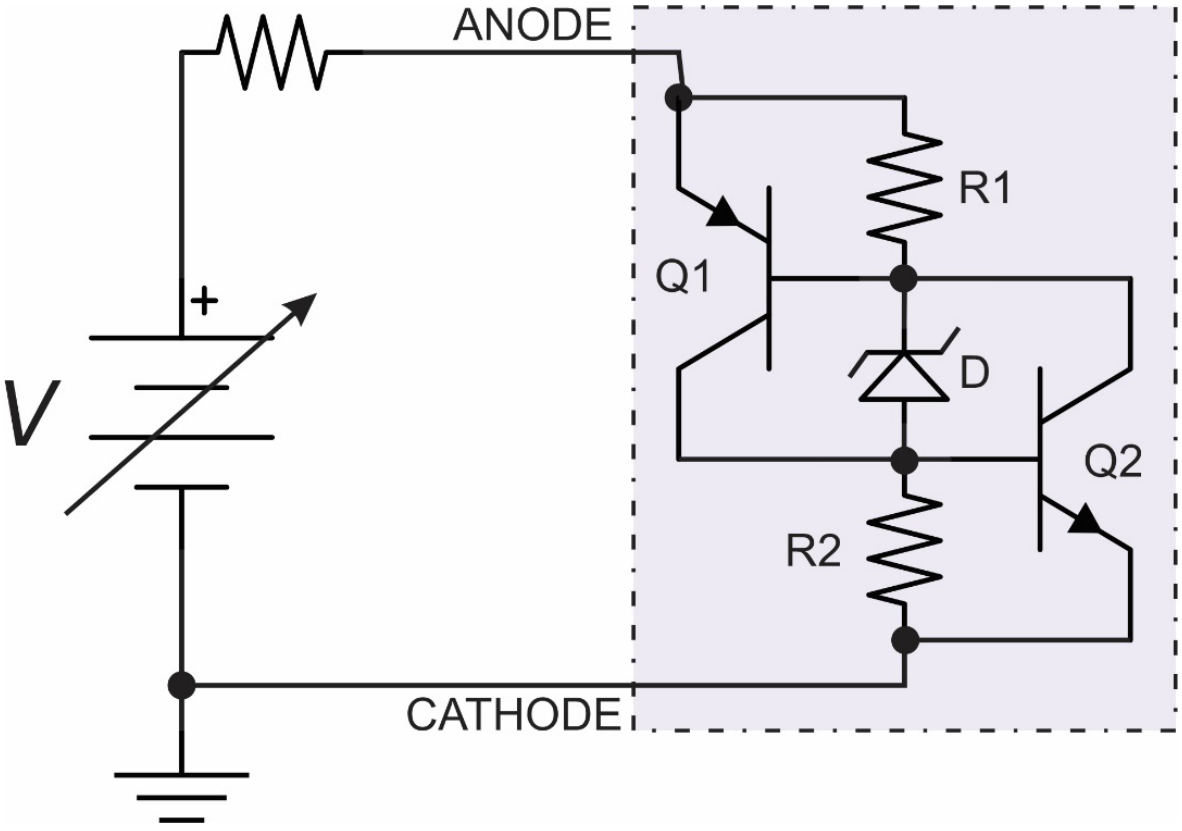


Figure 2 – Operating equivalent circuit of the Shockley diode

Referring to the equivalent circuit of Figure 2, in its OFF (forward blocking) state, with the anode positive relative to the cathode but below its breakover voltage, the Shockley diode equivalent remains in a high-impedance state. One internal junction is effectively reverse-biased, so only small leakage current flows. Electrically, the device behaves like a nearly open circuit (plus some junction capacitance).

As the forward voltage *V* increases, leakage and internal carrier injection increase until the device reaches a characteristic breakover voltage. At that point, internal feedback causes a rapid transition: current flowing in one of the internal transistor-like regions produces base drive for the other, and vice versa.

Avalanche diode D is there to represent the center junction's avalanche mechanism that provides the initial "kick" of current needed to start regeneration when the effective gains of the two transistor sections are still low.

Once the loop gain exceeds unity (often described as the condition $\alpha_1 + \alpha_2 \geq 1$, where α values represent the effective current gains of the internal PNP and NPN structures), the device "snaps" into conduction. This switching is abrupt: current rises quickly and the voltage across the diode collapses.

After turn-on, the Shockley diode conducts heavily with a relatively low ON-state voltage and low dynamic resistance (just few ohms). In this state the internal regions are strongly injected with carriers, so the device behaves like a closed switch.

A key feature is that the device latches: once it has switched ON, it will stay ON even if the anode–cathode voltage is reduced, as long as the current through the device remains above a characteristic holding current (I_H). To turn it OFF, you must reduce the current below I_H (for example by lowering the supply voltage, or by increasing series resistance). When current falls below I_H, the internal carrier concentrations drop, the regenerative feedback collapses, and the device returns to the high-impedance OFF state.

Resistors R1 and R2 are best thought of as internal shunts that (a) define the OFF-state, (b) moderate triggering, and (c) largely determine holding current and hysteresis in the two-transistor Shockley diode model.

A stylized voltage-current curve showing the various regimes of a Shockley diode is shown in Figure 3.

For a more detailed description of the Shockley diode, I refer you to Shockley's own "*Unique Properties of the 4-Layer Diode.* Technical Bulletin T-400" (1957).

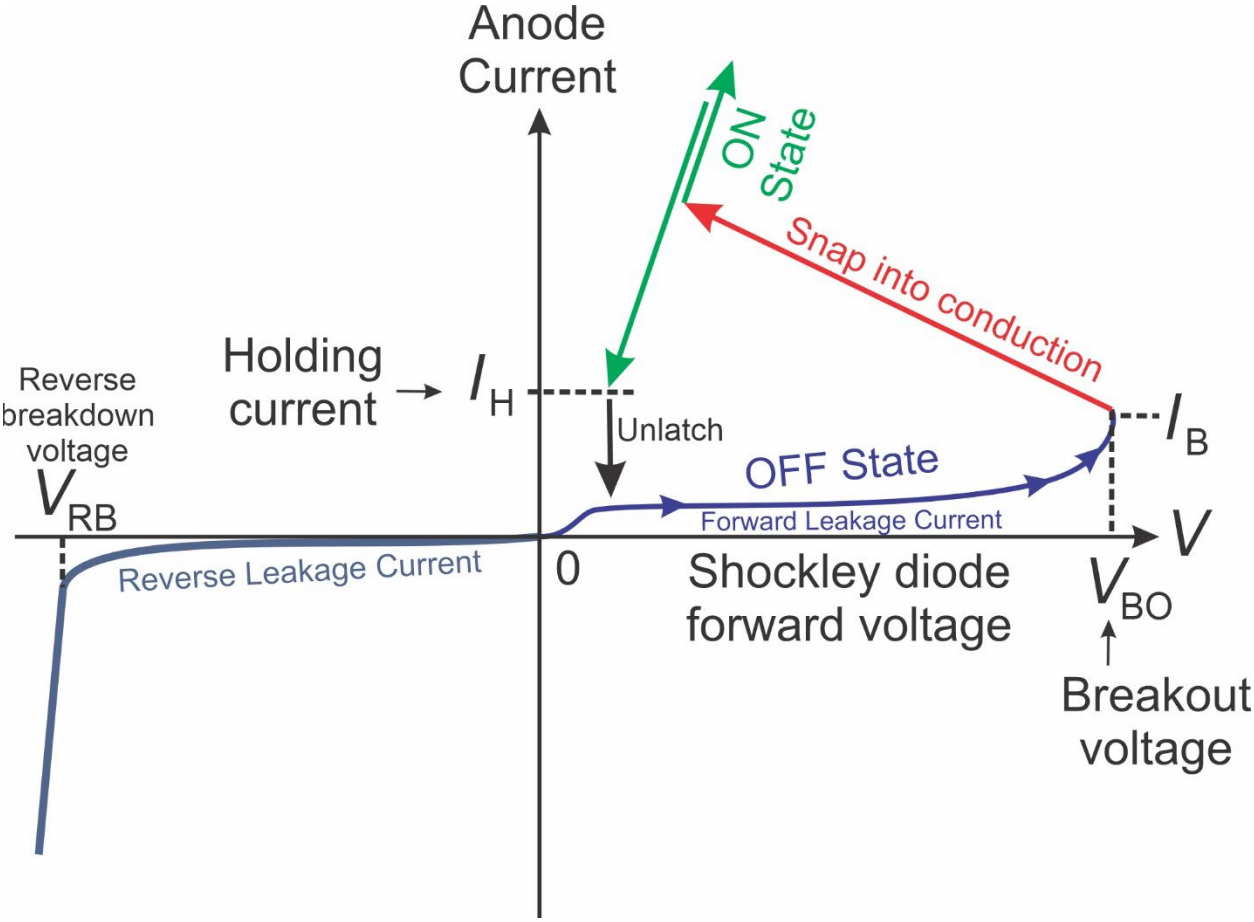


Figure 3 – Stylized current-voltage curve of Shockley diode. The device remains in high-impedance (OFF) mode until the voltage across it reaches its breakout voltage V_{BO}. At that point the device snaps into a low-impedance (ON) conduction mode that persists as long as the current through the diode is above the holding current I_H, at which the diode returns to the high-impedance(OFF) state.

Real Shockley Diodes

Shockley's first commercial four-layer diodes became available for sale in September 1958 and were sold in type a Type "D" package (Figure 4), which was a gold-plated metal can. Early Type D parts were not initially sold as a small set of fixed catalog voltages. Instead, Shockley selected devices by test and stamped the firing voltage on each unit, reflecting the realities of early process control. Soon after that, standardized part numbers based on firing voltage such as 4N20D (20V), 4N30D (30V), 4N40D (40V), and 4N50D (50V) became available [Shockley Transistor Corporation, 1959]. By late 1958 and into 1959, the product line expanded beyond the original Type D to include additional case style variants, including Type AD, Type J, and Type G, which were essentially packaging variants of the same basic two terminal PNPN breakover function. After the company was acquired by Clevite and manufacturing matured, a lower cost glass cased Type E style was introduced and was available by 1960, marking the final major packaging evolution of the original Shockley lineage.

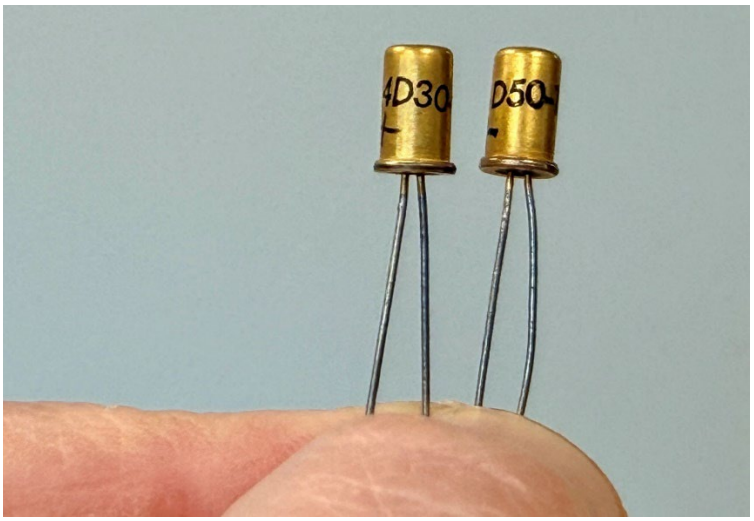


Figure 4 – Original 4ND30 (30V) and 4N50D (50V) Shockley diodes in Type D gold-plated metal can (from my vintage parts box).

As the device spread beyond Shockley Semiconductor/Clevite and became a common commodity, makers and distributors shifted away from the name “Shockley diode” and adopted the simpler, more generic term “four-layer diode.” The new wording described what the device was rather than who invented it, and it made it easier to list in catalogs and cross-reference across manufacturers. As usage broadened, alternative schematic symbols also began to appear in the literature, replacing the original symbol introduced by Shockley (Figure 5).

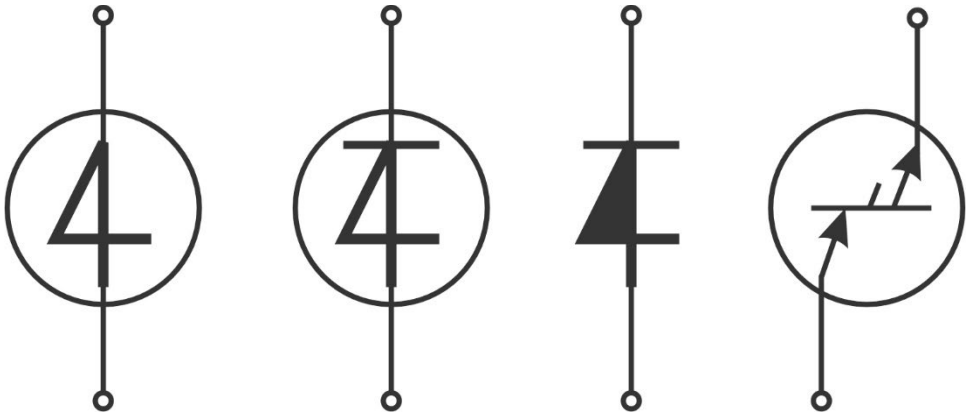


Figure 5 – Alternative symbols commonly used to represent the Shockley four-layer diode

ITT purchased Clevite in 1965 and continued manufacturing the Shockley four-layer diode product line, relabeling the technology as “four-layer diode thyristors.”

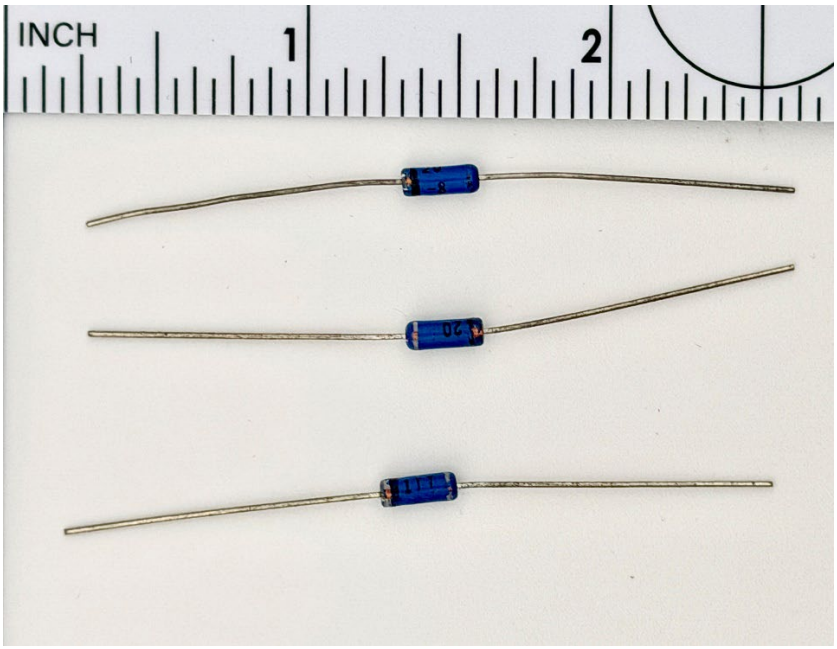


Figure 6 – Glass-packaged 4E20-8 Shockley diodes manufactured by ITT that they called "four-layer diode thyristors" in their catalogs and databooks. These are the type of Shockley diodes that I used in my experiments.

Also in 1965, Motorola introduced its line of four-layer diodes that featured lower trigger voltages (10V – 14V) [Motorola Semiconductor, 1970] than the devices made by Shockley and its successors. In the later 1960s, Motorola redesignated its M4L-series of 4-layer diodes to standard JEDEC 1N*xxxx* part numbers [Motorola Semiconductor Products Inc, 1974].

The following table shows the breakover voltage and holding current of common four-layer diodes:

Table 1 – Commercial four-layer diodes

Diode	**Breakover Voltage**	**Maximum Holding Current**	**Primary Manufacturer**
4N20D	20V ± 5V	50 mA	Shockley/Clevite/ITT
4N30D	30V ± 5V	50 mA	
4N40D	40V ± 5V	50 mA	
4N50D	50V ± 5V	50 mA	
4D20	20 ± 4V	4D*x*0-3: 6 mA 4D*x*0-12: 20 mA 4D*x*0-30: 45 mA	
4D30	30 ± 4V		
4D40	40 ± 4V		
4D50	50 ± 4V		
4D80	80 ± 8V	4D80-3: 6 mA 4D80-7: 10 mA	
4D120-3	120 ± 12V	6 mA	
4D-200-3	120 ± 20V	6 mA	
4E20	20 ± 4V	4E*x*0-3: 6 mA 4E*x*0-8: 15 mA 4E*x*0-28: 45 mA	
4E30	30 ± 4V		
4E40	40 ± 4V		
4E50	50 ± 4V		

Diode	Breakover Voltage	Maximum Holding Current	Primary Manufacturer
M4L3052 (1N5158)	10 V_{MAX}	20 mA	Motorola
M4L3053 (1N5159)	11 V_{MAX}	20 mA	
M4L3054 (1N5160)	12 V_{MAX}	20 mA	
M4L3055	13 V_{MAX}	20 mA	
M4L3056	14 V_{MAX}	20 mA	

Fabricating classic Shockley four-layer diodes with early semiconductor techniques could be challenging and inconsistent, so by 1966, semiconductor manufacturers, especially General Electric [GE, 1971] introduced the silicon unilateral switch, or SUS, which is an integrated circuit that acts like an ideal four-layer diode [Muth, 1966]. In practice the SUS offered tighter control of key electrical parameters such as switching behavior and on-state characteristics, along with better repeatability from part to part, and it could be easier to apply in trigger and timing circuits because its behavior was more predictable than many earlier discrete four-layer diodes. The following table shows the switching voltage and holding current of common SUS parts:

Table 2 - Common Silicon Unilateral Switch (SUS) parts. These are integrated circuits that behave like ideal four-layer diodes.

Model Number	ECG Equivalent	NTE Equivalent	Switching Voltage (V_s)	Maximum Holding Current (I_H max)	Primary Manufacturer
2N4987	ECG6404	NTE6404	8 V ±2 V	1.55 mA	General Electric (GE)
2N4988	ECG6405	NTE6405	8.25 V ±0.75 V	5 mA	
2N4989	ECG6404	NTE6404	7.85 V ±0.35 V	1.0 mA	
2N4990	ECG6404	NTE6404	8 V ±1 V	0.75 mA	
2N4991	ECG6404	NTE6404	8 V ±2 V	1.55 mA	

Curve-Tracing Real Shockley Diodes

The original circuits used by Shockley Semiconductor to curve-trace their diodes are described in:

> Shockley Transistor Corporation. *The Shockley 4-Layer Bistable Transistor Diode: For Computers, Telephony, Control, Pulse Circuitry*. Stanford Industrial Park, Palo Alto, CA: Shockley Transistor Corporation; 1959.

It's much easier to use a modern instrument to trace a Shockley diode's curve, but study of those circuits is necessary to understand how some of the parameters shown in the early datasheets are specified. I_B was arbitrarily defined as "the point at which the trace disappears on the scope display" when using a 100kΩ limiting resistor and a half-sinusoidal excitation. V_{BO}, I_H, and V_H are measured with a 1kΩ limiting resistor. Again, holding current I_H and holding voltage V_H "are read at the point on the plot where the trace disappears."

The graphs of Figure 7 show the current flowing through a 4E20-8 Shockley diode with the application of a current-limited (60mA) ramping voltage. I used a Keithley 2450 SourceMeter® to obtain these measurements.

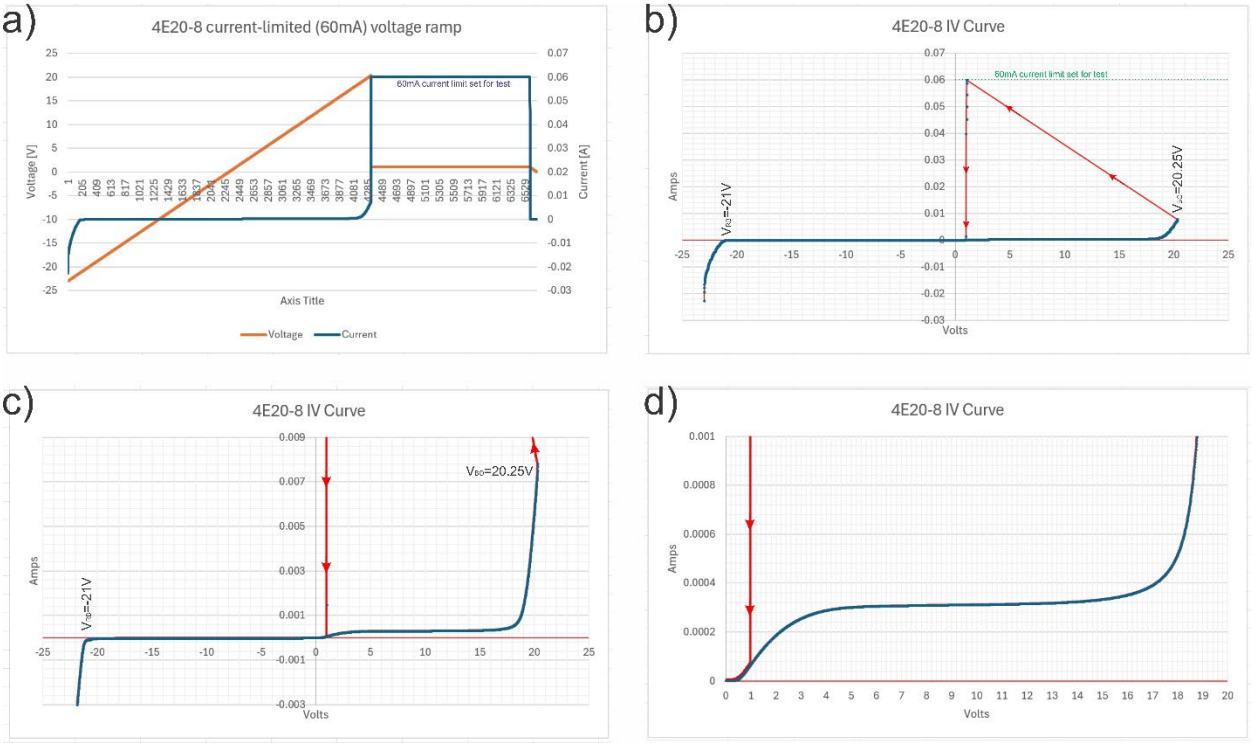


Figure 7 – Current flowing through a 4E20-8 Shockley diode with the application of a current-limited ramping voltage: ***a)*** *sampled current and voltage;* ***b)*** *complete IV curve;* ***c)*** *zoom-in;* ***d)*** *detail of the forward leakage current and return from latched state.*

Modeling the Shockley Diode

I wanted to simulate some of the RF pacemaker circuits, and was rather surprised that there were no Spice models for the Shockley diodes.

I set up the transistor equivalent model (Figure 2) under LTSpice, and spent considerable time trying to get it to work. It would trace the IV curve, but getting a simple relaxation oscillator to work got frustrating. In my desperation, I ran a deep search in multiple languages, and finally found a German website showing the same basic model running under TINA:

(https://de.wikibooks.org/wiki/Interessante_Messungen/_Vierschichtdiode/_Anwendungen/_S%C3%A4gezahn-Generator/_Simulation)

The same circuit that I couldn't get to work under LTSpice ran perfectly under TINA… I still can't explain why two different simulators based on the same SPICE engine would behave so differently for the same simple circuit, but TINA is now my favorite simulator!

In any case, the circuit of Figure 8 shows a Shockley diode modeled on its equivalent operating circuit (Figure 2) set up to be excited through a triangular ramp to show its trigger, hold, and release characteristics. In this simulation I used a 1N4747, which is a 20V Zener diode, yielding a trigger voltage of around 18V as shown in Figure 9.

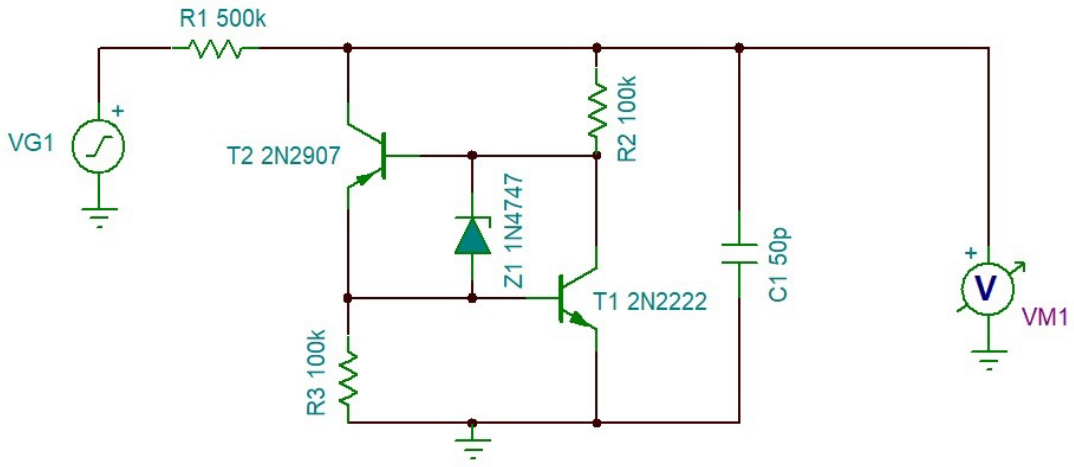


Figure 8 – Four-layer diode equivalent circuit set up for VI curve tracing under TINA

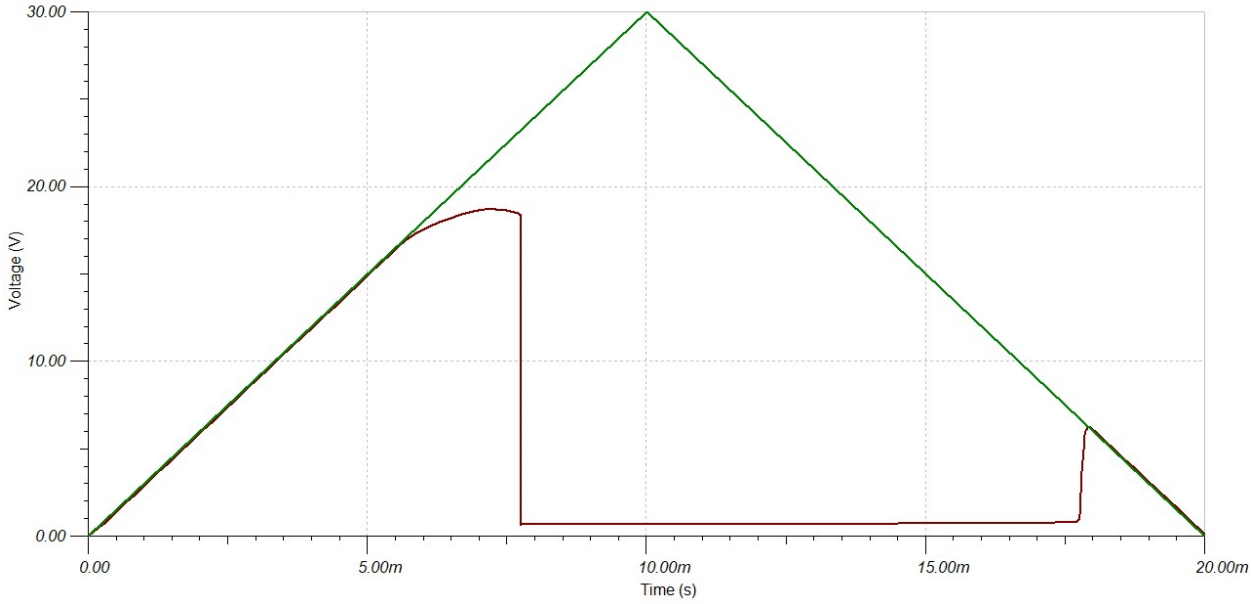


Figure 9 - Simulation results of Shockley-diode equivalent circuit set up for curve tracing. Green ramp is input voltage, red trace is voltage across diode equivalent. The diode snaps into conduction at the breakout voltage and remains at low impedance until the current flowing through the diode is below the holding current.

Figure 10 shows the same transistor-equivalent model of a four-layer diode set up as a relaxation oscillator, which behaves as shown in Figure 11.

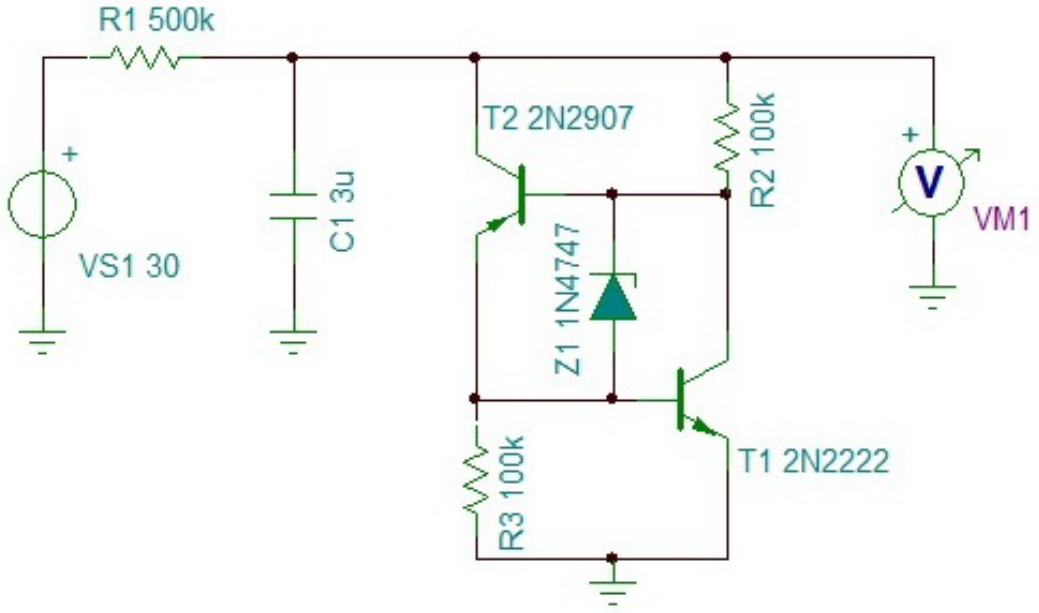


Figure 10 – TINA Spice relaxation oscillator circuit using transistor-equivalent model of four-layer diode.

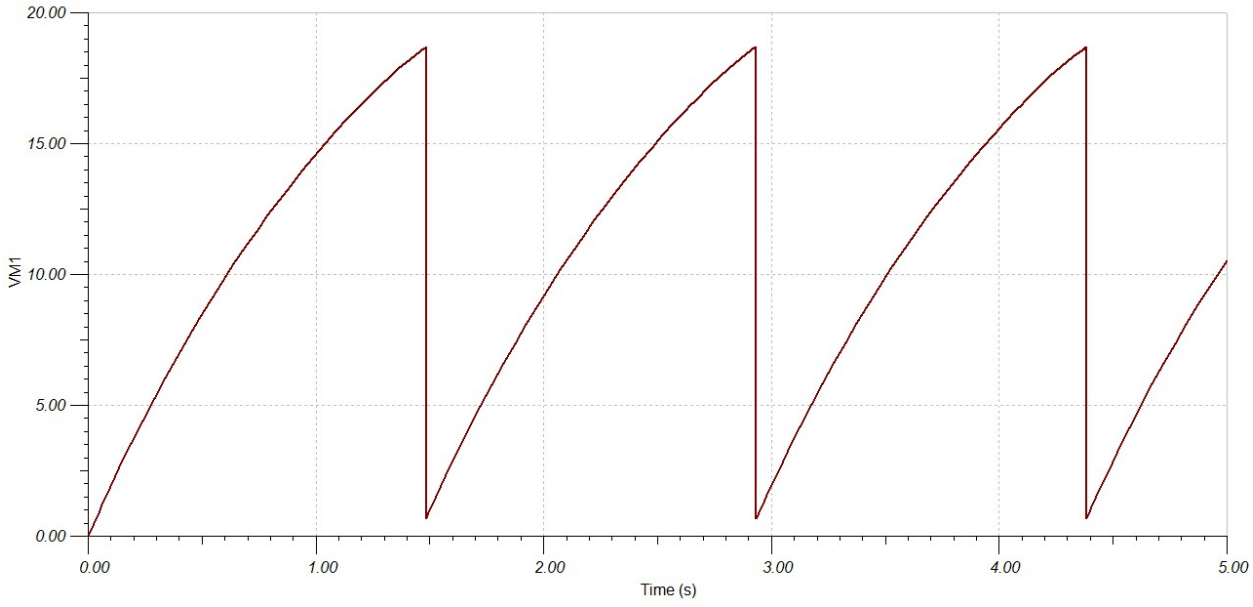


Figure 11 – Simulation results of relaxation oscillator circuit using transistor-equivalent model of four-layer diode (Figure 10)

Applications

Shockley diodes were promoted at their introduction as unusually versatile devices, particularly well suited to the ring counter stages common in telephone switching equipment, frequency counters, and related logic. Their main selling point was functional consolidation. A single, compact Shockley diode could implement a counter stage that otherwise required five discrete parts, typically two transistors, two resistors, and a Zener diode. However, the rapid adoption of integrated circuits eliminated most of the cost, size, and assembly advantages of such discrete simplifications. As a result, Shockley diodes largely disappeared from mainstream digital designs and persisted mainly in niche roles such as simple relaxation oscillators and trigger circuits. Here are some examples published in the 1960s and 1970s:

Lou Garner, Linear Sawtooth Generator (Popular Electronics, 1967)

Figure 12 (Figure 2 in original the article) shows a sawtooth generator having a minimum of parts, yet producing a very linear ramp. "D1 is a current-regulator diode, while D2 is a conventional four-layer diode. The design equation is $T= (C V_{BR}) /I_p$, where T is the period of one cycle, I, is the pinch-off current of diode D1, C is the timing capacitance in µF and V_{BR} is the breakover voltage of the four-layer diode."

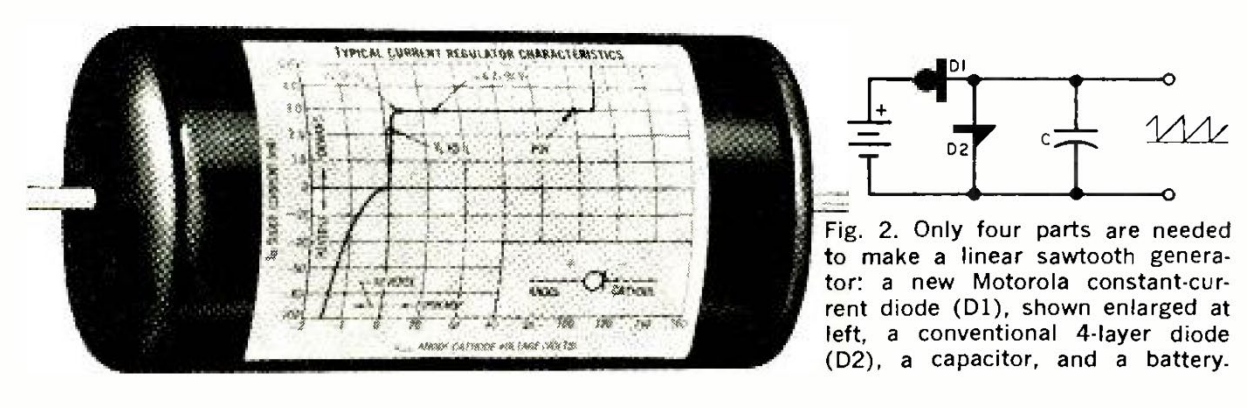


Fig. 2. Only four parts are needed to make a linear sawtooth generator: a new Motorola constant-current diode (D1), shown enlarged at left, a conventional 4-layer diode (D2), a capacitor, and a battery.

Figure 12 – Linear sawtooth generator using only 4 parts [Garner 1967]

I breadboarded the circuits shown in Figure 13. With a 4E20-8 Shockley diode, 23V supply voltage, and a 0.01µF capacitor, the circuit of Figure 13-b produces a 4.54kHz linear sawtooth with a 1N5297 1mA current-regulator diode. To produce the same frequency, the circuit of Figure 13-b needs a 1.95kΩ resistor, and is very sensitive to supply voltage. On the other hand, the circuit of Figure 13-b is insensitive to supply voltage for voltages above 19.5V.

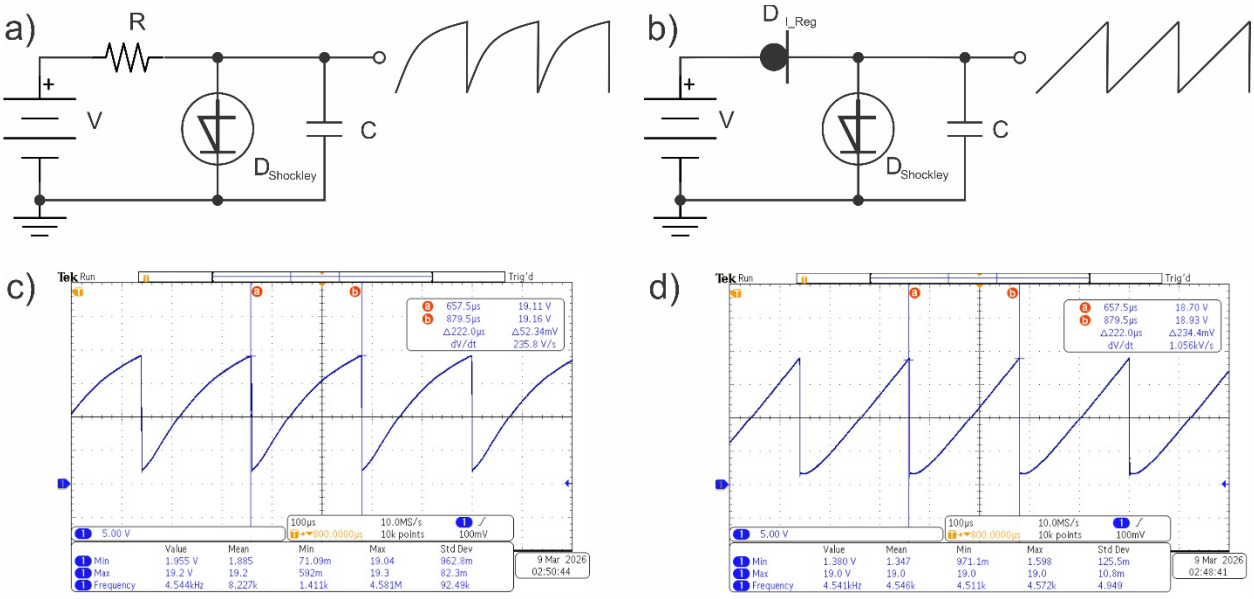


*Figure 13 – Sawtooth **(a)** and linear ramp **(b)** generators using Shockley diodes. 4.54 kHz outputs using 4E20-8 Shockley diode, 23V supply voltage, and a 0.01µF capacitor: **c)** circuit of (a) using 1.95kΩ resistor; circuit of (b) with 1N5297 1mA current-regulator diode.*

Don Lancaster, "Advanced Experimenter Project - Pulse Generator" (Popular Electronics, April 1966)

A simple pulse generator built around a four-layer diode relaxation oscillator, presented as a practical tool that can drive a speaker, serve as a signal injector, and even act as a metronome or darkroom timer. The article explains the "snap-on at ~12 V, stay on until current decays" behavior and shows the RC charge/discharge mechanism.

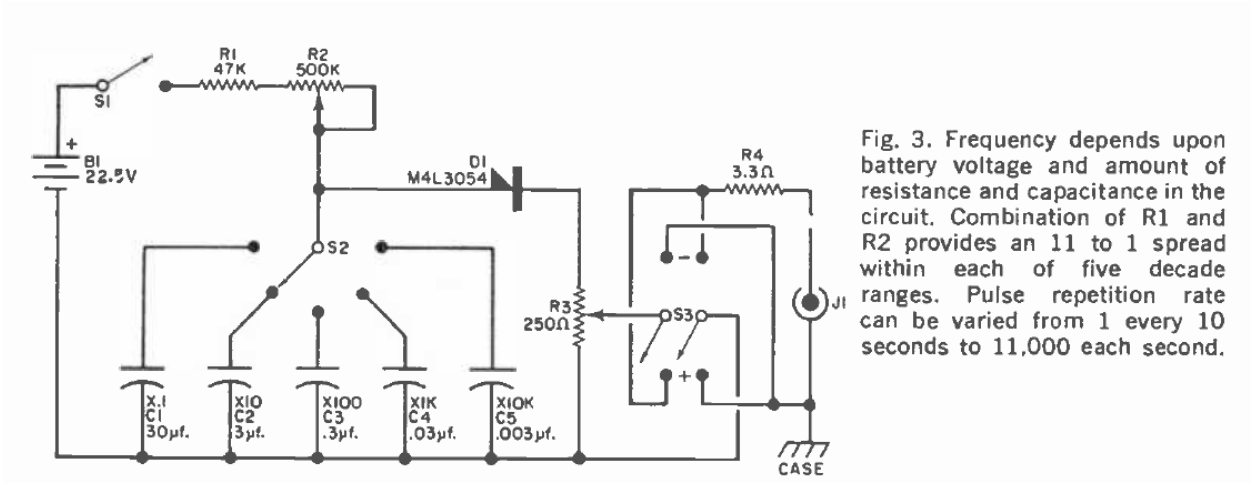


Figure 14 – Variable-frequency and amplitude pulse generator [Lancaster, 1966]

Forrest Mims, “The Four-Layer Diode” practical circuits (Popular Electronics, August 1977)

Audio Oscillator - Figure 15 (Figure 2 in the article) is a versatile oscillator “which can be used to produce audio frequencies ranging from the "pock…pock…pock" of a metronome to the ear-piercing sound of a 10,000 Hz tone. Switch S1 permits various values of capacitance to be selected. Potentiometer R2 varies the frequency of the circuit by altering the charging rate of the discharge capacitor. Diode D1 can be any common four-layer diode such as the 1N3831 through 1N3846, the 4E series or the M4L series.”

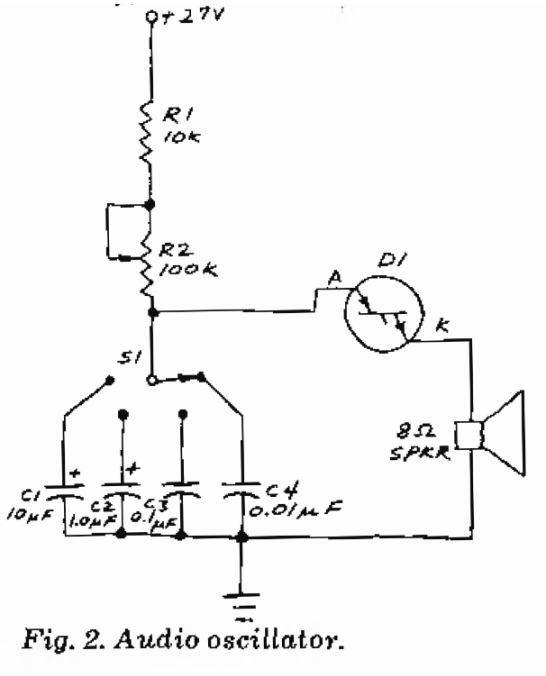


Fig. 2. Audio oscillator.

Figure 15 – Audio oscillator which can produce audio frequencies ranging from the "pock…pock…pock" of a metronome up to a 10 kHz tone [Mims, 1977]

LED laser pulse driver - Figure 16 (Figure 4 in the article) is a four-layer-diode-based relaxation oscillator that is used “as a subminiature, high-current driver for infrared LED's and semiconductor injection lasers.” … “The circuit using only three components which easily delivers 10-ampere pulses with a width of about 100 nanoseconds and a rate of about a kilohertz to a diode laser. A typical experimenter-grade laser diode will deliver up to several watts of invisible infrared at a wavelength of about 900 nanometers when driven by this circuit. Laser, pulser, and batteries can be easily built into a small pocket-size package. A simple lens can be added to squeeze the broad beam from the laser into the pencil-thin beam produced by the much more costly gas lasers.”

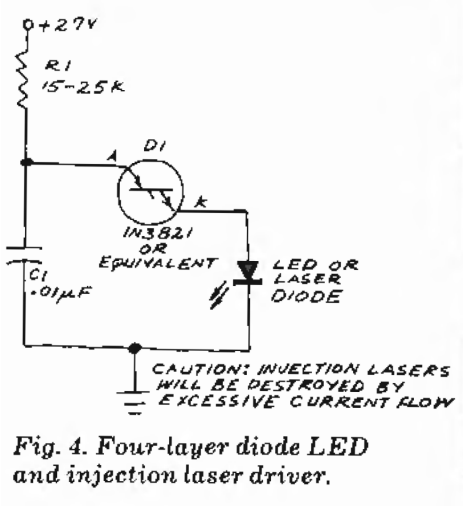


Fig. 4. Four-layer diode LED and injection laser driver.

Figure 16 – LED and injection laser pulse driver [Mims, 1977]

C. A. Huber, "Slow-Kick Windshield Wiper" (Popular Electronics, 1970)

In the circuit of Figure 17, four-layer diode D1 in a simple relaxation oscillator drives relay K1 which, in turn controls switch of electric windshield wiper motor. R2 determines rate at which C1 is charged to point where it breaks down D1 and operates wiper. When C1 discharges below 1 mA, D1 turns off and relay drops out for start of new cycle. Will work with either ground polarity.

Fig. 2. Very simple "slow-kick" circuit for electric windshield wiper motors is adaptable to any 12-volt electrical system, regardless to the ground polarity.

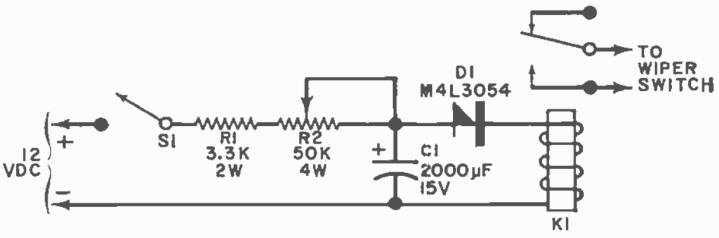


Figure 17 – Reader circuit for slow-kick windshield wiper submitted by C. A. Huber to Popular Electronics, April 1970, p 86.

R.B. Shreve, Compact tone-burst keyer for FM repeaters (Ham Radio, 1972)

The article describes a small, self-contained 1750 Hz tone generator intended to key FM repeaters that required a short audio burst for access. The circuit in Figure 18 uses four-layer diodes as relaxation oscillators and timing elements. In Shreve's design, a capacitor charges through a resistor until it reaches the breakover voltage of the four-layer diode. The device then switches abruptly into conduction, rapidly discharging the capacitor and producing a sharp pulse. Repetitive charge–discharge action generates a stable audio-frequency oscillation. A second four-layer diode stage is used to shape and limit the duration of the burst, ensuring a brief, repeatable tone packet rather than continuous oscillation. The advantages emphasized are simplicity, low parts count, and the sharp, well-defined triggering characteristics of the four-layer diode, which provide consistent tone frequency and burst length without requiring active transistor bias networks or complex timing circuitry.

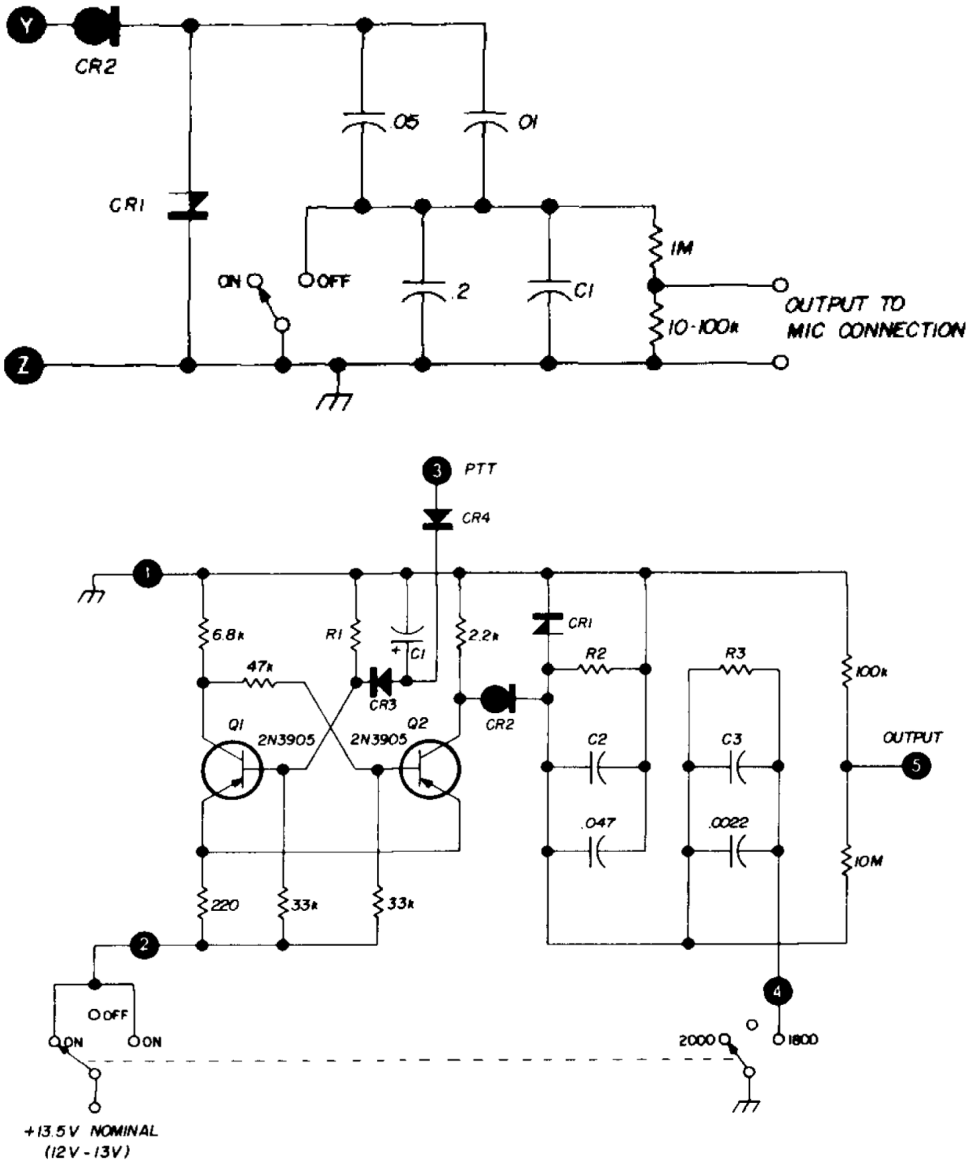


fig. 1. Simple tone-burst oscillator circuit provides tones of 1800 and 2000 Hz. Diodes CR3 and CR4 are general-purpose diodes. R1 and C1 are selected for desired burst duration; for value of C2, C3, R2 and R3 see text.

Figure 18 - tone-burst keyer for FM repeaters [Shreve, 1972]

Don Lancaster, The AMLIGNER RF generator (Popular Electronics, 1967)

The circuit Figure 19 was published by Don Lancaster as the "AMLIGNER," which is a tiny, cordless AM broadcast band signal source that works by using a four layer diode (Motorola M4L3054) as the switch element in a relaxation oscillator and a loopstick as both transformer and antenna. With the switch closed, capacitor C1 charges through R1 from the 22.5 V battery until the diode's snap over threshold (about 12 V) is reached, at which point the diode avalanches and rapidly discharges C1 through the loopstick primary; when the discharge current falls below roughly 1 mA, the diode snaps off and the charge discharge cycle

repeats at about 800 Hz, creating a sawtooth on C1 and narrow current pulses through the diode. Each snap off abruptly interrupts current in the coil, exciting a short burst of ringing in the L1–C2 tuned circuit at its resonant frequency in the AM band; the loopstick action simultaneously steps the transient up to several hundred volts across the tuning capacitor C2, and because the loopstick is also the radiator, it emits an AM carrier whose amplitude is keyed by the 800 Hz pulse train, letting a nearby receiver pick up a tone for tracing and alignment while C2 sets the RF frequency

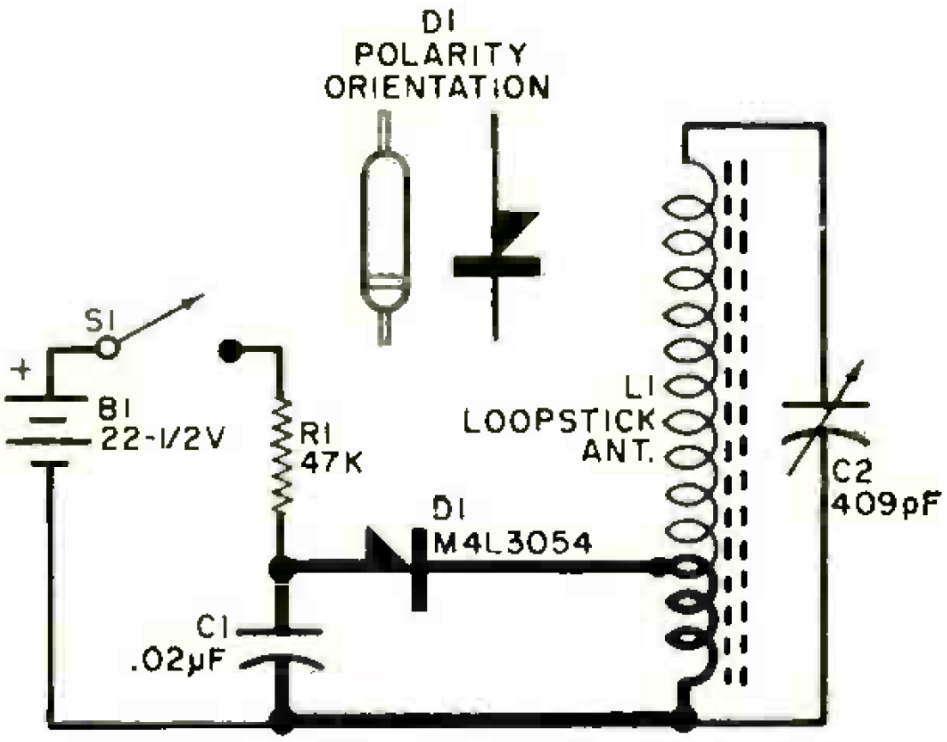
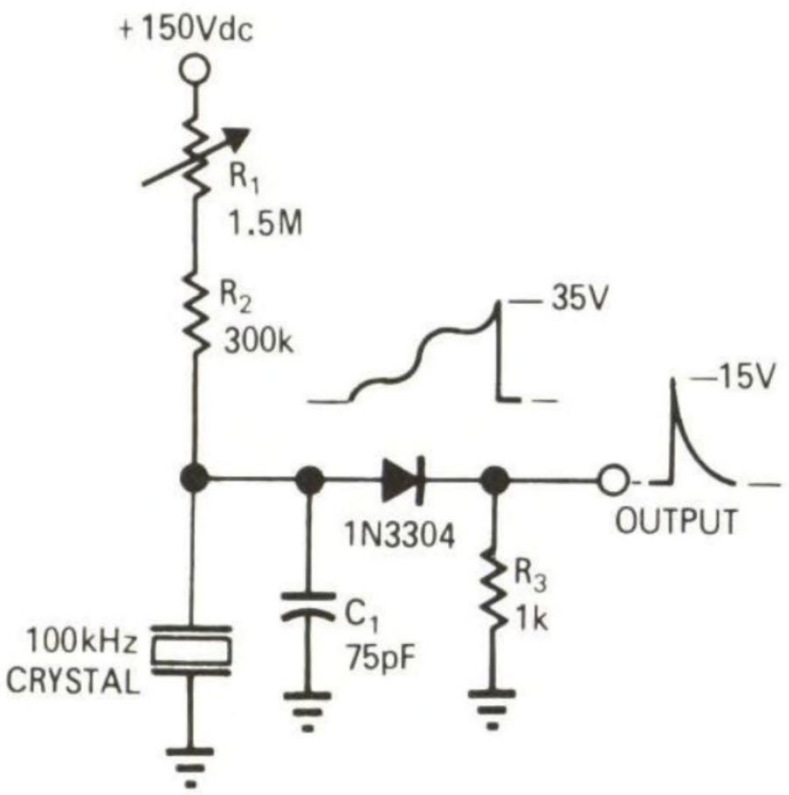


Fig. 1 The AMLIGNER is a free-running relaxation oscillator whose frequency is determined essentially by the value chosen for charging capacitor C1.

Figure 19 – Don Lancaster's AMLIGNER RF generator [Lancaster, 1967]

100kHz oscillator locked to crystal frequency (EDN, 1971)

The circuit of Figure 20 is a basic relaxation RC oscillator that is locked to the fundamental (or first sub-harmonic) of a crystal. R1 is selected such that the RC is close to the desired frequency, with the crystal providing resonance to fix the frequency.



100-kHz CRYSTAL-DIODE RELAXATION—Crystal-controlled relaxation oscillator uses 1N3304 four-layer diode as active element. R_1 adjusts RC time constant so oscillator locks at fundamental frequency of crystal or at half this frequency.—R. D. Clement and R. L. Starliper, Crystal-Controlled Relaxation Oscillator, *EDN/EEE Magazine,* Oct. 15, 1971, p 62 and 64.

Figure 20 – Relaxation oscillator locked to crystal frequency

J Bliss and D Zinder, Ring counter using four-layer diodes for sequential switching of loads (Motorola, 1961)

Figure 21 is a ring counter application demo that was published by Motorola for their 1N5158 four-layer diodes.

SEQUENTIAL SWITCHING OF LOADS—Ring counter using four-layer diodes D_N provides sequential switching of loads under control of input pulse-train signal. Indicator lamps are shown, but any load from 15 to 200 mA can be switched. After power is applied, reset switch must be pressed to establish current through L. When switch is released, this current flows through C_2 and breaks down D_2, allowing current to flow through first lamp I_1. Input pulse to transistor Q (normally held off by current through R_1) turns Q off and removes power from diode circuits, thus turning I_1 and D_2 off. At end of input pulse, Q comes on and restores power to diode circuits, but all loads will be turned off. Voltage on C_3 now adds to 6 V normally across D_4, making D_4 break down and turn on I_2. Next input pulse will break down D_6 in same manner. Output signals may be picked up as negative pulses at A or B or by current-sensing at C if required for controlling larger loads.—J. Bliss and D. Zinder, "4-Layer and Current-Limiter Diodes Reduce Circuit Cost and Complexity," Motorola, Phoenix, AZ, 1974, AN-221, p 5.

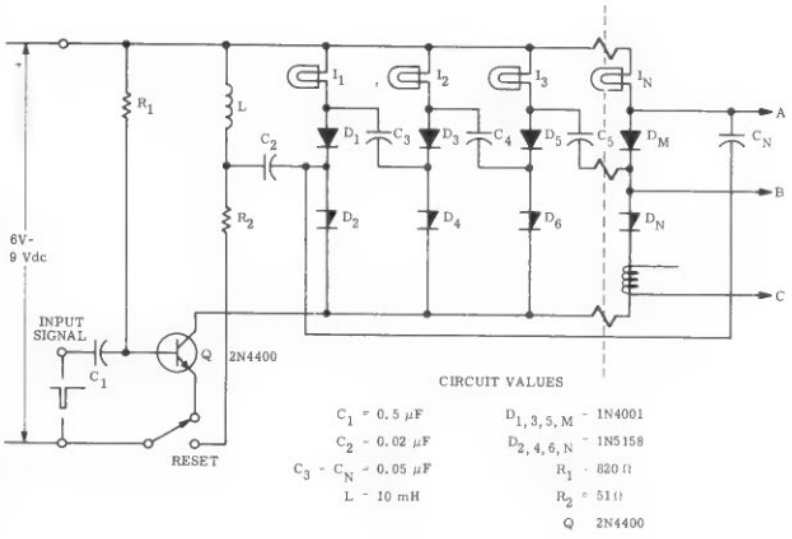


Figure 21 – Ring counter using four-layer diodes

William Shockley, Pulse Generators (Shockley, 1957)

In the pulse-generator circuits of Figure 22, the four-layer (PNPN) diode acts as a voltage-triggered switch controlling the rapid discharge of a capacitor. The capacitor is charged through a resistor toward the supply voltage while the diode remains in its high-impedance state. A trigger pulse applied to the input momentarily raises the voltage across the diode above its breakover threshold, causing the device to switch abruptly into its low-impedance conducting state. When this occurs, the stored charge in the capacitor is discharged quickly through the diode and the load resistor, producing a sharp output pulse. As the capacitor discharges, the current through the diode falls; when it drops below the holding current, the device returns to its non-conducting state. Because the capacitor must then recharge through the resistor before the breakover condition can be reached again, the trigger pulse can initiate only a single discharge event, ensuring that each input trigger produces just one output pulse. The difference between the two figures lies mainly in how the output is coupled and shaped, but the basic single-pulse mechanism—triggered breakover followed by rapid capacitor discharge and reset—is the same.

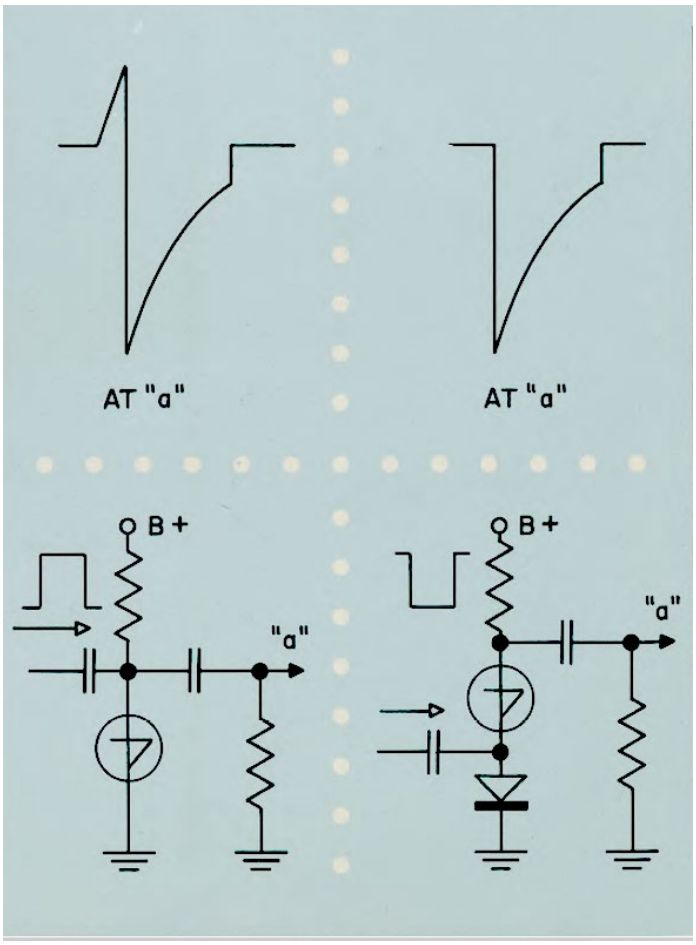


Figure 22 – Pulse generators based on Shockley 4-layer diode from Beckman Instruments, 1960 and Figures 3a and 3b in Technical Bulletin T-400 (Shockley 1957)

William Shockley, Bistable Circuit (Shockley, 1957)

In the circuit of Figure 23, two four-layer diodes are cross-coupled so that only one of them can conduct at a time, creating a circuit with two stable states. When one diode is in its conducting (low-impedance) state, the voltage conditions established through the coupling resistors keep the other diode below its breakover voltage, holding it in the non-conducting state. A trigger pulse applied to the input of the non-conducting side raises its voltage to the breakover level, causing that diode to switch on abruptly. The resulting change in current and voltage simultaneously removes the holding current from the previously conducting diode, forcing it to switch off. In this way the circuit "toggles" between two stable conditions, each corresponding to one diode conducting and the other off. Because the four-layer diode remains on as long as its current stays above the holding current, the circuit retains its state until another trigger pulse forces the opposite transition.

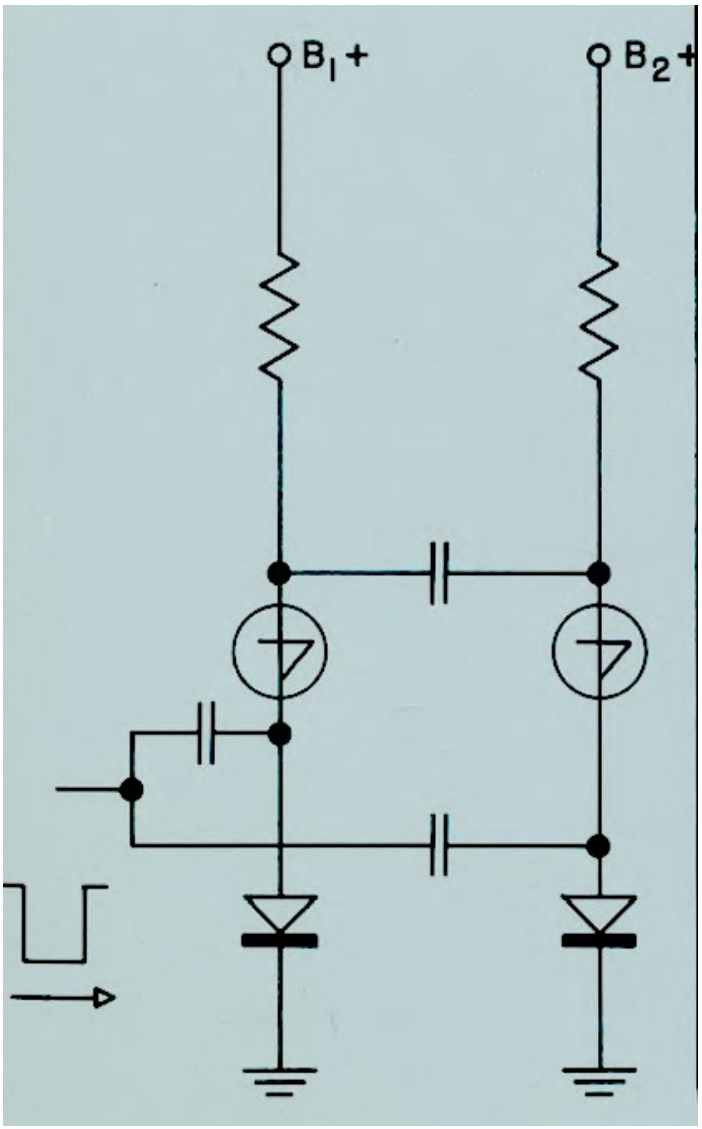


Figure 23 – Bistable circuit (flip/flop) based on Shockley 4-layer diodes from Beckman Instruments, 1960 and Figures 5 in Technical Bulletin T-400 (Shockley 1957)

Eisenberg et al., RF Pacemaker (IRE Trans Bio Med Electron, 1961)

As shown in Figure 24, an RF pacemaker is a medical device from the late 1950s and 1960s in which the implanted unit does not rely on an internal battery for energy; instead, an external transmitter generates radiofrequency power that is coupled across the skin by inductive coupling between external and implanted coils, so the implanted receiver can rectify the RF energy and deliver periodic stimulation pulses to the heart. In the external transmitter of many of these RF pacemakers, a Shockley four-layer diode was used at the core of the free-running relaxation oscillator that triggered the transmission of RF energy around once per second.

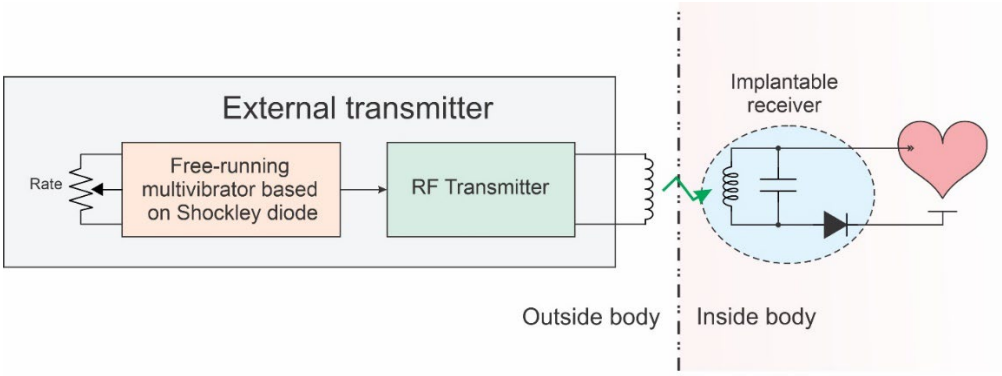


Figure 24 – Basic RF pacing system consisting of an external RF transmitter and a very simple implanted RF receiver that rectifies the RF and turns it into a pulse that stimulates the heart. The transmitter emits a short burst of RF approximately once per second under the control of a free-running multivibrator based on a Shockley four-layer diode.

Figure 25 shows the schematic of the RF pacemaker that sent me into this four-layer diode rabbit hole. Here, C2 is charged from the 28V battery by way of R2 and P1. When the voltage across Shockley diode T1 reaches 20V, it triggers and discharges the capacitor through R3 and TR1. TR1 steps-up the voltage to blink neon indicator Ne2. The pulse delivered to T2 via R4 is used to power the 2MHz oscillator built around T3.

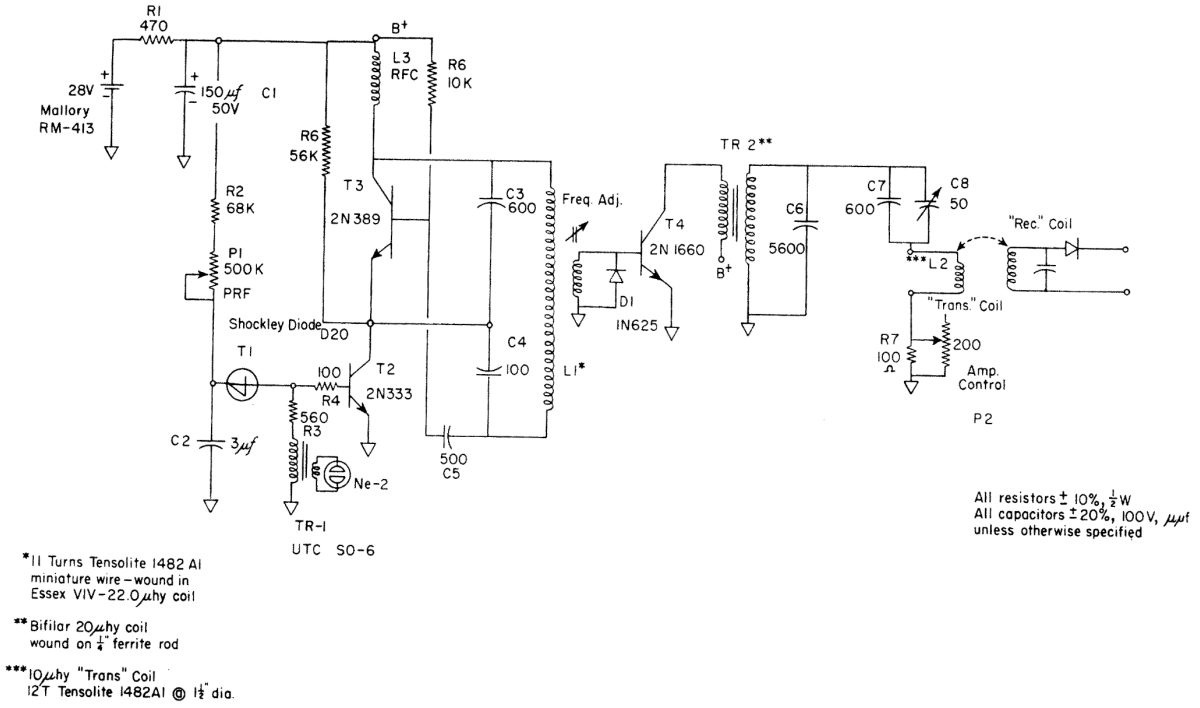


Figure 25 – RF pacemaker transmitter and receiver. [Eisenberg et al., 1961]

The Demise of the Shockley Diode

Although the Shockley four-layer diode initially attracted considerable attention as an elegant solid-state switching element, its practical importance was relatively short-lived. In the late 1950s and early 1960s the device offered an appealing way to consolidate several discrete components into a single compact element. Circuits such as pulse generators, ring counters, relaxation oscillators, and gating networks could be implemented with fewer parts because the device inherently provided a sharp breakover threshold and a latching conduction state. However, the rapid emergence of integrated circuits soon eliminated most of these advantages. Functions that previously required several discrete components could now be implemented more reliably and economically inside monolithic ICs, removing much of the incentive to use discrete four-layer diodes in digital and timing circuits.

During the early 1970s, another device temporarily assumed many of the roles previously served by the four-layer diode: the programmable unijunction transistor (PUT). The PUT is essentially a three-terminal PNPN device closely related to a small SCR, but with its triggering voltage determined externally by a resistive divider connected to the gate terminal. This allowed designers to create relaxation oscillators and timing circuits with an adjustable switching threshold, making the device popular for a time in hobbyist electronics, instrumentation, and triggering circuits. In many applications the PUT effectively replaced both the earlier four-layer diode and the traditional unijunction transistor. Like those devices, however, the PUT eventually declined in importance as inexpensive integrated timers, oscillators, and logic circuits became widely available. It's interesting to note that PUTs, especially the 2N6027 and 2N6028 are still available as standard parts.

Four-layer semiconductor structures themselves did not disappear from electronics. On the contrary, they evolved into one of the most important families of power devices: the thyristors, particularly the silicon controlled rectifier (SCR). Unlike the two-terminal Shockley diode, the SCR includes a gate terminal that allows controlled triggering of the regenerative PNPN structure. Beginning in the early 1960s, SCRs rapidly became the preferred devices for controlling high voltages and currents in industrial and consumer equipment. Their latching behavior made them ideally suited for phase-control circuits used in lamp dimmers, motor speed controllers, power regulators, and a wide variety of industrial power-conversion systems. Thus, while the discrete Shockley diode itself largely vanished from mainstream circuit design, the fundamental PNPN switching principle that it embodied survived and flourished in the broader thyristor family of devices that remain widely used today.

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- J Ward. The first silicon in Silicon Valley – Volume 1 - Shockley 4-Layer Bistable Transistor Diodes. Transistor Museum. www.transistormuseum.com.

Appendix – Shockley Four-Layer Diode Specifications

From: Shockley Transistor Corporation. *The Shockley 4-Layer Bistable Transistor Diode: For Computers, Telephony, Control, Pulse Circuitry*. Stanford Industrial Park, Palo Alto, CA: Shockley Transistor Corporation; 1959.

No.	V_b Volts	I_b μa	V_h Volts	I_h ma	R_h ohms
4N20D	20±5	<500	<2	<50	<10
4N30D	30±5	<500	<2	<50	<10
4N40D	40±5	<500	<2	<50	<10
4N50D	50±5	<500	<2	<50	<10
4N20-50DL	As above, and <4v drop for 3-amp pulse				

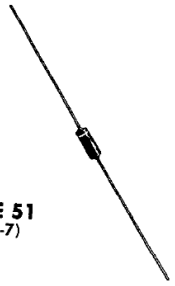
Appendix - Motorola 4-Layer Diode Specifications

From: Motorola Semiconductor. *4-Layer Diodes: M4L3052 thru M4L3054 (Now 1N5158 thru 1N5160)* [datasheet]. Phoenix (AZ): Motorola Semiconductor; 1970

4-Layer Diodes

M4L3052 thru M4L3054
NOW 1N5158 thru 1N5160

$V_{(BR)F}$ = 8-12V
$V_{RM(rep)}$ = 10-12V
I_F = 150 mA
P_D = 150 mW



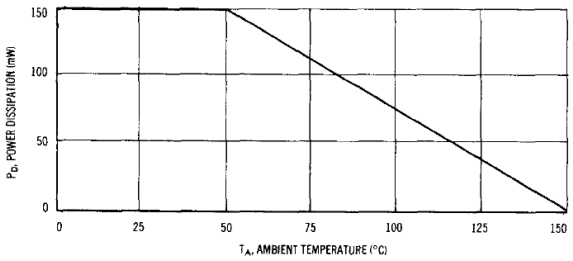
CASE 51
(DO-7)

PNPN 4-layer diodes, two-terminal, fast switching devices specifically designed for low voltage applications such as logic circuits, pulse generators, memory and relay devices, relay replacement, alarm circuit, multivibrators, ring counters, and signal switching circuits. These devices feature low breakover (switching) voltage, fast switching speeds, low junction capacitance, low breakover currents, and sub-miniature package.

MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
Peak Reverse Blocking Voltage M4L3052 M4L3053 M4L3054	$V_{RM(rep)}$	 10 11 12	Volts
Continuous Forward Current	I_F	150	mA
Steady State Power Dissipation @ T_A = 50°C Derate above 50°C	P_D	150 1.5	mW mW/°C
Peak Pulse Current (50 μs maximum pulse width)	I_{pulse}	10	Amp
Operating Junction Temperature Range	T_J	-65 to +150	°C
Storage Temperature Range	T_{stg}	-65 to +175	°C

POWER-TEMPERATURE DERATING CURVE



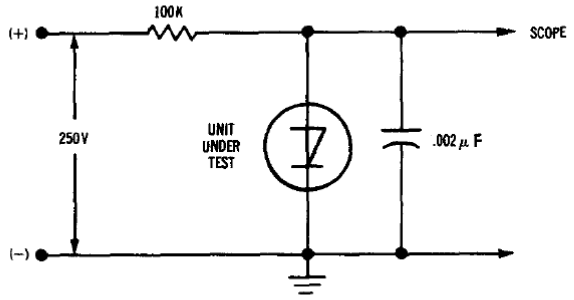
M4L3052 thru M4L3054 (continued)

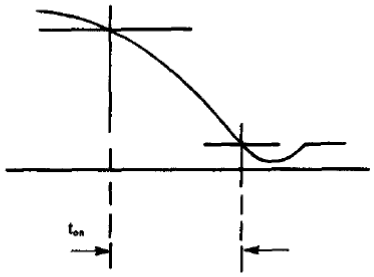
ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
Forward Breakover (Switching) Voltage M4L3052 M4L3053 M4L3054	$V_{(BR)F}$	 8 9 10	 — — —	 10 11 12	Volts
Forward Breakover (Switching) Current	$I_{(BR)F}$	—	5	50	μA
Forward Blocking Current (Measured at 75% of $V_{(BR)F}$)	I_{FM}	—	1	5	μA
Reverse Blocking Current (Measured at rated $V_{RM(rep)}$)	I_{RM}	—	2	10	μA
Holding Current	I_{HO}	1	4	20	mA
Forward On Voltage (I_F = 150 mAdc)	V_F	—	1.0	1.5	Volts
Junction Capacitance (AC Voltage = 10 mV, V_F = 0, f = 100 kHz)	C_J	—	42	—	pF
Turn-On Time*	t_{on}	—	50*	—	ns
Turn-Off Time*	t_{off}	—	100*	—	ns

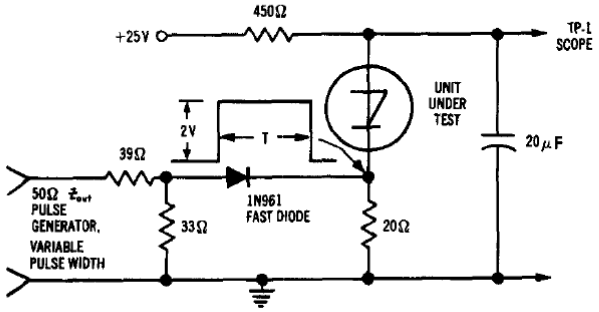
*Time depends on a wide variety of circuit conditions. Consult manufacturer for further information.

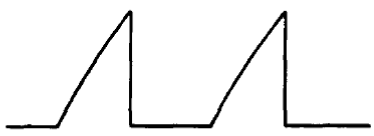
TURN-ON TIME TEST CIRCUIT





TURN-OFF TIME TEST CIRCUIT

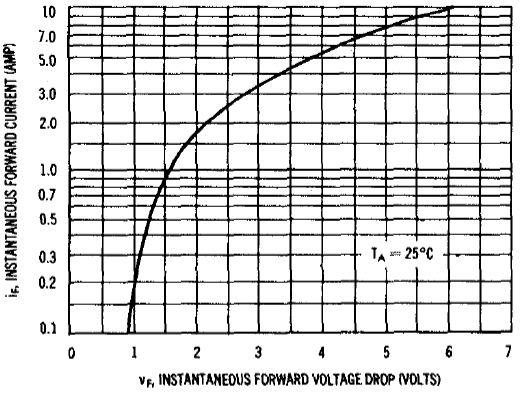




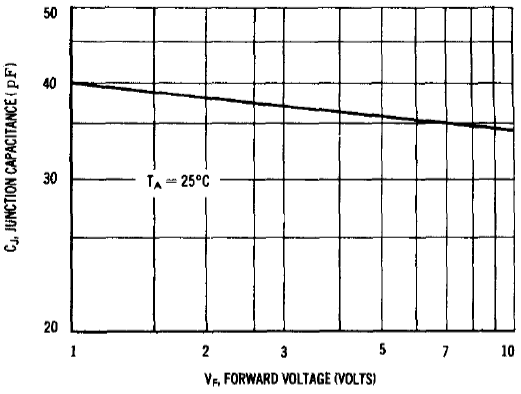
When sawtooth waveform appears at TP-1, $T = t_{off}$

M4L3052 thru M4L3054 (continued)

TYPICAL FORWARD CONDUCTION CHARACTERISTICS

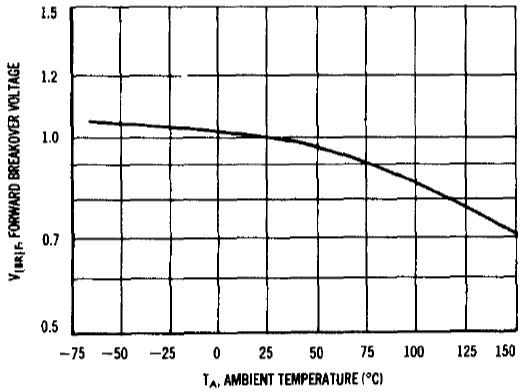


TYPICAL CAPACITANCE

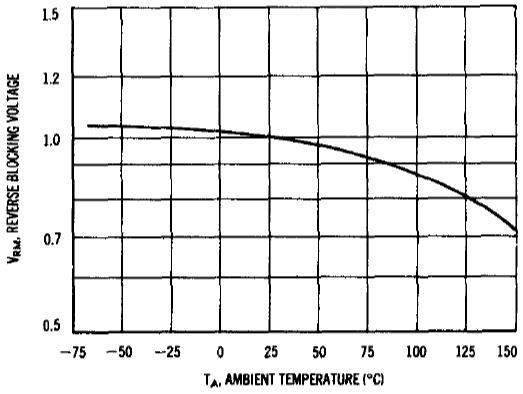


TYPICAL DC CHARACTERISTICS versus TEMPERATURE
(NORMALIZED to 25°C VALUE)

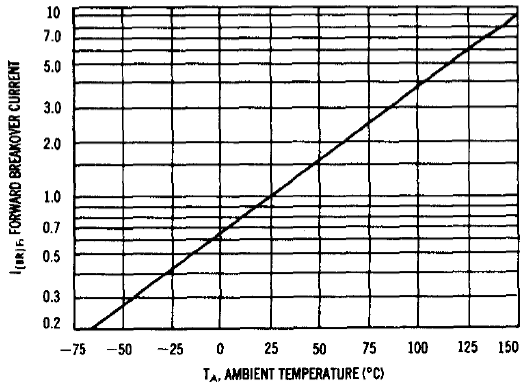
FORWARD BREAKOVER VOLTAGE



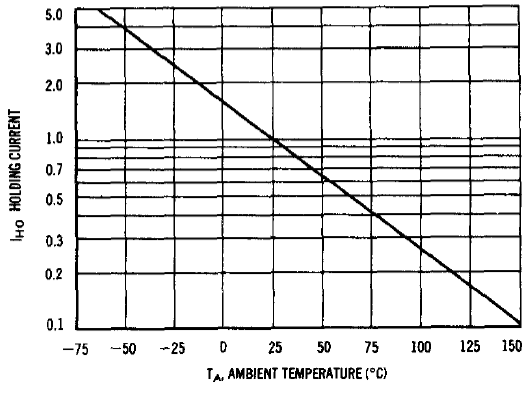
REVERSE BLOCKING VOLTAGE



FORWARD BREAKOVER CURRENT



HOLDING CURRENT



Appendix – 1N5158-1N5160 and 1N5779 – 1N5793 4-Layer Diode Specifications

From: Motorola Semiconductor Products Inc. *Discrete Products, Series A: Volume 2 (1N5000 and up), Semiconductor Data Library*. Phoenix, AZ: Motorola Semiconductor Products Inc; 1974.

1N5158 thru 1N5160
1N5779 thru 1N5793

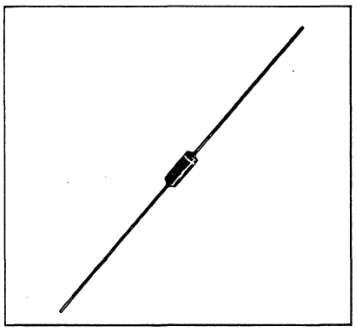
PNPN 4-LAYER DIODES

. . . two terminal, fast-switching devices specifically designed for low voltage applications such as logic circuits, pulse generators, memory and relay drivers, relay replacements, alarm circuits, multivibrators, ring counters, and telephone switching circuits. These devices feature:

- Low Breakover (Switching) Voltage – 10 to 15-Volt Ratings
- Fast Switching Speeds – t_{on} = 75 ns (Typ)
  t_{off} = 250 ns (Typ)
- Low Junction Capacitance – 45 pF (Typ)
- Low Breakover Currents
- Subminiature Glass Package

EPITAXIAL 4-LAYER DIODES

10-15 VOLTS
150 mW

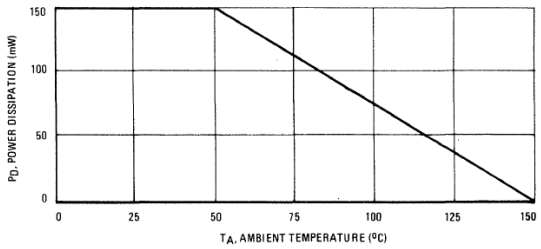


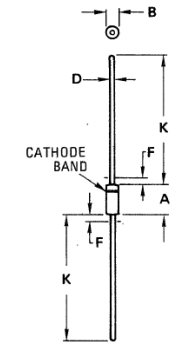
MAXIMUM RATINGS (T_A = 25°C unless otherwise noted)

Rating	Symbol	Value	Unit
*Reverse Voltage 1N5158, 1N5782, 1N5788 1N5159, 1N5783, 1N5789 1N5160, 1N5784, 1N5790 1N5779, 1N5785, 1N5791 1N5780, 1N5786, 1N5792 1N5781, 1N5787, 1N5793	V_{RM}	10 11 12 13 14 15	Volts
*Continuous Forward Current	I_F	150	mA
*Steady State Power Dissipation @ T_A = 50°C Derate above 50°C	P_D	150 1.5	mW mW/°C
*Peak Pulse Current (50 μs maximum pulse width)	I_{pulse}	10	Amps
*Operating Junction Temperature Range	T_J	-65 to +150	°C
Storage Temperature Range	T_{stg}	-65 to +175	°C

*Indicates JEDEC Registered Data.

FIGURE 1 – POWER-TEMPERATURE DERATING CURVE





DIM	MILLIMETERS MIN	MILLIMETERS MAX	INCHES MIN	INCHES MAX
A	5.84	7.62	0.230	0.300
B	2.16	2.72	0.085	0.107
D	0.46	0.56	0.018	0.022
F	–	1.27	–	0.050
K	25.40	–	1.000	–

All JEDEC dimensions and notes apply

CASE 51-02
DO-7

ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic		Symbol	Min	Typ	Max	Unit
*Forward Switching Voltage	1N5158, 1N5782, 1N5788	V_S	8.0	–	10	Volts
	1N5159, 1N5783, 1N5789		9.0	–	11	
	1N5160, 1N5784, 1N5790		10	–	12	
	1N5779, 1N5785, 1N5791		11	–	13	
	1N5780, 1N5786, 1N5792		12	–	14	
	1N5781, 1N5787, 1N5793		13	–	15	
*Forward Switching Current	1N5158 thru 1N5160, 1N5779 thru 1N5781	I_S	–	5.0	50	μA
	1N5782 thru 1N5793		–	10	100	
*Forward Off-State Current (V_F = 0.75 x V_S)		I_{FM}	–	1.0	5.0	μA
*Reverse Current (V_R = V_{RM})		I_{RM}	–	2.0	10	μA
*Holding Current	1N5158 thru 1N5160, 1N5779 thru 1N5781	I_H	1.0	4.0	20	mA
	1N5782 thru 1N5787		10	–	50	
	1N5788 thru 1N5793		0.1	–	2.0	
*Forward On Voltage (I_F = 150 mAdc)		V_F	–	1.0	1.5	Volts
*Critical Rate of Applied Forward Voltage		dv/dt				V/μs
(V_S = 6.0 Vdc)	1N5158, 1N5782, 1N5788		–	–	0.1	
(V_S = 6.75 Vdc)	1N5159, 1N5783, 1N5789		–	–	0 1	
(V_S = 7.5 Vdc)	1N5160, 1N5784, 1N5790		–	–	0.1	
(V_S = 8.25 Vdc)	1N5779, 1N5785, 1N5791		–	–	0.1	
(V_S = 9.0 Vdc)	1N5780, 1N5786, 1N5792		–	–	0.1	
(V_S = 9.75 Vdc)	1N5781, 1N5787, 1N5793		–	–	0.1	
Junction Capacitance (AC Voltage = 10 mV, V_F = 0, f = 100 kHz)		C_J	–	45	–	pF
Turn-On Time (Figure 2)		t_{on}	–	75(1)	–	ns
Turn-Off Time (Figure 3)		t_{off}	–	250(1)	–	ns

*Indicates JEDEC Registered Data. (1) Time depends on a wide variety of circuit conditions. Consult manufacturer for further information.

FIGURE 2 – TURN-ON TIME TEST CIRCUIT

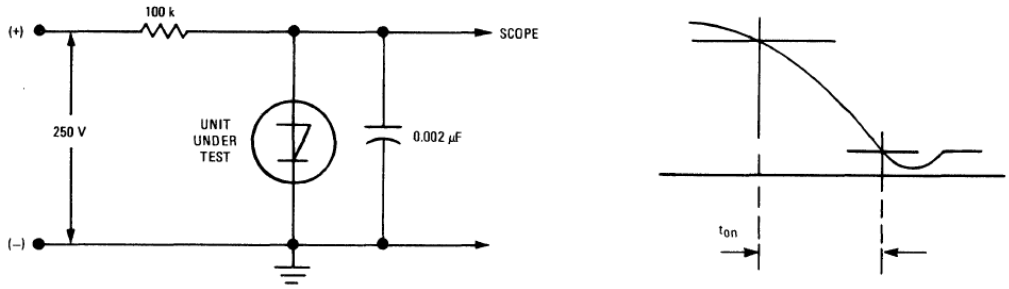


FIGURE 3 – TURN-OFF TIME TEST CIRCUIT

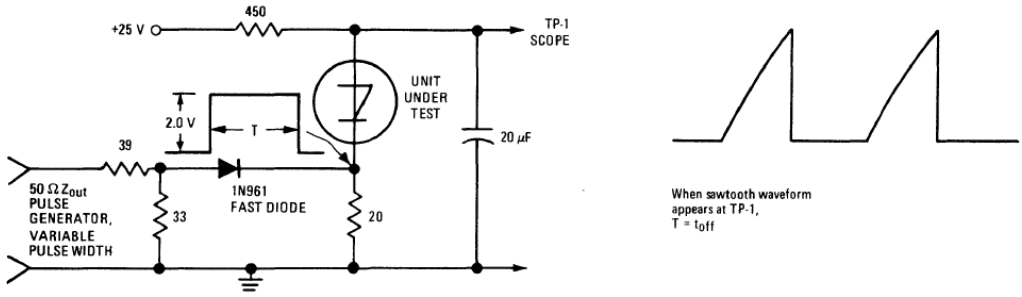


FIGURE 4 – TYPICAL FORWARD CONDUCTION CHARACTERISTICS

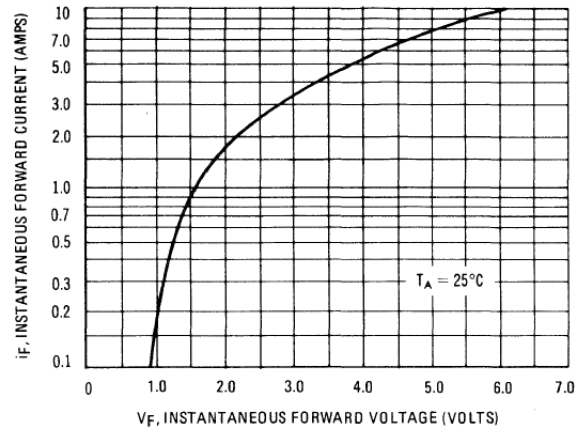
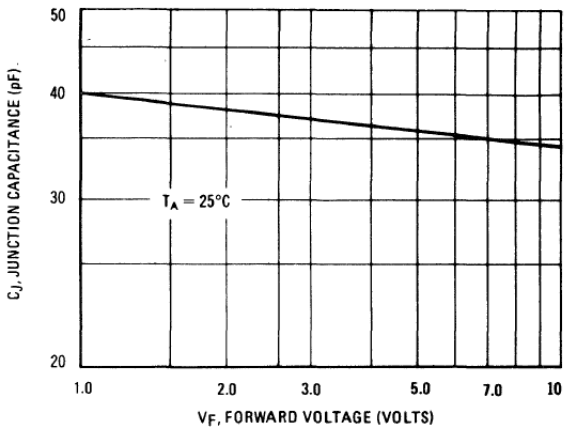


FIGURE 5 – TYPICAL CAPACITANCE



TYPICAL DC CHARACTERISTICS versus TEMPERATURE

(NORMALIZED to 25°C VALUE)

FIGURE 6 – FORWARD BREAKOVER VOLTAGE

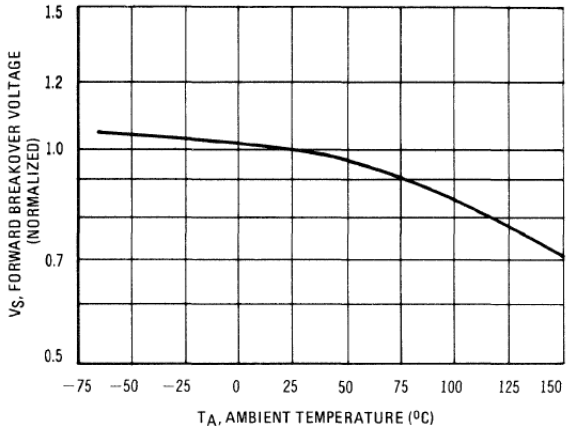


FIGURE 7 – REVERSE BLOCKING VOLTAGE

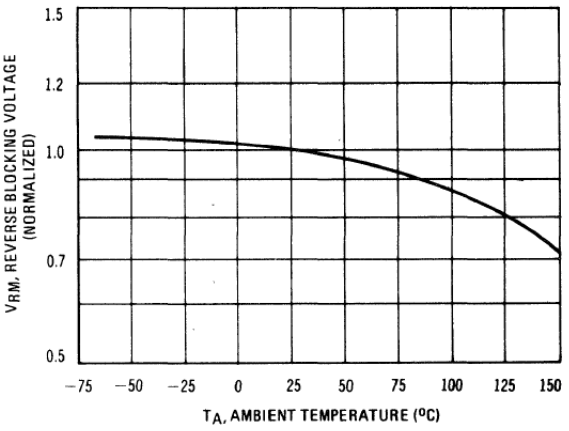


FIGURE 8 – FORWARD BREAKOVER CURRENT

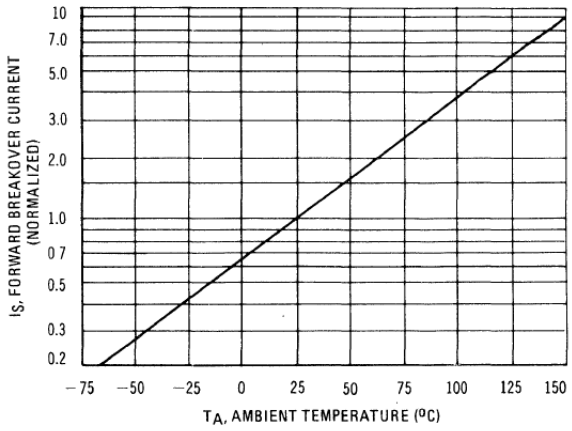
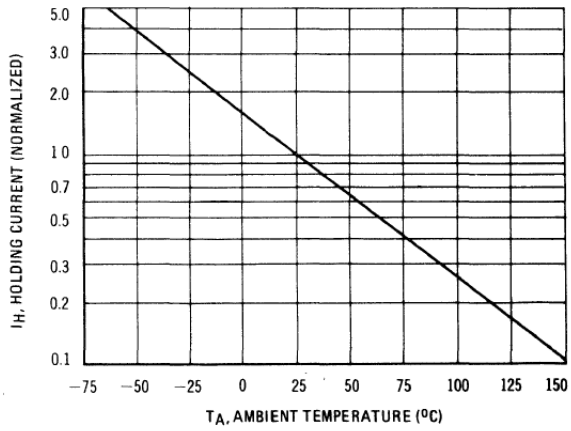
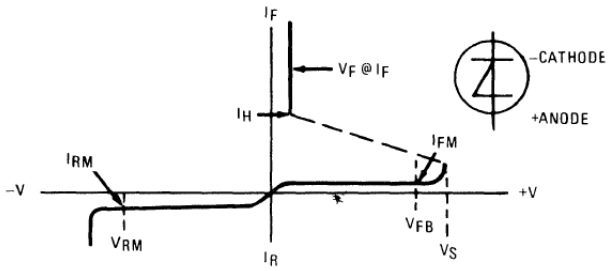


FIGURE 9 – HOLDING CURRENT



4-LAYER DIODE SYMBOLS AND DEFINITIONS



dv/dt **FORWARD VOLTAGE APPLICATION RATE (V/μs)** – The rate of rise of forward voltage.

I_S **FORWARD BREAKOVER (SWITCHING) CURRENT** – The value of anode current at the instant the device switches from the blocking to the "on" state, specified at a particular junction temperature.

I_F **FORWARD CURRENT** – The continuous or DC value of forward current during the "on" state.

I_{FM} **PEAK FORWARD BLOCKING CURRENT** – The peak anode current when the 4-layer diode is in the "off" state for a stated anode-to-cathode voltage and junction temperature.

I_H **HOLDING CURRENT** – That value of forward anode current below which the 4-layer diode switches from the conducting state to the forward blocking condition.

I_{pulse} **PEAK PULSE CURRENT** – The peak repetitive current that can flow through the device for the time duration stated.

I_{RM} **PEAK REVERSE BLOCKING CURRENT** – The peak current when the 4-layer diode is in the reverse blocking state for a stated anode-to-cathode voltage and junction temperature.

P_D **STEADY-STATE POWER DISSIPATION**

T_A **AMBIENT TEMPERATURE**

T_J **JUNCTION TEMPERATURE**

T_{stg} **STORAGE TEMPERATURE**

t_{on} **TURN-ON TIME** – The time interval between the 90% point (90% of forward blocking voltage) and the point 10% above the "on" voltage under stated conditions.

t_{off} **TURN-OFF TIME** – The time interval required for the device to regain control of its forward blocking characteristic after interruption of forward anode current.

V_S **FORWARD BREAKOVER (SWITCHING) VOLTAGE** – The positive anode voltage with respect to cathode required to switch the device from the high impedance blocking state to the low impedance "on" state, specified at a particular junction temperature.

V_F **FORWARD VOLTAGE** – The forward voltage across the device in the "on" state under stated conditions of current and temperature.

V_{FB} **FORWARD BLOCKING VOLTAGE** – The anode-to-cathode voltage when the 4-layer diode is in the "off" state.

V_{RM} **PEAK REVERSE VOLTAGE** – The maximum allowable instantaneous value of reverse voltage (repetitive or continuous DC) which can be applied to the device at a stated temperature without damage to the device.

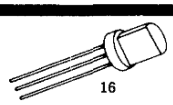
MECHANICAL CHARACTERISTICS

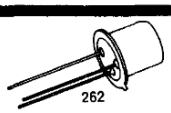
CASE: Hermetically sealed all glass case
DIMENSIONS: JEDEC DO-7 Outline
FINISH: All external surfaces are corrosion resistant with readily solderable leads.
POLARITY: Cathode end indicated by color band.
WEIGHT: 0.2 grams (approx.)
MOUNTING POSITION: Any

Appendix – GE Silicon Unilateral Switch Specifications

From: General Electric Company, Semiconductor Products Dept. *Semiconductor Data Handbook*. Syracuse (NY): General Electric Company; 1971. p. 126, 521–524.

SILICON UNILATERAL AND BILATERAL SWITCHES
(SUS, SBS)





The General Electric SUS is a silicon, planar monolithic integrated circuit having thyristor electrical characteristics closely approximating those of an "ideal" four-layer diode. The device is designed to switch at 8 volts with a typical temperature coefficient of 0.02%/°C. A gate lead is provided to eliminate rate effect, obtain triggering at lower voltages, and to obtain transient-free waveforms.

The SBS is a bilateral version of the forward characteristics of the SUS. It provides excellently matched characteristics in both directions with the same low temperature coefficient.

	GE Type	V_{ACR} Reverse Voltage Max. (V)	I_F Continuous Forward Current Max. (mA)	I_F Peak Recurrent Forward Current @ 100°C, 10 μs, 1% duty cycle (A)	P_T Dissipation (mW)	T_C Temperature Coefficient of Switching Voltage (%/°C)	V_S Switching Voltage Min. (V)	V_S Switching Voltage Max. (V)	I_S Switching Current Max. (μA)	I_B Forward Blocking Current @ 5V (μA)	V_F Forward Voltage @ 200mA (V)	I_H Holding Current (mA)	V_O Peak Pulse Voltage Min. (V)	Package
Unilateral	2N4987	30	175	1.0	300	—	6	10	500	1.0	1.5	1.5	3.5	16
	2N4988	30	200	1.0	350	±.05	7.5	9	150	0.1	1.5	.5	3.5	
	2N4989	30	200	1.0	350	±.02	7.5	8.2	300	0.01	1.5	1.0	3.5	H
	2N4990	30	175	1.0	300	—	7	9	200	0.1	1.5	.75	3.5	
	2N4983	30	175	1.0	300	—	6	10	500	1.0	1.5	1.5	3.5	G
	2N4984	30	200	1.0	350	±.05	7.5	9	150	0.1	1.5	.5	3.5	
	2N4985	30	200	1.0	350	±.02	7.5	8.2	300	0.01	1.5	1.0	3.5	
	2N4986	30	175	1.0	300	—	7	9	200	0.1	1.5	.75	3.5	262
Bilateral	2N4991	—	175	1.0	300	—	6	10	500	1.0	1.7	1.5	3.5	16
	2N4992	—	200	1.0	350	±.05	7.5	9	120	0.1	1.7	.5	3.5	
	2N4993	—	175	1.0	300	—	6	10	500	1.0	1.7	1.5	3.5	262