Megahertz UJT Oscillator

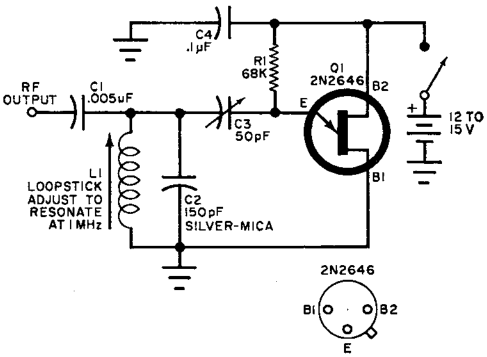
THEY SAID IT COULDN'T BE DONE

BY FRANK H. TOOKER

USED in simple relaxation oscillators, unijunction transistors (UJT's)—particularly those of the inexpensive variety—will not operate very far into the low radio-frequency range. However, the circuit shown at right enables sine-wave output from 2N2646 UJT's at 1 MHz. With selected UJT's of this type, the circuit will continue to operate up to about 1.5 MHz, above which frequency performance is poor.

In the circuit, *L1* and *C2* make up a tuned circuit which is resonated at 1 MHz by adjusting the core of *L1*. Components *C3* and *R1*, in series with *L1-C2*, comprise a relaxation oscillator circuit. Capacitor *C3* charges through *R1*, and when the peak-point emitter voltage of UJT *Q1* appears across *C3*, the UJT fires, discharging *C3* across the *L1-C2* tuned circuit. This sets the tuned circuit into oscillation and, thereafter, the positive-going excursions of the voltage across *L1-C2* add to the voltage across *C3* to fire the UJT.

Conventional UJT's will not operate at 1 MHz—and even selected ones operate poorly at 500 kHz—but at lower submultiples of 1 MHz (333 kHz, 250 kHz, and 200 kHz), the UJT fires dependably. The setting of variable capacitor *C3* determines *Q1*'s firing rate. Thus, by adjusting *C3*, the firing of the UJT can be synchronized (accurately locked-in) with every third, fourth, or fifth cycle of oscillation of the *L1-C2* tuned circuit.



The UJT operates at submultiple of output frequency and shock-excites tank circuit to generate r.f. output. This oscillator circuit can reach 1.5 MHz.

Since a comparatively large voltage is developed across *L1-C2*, the lock-in setting of *C3* isn't especially critical. In practice, all that is necessary is to adjust *C3* to the minimum value of capacitance that will produce a maximum signal at the oscillator's r.f. output terminal. To avoid hand-capacitance effects while you're adjusting *C3*, it is essential that its stator (not the rotor) be connected to the emitter of the UJT.

If you have several UJT's, try each one, for some 2N2646's work better in this circuit than others. The output of the oscillator is at a very high impedance; thus, if it is to be loaded at all, it must be worked into a high impedance to maintain oscillation.

—30—

DUAL UJT MULTIVIBRATOR

By FRANK H. TOOKER

Unijunction transistors in a multivibrator circuit can produce excellent square waves without the aid of other semiconductors.

UNIJUNCTION transistors have long been used in hybrid circuits—with another diode or bipolar transistor—to obtain multivibrator performance. But UJT's can produce excellent square waves without help from any other kind of semiconductor device.

In Fig. 1, the charging and discharging of a single timing capacitor, *C*1, fires the two UJT's, *Q*1 and *Q*2 alternately, and produces a rectangular wave at the base of each of the transistors.

It's easy to understand the operation of the dual-UJT multivibrator if we inspect the simultaneous waveforms shown in Fig. 2. Assume *Q*1 fires first, then at the instant of firing, the potential at the emitter of *Q*1 drops abruptly from point A in time to point B. (*Q*1 is held "on" until point C is reached.) During the interval between points B and C, capacitor *C*1 is charging in such a direction as to make the emitter of *Q*2 more positive. When this potential has increased sufficiently, *Q*2 fires. At this point, the potential at the emitter of *Q*1 drops abruptly below the hold-on level (from point C to point D) and *Q*1 turns "off."

The firing of *Q*2 initiates an identical sequence of events at the emitter of *Q*2. During the interval *Q*2 is "on" and *Q*1 is "off," capacitor *C*1 charges and makes the emitter of *Q*1 more positive (point D to point E in Fig. 2). When point E is reached, *Q*1 fires and turns "on." *Q*2 is turned "off" and the cycle repeats. The result is an output signal of rectangular waveform at the base-2 of each of the two UJT's and a triangular waveform across timing capacitor *C*1.

When the two unijunction transistors have identical characteristics, and the base-2 and emitter resistors in each side of the circuit have identical values, the output waveform is symmetrical, *i.e.*, mark and space ("on" and "off") times are equal. If the emitter resistors, *R*2 and *R*3, are made unequal in value, the mark-to-space ratio of the output signal will be changed accordingly.

In general, the repetition rate is determined by all the component values in the circuit, especially the UJT characteristics. For the component values given in Fig. 1, the repetition rate is about 180 Hz. The d.c. current drain with a 12-volt power supply is less than 2 mA.

In certain experimental circuits, dual-UJT multivibrators have been operated at a switching rate as low as one cycle every 30 seconds. In this case, emitter resistors *R*2 and *R*3 each have a value of 20 megohms, and capacitor *C*1 is 10 μF. But, because *C*1 reverses polarity, electrolytic capacitors are not recommended for this application.

The single-transistor circuit of Fig. 3 is unique in that it combines the function of two UJT's in one. Furthermore, it produces a triangular waveform at E while providing a rectangular signal at B2. Although triangular waves are customarily obtained as an integration of a square wave, the circuit of Fig. 3 accomplishes this automatically by the action of resistor *R*2 and capacitor *C*2.

Pulse repetition rate is determined largely by *R*1 and *C*2, while waveform symmetry is determined by *R*1 and *R*2. The value of feedback capacitor *C*1 is not critical. For the component values given in Fig. 3, the repetition rate is about 60 Hz. ▲

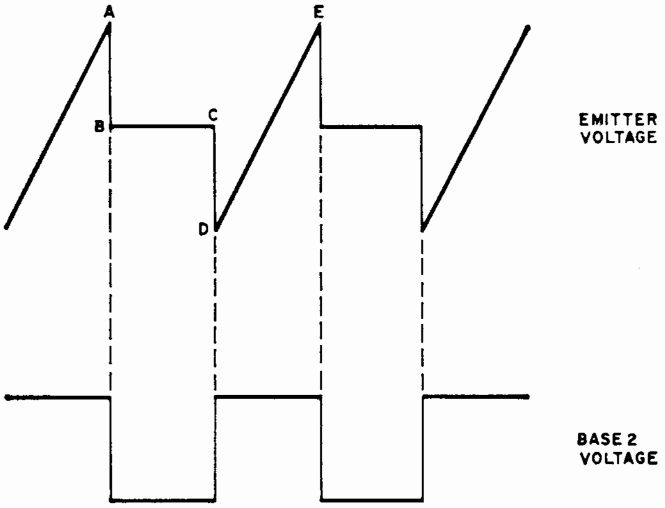
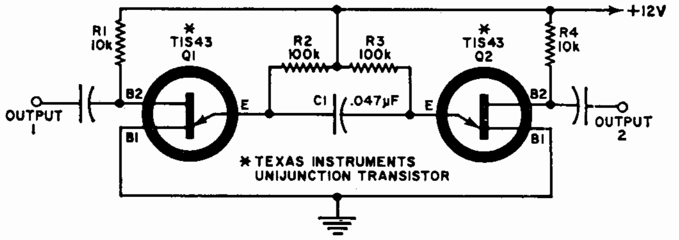


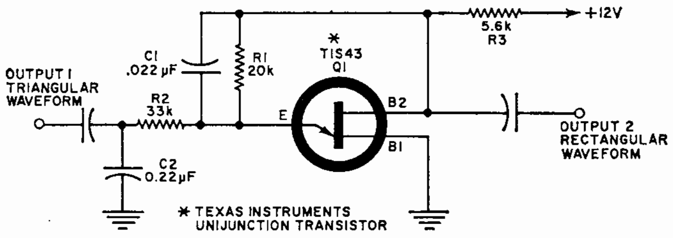
Fig. 2. Timing diagram of UJT multivibrator.

Fig. 1. Dual UJT multivibrator has square-wave output.



* TEXAS INSTRUMENTS UNIJUNCTION TRANSISTOR

Fig. 3. Single UJT combines functions of two units.

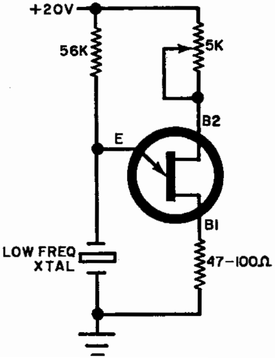


* TEXAS INSTRUMENTS UNIJUNCTION TRANSISTOR

UJT Oscillator Stabilization

Q. ***Is there any way to stabilize a UJT oscillator?***

A. Not many people know it, but you can control a UJT oscillator with a crystal as shown in the sketch. Use a low-frequency (100 kHz as a good start) crystal instead of the usual timing capacitor and adjust the potentiometer in the B2 leg for the desired waveform at the emitter. You can parallel the crystal with some low-value capacitor to change the frequency.



APPLICATION ENGINEERING
ICONDUCTOR PRODUCTS DEPARTMENT
ELECTRONICS PARK BUILDING 7
SYRACUSE, NEW YORK

APPLICATION NOTE

90.12
4/62

Unijunction Temperature Compensation

by

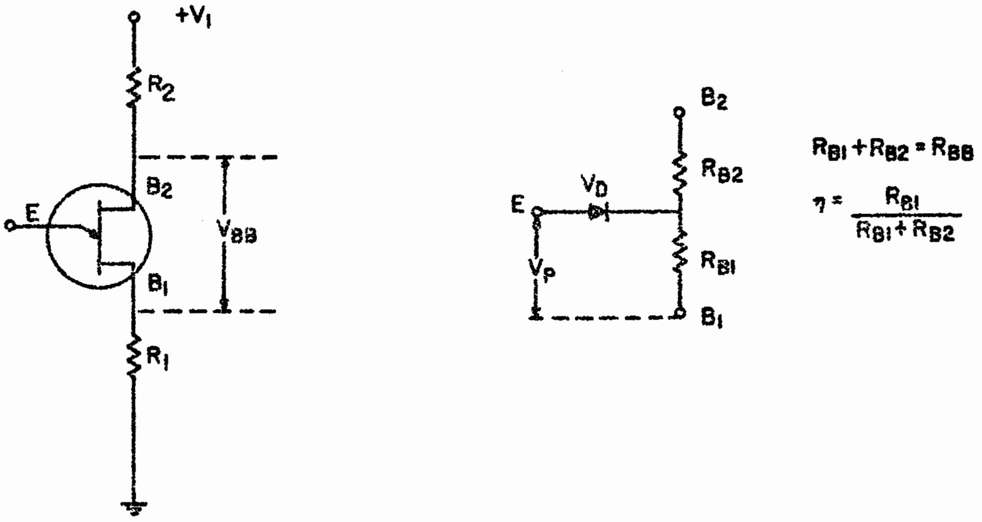
D. V. Jones

The peak point voltage (V_P) of the unijunction (UJT) determines the triggering voltage in bistable circuits and the frequency of relaxation oscillators. From the equivalent circuit of the UJT shown in Figure 1,

$$V_P = \eta V_{BB} + V_D \qquad (1)$$

where V_{BB} = interbase voltage
η = standoff ratio
V_D = voltage drop across the emitter diode

The principal variation of V_P with temperature is due to the variation of V_D with temperature. This effect may be compensated by means of a small resistor (R_2) as shown in Figure 1. As the ambient temperature increases the interbase resistance (R_{BB}) will increase and V_{BB} will also increase due to the voltage divider action of R_2, R_{BB} and R_1.



TYPICAL UJT
BIAS CIRCUIT

UJT EQUIVALENT CIRCUIT
FOR PEAK POINT

FIGURE 1

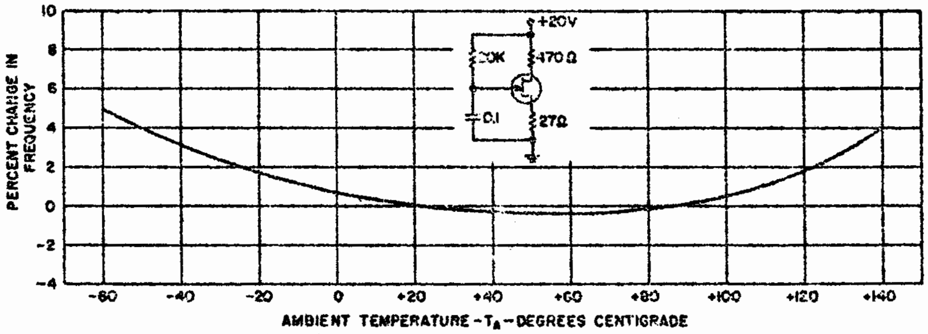
If R_2 is chosen correctly the increase in interbase voltage will compensate for the decrease in V_D. The approximate value of R_2 is,

$$R_2 \cong \frac{0.70\ R_{BB}}{\eta\ V_1} + \frac{(1-\eta)R_1}{\eta} \qquad (2)$$

If R_2 satisfies this equation the peak point voltage will be given by,

$$V_P = \eta V_1 \qquad (3)$$

Figure 2 shows a typical variation of relaxation oscillator frequency with temperature where the UJT was the only component submitted to the varying ambient temperature. Frequency stability could thus be improved if the other components had compensating temperature coefficients. The value of the compensating resistor in series with base 2 was selected using equation 2.



ONLY THE UNIJUNCTION SUBMITTED TO TEMPERATURE

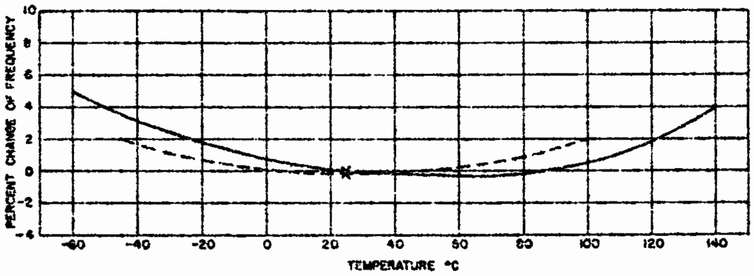
FIGURE 2

Individual Compensation

If the compensating resistor is adjusted or selected for each unit (by placing the circuit in an oven and adjusting R_2 of each circuit) the frequency change from 25° to 100°C will generally be less than ¼%. It is easier and often adequate to place a thermal probe (set for the desired maximum temperature) on the UJT and adjust R_2 for minimum frequency change from room ambient conditions. This method gives very good results when the values of the resistors and capacitors are quite stable with temperature.

General Compensation

If an average value of resistance is determined for R_2 by taking a random sample of unijunctions, and determining the average fixed resistance which compensates the best over a more limited temperature range than is shown in Figure 2, it is possible to achieve better stability. The reason being that the temperature coefficient of the UJT is not perfectly linear, and since equation 2 is for the tempeature range of 25 to 140°C, over a more limited range the actual slope of the temperature coefficient can be compensated more accurately with R_2. For temperatures less than 100°C, more accurate compensation can be obtained by using a value for R_2 that is approximately one-half that given by equation 2.



TYPICAL FREQUENCY VS TEMPERATURE CURVE
FIGURE 3

Frequency Stability from 0°C to 100°C

	Typical	Maximum
Individual Compensation	<¼%	<1%
General Compensation	<½%	<2%

Compensation Below 25°C

The solid curve in Figure 3 is the same as Figure 2. If the value of R_2 is decreased it causes the curve to rotate counter-clockwise with 25°C as the pivot point. (see dashed curve) Thus if the temperature range of interest is from -45° to 100°C, then the value of R_2 can be decreased to compromise between the ½% deviation at 100°C and the 3-½% at -45°C, to give approximately 2% at each temperature extreme as shown by dashed curve of figure 3.

More accurate compensation may be obtained below 25°C by using a thermistor as part of R_T, see Figure 4.

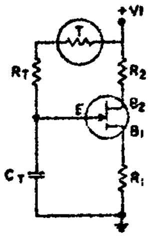
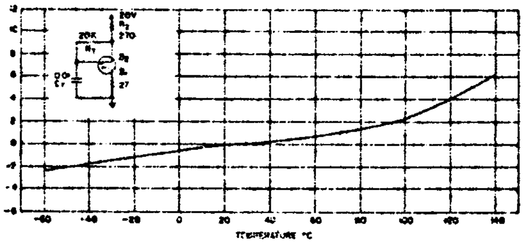


FIGURE 4

At higher frequencies where C_T is less than .02 µf the capacitor has more influence on the circuit in regards to emitter voltage fall time, temperature effect, and peak-to-peak emitter voltage, see pages 40 and 41 of application note 90.10 which gives a detailed discussion on the UJT. Because of these capacitor effects, the stability at temperatures below 25°C can be improved by returning R_T to base 2 of the UJT as in Figure 5. R_2 may be tapped at an optimum point for best negative temperature compensation for the particular supply voltage and temperature range.



TYPICAL FREQUENCY VS. TEMPERATURE
UJT ONLY SUBJECTED TO TEMPERATURE

FIGURE 5

Precision Stabilization

If a stability of better than .05% is required over a considerable ambient temperature range, then the complete relaxation circuit can be operated in a small components (crystal) oven to obtain this stability.

NORTHERN ALBERTA INSTITUTE OF TECHNOLOGY
EDMONTON ALBERTA

ELECTRONICS DEPARTMENT

AN-293

Application Note

THEORY AND CHARACTERISTICS OF THE UNIJUNCTION TRANSISTOR

INTRODUCTION

The unijunction transistor or UJT is by no means a newcomer to the semiconductor industry. In 1948 the feasibility of such a device was demonstrated by Heinrich Welker in France and a year later Shockley and Haynes wrote a paper describing the basic principles of UJT operation. The first commercially available UJT was developed by I.A. Lesk* in 1952.

This note will first discuss the theory associated with UJT operation, followed by a table explaining unijunction transistor nomenclature. The conventional UJT structures are then described as well as the annular method by which the Motorola UJT is manufactured. Finally, some of the more important characteristics of the UJT and their behavior under different operating conditions will be discussed.

THEORY OF OPERATION

The unijunction transistor (UJT) is a three terminal device, the three terminals being the emitter, base one and base-two.

The UJT (or double base diode as it was called in early papers) has, as the name implies, only a single P-N junction, and the characteristics of the UJT are for this reason quite different from those of the conventional transistor. Table I shows the commonly used UJT symbols and their proper definitions in accordance with the Joint Electron Device Engineering Council (JEDEC) Standard.

In order to explain the operation of the unijunction transistor it is convenient to use the so called bar structure as a model (the bar structure will be discussed in detail later in the paper). This structure is shown somewhat simplified in Figure 1a and the electrical equivalent circuit is shown in Figure 1b. The equivalent circuit is valid for emitter currents equal to or less than the peak point current.

When voltage V_{B2B1} is applied, a current will flow in the silicon bar from base-two to base-one. Since the bar is essentially a resistor of magnitude r_{BB}, the current that flows into base-two is determined by $I_{B2} = \frac{V_{B2B1}}{r_{BB}}$.

A fraction of the applied voltage V_{B2B1} will appear at point A where the emitter is alloyed onto the silicon bar, and this fraction is denoted as η. The voltage at point A is therefore η V_{B2B1}, the P-N junction formed by the emitter and the silicon bar is reverse biased and only a small reverse leakage current flows in the emitter lead.

As the voltage V_E at the emitter is increased, a point will be reached where V_E equals the voltage at point A plus the forward voltage drop of the P-N junction, V_D. The emitter voltage at this point is called the peak point emitter voltage V_p. The peak point voltage can be written as:

$$V_p = V_D + \eta V_{B2B1}. \tag{1}$$

The P-N junction is now forward biased, and holes will be injected from the emitter into the silicon bar. The electric field inside the bar set up by V_{B2B1} is of such a direction that the injected holes will be moved toward the base-one terminal. Conductivity σ of a semiconductor material is given by the equation:

$$\sigma = q\,(\mu_e n + \mu_h p) \tag{2}$$

where q = electronic charge (1.6×10^{-19} coulomb)

μ_e = mobility of conduction electrons

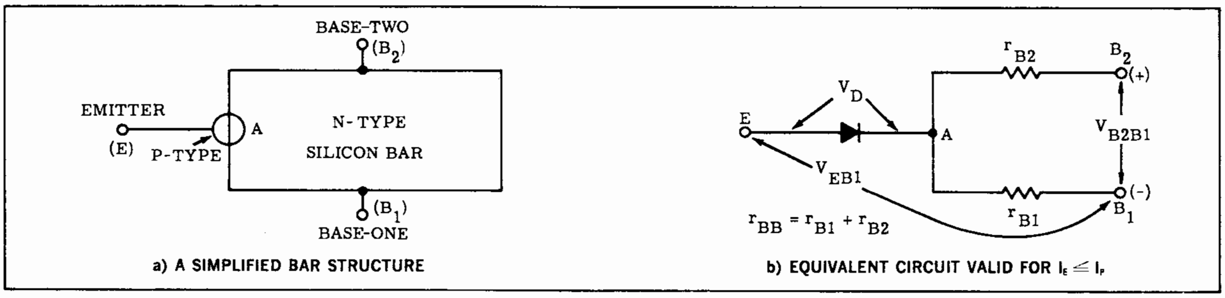
μ_h = mobility of conduction holes

n = electron concentration

p = hole concentration

---

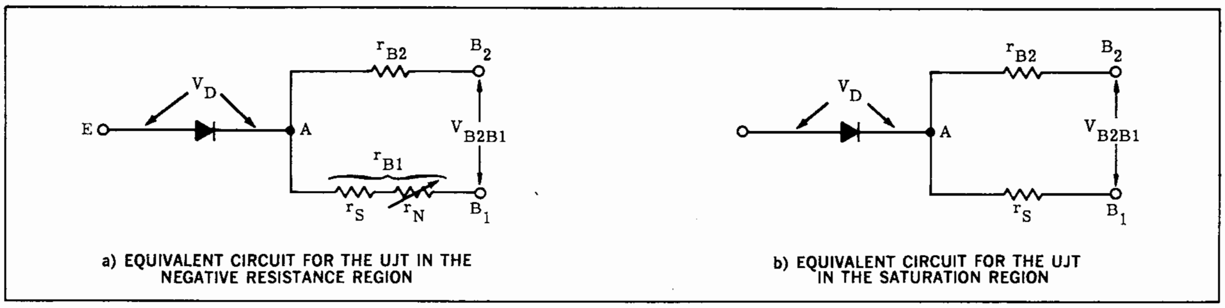
*Presently Director of Engineering, Motorola Semiconductor Products Division.



a) A SIMPLIFIED BAR STRUCTURE

b) EQUIVALENT CIRCUIT VALID FOR $I_E \leq I_P$

FIGURE 1



a) EQUIVALENT CIRCUIT FOR THE UJT IN THE NEGATIVE RESISTANCE REGION

b) EQUIVALENT CIRCUIT FOR THE UJT IN THE SATURATION REGION

FIGURE 2

When the holes are injected into the bar from the emitter, an equal amount of electrons will be injected from base-one to maintain charge neutrality. Since both the electron and hole concentrations increase in the silicon bar between the emitter and base-one, the conductivity will also increase according to equation (2). Resistivity ρ is defined as the reciprocal of conductivity or:

$$\rho = \frac{1}{\sigma} \qquad (3)$$

and hence the resistivity will decrease. This process is called "conductivity modulation". The decrease in resistivity will cause a decrease in the voltage drop from emitter to base-one, which in turn allows more holes to be injected from the emitter, and the conductivity will increase further. This is clearly a regenerative process, and the UJT is now in the so-called negative resistance region. An equivalent circuit for this region is shown in Figure 2a. At emitter currents equal to or less than I_p the resistance r_{BB} can be divided into two parts; r_{B1} and r_{B2} according to the relations:

$$r_{B1} = \eta\, r_{BB} \text{ and } r_{B2} = r_{BB} - r_{B1}. \qquad (4)$$

(As shown in Figure 1b)

In the negative resistance region, resistor r_{B1} can be thought of to consist of a fixed portion r_s, and a variable portion r_N, where r_s is the saturation resistance and r_N is the negative resistance, the magnitude of which decreases with increasing emitter current. r_N will be equal to zero when the hole concentration in the silicon bar is approximately $10^{16}\ \frac{\text{carriers}}{\text{Cm}^3}$ [†] and under that condition the saturation resistance r_s will be only resistance between emitter and base-one. When $r_{B1} = r_s$, the UJT is no longer in the negative resistance region. The reason for this is that the high density of carriers in the bar has decreased the lifetime τ of the carriers sufficiently to counteract the effects of the new carriers being generated. Mobility is related to lifetime by the equations:

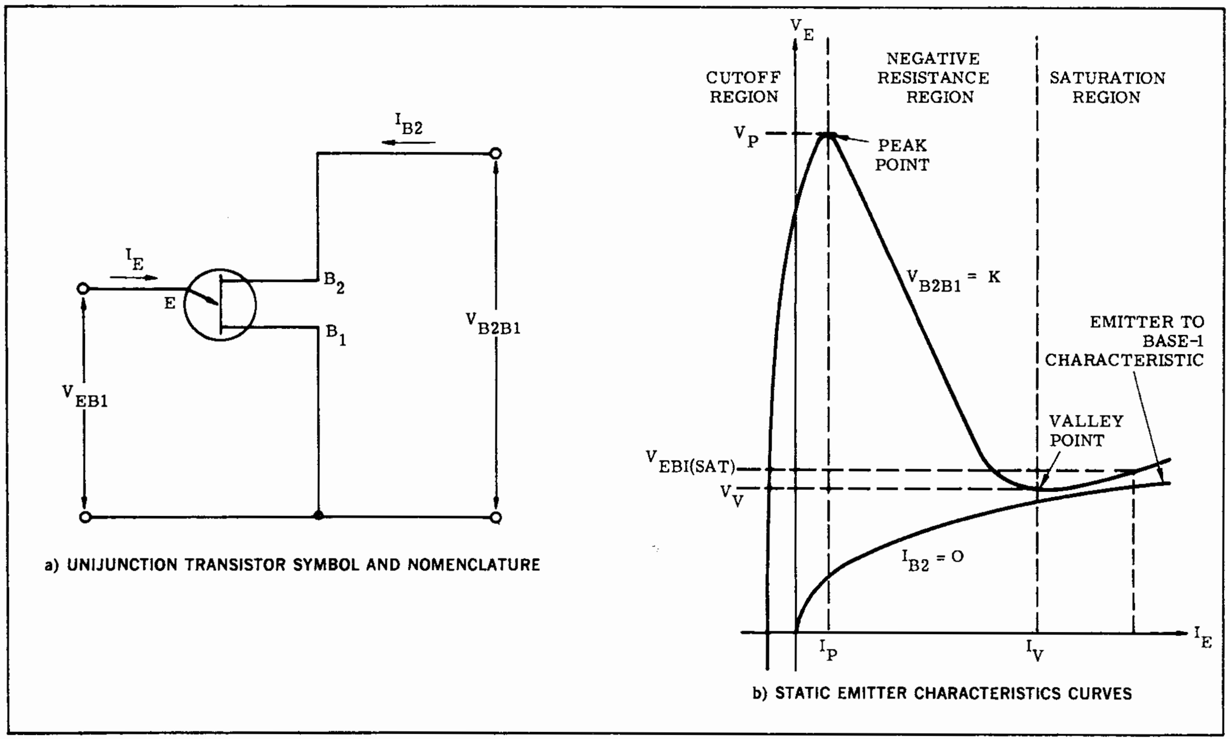
$$\mu_e = \frac{q\tau}{m_e} \quad \text{and} \quad \mu_h = \frac{q\tau}{m_h} \qquad (5)$$

where m_e and m_h are the effective mass of electrons and holes, respectively. Mobility therefore decreases when lifetime decreases, and the conductivity given by equation (2) is found to remain relatively constant for emitter currents up to 500 mA.

The point on the emitter characteristic where r_{B1} just reaches its minimum value is called the valley point. The emitter current and voltage at this point are the valley point emitter current I_V, and the valley point emitter voltage V_V.

When the emitter current is increased beyond I_V, the unijunction transistor enters the so-called saturation region where the emitter current is essentially a linear function of the emitter voltage. The equivalent circuit for the saturation region is shown in Figure 2b.

The standard unijunction transistor symbol with appropriate terms for current and voltage is given in Figure 3a. and a static emitter characteristic curve for a single value of V_{B2B1} is shown in Figure 3b. It should be noted that the emitter curve is not drawn to scale in order to show the different operating regions in more detail. The region to the left of the peak point is called the "cutoff region", the emitter junction being reverse biased in most of this region and slightly forward biased at the peak point. The region between the peak point and the valley point, where the emitter junction is forward biased and conductivity modulation takes place, is called the "negative resistance region". The region to the right of the valley point, where the emitter current is limited by r_s, is called the "saturation region". The curve for base-two current (I_{B2}) equal to zero is essentially the forward characteristic of a silicon diode.



a) UNIJUNCTION TRANSISTOR SYMBOL AND NOMENCLATURE

b) STATIC EMITTER CHARACTERISTICS CURVES

FIGURE 3 — UJT SYMBOLS, NOMENCLATURE, AND EMITTER CHARACTERISTICS

[†] R.B. Adler, et al: Introduction to Semiconductor Physics page 34 Wiley

VARIOUS UJT STRUCTURES

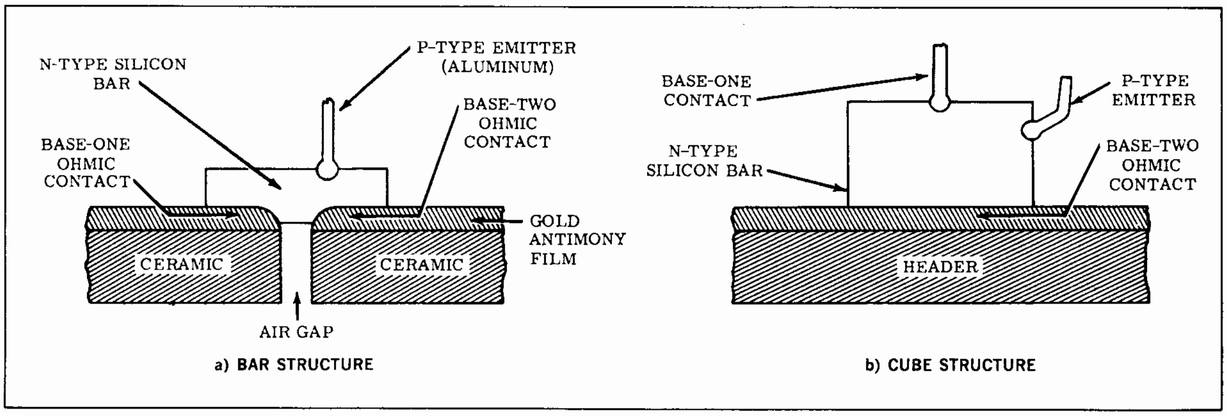
Early unijunction transistors were the bar structure and the cube structure, the cross-section diagrams of which are shown in Figure 4a and 4b, respectively.

The bar structure in Figure 4a is formed by mounting a high resistivity N-type silicon bar on a ceramic platform having an air gap in the center and gold-antimony film deposited on each side of the gap. Base-one and base-two are ohmic contacts that are formed between the silicon bar and the gold. A single P-type emitter is formed by alloying an aluminum wire onto the bar opposite from the base contacts.

The cube structure, shown in Figure 4b, employs a high resistivity N-type silicon cube. The cube is mounted on a header with a gold-antimony alloy contact between the bottom of the cube and the header. The base-two ohmic contact is made to the gold-antimony area. Base-one is formed by alloying a gold wire to the top of the silicon bar and the emitter is similarly formed by alloying an aluminum wire to a side of the cube.

Although the bar and cube structures have been in use for many years, they are not readily adapted to modern automatic production methods. For this reason, Motorola has evolved a new and different design in which the die is fabricated using processes similar to those used for silicon annular overlay transistors. A simplified outline of the production steps is given in Figure 5. Referring to Figure 5a, using photo-resist techniques and starting with an oxide passivated die of high resistivity N-type silicon, the emitter is diffused in using P-type boron. In Figure 5b the whole structure is again oxide protected. Windows are then etched in the oxide, and base-one and the annular ring are formed by the diffusion of N-type phosphorus. The structure is oxide protected again in Figure 5c, followed by a selective etching that removes the oxide in the emitter and base-one areas. Aluminum is then evaporated onto the structure to make contact with the emitter and base-one, while gold is evaporated onto the bottom of the die to form the base-two contact. In Figure 5d the exact contact geometries are determined by a final etch. In practice the above production steps are not performed on a single die but to a whole wafer. After the final etch the wafers are tested, scribed, and broken into several hundred dice.

Figure 6 shows a photo micrograph of the 2N4851 UJT geometry. In actual practice two base-one regions are formed, and before the bonding is performed, the die is probed and the base-one region providing the optimum characteristics is selected.



a) BAR STRUCTURE b) CUBE STRUCTURE

FIGURE 4 — EARLY UJT STRUCTURES

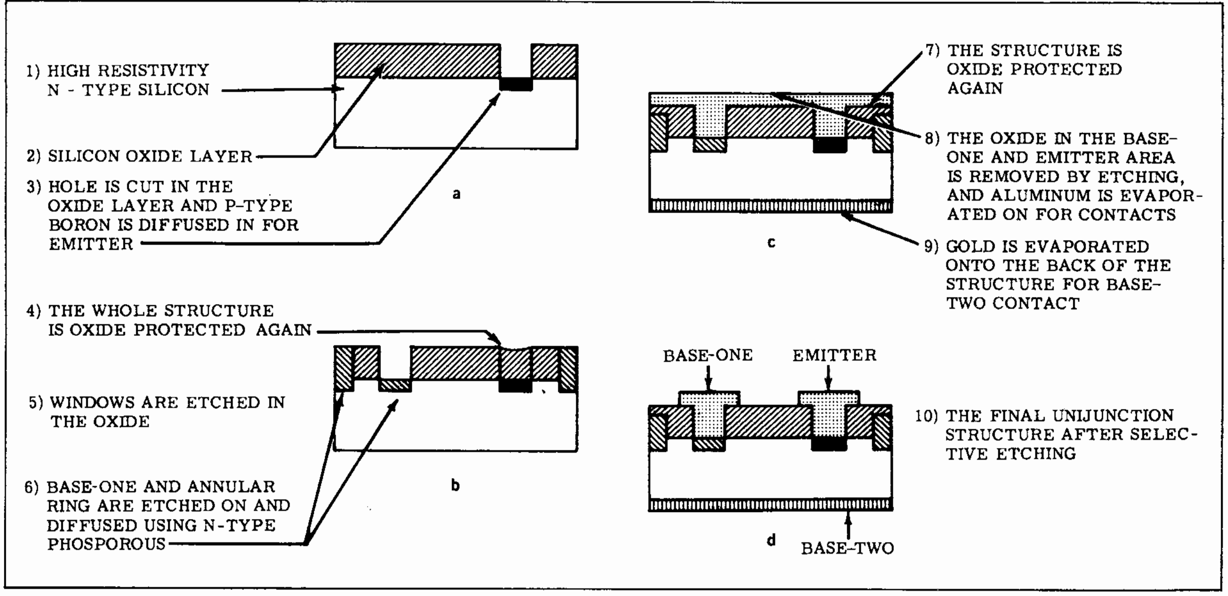


FIGURE 5 — THE ANNULAR UNIJUNCTION

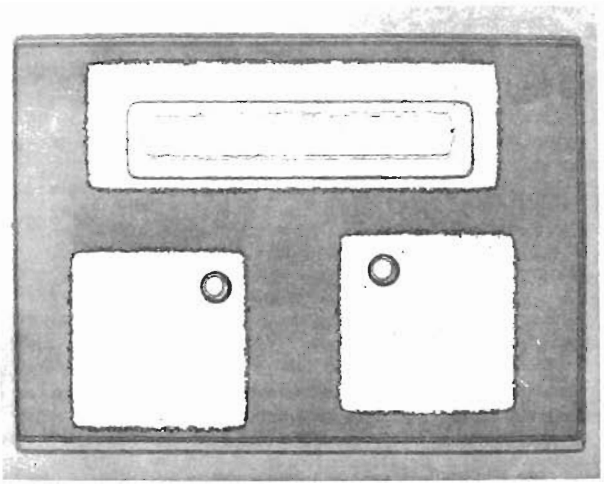


FIGURE 6 – PHOTOMICROGRAPH OF MOTOROLA ANNULAR UJT STRUCTURE

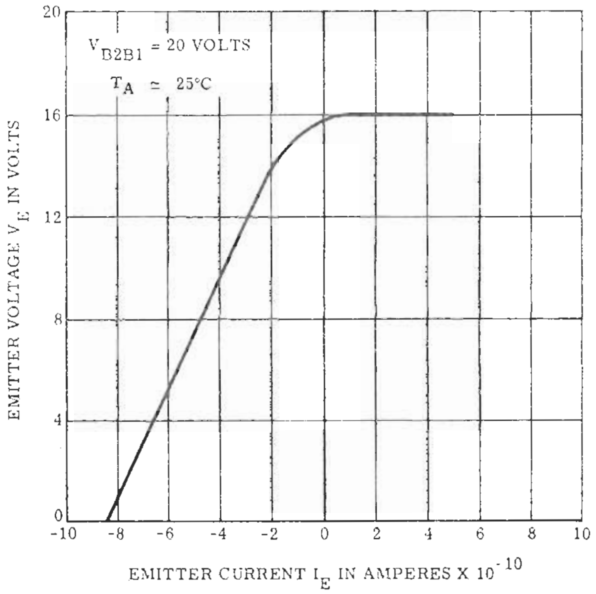


FIGURE 7a – STATIC EMITTER CHARACTERISTIC

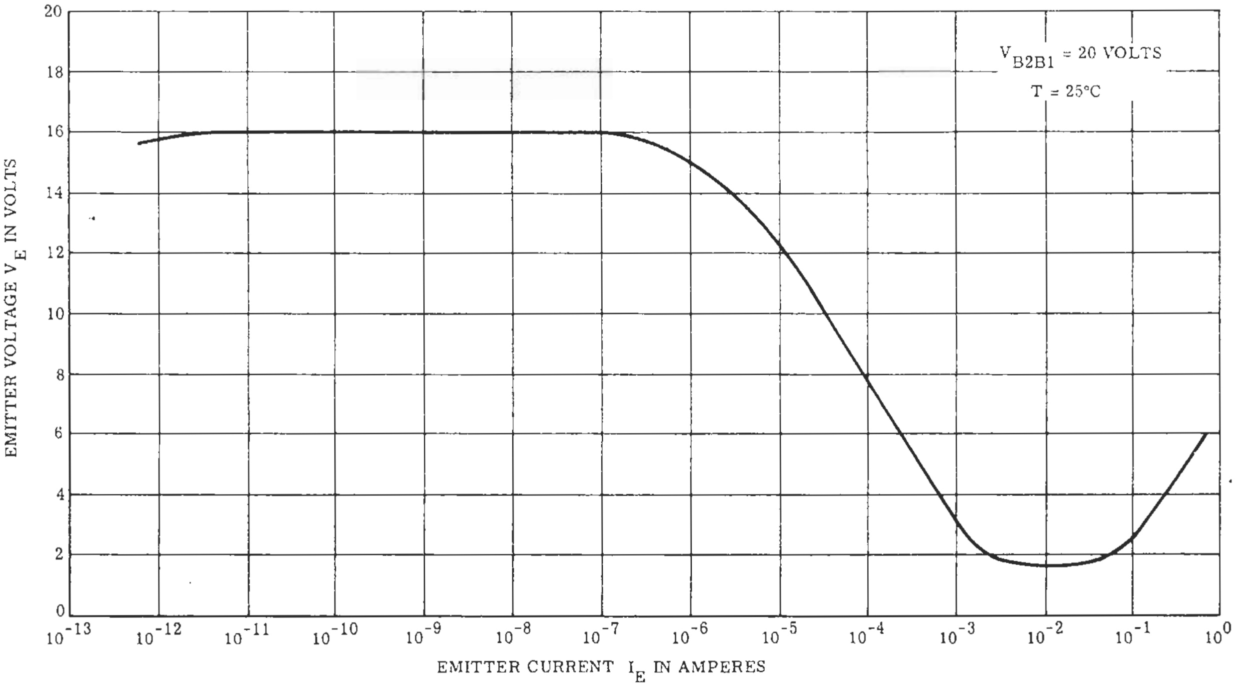


FIGURE 7b – STATIC EMITTER CHARACTERISTIC

STATIC EMITTER CHARACTERISTICS

As previously mentioned, the emitter characteristic shown in Figure 3b was not drawn to scale for the reasons explained. Figure 7a and 7b, however, shows a typical emitter curve for $V_{B2B1} = 20$ volts drawn to scale. Figure 7a shows part of the cutoff region plotted on linear scale. When the emitter voltage is zero, the emitter current is negative, i.e.: out of the emitter terminal, and is approximately equal to 1 nanoampere. Peak point voltage is reached at a forward emitter current of about 10 pA and as can be seen from Figure 7B the voltage remains constant until the emitter current reaches approximately 0.1 μA, at which point the voltage starts to decrease. From the definition of peak current, I_p for this particular device is therefore 0.1 μA and V_p equals 16 volts. Referring to Figure 7b, valley voltage can be seen to be about 1.6 volts and the valley current approximately 8 mA. The saturation resistance r_s can be found from the slope of the emitter characteristic in the saturation region (above 8 mA) and is in this case approximately 5.0 ohms. The characteristic in the negative resistance region was determined by the use of a constant-current source.

THE DIODE VOLTAGE DROP V_D

Some of the most important characteristics of the UJT are those that appear in the formula for peak voltage:

$$V_p = V_D + \eta V_{B1B2} \qquad (6)$$

Changes in the peak voltage would be very undesirable in applications like timers and oscillators, the accuracy of which depends on the repeatability of V_p.

V_D is defined as the forward voltage drop of the emitter junction and since it is essentially equivalent to the forward voltage drop of a silicon diode, the value of V_D is dependent both on forward current and temperature. V_D can be measured several ways, but it is important to hold the emitter current near I_p when the measurement is made since it really is V_D at I_p that is required in equation 6. One simple way of measuring V_D is shown in Figure 8. A constant current equal to I_p is applied between the emitter and base-one, and a potentiometric voltmeter is used to measure the voltage from emitter to base-two. This type of voltmeter has essentially infinite input impedance when the meter is "nulled" and there is no current flowing in the base-two lead. The voltage measured is therefore equal to V_D.

Figure 9 shows V_D as a function of temperature for an emitter current of 1 μA. The variation of V_D is essentially linear over the temperature range considered and is equal to -2.7 mV/°C. The diode voltage drop therefore decreases with increasing temperature and V_D can be written as:

$$V_D = V_{DN} - (T - 25) \circ K_D$$

where V_{DN} is the value of V_D at $T_A = 25°C$ and $K_D = -2.7$ mV/°C. (Note that K_D is current dependent and the value for K_D given applies only at 1 μA.)

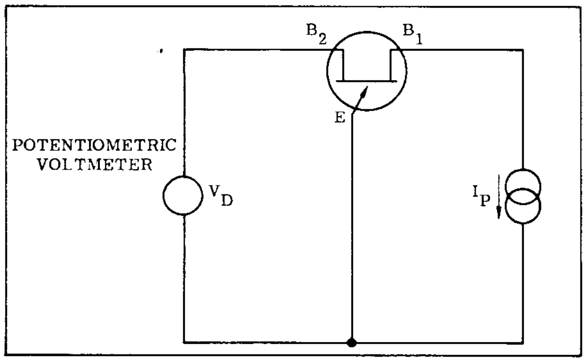


FIGURE 8 — CIRCUIT FOR MEASURING V_D

THE INTRINSIC STANDOFF RATIO η

The intrinsic standoff ratio defined by:

$$\eta = \frac{V_p - V_D}{V_{B2B1}} = \frac{r_{B1}}{r_{BB}} \qquad (7)$$

is generally believed to be essentially independent of temperature variations. However, this is not true. Figure 10 shows typical variations of η with temperature for unijunctions from three different manufacturers. There may be several reasons why η varies with temperature; the interbase resistance r_{BB} might not have a uniform temperature coefficient throughout the base-two, base-one region, or the temperature might not be uniform over the entire interbase resistance. Surface recombination might also be a factor.

η can be measured directly or it can be calculated from equation (7) when V_p and V_D are known.

The curve A-A in Figure 10 represents the Motorola annular UJT, and the variation of η is relatively linear with temperature over the temperature region considered. η can therefore be expressed by the formula:

$$\eta = \eta_N - (T - 25)\ K_\eta$$

where η_N is the value of η at 25°C, and K_η is a temperature coefficient expressed in %/°C. For the Motorola annular devices $K_\eta \cong \frac{0.06\%}{°C}$.

The intrinsic standoff ratio is also slightly dependent on V_{B2B1}, but the variation is so small that for all practical purposes η can be said to be independent of voltage.

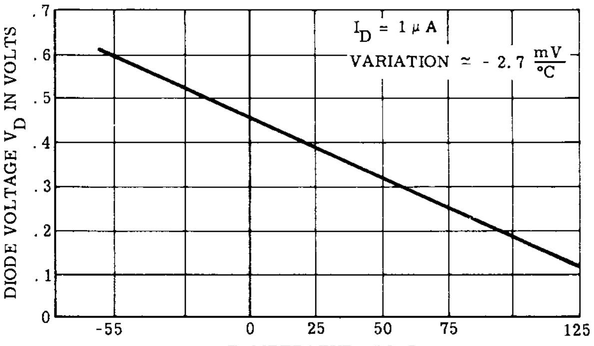


FIGURE 9 — DIODE VOLTAGE V_D versus TEMPERATURE FOR THE ANNULAR UNIJUNCTION

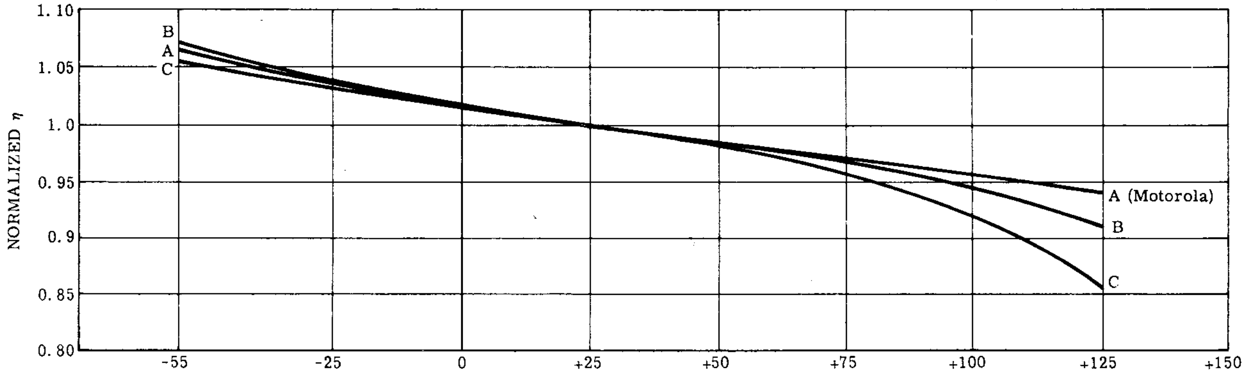


FIGURE 10 — NORMALIZED INTRINSIC STANDOFF RATIO versus TEMPERATURE FOR 3 DIFFERENT MANUFACTURERS (A, B, & C)

THE INTERBASE RESISTANCE r_{BB}

The resistance from base-two to base-one is highly temperature dependent. A typical r_{BB} vs. temperature characteristic curve for V_{B2B1} = 3 volts is shown in Figure 11. At very low temperatures, near absolute zero, few of the impurity atoms in the semiconductor material are ionized and the resistivity of the doped silicon is quite high. At -55°C however, most of the impurity atoms are fully ionized, and the carrier concentration is relatively constant as the temperature is increased. The lattice mobility decreases with increasing temperature due to increased lattice scattering, and hence the resistivity will increase. As the temperature is increased beyond 125°C, the impurity concentration becomes swamped by carriers produced by thermal generation, and the resistivity decreases rapidly as the temperature is increased. The measurements were performed on a pulsed basis to avoid heating due to power dissipation. In the temperature region from 0 to +125°C, the increase in r_{BB} with temperature is essentially linear, and r_{BB} can be expressed by the formula:

$$r_{BB} = r_{BBN} + (T - 25) \; . \; K_r$$

where r_{BBN} is the value of r_{BB} at 25°C, and K_r is given as a %/°C variation of r_{BBN}. For the annular devices K_r is found to be:

$$K_r \simeq 0.8\%/°C \; . \; r_{BBN}$$

In addition, r_{BB} is also found to vary with interbase voltage V_{B2B1}. A typical curve is shown in Figure 12 where r_{BBN} is normalized to the value of r_{BB} for V_{B2B1} = 3 volts, the voltage usually specified on the manufacturer's data sheet.

This increase in r_{BB} with voltage is in part due to a current limiting effect in the base one contact area. Knowing r_{BB} at V_{B2B1} = 3 V. for an annular device, r_{BB} at any other value of V_{B2B1} can be found with a reasonable degree of accuracy from Figure 12. These readings have also been obtained by a low duty-cycle pulse method in order to avoid heating due to power dissipation. T_j is therefore approximately equal to T_A. For normal operating conditions, the temperature rise in the base-one, base-two region must be calculated and the change in r_{BB} due to temperature taken into account.

THE PEAK POINT CHARACTERISTICS

Both V_p and I_p decrease as temperature is increased. That V_p will decrease is evident from the formula for V_p since both η and V_D were found to decrease. The variation of V_p with temperature can be minimized by the addition of an external resistor in the base two circuit. This procedure is discussed in detail in Motorola Application Note AN-294. V_p varies with interbase voltage in accordance with equation (6).

THE VALLEY POINT CHARACTERISTICS

Both valley point voltage V_V and current I_V decrease as ambient temperature is increased. A curve showing typical temperature behavior for the annular device is given in Figure 13 where the curves are normalized to the value at 25°C.

I_V and V_V are also dependent on the interbase voltage. When V_{B2B1} increases both I_V and V_V will increase also. Typical curves showing this behavior are given in Figure 14. I_V and V_V are normalized to the value at 10 volts V_{B2B1}.

Valley current is a relatively difficult characteristic to measure since, as can be seen in Figure 7b, the voltage is relatively constant for large variations in emitter current around the valley point.

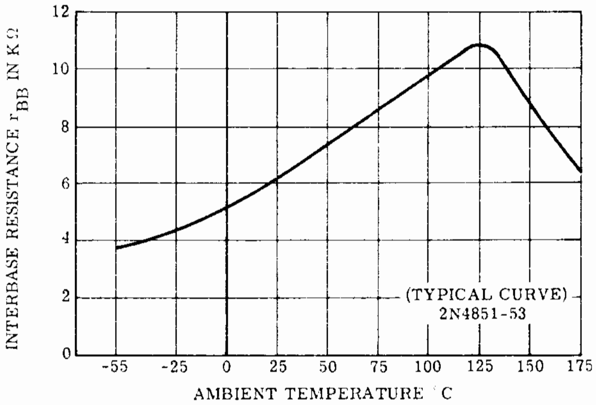


FIGURE 11 – INTERBASE RESISTANCE r_{BB} versus TEMPERATURE

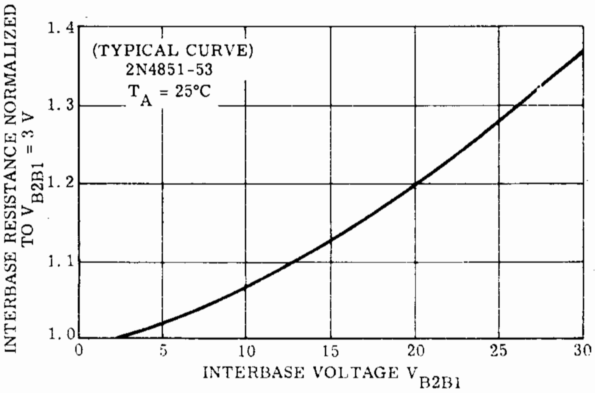


FIGURE 12 – TYPICAL VARIATION OF r_{BB} AS A FUNCTION OF INTERBASE VOLTAGE V_{B2B1}

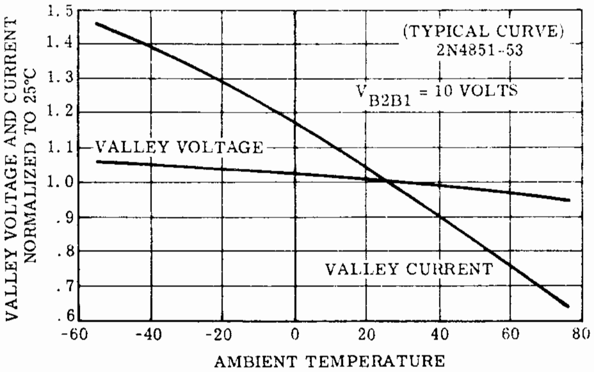


FIGURE 13 – VALLEY VOLTAGE AND VALLEY CURRENT versus AMBIENT TEMPERATURE

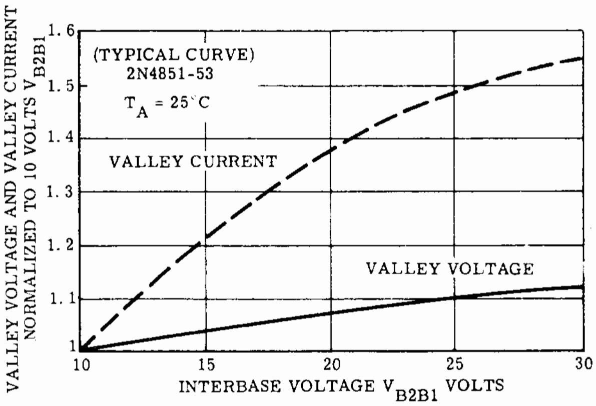


FIGURE 14 – VALLEY VOLTAGE AND VALLEY CURRENT versus INTERBASE VOLTAGE V_{B2B1}

THE EMITTER REVERSE CURRENT I_{EO} (or I_{EB2O})

The emitter reverse current is generally specified as the current flowing from base-two to the emitter with 30 volts applied between base-two and the emitter, (positive at base-two), and the base-one terminal open circuited. I_{EO} is highly temperature dependent since it actually is the leakage current of a silicon diode. This leakage current consists mainly of charge generation current, since diffusion current has little effect in silicon in the temperature range considered.

A curve showing typical variation of I_{EO} with temperature for a 2N4851 is shown in Figure 15 with I_{EO} being approximately 1.5 nA at 25°C.

INTERBASE CHARACTERISTICS

The measurement of base-two current I_{B2} as a function of interbase voltage and emitter current was performed on a sweep basis to avoid heating effects due to power dissipation. The test circuit for this measurement is shown in Figure 16a. A constant current was applied to the emitter from time t_0 to time t_1 and simultaneously a voltage ramp going from 0 to 30 volts was applied to base-two. Base-one was grounded. The current I_{B2} was measured with a current probe and applied to the vertical input of an oscilloscope, and the voltage ramp was applied to the horizontal input. As I_E and the ambient temperature were varied, the curves shown in Figure 16b, c, and d were observed.

It can be seen from the curves that the percentage increase in I_{B2} decreases with increasing emitter current and temperature. The modulated interbase current $I_{B2(mod)}$ is usually measured at $I_E = 50$ mA and $V_{B2B1} = 10$ volts. From Figure 16c this can be found to be approximately 11 mA.

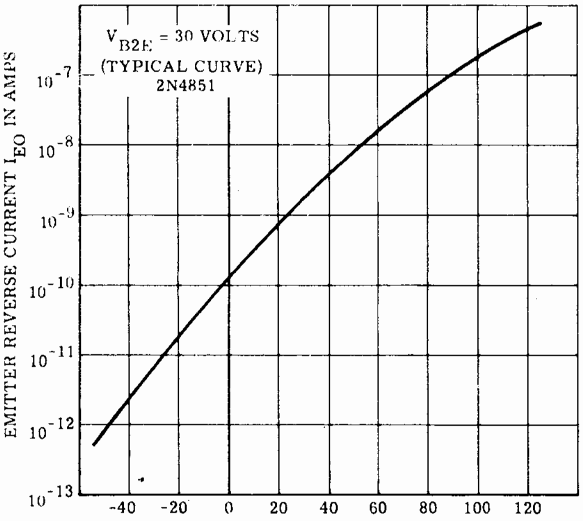


FIGURE 15 — EMITTER REVERSE CURRENT I_{EO} versus AMBIENT TEMPERATURE

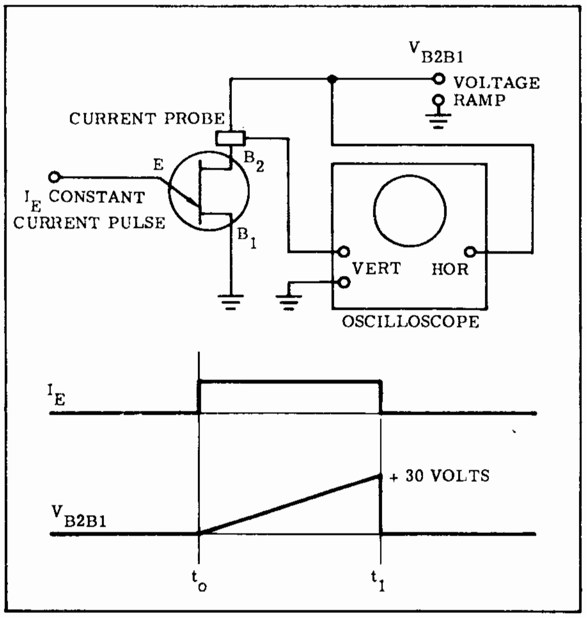


FIGURE 16a — TEST CIRCUIT USED TO DETERMINE THE INTERBASE CHARACTERISTIC

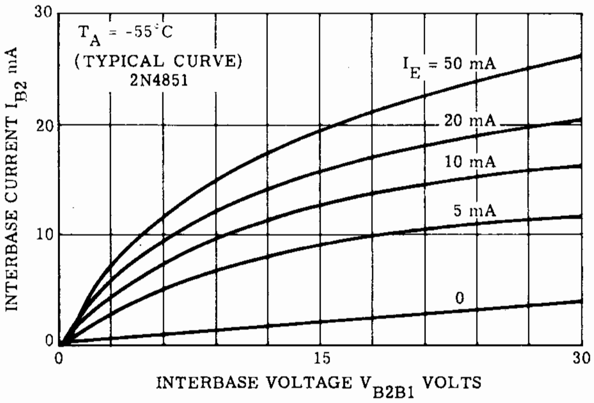


FIGURE 16b — INTERBASE CHARACTERISTIC

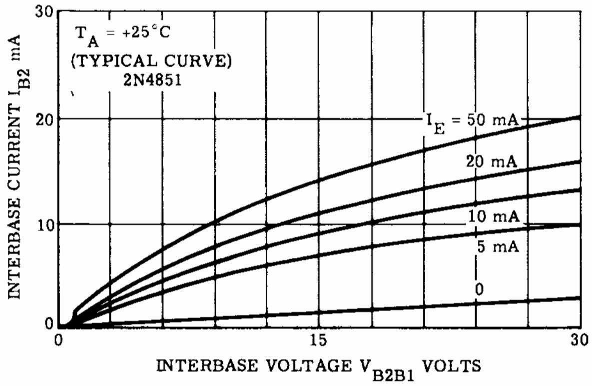


FIGURE 16c — INTERBASE CHARACTERISTIC

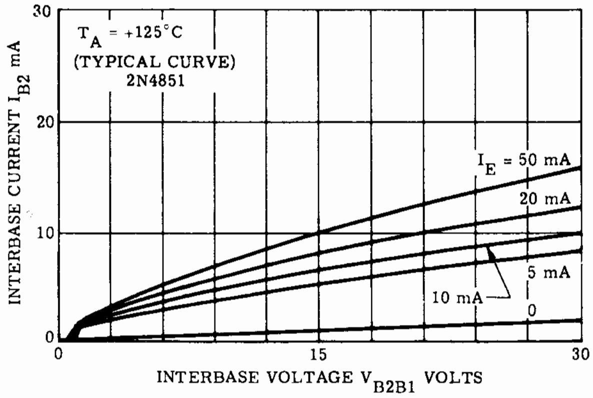


FIGURE 16d — INTERBASE CHARACTERISTIC

TRANSIENT CHARACTERISTICS

Switching times as specified for conventional junction transistors are generally not given on a UJT data sheet. Rather a parameter f_{max} is given which indicates the maximum frequency of oscillation that can be obtained using the UJT in a specified relaxation oscillator circuit.

In some applications such as critical timers, however, it might be of interest to determine "turn-on" and "turn-off" times associated with the UJT. Since these parameters are generally not specified, no fixed procedure has been established for their measurement, and two different methods with accompanying results will therefore be discussed here.

The circuit shown in Figure 17 was used to measure t_{on} and t_{off} for the case where the emitter circuit is purely resistive. Typical switching time values were found to be $t_{on} = 1$ µsec and $t_{off} = 2.5$ µsec. The waveform observed at the base-one terminal when the UJT turns off is shown in Figure 18. When the emitter is returned to ground, the stored charge in the junction will cause a current to flow out of the emitter and the output voltage across R_1 will be smaller than the steady state off value. Immediately following the removal of the excess charge, the voltage across R_1 will go higher than the steady state off value because r_{B1} has still not returned to normal following the conductivity modulation in the on state, and I_{B2} will be larger than the steady state off value. Steady state is reached after approximately 2.5 µsec.

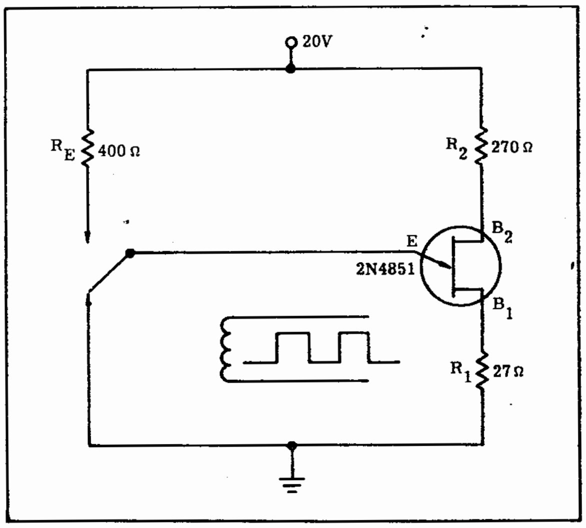


FIGURE 17 — CIRCUIT FOR t_{on} AND t_{off} MEASUREMENTS

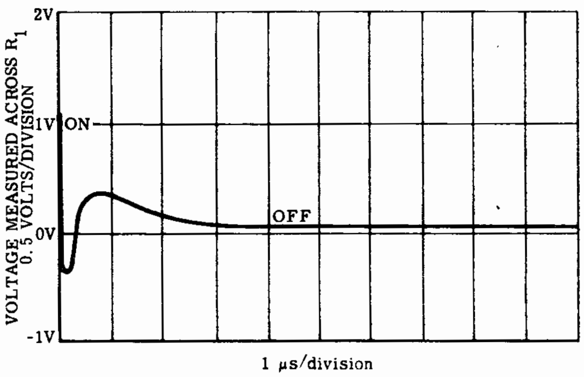


FIGURE 18 — "TURN-OFF" WAVEFORM FOR THE UJT AS MEASURED IN THE CIRCUIT IN FIGURE 17

In most practical applications, however, there will be both a resistor and a capacitor in the emitter circuit, and it is therefore of interest to determine what the switching times are under these conditions. The test circuit in this case was the relaxation oscillator circuit shown in Figure 19a, and turn-on and turn-off waveforms as observed at base-one are shown in Figure 19b, and 19c. Turn-on time measured from the start of turn-on to the 90% point is approximately 0.5 µsec and increases with increasing capacitance C_E. Turn-off time measured from the start of turn-off to the 90% point is about 12 µsec, due to the long discharge time of the capacitor. t_{off} also increases with C_E.

The effect of the capacitance C_E on switching time is shown in Figure 20a and 20b.

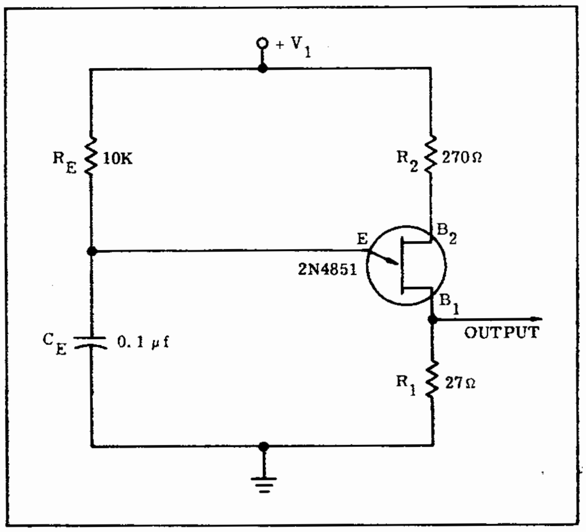


FIGURE 19a — RELAXATION OSCILLATOR CIRCUIT FOR t_{on} AND t_{off} MEASUREMENTS

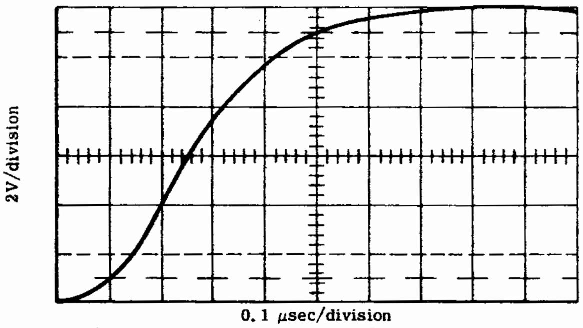


FIGURE 19b — TURN-ON WAVEFORM FOR CIRCUIT SHOWN IN FIGURE 19a

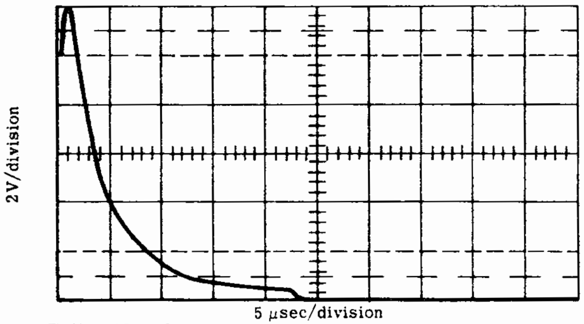


FIGURE 19c — TURN-OFF WAVEFORM FOR THE CIRCUIT SHOWN IN FIGURE 19a

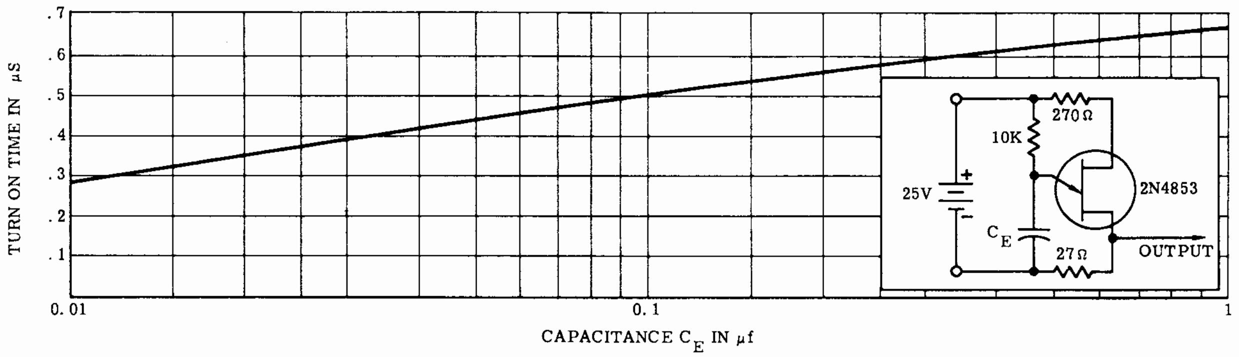


FIGURE 20a — TURN-ON TIME versus EMITTER CAPACITANCE C_E

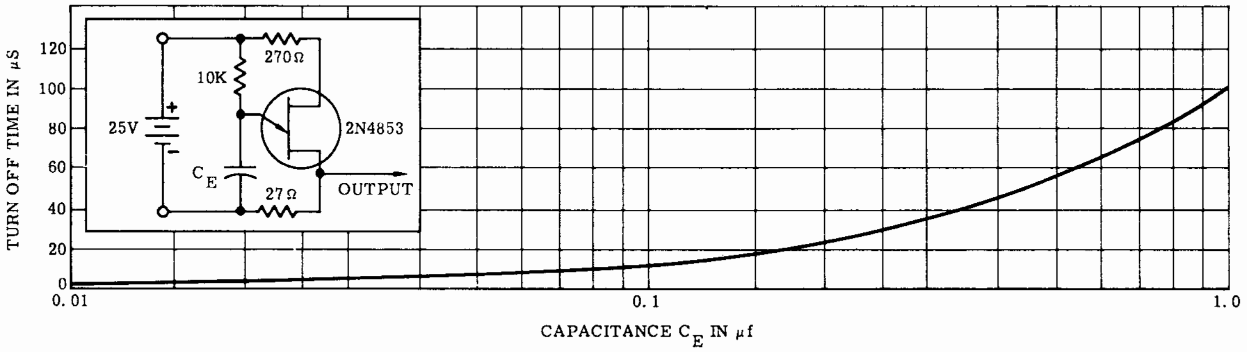


FIGURE 20b — TURN-OFF TIME versus EMITTER CAPACITANCE C_E

TABLE 1 — UNIJUNCTION TRANSISTOR NOMENCLATURE

Symbol	Definition
I_E	Emitter current.
I_{EO}	Emitter reverse current. Measured between emitter and base-two at a specified voltage, and base-one open-circuited.
I_P	Peak point emitter current. The maximum emitter current that can flow without allowing the UJT to go into the negative resistance region. (Peak point is the lowest current on the emitter characteristic where: $\frac{d\ V_{EB1}}{d\ I_E} = 0$.)
I_V	Valley point emitter current. The current flowing in the emitter when the device is biased to the valley point. (Valley point is the second lowest current on the emitter characteristic where: $\frac{d\ V_{EB1}}{d\ I_E} = 0.$)
r_{BB}	Interbase resistance. Resistance between base-two and base-one measured at a specified interbase voltage.
V_{B2B1}	Voltage between base-two and base-one. Positive at base-two.
V_P	Peak point emitter voltage. The maximum voltage seen at the emitter before the UJT goes into the negative resistance region.
V_D	Forward voltage drop of the emitter junction.
V_{EB1}	Emitter to base-one voltage
$V_{EB1(SAT)}$	Emitter saturation voltage. Forward voltage drop from emitter to base-one at a specified emitter current (larger than I_V) and specified interbase voltage.
V_V	Valley point emitter voltage. The voltage at which the valley point occurs with a specified V_{B2B1}.
V_{OB1}	Base-one peak pulse voltage. The peak voltage measured across a resistor in series with base-one when the unijunction transistor is operated as a relaxation oscillator in a specified circuit.
η	Intrinsic standoff ratio. Defined by the relationship: $= \frac{V_p - V_D}{V_{B2B1}}$
α_{rBB}	Interbase resistance temperature coefficient. Variation of resistance between B_2 and B_1 over the specified temperature range and measured at the specific interbase voltage and temperature with emitter open circuited.
I_{B2}(mod)	Interbase modulation current. B2 current modulation due to firing. Measured at a specified interbase voltage, emitter and temperature.

TABLE 2 — COMPARISON OF KEY PARAMETERS FOR THE THREE DIFFERENT UJT STRUCTURES.
Typical values are shown.

PARAMETER	TYPICAL VALUES FOR Bar	Cube	Annular
Intrinsic Standoff Ratio η	0.6	0.65	0.7
Interbase Resistance r_{BB}	7 K	7 K	7 K
Emitter Saturation Voltage $V_{EB1\ (SAT)}$	3 V	1.5 V	2.5 V
Peak Point Current I_p	2 μA	1 μA	0.1 μA
Valley Point Current I_V	15 mA	10 mA	7 mA
Emitter Reverse Current I_{EO}	1 μA	0.1 μA	5 nA

CONCLUSION

The basic theory of UJT operation has been given, and the difference between the three UJT structures discussed. The unijunction transistor has been shown to possess some rather unique capabilities such as;

1) An emitter firing voltage V_p that is a certain fraction of the interbase voltage.

2) A negative resistance region which suggests oscillators and trigger circuits as possible areas of applications.

In addition, the annular device was found to have a low peak point current and emitter reverse current which is advantageous in long duration timers. Low valley current and voltage assures low power dissipation in the ON condition. The annular UJT is also a low cost device which allows its application in the consumer products area. The most common UJT parameters and their behavior have also been covered, and most of them were found to be either temperature or voltage dependent, or both.

To give the reader an idea of how the annular device compares with the bar and cube structures, typical values of six parameters for each type are given in Table 2. Most of the values are relatively uniform for the three types, with the annular device offering slightly lower peak point current I_p and emitter reverse current I_{EO}.

INTRODUCTION

The unijunction transistor (UJT) is a three-terminal device. One terminal is called the emitter, while the two other terminals are called base-one and base-two, respectively.

The UJT has only a single P-N junction, and the characteristics of the device are for this reason quite different from the conventional junction transistor. Some of the characteristics are in fact quite unique; for example, a negative resistance region, and an emitter firing voltage V_p that is a certain fraction of the interbase voltage V_{B2B1} (1).

In addition, the annular* UJT manufactured by Motorola has extremely low peak point current and emitter reverse current, which are advantageous in many types of circuit applications, and particularly in timer and oscillator circuits.

This paper will first discuss the UJT relaxation oscillator, which is the basic building block in most timer and oscillator circuits. The conditions required for oscillation will be derived, and load lines for different circuit conditions will be shown. A variety of practical timer and oscillator circuits are then shown and circuit values given.

The peak point voltage, V_p, is quite temperature dependent, and methods of temperature stabilization of this point are given in the appendix. Also in the appendix are included dynamic operating paths for different types of loads.

THE BASIC RELAXATION OSCILLATOR CIRCUIT

The UJT relaxation oscillator which is the basic building block in most UJT timer and oscillator circuits is shown in Figure 1A. The circuit operation is as follows:

When power is applied, the capacitor C_E charges exponentially through the resistor R_E until the voltage on the capacitor equals the emitter firing voltage V_p. At this voltage, the emitter base-one junction becomes forward biased and the emitter characteristic goes into the negative resistance region. The capacitor C_E discharges through the emitter and a positive going pulse will be available at base-one. This pulse is shown in Figure 1B for a circuit having
R_E = 10 kΩ C_E = 0.01 µF, R2 = 200Ω, R1 = 47Ω, and V1 = 20 V.

Prior to firing, a current I_{B2} is flowing from base-two to base-one. When emitter current starts to flow, this current will increase to $I_{B2(mod)}$ since the resistance from base-two to ground is decreasing. A negative going voltage pulse will therefore appear at base-two, and this waveform is shown in Figure 1C.

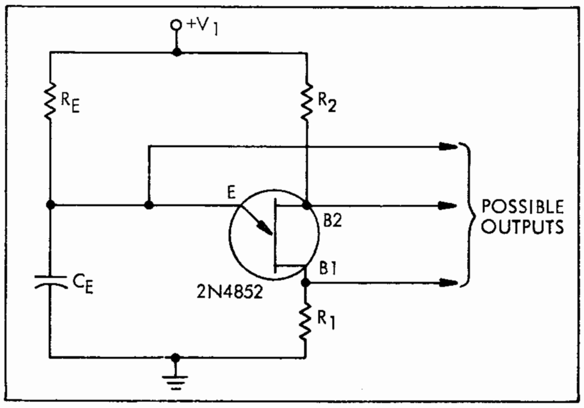


FIGURE 1A - UJT RELAXATION OSCILLATOR

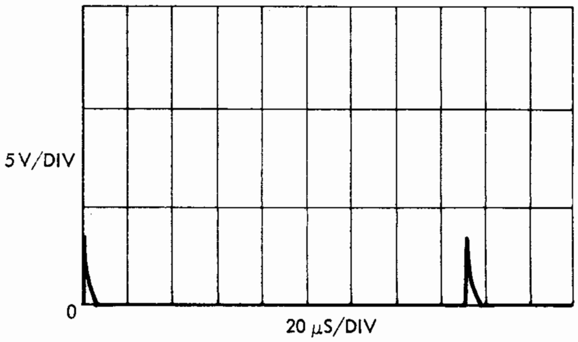


FIGURE 1B - BASE-ONE WAVEFORM

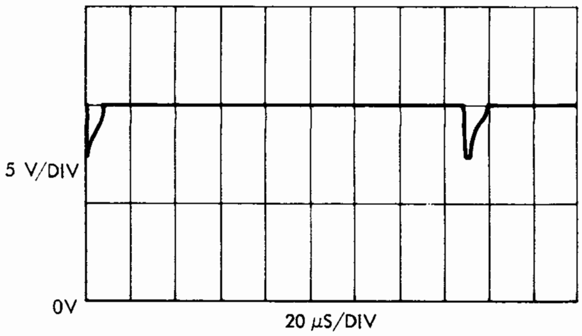


FIGURE 1C - BASE-TWO WAVEFORM

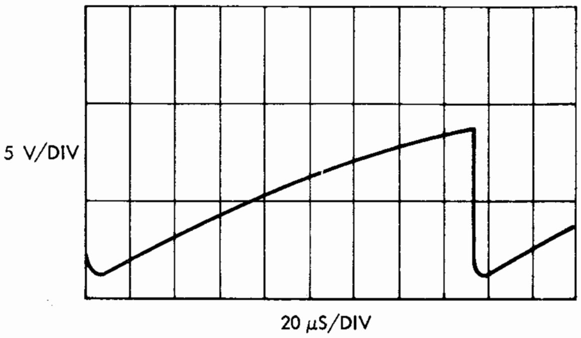


FIGURE 1D - EMITTER WAVEFORM

---

(1) UJT theory and characteristics are treated in Application Note AN293

*Annular, Trademark of Motorola Inc.

When the voltage at the emitter has decreased to V_0, a voltage approximately equal to the valley voltage when R1 is purely resistive, the UJT will turn off if R_E meets certain conditions. C_E will start to charge up again, and the cycle repeats. The waveform that appears at the emitter is shown in Figure 1D.

In order for the above sequence of events to take place, R_E has to meet certain conditions. What these conditions are can best be explained by means of the emitter characteristic curve in Figure 2. (This curve is not drawn to scale in order to show more detail.)

The emitter capacitor C_E, will charge until the emitter voltage is equal to V_p. At this point on the characteristic curve peak point emitter current I_p will be flowing, and in order to fire the unijunction, the value of emitter resistor R_E must be small enough to allow a current somewhat larger than I_p to flow. R_E must, therefore, meet the following requirement:

$$R_E < \frac{V_1 - V_p}{I_p} = R_{E\,(max)} \qquad (1)$$

where V1 is the applied bias voltage.

Referring to Figure 2, this means that a load line intersecting the characteristic curve in the cutoff region, as illustrated by load line one, would keep the UJT from ever firing.

Having selected $R_E < R_{E(max)}$, the UJT will turn on, and C_E will discharge through the emitter. If R_E is too small, however, and allows an emitter current larger than the valley current I_V to flow, the UJT will not turn off. A stable state in the saturation region will result, and the load line will intersect the emitter characteristic curve somewhere to the right of the valley point. Load line 2 in Figure 2 intersecting the characteristic curve at P2 illustrates this condition.

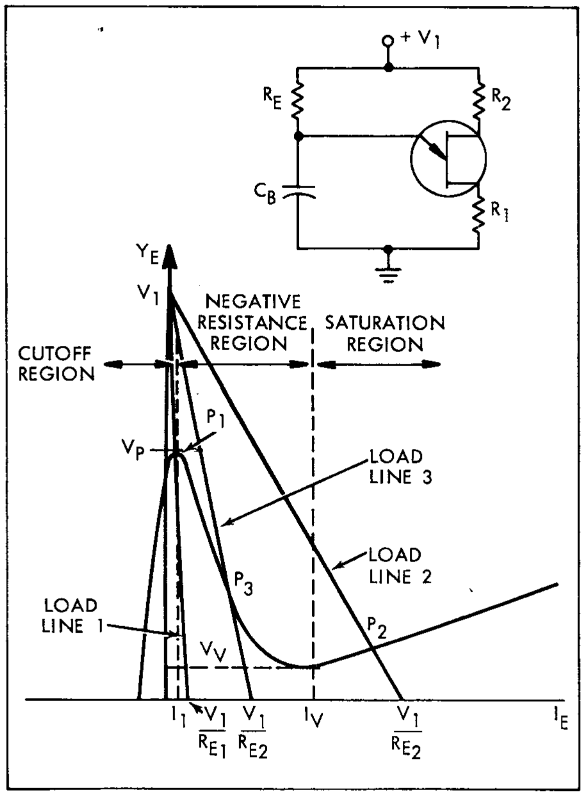


FIGURE 2 - UJT EMITTER CHARACTERISTIC LOAD LINES

The minimum R_E that can be used in order to assure oscillation can be defined by this formula:

$$R_E > \frac{V_1 - V_v}{I_v} = R_{E(min)} \qquad (2)$$

where V_v is the valley voltage.

An emitter resistance selected to meet the requirements in equations (1) and (2) will result in a load line which intersects the characteristic curve somewhere in the negative resistance region. An example is given by load line 3, intersecting the curve at P3.

In practice, however, the variation of the emitter voltage in the neighborhood of the valley point is so small that in order to assure turn-off, R_E should be selected two to three times larger than $R_{E(min)}$. The theory explaining the turn-off will be given in the appendix.

The time required for a complete period can be calculated. The voltage on C_E at any time is given by the equation:

$$V_{CE} = V_v + (V_1 - V_v)\,(1 - e^{-t/R_EC_E}) \qquad (3)$$

Substituting $V_{CE} = V_p = V_D + \eta V_{B2\,B1}$ *

$$V_D + \eta V_{B2\,B1} = V_v + (V_1 - V_v)\,(1 - e^{-t/R_EC_E}) \qquad (4)$$

Solving this equation for t will give the time to charge C_E from V_v to V_p.

$$t = R_E\,C_E\,\ln \frac{V_1 - V_v}{V_1 - V_D - \eta V_{B2\,B1}} \qquad (5)$$

A complete period T also includes the switching time of the UJT and the formula for T becomes:

$$T = R_E\,C_E\,\ln \frac{V_1 - V_v}{V_1 - V_D - \eta V_{B2\,B1}} + t_{on} + t_{off} \qquad (6)$$

The following simplifications can be made in this formula:

The turn-on time is generally much smaller than t_{off} and can be omitted. V1 is also usually an order of magnitude larger than V_D or V_v, and when R1 and R2 are small, $V_{B2\,B1} \approx$ V1. Equation (6) can therefore be written:

$$T \approx R_E\,C_E\,\ln \frac{1}{1 - \eta} + t_{off} \qquad (7)$$

To summarize: The condition for stable operation of the relaxation oscillator in Figure 1 is that R_E must be chosen such that the load line intersects the emitter characteristic in the negative resistance region. The approximate period can be found from Equation (7).

---

*Symbols & definitions Table I

PRACTICAL TIMER CIRCUITS

A Simple Time Delay

The basic building block can be used without modification in simple time delay circuits. One such circuit is shown in Figure 3. The circuit operation is as follows:

The circuit values are determined by means of the equations developed previously. The value of the emitter resistor R_E is chosen by means of Equation (1) and (2) to meet the requirements.

$$R_{E(min)} < R_E < R_{E(max)}$$

When $R_E = 10\ M\Omega$, $C_E = 10\,\mu F$, and $\eta = 0.8$, the time required for one complete period can be found from Equation (7) to be:

$$T \approx R_E C_E \ln \frac{1}{1 - \eta} = 10 \bullet 10^6 x 10 \bullet 10^6 x \ln \frac{1}{1 - 0.8}$$

$$T \approx 160 \text{ seconds}$$

R2 is selcted as 1 KΩ to provide maximum temperature compensation with the UJT used. The theory of temperature compensation is given in the appendix.

After the first cycle, the relay will normally be energized. When push-button S1, being normally closed, is activated the SCR turns off, the relay is de-energized, and power is applied to the relaxation oscillator and the load. After a time delay varying from less than a second to approximately 2.5 minutes, as determined by the setting of the 10 MΩ pot, the unijunction will fire and turn on the SCR. The relay will energize and power is removed from the oscillator and the load. The relay K1 will stay energized until the push button S1 is pushed again.

A variation of this same circuit is shown in Figure 4. Here the relay is replaced by an SCR which generally reduces circuit cost. After one cycle of operation, SCR #1 will be on, and a low value of voltage is applied to the UJT emitter circuit, thus interrupting the timing function. When push button S1 is pushed, or a positive going pulse is applied at point A, SCR #2 will turn on, and SCR #1 will be turned off by commutating capacitor C_C. With SCR #1 off, the supply voltage will be applied to R_E and the circuit will begin timing again. After a period of time determined by the setting of R_E, the UJT will fire and turn SCR #1 on and commutate SCR #2 off.

A LONG DURATION TIME DELAY

The time delay is, as previously shown, determined by the charge time of the capacitor. In order to achieve long time delays, R_E, C_E, or both will have to be large. For good accuracy and repeatability, the capacitor must have a leakage current that is much smaller than the charge current. A Mylar type capacitor has been found to be good for this purpose, but since this type of capacitor is fairly expensive for large values of capacitance, it is preferable to increase R_E in order to obtain long time delays. Large values of R_E, however, creates a problem due to the UJT peak point emitter current I_p. When the capacitor is charged almost to the peak point, only a small voltage will appear across R_E, and if R_E is very large, only a small current will be flowing. If the peak current of the UJT is appreciable, the device will never fire if the current through R_E is not sufficient to supply

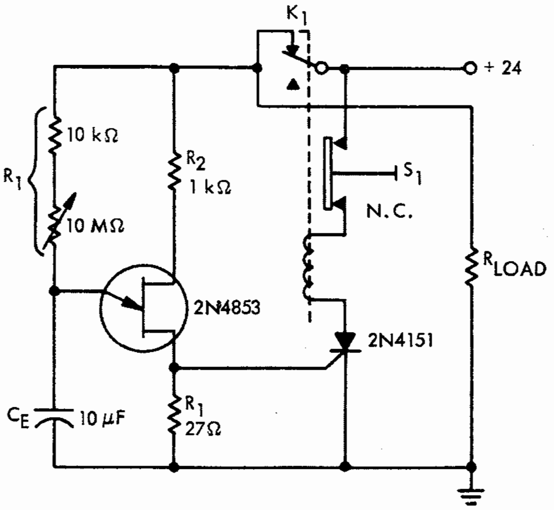
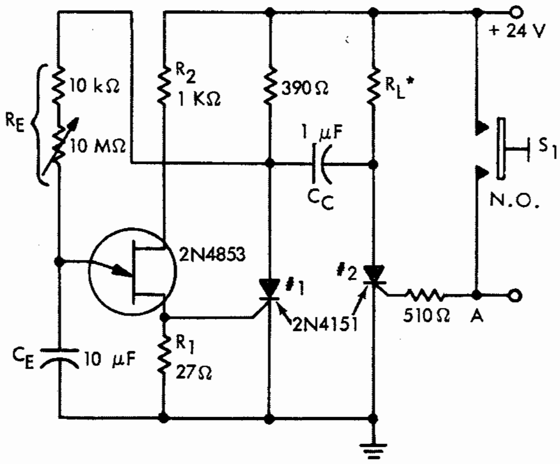


FIGURE 3 - A SIMPLE TIME DELAY CIRCUIT



*Value of R_L must be low enough to allow hold current to flow in the SCR.

FIGURE 4 - A SIMPLE TIME DELAY CIRCUIT USING TWO SCR'S

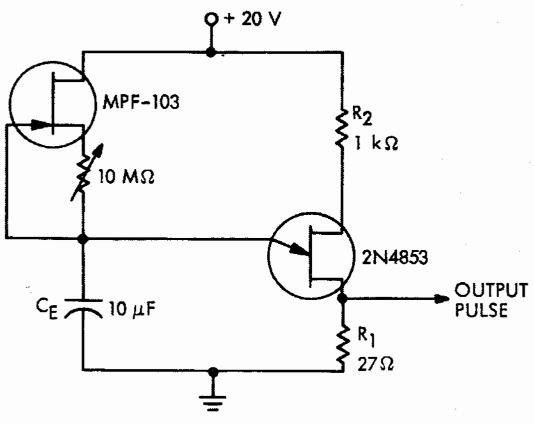


FIGURE 5 - A TIME DELAY CIRCUIT FEATURING CONSTANT CURRENT CHARGING

I_p. The annular device, having a typical I_p of 0.2 μA @ V_{B2B1} = 25 Vdc, offers an advantage in this area and large values of R_E can be used. However, when charging through a resistor, the charge current will initially be relatively large while the charge current when the voltage on the capacitor is close to V_p will be small. It would, for this reason, be advantageous to charge with a constant small current. This can be accomplished by simply replacing R_E by a junction field effect transistor as shown in Figure 5. Since the JFET is fully on when there is no voltage from gate to source, the 10 MΩ resistor will determine the amount of off bias applied to the FET. A constant current of less than 1 μA can easily be obtained which results in time delays up to 10 minutes.

When the capacitor is charged with a linear current, the charge time can be found from the equation:

$$t_{charge} = \frac{(V_p - V_v) \cdot C_E}{I_{charge}} \qquad (8)$$

When C_E is in microfarads and I_{charge} is in microamperes, t will be in seconds.

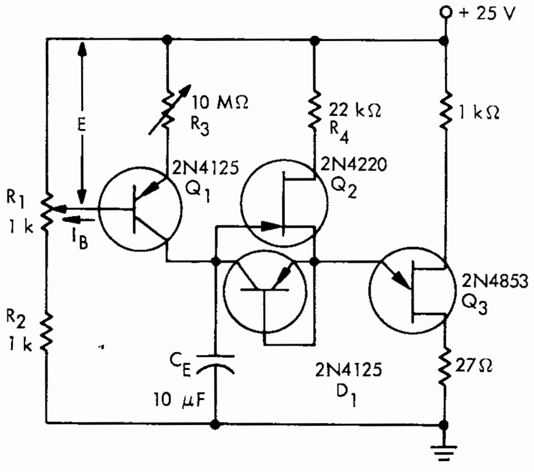


FIGURE 6 - LONG DURATION TIME DELAY

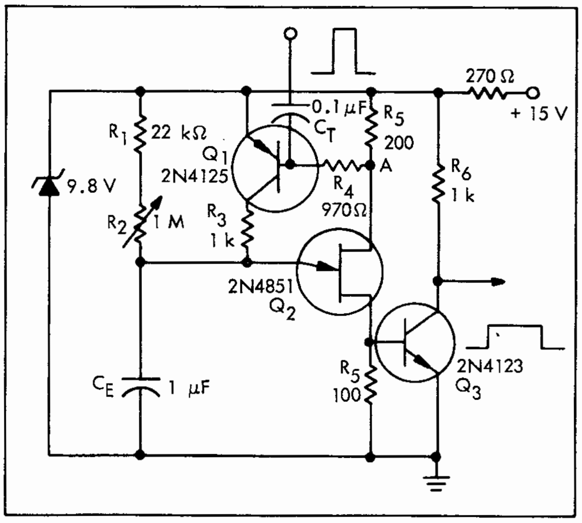


FIGURE 7 - A UJT MONOSTABLE CIRCUIT

However, even an emitter peak current as low as 0.2 μA is objectionable if longer time delays are desired. In the circuit shown in Figure 6, the peak current is supplied separately from the charging current and extremely long time delays are possible. Transistor Q1 and resistors R1, R2, and R3 form a constant current source and the charge current might be adjusted to be as low as a few nanoamperes. This current would, of course, not be sufficient to fire the UJT where I_P = 0.2 μA unless the peak current was supplied from another source. Field effect transistor Q2, acting as a source follower, supplies the current flowing into the emitter lead prior to firing and diode D1 provides a low impedance discharge path for C_E. D1 must be selected to have a leakage much lower than the charge current.

The charge current to C_E is given by the formula:

$$I_{charge} = \frac{E - V_{BE}}{R3} - I_B \qquad (9)$$

Since I_B is small, the delay time will vary linearly with R3. The voltage E, applied across R3 and the base emitter junction of Q1, is set by the variable resistor R1. Time delays up to 10 hours are possible with this circuit. Resistor R4 in series with the FET drain terminal must be large enough not to allow currents in excess of I_V to flow when the UJT is on, otherwise the UJT will not turn off and the circuit will latch up.

MONOSTABLE CIRCUITS (One Shots)

In the circuit shown in Figure 7 the UJT is normally on and the emitter saturation current is supplied by transistor Q1 which is also on. When a positive trigger pulse is applied to the base of Q1, this transistor is turned off and since the emitter current of Q2 becomes less than I_V, the UJT turns off also. This starts the timing cycle. The capacitor will start charging from the same voltage every time, namely the saturation voltage of the UJT. C_E charges through R1 and R2 and when the voltage on C_E equals V_p, the UJT fires. This will cause a drop in the voltage at point A and transistor Q1 will turn on and supply the emitter current required to keep the UJT on. Transistor Q3 serves as an output device and delivers the pulse shown in Figure 7. The starting pulse required at the base of Q1 could very well be generated by another UJT circuit. The circuit is sensitive to changes in voltage and a zener diode is used for voltage regulation.

Another monostable circuit is shown in Figure 8. In this circuit, the UJT is normally off. The circuit operation is as follows: When an input trigger pulse of positive polarity is applied to the base of Q1, this transistor will turn on and Q2 will turn off. A voltage is now applied to charge capacitor C_E and when the voltage on C_E reaches V_p, the UJT (Q3) will fire. The positive voltage developed across the 27Ω resistor is used as the output signal and also as a trigger signal to the base of Q2. The signal will trigger the flip-flop and Q2 will turn on. This leaves only a very small voltage applied to C_E until the start of the next cycle. The voltage on C_E will always be the same at the start of a cycle, no matter how long a time has elapsed since the last cycle was completed. This circuit is nearly insensitive to changes in the supply voltage and a change in V1 from 10 volts to 30 volts results in a variation of approximately 2% in timing. The output signal could also be taken from the flip-flop in which case the output would be a clean square wave.

The monostable circuits offer the following advantages over conventional transistor one shots: (1) The time delay available can generally be made longer. (2) The circuit can be triggered again immediately after the completion of one cycle. (3) The circuit of Figure 8 is relatively independent of changes in the bias voltage, contrary to the behavior of conventional one shots.

SEQUENTIAL UJT-SCR TIMER CIRCUIT

A sequential timer circuit using UJTs and SCRs is shown in Figure 9. Only three stages are shown, but as many additional stages as required can be added. The loads are in series with the anodes of SCR1, SCR2, and SCR3, while the function of SCR4 is to turn off SCR3. The circuit operation is as follows: When a trigger pulse is applied to the terminals marked start pulse, SCR1 turns on and power is applied to the load R_{L1}. The drop in voltage at the anode of SCR1 allows base current to flow in Q1, and this transistor, which supplies charge current to C_{E1}, is turned on. When the voltage on C_{Ei} reaches V_p of Q2, the UJT will fire and trigger SCR2. This causes two things to happen: Transistor Q3 turns on and starts the charging cycle of Q4, and SCR1 is commutated off through the 1 μF capacitor. Next, Q4 will fire triggering SCR3 on, and so on. When SCR4 is turned on, it will remain on only long enough to discharge C3 since the current flowing in the 10 k anode is less than the holding current of the SCR. The duration that power is applied to the different loads can be adjusted individually, with the 5 MΩ variable resistors in series with C_{E1}, C_{E2}, and C_{E3}. The last stage of the circuit can be made to trigger the first stage if so desired, and the time pulses would then continue indefinitely after the sequence were initially started.

This circuit could be useful in washing machine controls, etc., where different cycles require different time durations.

UJT OSCILLATOR CIRCUITS

Most UJT oscillator circuits employ the basic relaxation oscillator circuit in some way or another. As mentioned previously, either the output at base-one, base-two, or the emitter can be utilized in order to fulfill a specified requirement.

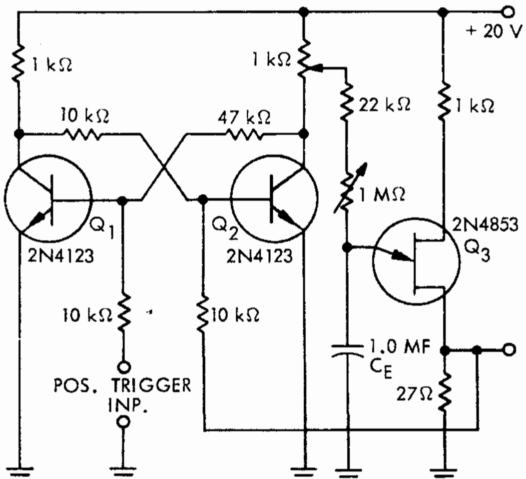
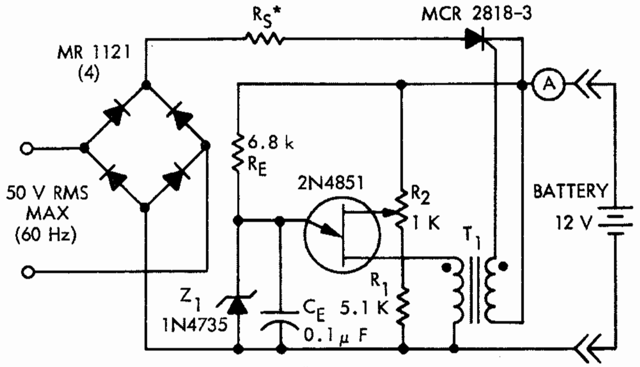


FIGURE 8 - A UJT MONOSTABLE CIRCUIT INSENSITIVE TO CHANGE BIAS VOLTAGE



T_1 - PRIMARY = 30 TURNS #22

SECONDARY = 45 TURNS #22

CORE = FERROXCUBE 203 F 181-3C3

* R_S - SERIES RESISTANCE TO LIMIT CURRENT THROUGH SCR.

MCR 2818-3 IS RATED AT 20 AMPS RMS.

FIGURE 10A - A 12 VOLT BATTERY CHARGER CONTROL (20 AMPS RMS MAX.)

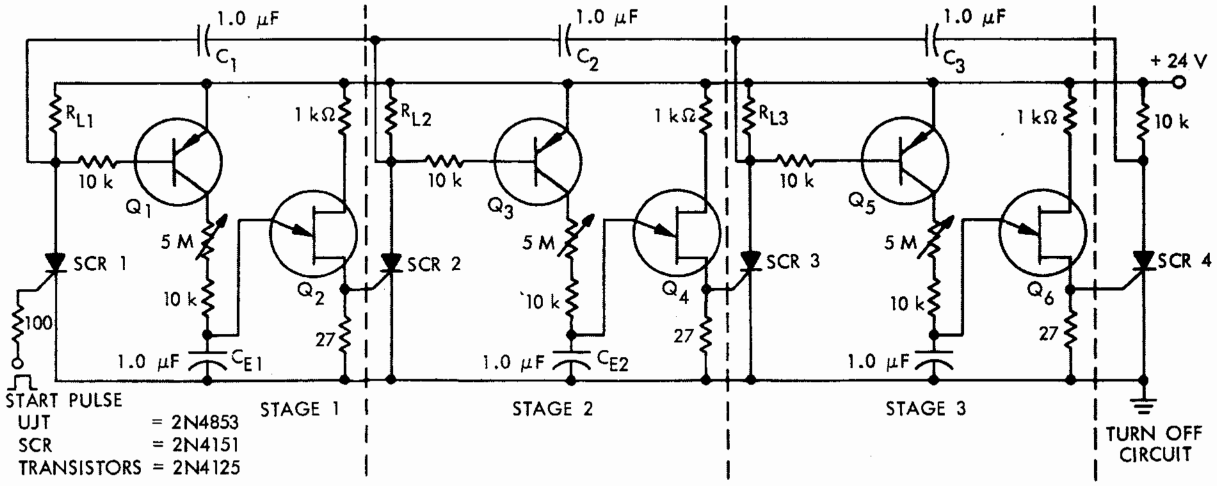


FIGURE 9 - A SEQUENTIAL UJT TIMER CIRCUIT

BATTERY CHARGER

The battery charger circuit shown in Figure 10A is a very simple circuit utilizing the relaxation oscillator.

The circuit will not work unless the battery to be charged is connected with proper polarity. The battery voltage controls the charger and when the battery is fully charged, the charger will not supply current to the battery.

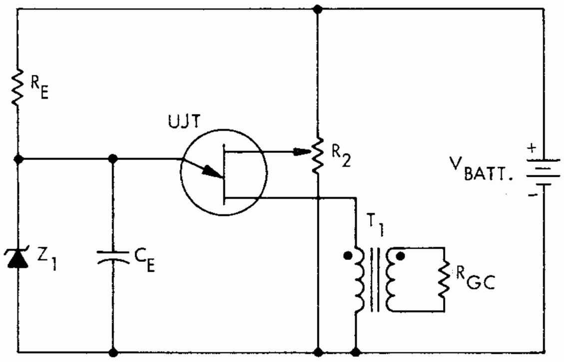
The circuit operation is as follows: The battery charging current is obtained through the SCR when it is triggered into the conducting state by the UJT relaxation oscillator. The oscillator is only activated when the battery voltage is low. V_{B2B1} of the UJT is derived from the voltage of the battery to be charged, and since $V_p = V_D + \eta V_{B2B1}$, the higher V_{B2B1}, the higher V_p. When V_p exceeds the breakdown voltage of the zener diode Z1, the UJT will cease to fire and the SCR will not conduct. This indicates that the battery has attained its desired charge as set by R2.

The relaxation oscillator itself and the waveforms associated with the operation is shown in Figure 10B. (The voltage increase will tend to change the pulse repetition rate, but this is not important, since the battery will tend to average the output.)

POWER SUPPLY SWITCHING MODE REGULATOR

The operation of the switching mode regulator depends on the fact that the output voltage is directly proportional to the input voltage by the duty cycle of the switched voltage.

A block diagram of a switching regulator is shown in Figure 11A. The block called "duty cycle control" consists of two UJT relaxation oscillators and a bistable multivibrator. The pulses generated by the two UJT circuits trigger the bistable multivibrator to generate the variable duty cycle pulses. This part of the circuit is shown in Figure 11B. The oscillator circuit utilizing Q1 sets the basic operating frequency of the regulator at 5 kHz, while the Q4 oscillator controls the duty cycle.



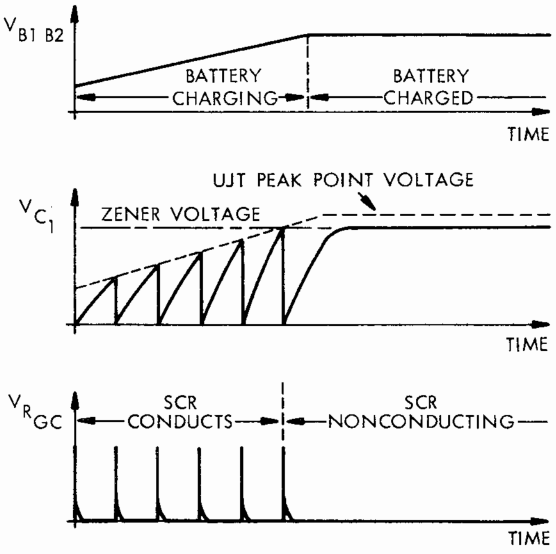


FIGURE 10B - WAVEFORMS ASSOCIATED WITH BATTERY CHARGER OPERATION

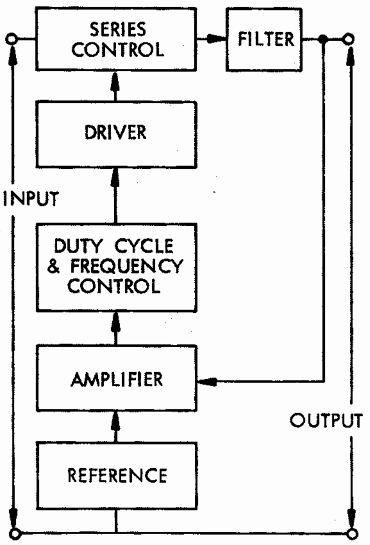


FIGURE 11A - BLOCK DIAGRAM OF SWITCHING MODE REGULATOR

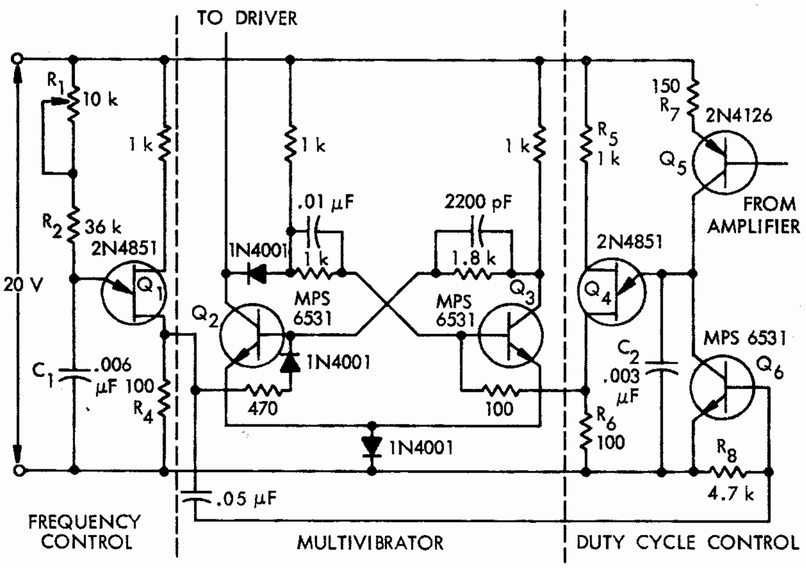


FIGURE 11B - DUTY CYCLE AND FREQUENCY CONTROL OF THE SWITCHING REGULATOR

To obtain an understanding of the operation of the switching mode regulator, the generation of one cycle of voltage into the filter circuit will be established with the aid of Figures 12A through E. The pulses in Figure 12A are the trigger pulses generated by the 5 kHz relaxation oscillator Q1. These pulses trigger one side of the bistable multivibrator on and the collector current of the "on" transistor (Q2) is shown in Figure 12B. The 5kHz trigger pulse also discharges capacitor C2 via transistor Q6 so that C2 will begin charging from zero each time Q2 is turned on. The charging current for C2 is provided by a current source comprised of Q5 and R7. The waveforms are shown in Figure 12C. When the voltage on the capacitor reaches the firing voltage of Q4, the capacitor is discharged through R6 and generates the pulse in Figure 12D. This pulse triggers the opposite side of the multivibrator, and collector current ceases to flow in Q2. This completes one cycle of the duty cycle control circuit. The voltage that is applied to the filter circuit is shown in Figure 12E. This voltage is averaged by the filter to give a constant dc output.

The charging current provided by transistor Q5 is controlled by the amplifier (see Figure 11A). The amplifier senses a portion of the output of the regulator and compares this voltage to the reference. The voltage difference is amplified by the amplifier and applied as a current to the base of Q5 to control the charging of C2.

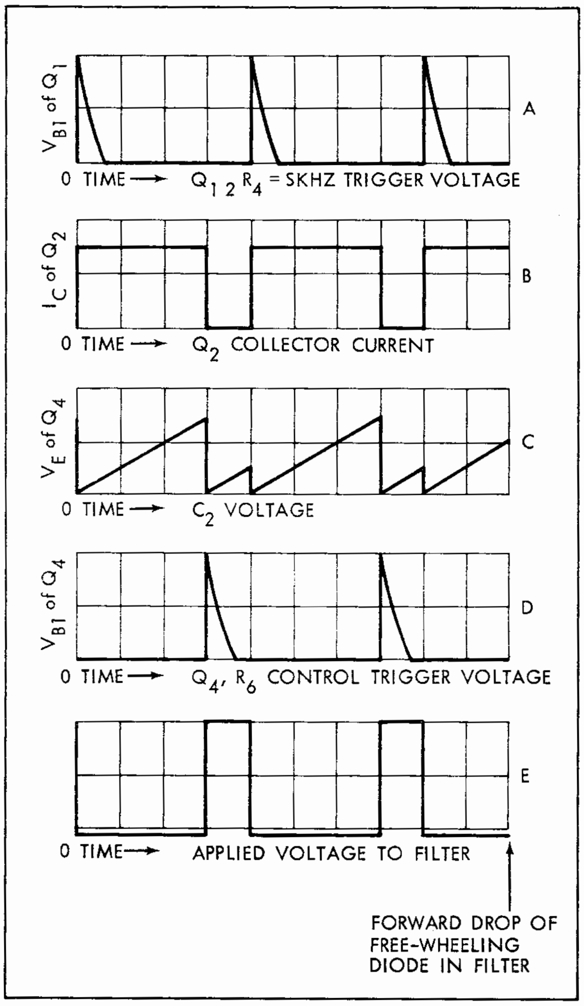


FIGURE 12 - CIRCUIT WAVESHAPES

A SPACE-MARK GENERATOR WITH VOLTAGE-CONTROLLED DUTY CYCLE

Both the frequency and the duty cycle of the output pulse of the circuit in Figure 13 are variable. The frequency may be varied by means of resistor R_E in the source of Q1, while the duty cycle varies linearly with the reference voltage applied to the base of Q5.

The circuit operation is as follows: Field effect transistor Q1 acts as a constant current source charging C_E, and the rate of current flow is adjusted by R_E. A linear ramp is generated at the emitter of Q2, and this

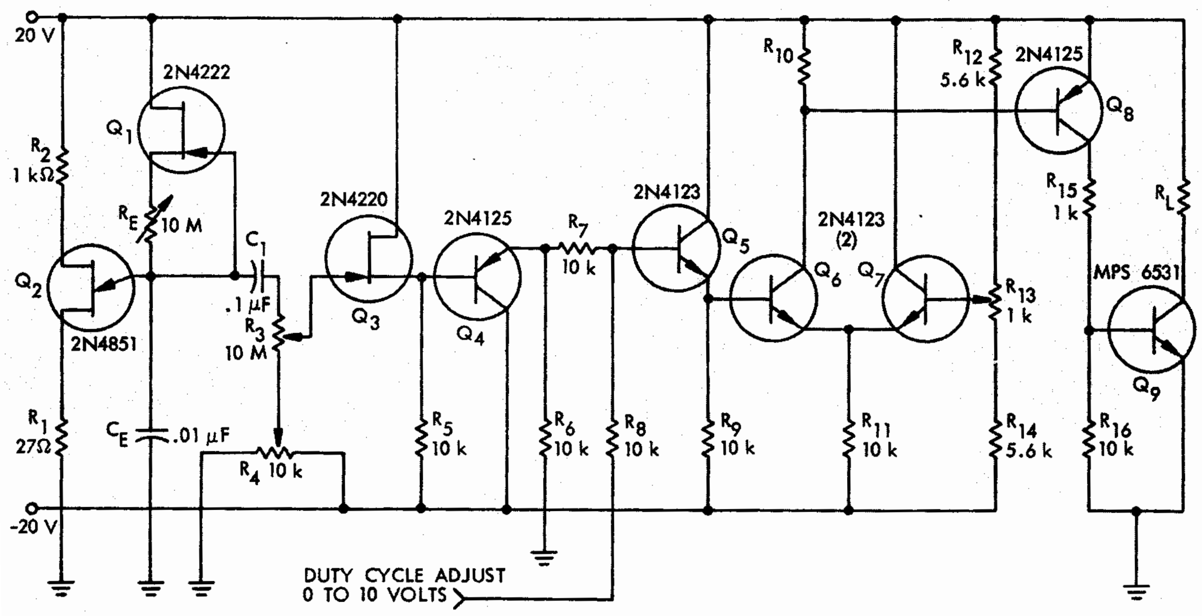


FIGURE 13 - SPACE MARK GENERATOR WITH VOLTAGE CONTROLLED DUTY CYCLE

ramp is applied to the gate of FET Q3. The ramp is shifted up or down in voltage by means of the variable resistors R3 and R4 until a ramp going from -10 volts to zero is observed at the emitter of Q4. Transistor Q6 and Q7 form a differential amplifier. The base of Q7 is biased such that the other half of the differential amplifier Q6 will fire when the voltage at the base of Q5 crosses zero. The time at which the zero crossing occurs depends on the duty cycle adjust voltage applied to resistor R8. When Q6 turns on, Q8 and Q9 are also turned on, and power is applied to the load R_L. When the voltage on C_E reaches the emitter peak point voltage of the UJT Q2, it will fire and Q9 turns off. Then the cycle repeats. The duty cycle can be varied from 0 to 100%.

CONCLUSION

The application of the unijunction transistor in a variety of practical timer and oscillator circuits has been shown.

A UJT timer circuit employing relatively few parts offers timing capabilities ranging from milliseconds to several hours. The UJT is compatible with other solid state devices and works particularly well with SCRs.

Oscillators and pulse generators with variable frequency and/or pulse width can be constructed using the UJT and amazingly few extra components.

The annular UJT offers improved characteristics important in timer and oscillator design, such as low I_p, low I_{EO}, and low I_V.

APPENDIX

TABLE I

Unijunction Transistor Nomenclature

Symbol	Definition
I_E	Emitter current
I_{EO} (I_{EB2O})	Emitter reverse current. Measured between emitter and base-two at a specified voltage, and base-one open-circuit.
I_p	Peak point emitter current. The maximum emitter current that can flow without allowing the UJT to go into the negative resistance region. (Peak point is the lowest current on the emitter characteristic where: $\frac{dV_{EB1}}{dI_E} = 0.$)
I_V	Valley point emitter current. The current flowing in the emitter when the device is biased to the valley point. (Valley point is the second lowest current on the emitter characteristic where $\frac{dV_{EB1}}{dI_E} = 0.$)
r_{BB}	Interbase resistance. Resistance between base-two and base-one measured at a specified interbase voltage.
V_{B2B1}	Voltage between base-two and base-one. Also called interbase voltage.
V_p	Peak point emitter voltage. The maximum voltage seen at the emitter before the UJT goes into the negative resistance region.
V_D	Forward voltage drop of the emitter junction. Also called $V_{F(EB1)}$ or V_F.
V_{EB1}	Emitter to base-one voltage.
$V_{EB1(sat)}$	Emitter saturation voltage. Forward voltage drop from emitter to base-one at a specified emitter current larger than I_V and specified interbase voltage.
V_v	Valley point emitter voltage. The voltage at which the valley point occurs with a specified V_{B2B1}.
V_{OB1}	Base-one peak voltage. The peak voltage measured across a resistor in series with base-one when the unijunction transistor is operated as a relaxation oscillator in a specified circuit.
η	Intrinsic standoff ratio. Defined by the relationship: $\eta = \frac{V_p - V_D}{V_{B2B1}}$
α_{rBB}	Interbase resistance temperature coefficient. Variation of resistance between B2 and B1 over the specified temperature range and measured at the specific interbase voltage and temperature with emitter open-circuited.
$I_{B2\,(mod)}$	Interbase modulation current. B2 current modulation due to firing. Measured at a specified interbase voltage, emitter current and temperature.

TEMPERATURE STABILIZATION OF THE PEAK POINT VOLTAGE

It has been shown in AN293 how practically all UJT characteristics are temperature dependent. The interbase resistance r_{BB} and emitter reverse current I_{EO} increase, while the peak and valley voltage and current, the intrinsic standoff ratio η and the junction diode drop decrease with increasing temperature.

The peak point voltage is given by the equation:

$$V_p = V_D + \eta V_{B2B1} \qquad (10)$$

Since both V_D and η decrease with temperature, V_p will also decrease. This is, of course, a very undesirable condition in many applications, and particularly in timers and oscillator circuits. It has been found, however, that the change in V_p can be compensated for by adding a resistor R2 in series with the base two terminal.

If this resistor is selected properly, V_p can be made to vary less than 1% over a 50°C temperature variation. An equivalent circuit for the UJT in the cutoff region, including the external resistor R2, is shown in Figure 1. The peak point voltage is now given by:

$$V_p = V_D + \frac{\eta V_1 r_{BB}}{(r_{BB} + R2)} \qquad (11)$$

When temperature is increased, V_D decreases, and for V_p to remain unchanged, the second term in Equation (6), representing the voltage at point A, must increase. Since r_{BB} will increase and R2 will remain unchanged, the second term in the equation will indeed increase.

It would seem like a relatively simple task to calculate R2 from Equation (11) by taking the derivative of V_p with respect to temperature, setting $\frac{dV_p}{dt}$ equal to zero, and solve for R2. This procedure would result in the following equation for R2.

$$R2 = 1/2 \left[-\left(2\, r_{BB} + V_1\, \eta \frac{K_2}{K_1} + V_1\, r_{BB} \frac{K_3}{K_1}\right) \pm \left(2\, r_{BB} + V_1\, \eta \frac{K_2}{K_1} + V_1\, r_{BB} \frac{K_3}{K_1} - 4 r_{BB} \left(1 + V1 \frac{K_3}{K_1}\right)\right) \right] \qquad (12)$$

where $K_1 = \frac{dV_D}{dT} = -2.7\ \mathrm{mV}/{}^{\circ}\mathrm{C}$

$$K_2 = \frac{d\, r_{BB}}{dt} = \frac{r_{BBN} \cdot 0.77}{100}\ /{}^{\circ}\mathrm{C}$$

$$K_3 = \frac{d\eta}{dT} = -\frac{\eta_N \cdot 0.06}{100}\ /{}^{\circ}\mathrm{C}$$

and the subscript N denotes the value at 25°C.

When solving this equation, it would also have to be taken into account that r_{BB} is voltage dependent and when V_{B2B1} is increased by one volt, r_{BB} increases 1.2% (based on the value of r_{BB} at $V_{B2B1} = 3$ V). Furthermore, the temperature dependency of r_{BB} affects not only terms containing K2 but also terms containing r_{BB} itself.

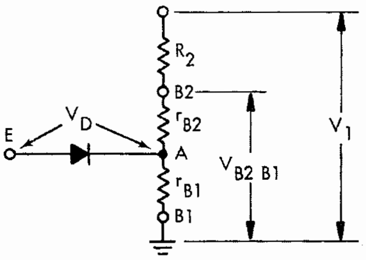


FIGURE I - ELECTRICAL EQUIVALENT CIRCUIT FOR THE UJT WITH THE EXTERNAL COMPENSATING RESISTOR R2. THE EQUIVALENT CIRCUIT IS VALID IN THE CUTOFF REGION ONLY

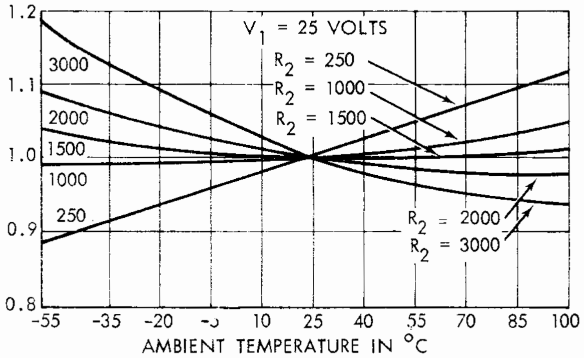


FIGURE II - FREQUENCY VERSUS TEMPERATURE FOR A UJT RELAXATION OSCILLATOR CIRCUIT. (FREQUENCY IS NORMALIZED TO 25°C AND R2 IS A VARIABLE PARAMETER)

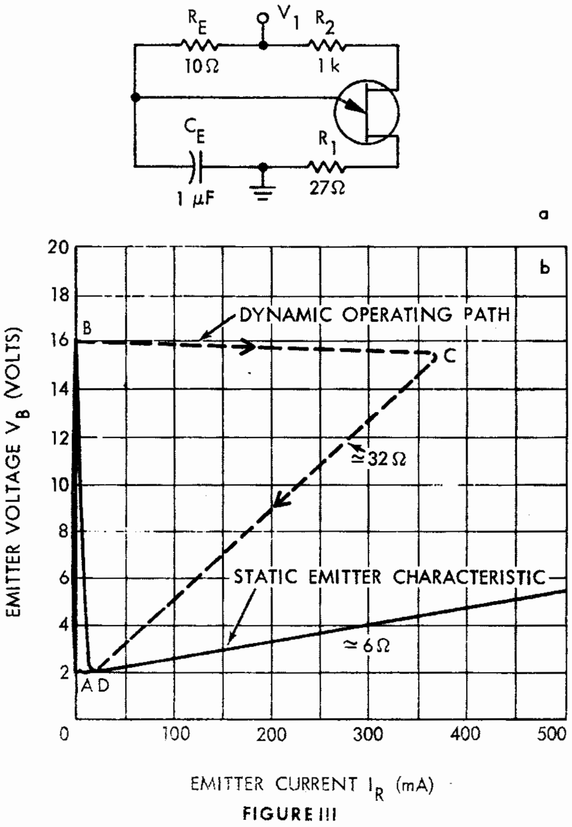


FIGURE III

In equation (12), r_{BB}, K1, K2, and η are voltage dependent and V_{B2B1} is dependent on R2. This interdependency results, in a very complex equation that is difficult to solve which in turn greatly reduces the usefulness of Equation (12).

An empirically derived formula for R2 given in Equation (13) will generally result in a value for R2 relatively close to the optimum value.

$$R2 = 0.015 \bullet V_1 \bullet r_{BB} \bullet \eta \qquad (13)$$

If a high degree of accuracy is required, however, a final adjustment of R2 should be made in the actual operating circuit.

Frequency variation as a function of temperature for a typical annular UJT is shown in Figure II. Temperature curves for several values of R2 ranging from 250 ohms to 3 kohms are shown, and an R2 of approximately 1.5 kohms can be seen to compensate very well from -5°C to +85°C. A smaller resistor should be used for operation below -5°C.

DYNAMIC OPERATING PATHS

In order to determine the dynamic operating path of the relaxation oscillator, the circuit in Figure IIIa can be used. Figure IIIb shows the emitter characteristic curve for V_{B2B1} = 20 volts with the dynamic operating path of the oscillator shown with dotted lines. (V_1 in Figure IIIa is adjusted for V_{B2B1} = 20 volts.)

At the beginning of a cycle, C_E will start to charge from point A on the characteristic curve. At point B, where the voltage of C_E equals V_p, the UJT will fire and the characteristic curve goes into the negative resistance region. The voltage on the capacitor cannot change instantaneously, however, and the dynamic operating path will move from point B to point C. The time required to move from B to C is approximately 1 μsec. From point C, the operating path follows an essentially straight line to point D, which is approximately equal to the valley point. This straight line has a slope of approximately 32 volts/ampere or 32 ohms, and is composed of R1 and the UJT emitter base one saturation resistance. There is not enough emitter current available to sustain operation at point D, and the operating path tries to follow the characteristic curve to the point where it is intersected by the load line determined by R_E (similar to load line 3 in Figure 2). If the emitter circuit of the UJT were purely resistive (i.e. no capacitor C_E), this intersection point would be a stable operating point. To reach this point, however, the emitter voltage must increase. The resistance from emitter to base-one will also increase, and the emitter current will decrease somewhat. When the emitter voltage increases, however, current starts to flow into the capacitor and the emitter current is reduced more than that required by the characteristic curve. So, with a capacitor C_E in the emitter circuit, there are no stable operating points in the negative resistance region, and from point D, therefore, the operating path goes to point A again and the cycle repeats. It takes about 180 μsec to traverse the path from point C to point A in the circuit shown.

The shape of the dynamic operating path is determined by the capacitor C_E, the bias voltage, and the resistor R1. Figure IVa shows operating paths for different values of C_E while Figure IVb shows operating paths for fixed C_E but varying interbase voltage.

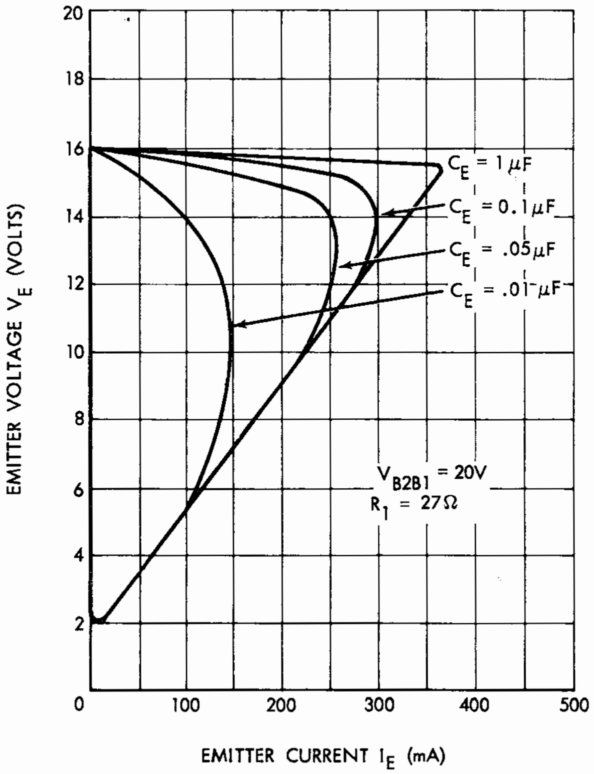


FIGURE IVa - DYNAMIC OPERATING PATH VERSUS EMITTER CAPACITANCE (CIRCUIT - FIGURE IIIA)

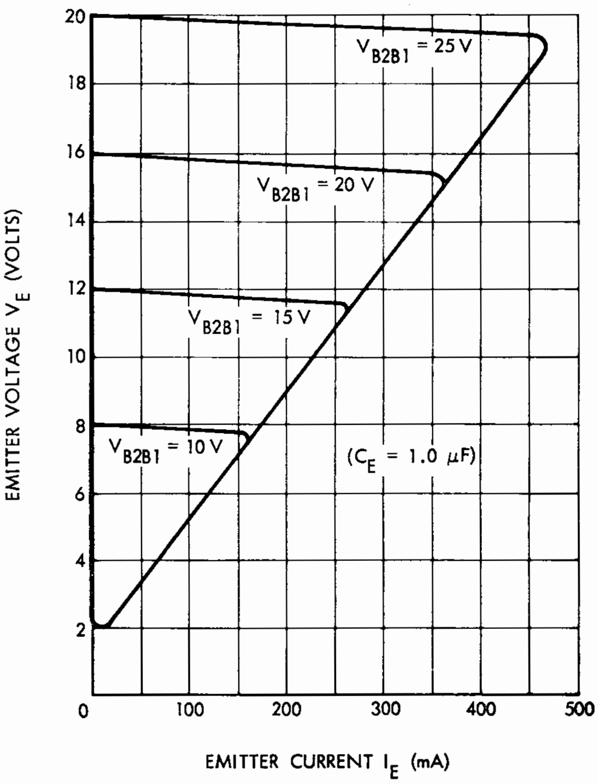


FIGURE IVb - DYNAMIC OPERATION PATH VERSUS INTERBASE VOLTAGE (CIRCUIT - FIGURE IIIA)

When an inductive load, like a relay coil, for example, is substituted for R1, the dynamic operating path will be somewhat different. Figure Va shows a relaxation oscillator having a pulse transformer instead of R1, and Figure Vb shows the resulting dynamic operating path. An important difference here is that the emitter no longer ceases to conduct when valley voltage is reached but goes down to less than 0.5 volts before turning off. Figure Vc shows how the turn-off voltage is dependent on the bias voltage.

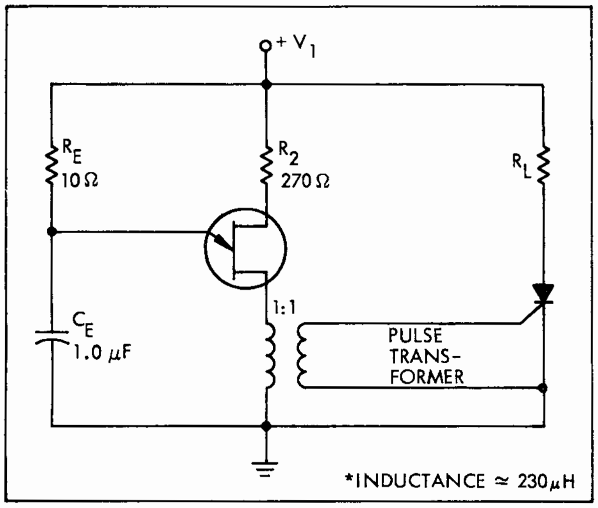


FIGURE Va - A RELAXATION OSCILLATOR WITH INDUCTIVE* LOAD

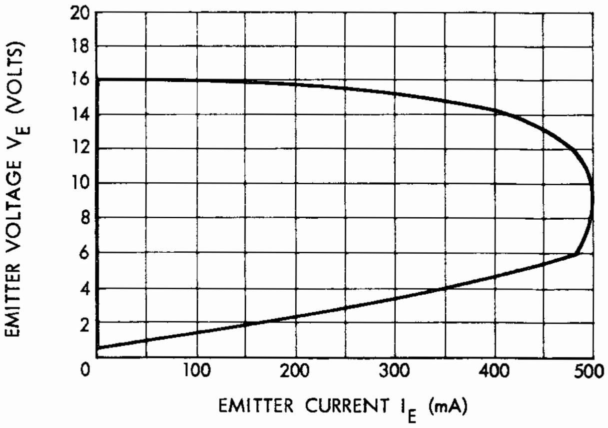


FIGURE Vb

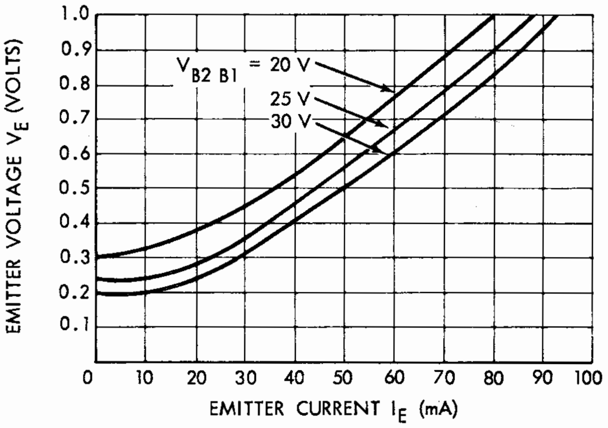
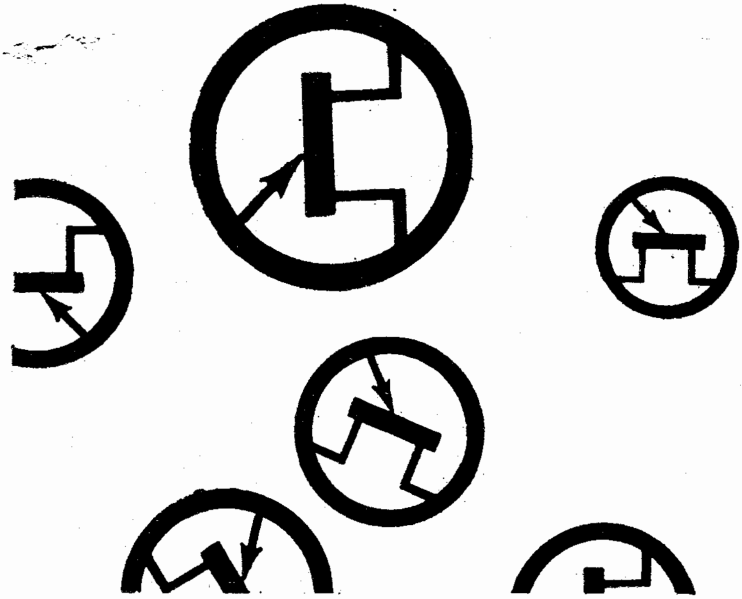


FIGURE Vc



UJT

AN ALL-ROUND SIGNAL GENERATOR: SAW-TOOTH, SQUARE-WAVE, SINE-WAVE

ALMOST EVERYONE who has an interest in electronics is aware of the existence of a device called the unijunction transistor, or UJT. (If he remembers it from its very beginning, he might recall that it was originally referred to as a "double-base diode.") The UJT is used most often in circuits requiring a positive-going spike pulse and, occasionally, as a generator of sawtooth waveforms.

However, the UJT is actually much more versatile than these two uses would imply. It can also be used to generate square waves and, believe it or not, sine waves having quite pure waveforms. It behooves the serious electronics experimenter to learn more about all of these uses—and to do so, he will need to know more about the UJT itself.

How the UJT Works. The UJT can be represented by a circuit approximation consisting of two resistances in series, with a diode connected at their junction as in Fig. 1. (Also shown in the figure is the accepted schematic symbol and base diagram for the UJT. Note that in both cases the leads are identified as E, B1, and B2 for emitter, base-1, and base-2.) The resistance approximation is a *passive* representation of the UJT. In simple terms, this means that a pair of resistors and a diode connected as shown will *not* operate as a unijunction transistor. The approximation is simply a means by which operation of the UJT can be explained.

In the majority of applications, the

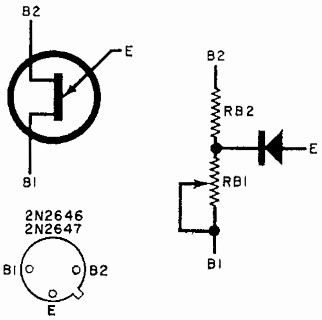


FIGURE 1

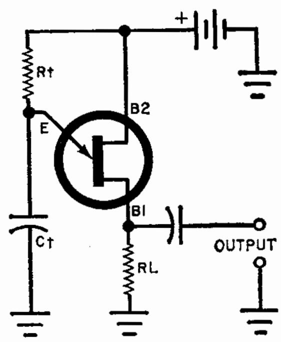


FIGURE 2

emitter is the control electrode of the UJT. The magnitude and polarity of a potential applied to the emitter determine whether or not the UJT will fire. With the emitter circuit open (diode nonconducting), resistance *RB1* is maximum, and the sum of *RB1* and *RB2,* called interbase resistance, is between 5000 and 10,000 ohms for the 2N2646 and 2N2647 (two typical, useful UJT's).

Resistance *RB1* is shown variable because current flow in the emitter circuit causes a decrease in the ohmic value of this resistance. The greater the current flow, the lower the resistance. Hence, a UJT exhibits negative resistance, a characteristic that can be thought of as amplification. What actually happens inside the UJT is that current flowing into the E-to-B1 circuit "pulls" current carriers from the B2 area, increasing the circuit's conductance.

The supply voltage, usually applied through a series resistor, is connected across the interbase resistance, B1 to B2, with B2 positive with respect to B1. To fire the UJT, a positive potential (called the peak-point voltage) is applied to the emitter.

The ratio of *RB1* to the interbase resistance is called η (Greek eta), or the intrinsic standoff ratio. The peak-point voltage is this ratio times the supply voltage plus the potential hill of the diode (about 0.5 volt). Thus, the voltage required for firing the UJT varies as the supply voltage is varied, and in the same direction.

UJT Relaxation Oscillators. The schematic diagram in Fig. 2, or some variation of it, is probably familiar to most experimenters. It is the one most commonly used circuits for relaxation oscillators by circuit designers.

Referring to the diagram, capacitor *Ct* charges up through resistor *Rt* at a rate determined by the *RC* time constant of these two components. The larger these values, the slower the charging rate. During the charging interval, the emitter junction is reverse biased, and the only current flowing in the emitter circuit is due to leakage (similar to the I_{co} of a bipolar transistor). Emitter leakage for the 2N2646 is a maximum of 2 μA, and for the 2N2647, only 0.2 μA.

When the potential across *Ct* reaches the value of peak-point voltage for the particular UJT being used in the circuit, the emitter junction goes suddenly into conduction. Using the UJT approximation shown in Fig. 1, *RB1* promptly drops to a much lower value and *Ct* in Fig. 2 discharges abruptly through load resistor *RL,* producing a spike pulse of voltage across the output terminals.

Capacitor *Ct* does not discharge to zero potential. Rather, it is discharged to a value determined by the series resistance between the emitter and ground and the magnitude of the discharge current. The actual value to which *Ct* discharges is termed the "valley voltage." When *Ct* discharges to this value, the emitter junction of the UJT becomes reverse biased again; then *Ct* begins to recharge, and the cycle repeats. The charge-discharge action of *Ct* produces a sawtooth waveform signal.

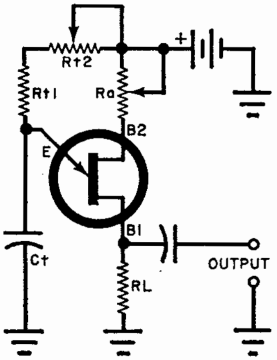


FIGURE 3

When It Doesn't Work. The operation of a UJT relaxation oscillator involves more than just raising the potential across timing capacitor *Ct* to the firing level. A certain value of current, called the "peak-point emitter current," is required to fire the unijunction transistor. This current must be supplied through timing resistor *Rt* (see Fig. 2). If the current through *Rt* is too low, capacitor *Ct* will charge to a value that is below the peak-point voltage, and operation will cease. The UJT will not fire. This need for sufficient emitter current becomes important when *Rt* must have a large value to operate the UJT at a very low repetition rate.

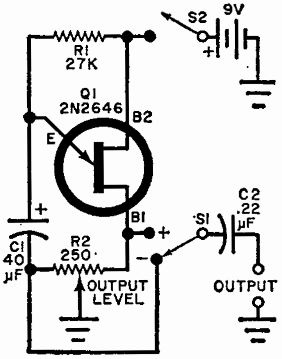


FIGURE 4

The peak-point emitter current for the 2N2646 is about 5 µA; for the 2N2647 it is only 2 µA. It is important to bear in mind that even though the 2N2647 is 2.5 times better than the 2N2646, if an electrolytic capacitor is used in the circuit, the leakage current of the capacitor has the same effect as an identical increase in the peak-point emitter current of the UJT. Consequently, care must be exercised in choosing a capacitor with the lowest leakage or the value of the 2N2647 might be lost.

Characteristics vary from one UJT to another, even for those with the same type number. Thus, if the relaxation oscillator is to have a definite repetition rate, the value of timing resistor *Rt* should be made adjustable to allow you to "trim" the circuit to the desired frequency or repetition rate.

The circuit shown in Fig. 3 has trimming facilities. Varying the resistance of either *Ra* or *Rt2* varies the interbase voltage, thereby altering the peak-point voltage and, thus, the repetition rate. The value of potentiometer *Ra* in such a circuit should be limited to a maximum of 5000 ohms.

Negative-Pulse Generator. Pulses obtained at the B1 terminal of a UJT are positive-going. Negative-going pulses can be obtained from the B2 terminal when a resistor is connected between B2 and ground. Negative pulses can also be obtained from a resistor connected in series with the lower end of the timing capacitor.

The circuit shown in Fig. 4 provides a choice of either positive or negative pulses, depending on the setting of *S1*. Adjusting the setting of level control potentiometer *R2* adds resistance to one of the two circuits, while it subtracts an equal amount of resistance from the other circuit. So, when *R2* is set for maximum amplitude of a negative output pulse, resistance in the positive side of the circuit is zero, and vice versa. This gives the circuit maximum efficiency, providing maximum pulse amplitude in either direction.

The repetition rate of the circuit with the component values shown is about one pulse in every two seconds. This rate was selected to provide a useful instrument for checking experimental hookups

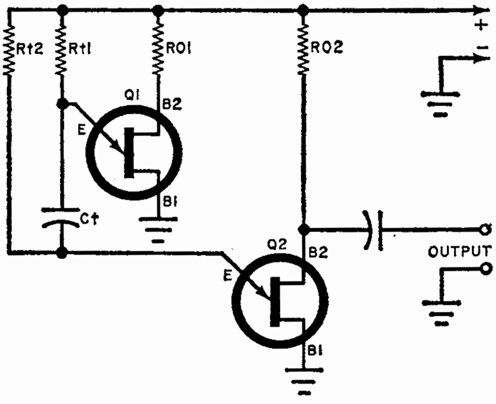


FIGURE 5

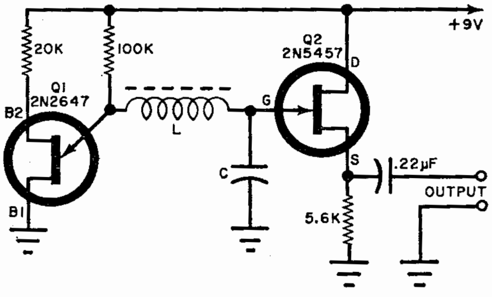


FIGURE 6

of JK flip-flops, SCR's, SCS's, and other pulse-operated devices.

Square-Wave Generator. The circuit of a square-wave generator (actually a dual-UJT multivibrator) is shown in Fig. 5. This circuit generates excellent square waves within the frequency range of efficient operation of the unijunction transistors.

When the power is applied to the dual-UJT circuit, both emitters are made positive with respect to ground through resistors *Rt1* and *Rt2*. One UJT fires promptly, bringing both ends of the timing capacitor, *Ct*, to a value well below the peak-point voltage. This UJT remains conducting while *Ct* charges through the timing resistor of the other UJT circuit.

As soon as the second UJT's emitter becomes sufficiently positive with respect to ground, it suddenly conducts, driving the first UJT negative and causing it to stop conducting. With the second UJT conducting and the first cut off, *Ct* starts charging in the opposite direction, through the timing resistor of the first UJT. Now, when the emitter of the first UJT becomes sufficiently positive, it fires, and the second UJT cuts off. The alternate-stage fire/cutoff cycle is self repeating whenever power is applied to the circuit, and the output of the system is a train of rectangular pulses.

Sine-Wave Generator. Sine waves are produced by allowing a UJT circuit to charge and discharge a capacitor through an inductance. When the charge-discharge period is equal to the resonant frequency of the *LC* circuit, sine waves are generated across the capacitor. A schematic diagram of a UJT sine-wave generator is shown in Fig. 6.

The tuned circuit of the generator is made up of inductor *L* and capacitor *C*. Field effect transistor *Q2* operates as a source follower to prevent loading down the tuned circuit; this stage is not otherwise essential to the operation of the oscillator as a sine-wave generator. The circuit shown has operated well up to 50,000 Hz.

The output of the sine-wave generator is obtained across *Q1*'s source resistor. The waveform here is cleanest when the ratio of inductance to capacitance is high.

Modulate a Relaxation Oscillator. A UJT relaxation oscillator can be frequency modulated by applying the modulating signal across a resistor in the B2 circuit as shown in Fig. 7. The waveform of the modulating signal can be sine, sawtooth, square, triangular, or irregular.

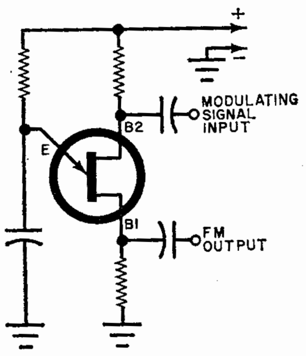


FIGURE 7

A practical example of a modulated UJT oscillator is shown in Fig. 8. This circuit is known as a "bell-tone" oscillator. In operation, *Q2* and its associated components make up a relaxation oscillator which, when unmodulated, has an operating frequency of about 700 Hz. Unijunction transistor *Q1* and its associated components make up a low-frequency astable multivibrator. The wave-form of the *Q1* setup is not as good as that of the circuit in Fig. 6, but it

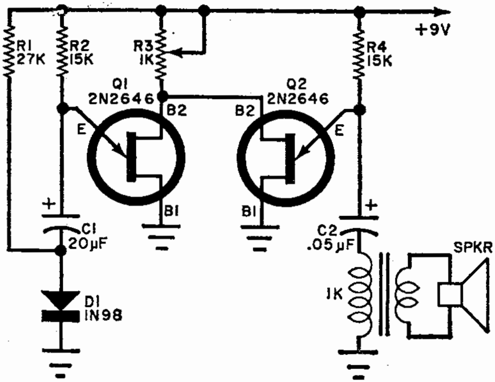


FIGURE 8

serves the purposes of the bell-tone oscillator well.

In the multivibrator, *C1* charges through *R2*, while diode *D1* is maintained in a forward conducting state by the charging current and the current through *R1*. When *Q1* fires, reverse bias is applied to *D1*, and the diode appears as an open circuit. Transistor *Q1* remains conducting while capacitor *C1* discharges through resistor *R1*. At the end of this interval, *D1* begins conducting again, *Q1* cuts off, and the cycle repeats. The result is a rectangular signal across *R3*.

Since the B2's of *Q1* and *Q2* are tied together, each time *Q1* fires, its B2 signal decreases the interbase voltage of *Q2* and causes an increase in *Q2*'s operating frequency. As *Q2* conducts and cuts off, the pitch of the sound heard from the loudspeaker rises and falls sharply, giving the sound a distinct bell-like quality. The speaker is preferably a small one, such as a 3″ replacement type, to provide "tinny" reproduction. When working with the circuit, adjust potentiometer *R3* to obtain the most pleasing sound.

Bipolar transistor pair simulates unijunction

by N.A. Shyne
Montana State University, Bozeman, Mont.

The negative-resistance characteristic of a programable unijunction transistor (PUT) can be simulated by interconnecting two discrete bipolar transistors. This equivalent PUT can not only switch faster than a conventional unijunction transistor, but it also offers better temperature stability. And parts cost can be as low as $1.

The four-layer structure of a PUT is approximated by arranging complementary transistors Q_1 and Q_2 as shown in the figure. Applied bias voltage V tends to place the quiescent operating point of both transistors in their forward active regions. Current I is given by:

$$I = (I_{CO1} - I_{CO2})/(1 - \alpha_{F1} - \alpha_{F2})$$

where α_{F1} and α_{F2} are the common-base short-circuit forward current gains of transistors Q_1 and Q_2, respectively; and I_{CO1} and I_{CO2} are the respective reverse saturation currents of the base-collector junctions of Q_1 and Q_2. (Current I_{CO1} is negative.)

In general, the numerator of this equation is not zero. As the sum of α_{F1} and α_{F2} approaches unity, current I increases without limit. The feedback between the two transistors is positive, since the collector current of Q_1 is the base current of Q_2, and vice versa. The condition for regenerative feedback, then, is:

$$\alpha_{F1} + \alpha_{F2} = 1$$

or:

$$\beta_{F1}\,\beta_{F2} = 1$$

where β_{F1} and β_{F2} are the common-emitter short-circuit forward current gains of transistors Q_1 and Q_2, respectively.

Resistors R_1 and R_2 permit the value of the equivalent PUT's intrinsic standoff ratio, η, to be varied. Let base B1 be the voltage reference point (ground), while base B2 is at a positive potential, V_{BB}. With the PUT's emitter (E) terminal open, the voltage at point B can then be expressed as:

$$V_B = [R_1/(R_1+R_2)]V_{BB} = \eta V_{BB}$$

so that:

$$H = R_1/(R_1+R_2$$

If emitter voltage V_E is now increased to:

$$V_E = \eta V_{BB} + V_D$$

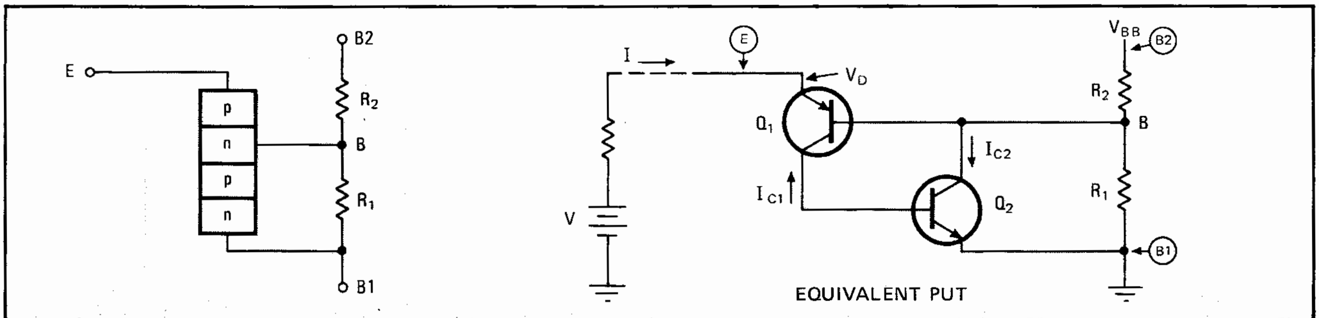
where V_D is the base-emitter voltage of transistor Q_1, both transistors will become saturated, and the PUT circuit will switch. When switching occurs, resistor R_1 is shorted out by transistor Q_2, and:

$$V_{Emin} = V_D + V_{CE2sat}$$

where V_{CE2sat} is the collector-emitter saturation voltage of transistor Q_2. This value of V_{Emin} is usually lower than that of a conventional unijunction transistor. (Generally, it is best to use silicon transistors to keep leakage currents low so that the sum of α_{F1} and α_{F2} is less than unity with the PUT's emitter open.)

The switching speed of this equivalent PUT is limited only by the maximum operating frequency of the bipolar transistors used for Q_1 and Q_2. Usually, the switching speed is considerably faster than that of a conventional unijunction transistor.

If silicon transistors are used, the value of switching voltage V_D drifts only 3 millivolts/°C. And with the proper selection of resistors R_1 and R_2, intrinsic stand-



PERFORMANCE COMPARISON

PARAMETER	CONDITION	EQUIVALENT PUT*	TYPICAL UJT**
R_{BB}, interbase resistance	V_{BB} = 3 V, I_E = 0	9.4 kΩ	6.2 – 9.1 kΩ
η, intrinsic standoff ratio	V_{BB} = 10 V	0.5	0.51 – 0.62
I_P, peak point current	V_{BB} = 25 V	−160 nA	12 μA max
I_{EO}, emitter reverse current	25° C	1 nA	2 μA max
I_V, valley current	V_{BB} = 10 V	−200 μA	8 mA

* Q_1 = 2N4126, Q_2 = 2N4124, R_1 = R_2 = 4.7 kΩ ** UJT = 2N490A

Simulating a unijunction transistor. An equivalent programable unijunction transistor (PUT) can be realized by wiring complementary bipolar transistors as shown. The resulting equivalent PUT offers faster switching and less temperature drift than an ordinary unijunction transistor (UJT). The table compares the major characteristics of the equivalent circuit to a typical UJT.

off ratio η can be made essentially independent of changing temperature.

The table compares the performance of the equivalent PUT to the performance of a typical unijunction transistor, a type 2N490A device. For the comparison, $R_1 = R_2 = 4.7$ kilohms and $^{g} = 0.5$. A complementary (to the one shown) equivalent PUT can be made by just interchanging the positions of transistors Q_1 and Q_2. □

NORTHERN ALBERTA INSTITUTE OF TECHNOLOGY
EDMONTON ALBERTA

ELECTRONICS DEPARTMENT

UNIJUNCTION TRANSISTORS

SILICON ANNULAR⁺ PN UNIJUNCTION TRANSISTORS

. . . designed for use in pulse and timing circuits, sensing circuits and thyristor trigger circuits. These devices feature:

Low Peak Point Current -- as low as .4μAMax
Low Emitter Reverse Current -- as low as 50nA Max
Fast Switching Speed -- 1MHz frequency of oscillation
Passivated Surface for Reliability and Uniformity

MAXIMUM RATINGS ($T_A = 25^{\circ}C$ unless otherwise noted)

CHARACTERISTIC	SYMBOL	RATING	UNIT
RMS Power Dissipation*	P_D	300*	mW
RMS Emitter Current	I_e	50	mA
Peak Pulse Emitter Current**	i_e	2**	Amps
Emitter Reverse Voltage	V_{B2E}	30	Volts
Interbase Voltage	V_{B2B1}	35	Volts
Operating Junction Temperature Range	T_J	-65 to +125	°C
Storage Temperature Range	T	-65 to +150	°C

* Derate 3.0mW/°C increase in ambient temperature. The total power dissipation (available power to Emitter and Base-Two) must be limited by the external circuitry.

** Capacitor discharge -- 10μf or less, 30 volts or less.

\+ Annular Semiconductors Patented by Motorola, Inc.

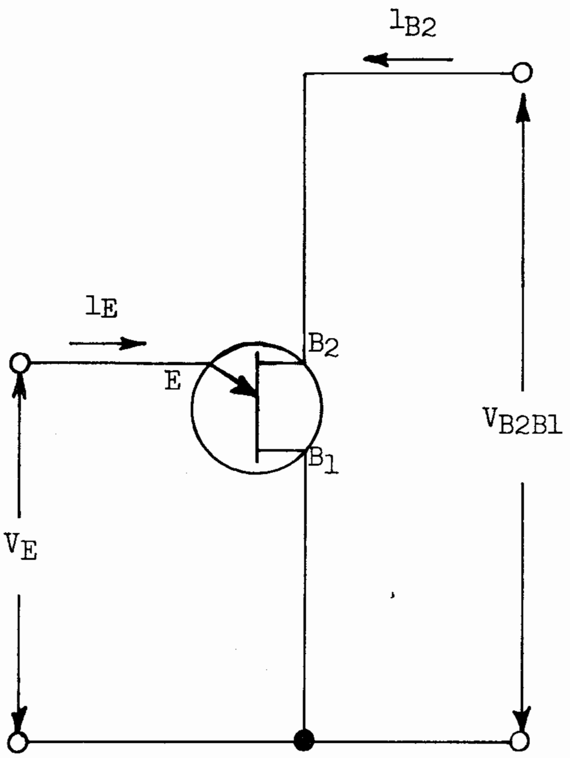


Figure 1.

Unijunction Transistor
Symbol and Nomenclature

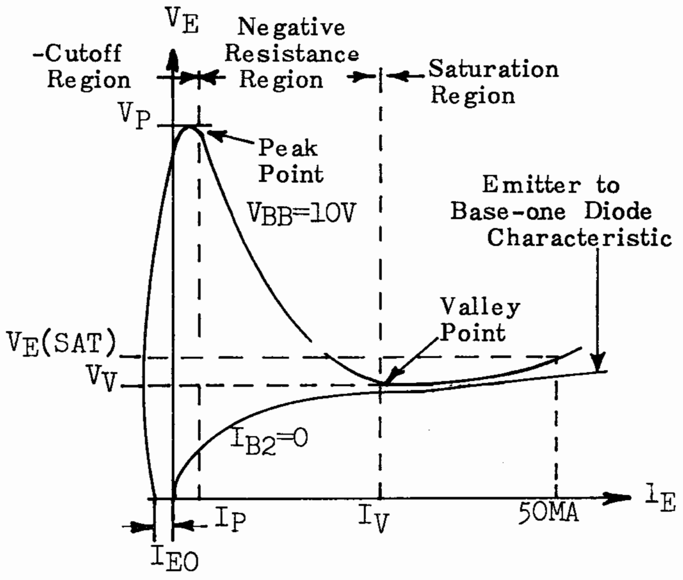


Figure 2.

Static Emitter Characteristics Curves
(Exaggerated to Show Details)

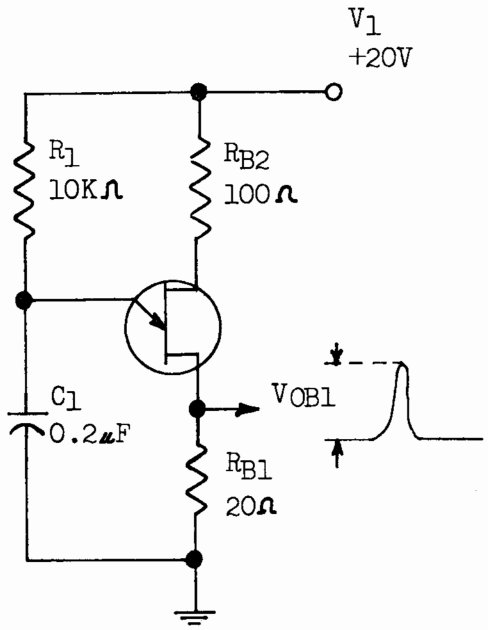
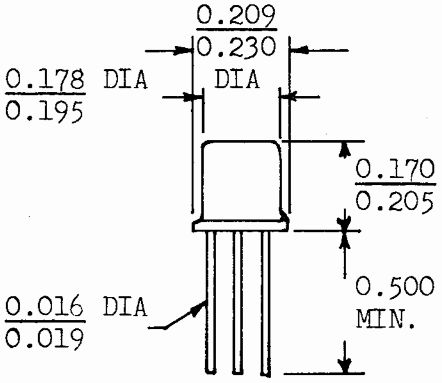
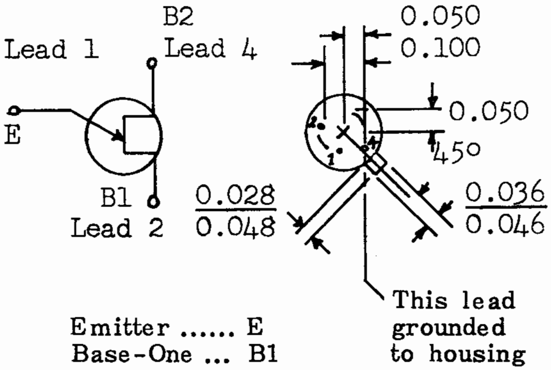


Figure 3.

V_{OB1} Test Circuit
(Typical Relaxation Oscillator)



Approximate Weight .015 oz.



Emitter ...... E
Base-One ... B1
Base-Two ... B2

T0-18 Outline except for lead position

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

Characteristic	Symbol	Min.	Type	Max.	Unit
Intrinsic Standoff Ratio (V_{B2B1} = 10V) (Note 1, Figure 4) 2N4851 2N4852 2N4853	η	.56 .70 .70	- - -- --	.75 .85 .85	--
Interbase Resistance (V_{B2B1} = 3V, I_E = 0)	R_{BBO}	4.7	7.0	9.1	K ohms
Interbase Resistance Temperature Coefficient (V_{B2B1} = 3V, I_E = 0, T_A = -65°C to + 125°C) (Note 2)	αR_{BBO}	.20	--	.80	%/°C
Emitter Saturation Voltage (V_{B2B1} = 10V, I_E = 50mA) (Note 3)	V_{EB1} (sat)	--	2.5	--	Volts
Modulated Interbase Current (V_{B2B1} = 10V, I_E = 50mA)	I_{B2} (mod)	--	15	--	mA
Emitter Reverse Current (V_{B2E} = 30V, I_{B1} = 0) 2N4851 & 52 2N4853	I_{EB20}	-- --	0.010 0.005	0.10 0.05	μA
Peak Point Emitter Current (V_{B2B1} = 25V) 2N4851 & 52 2N4863	I_p	--	.5 .1	2.0 .4	μA
Valley Point Current (V_{B2B1} = 20V, R_{B2} = 100 ohms) (Note 3) 2N4851 2N4852 2B4853	I_v	2 4 6	5 7 9	--	mA
Base-One Peak Pulse Voltage (Note 4, Figure 3) 2N4851 2N4852 2N4853	V_{OB1}	3 5 6	6 8 9	-- --	Volts
Maximum Frequency of Oscillation (Figure 5)	$f_{(max)}$	1	1.25	--	MH_z

NOTES:

1. The intrinsic standoff ratio, η, is essentailly constant with temperature and interbase voltage. η is defined by the equation:

$$\eta = \frac{V_P - V_{F(EB1)}}{V_{B2B1}}$$

   Where: V_p = Peak Point Emitter Voltage; V_{B2B1} = Interbase **Voltage**; $V_{F(EB1)}$ = Emitter to Base-One Junction Diode Drop ($\approx 0.5V$).

2. Suggested nominal temperature compensating resistor (R_{B2}) for injunctions over the ambient temperature range of -55°C to +100°C in a circuit similar to Figure 3 is approximately 270 ohms.

3. When testing for Emitter Saturation Voltage ($V_{EB1(sat)}$) and Valley Point Current (I_V) the Emitter Current should be limited to avoid internal heating resulting in erroneous readings.

4. The Base-One Peak Pulse Voltage is measured in the circuit of Figure 3. This specification is used to ensure a minimum pulse amplitude for applications in SCR firing circuits and other types of pulse circuits.

η- Intrinsic Stand off Ratio - This parameter is defined in terms of the peak-point voltage, V_p by means of the equation: $V_p = V_{B2B1} + V_F$ where V_F is about .49 volt at 25 °C and decreases with temperature at about 2 millivolts/C°. It is found that η is constant over wide ranges of temperature and interbase voltage. The circuit used to measure η is shown in the figure. In this circuit, R_1, C_1, and the unijunction transistor form a relaxation oscillator, and the remainder of the circuit serves as a peak-voltage detector with the diode D_1 automatically subtracting the voltage V_F. To use the circuit, the "cal" button is pushed, and R_3 is adjusted to make the current meter M_1 read full scale. The "cal" button then is released and the valve of η is read directly from the meter, with $\eta \approx 1$ corresponding to full-scale deflection of 10 a. D_1, 1N457, or equivalent, with the following characteristics:

$$V_F = .490v \text{ at } 1_F = 10\mu a$$

$$1_R \leq 2 \text{ a at } V_R = 20 \text{ v}$$

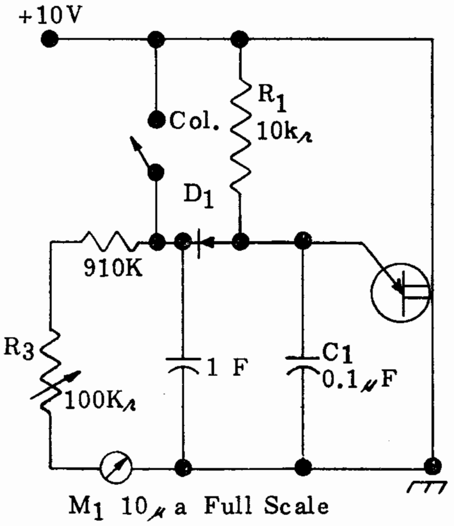


Figure 4

Test Circuit for Intrinsic Standoff Ratio (η)

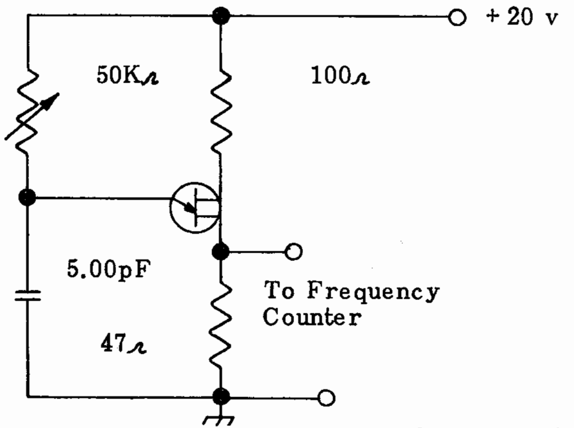
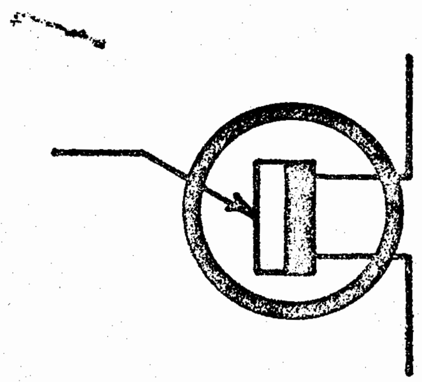


Figure 5 f_{max} Test Circuit



20 UNIJUNCTION

Part II of 2 parts—to acquaint you

IN PART I OF THIS SERIES (JUNE 1968) you were introduced to the unijunction transistor. You saw how it works, and were given 11 applications for it. Here are 9 more. For your convenience, the basing diagram (Fig. 1) and the characteristics (Table 1) of the 2N2646 UJT used in these circuits are shown once again.

Diode-pump counter

Circuit shown in Fig. 2 acts as a frequency divider or counter, but gives a nonlinear staircase output. It has the advantage, however, that counting is almost independent of the shape of the input signal.

With no input applied, Q1 is cut off and C3 charges via R3, C2 and D1; C2 and C3 act as a voltage divider, and a fixed fraction of the supply voltage appears across C3. When an input pulse is applied, Q1 is driven to saturation and C2 is discharged via Q1 and D2; C3 is prevented from discharging by D1. When the pulse is removed again, C2 again charges via D1 and C3, and places another fraction of the supply voltage on C3.

Thus, at the end of each pulse, the C3 voltage increases by a fixed step (smaller than the previous one) until eventually the UJT fires, discharges C3, and the counting cycle starts over again. Pulse shape has virtually no effect on circuit operation.

The division ratio, $\frac{f_{out}}{f_{in}}$, is roughly equal to $\frac{C2}{C2 + C3}$. The ratio is, however, affected by a number of variable factors, including operating frequency, so the values of these two components are best found by trial and error. Once components have been selected, the circuit will give stable division over quite a wide range of input frequency variation Stable division ratios up to 10 to 1 can be easily obtained.

Synchronized frequency divider

Divider shown in Fig. 3 generates precise frequency or timing-interval signals. Positive-going pulses from a 100-kHz crystal oscillator are fed, via C1, to base 2 of Q1. R1 is adjusted so that the UJT locks firmly to an operating frequency of 10 kHz, the 100-

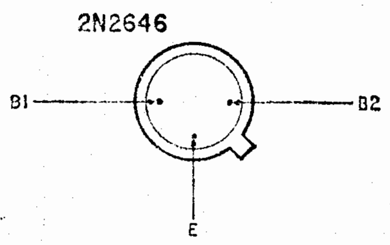


Fig. 1—Base connections of 2N2646 UJT. B2 is electrically connected to case.

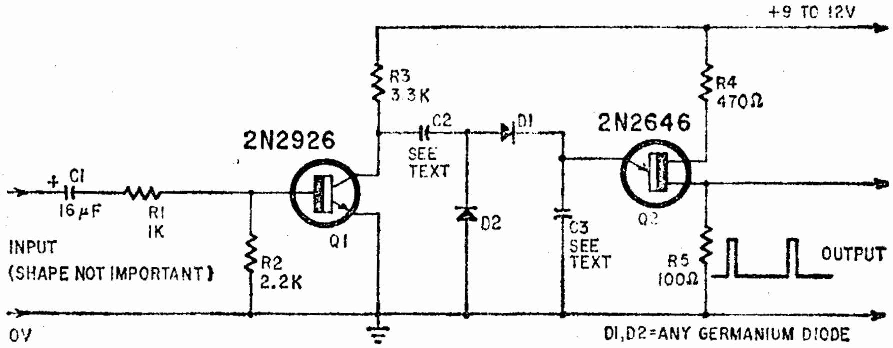


Fig. 2—Diode pump counter.

Table 1—2N2646 Characteristics

Emitter reverse voltage (max)	20 volts
Interbase voltage (max)	35 volts
Peak emitter current	2 amps
Rms emitter current	50 mA
Power dissipation (max)	300 mW
Intrinsic standoff ratio (η)	0.56–0.75
Interbase resistance (R_{BB})	4,700–9,100 ohms
Peak-point emitter current (I_p) (max)	5 μA (1) 25 μA (2)
Valley-point current (I_v) (min)	4 mA
Case	TO–18

(1) GE
(2) Motorola

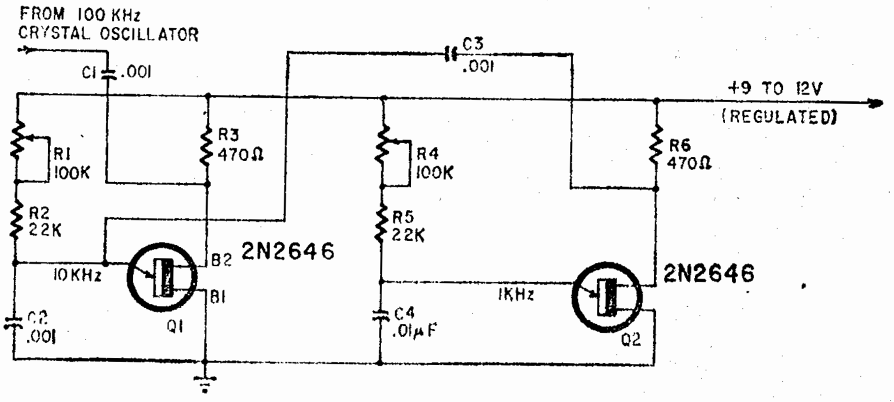


Fig. 3—Synchronized frequency divider.

TRANSISTOR APPLICATIONS

further with this useful solid-state device

By R. M. MARSTON

kHz signals acting as sync pulses. The 10-kHz signal from Q1's emitter is fed to Q2 via C3, and R4 is adjusted so that Q2 locks to an operating frequency of 1 kHz. Thus, the circuit makes available standard frequencies (and timing intervals) of 100 kHz (10 μsec), 10 kHz (100 μsec), and 1 kHz (1-msec). Stability is very good if a Zener-regulated power supply is used for this circuit.

Division ratios other than 10 can be obtained by adjusting R1 and R4. Outputs can be taken, via a high-impedance emitter-follower buffer stage, from the emitter of each UJT and from the crystal oscillator.

Wide-range square-wave generators

The unijunction transistor can be used as the heart of a whole range of waveform generators. Figs. 4 and 5 show how it can be used to generate square waves.

In Fig. 4, Q2 and Q3 form an npn bistable multivibrator or divide-by-2 circuit. At the end of each UJT cycle, the positive-going pulse from R4 is fed to the emitters of Q2 and Q3 and causes the multivibrator to change state. Two cycles of the UJT produce a single complete cycle of the multivibrator. The multivibrator output, taken from either collector, is therefore a perfect square wave at half the UJT frequency. The two collector signals are opposite in phase.

Fig. 5 shows the pnp version of the same circuit. In this case, the circuit uses the negative-going pulses from R3 to trigger the bistable multivibrator, but the two circuits are otherwise similar to each other.

It's important to note that in both these circuits C2 and C3 are of equal value — approximately $\frac{C1}{100}$ That is, if Cl is 0.1 μF, C2 and C3 should be .001 μF (1000 pF). C2 and C3 should, however, have a minimum value of about 100 pF.

Both circuits (Figs. 4 and 5) will

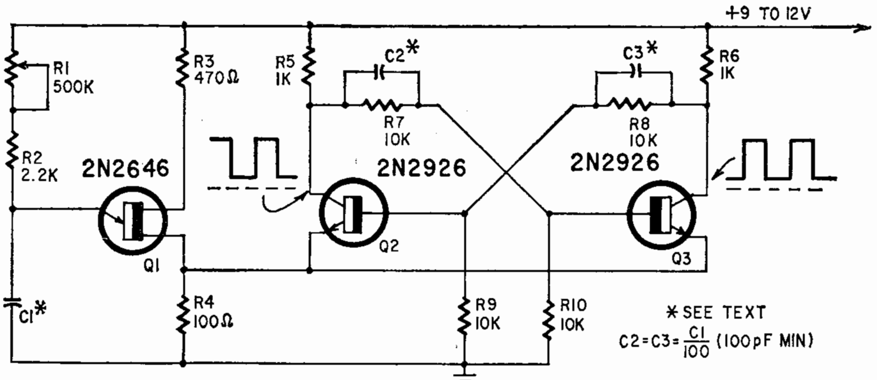


Fig. 4—Wide-range square-wave generator employing npn transistors.

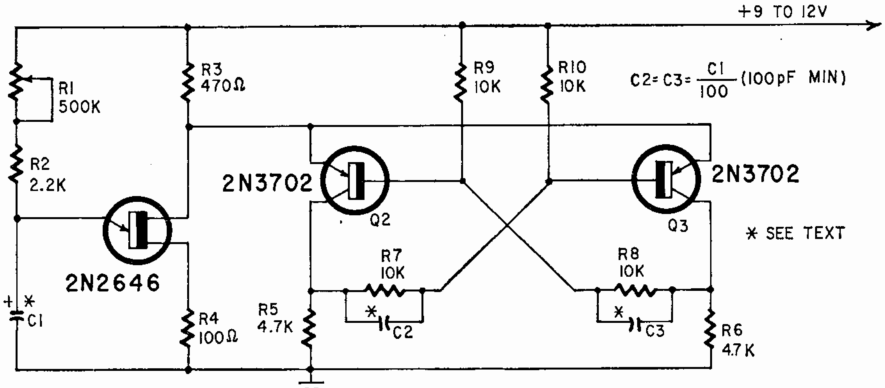


Fig. 5—Pnp transistors in a square-wave generator.

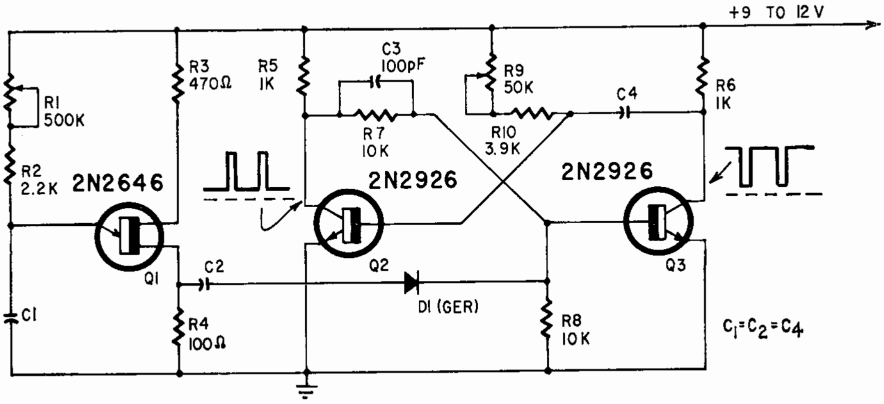


Fig. 6—Variable-frequency pulse generator.

generate square waves over a 100:1 frequency range, using a single set of component values.

Variable-frequency pulse generator

The circuit of Fig. 6 generates a constant-width pulse that can be varied in repetition frequency over a 100:1 range. It may, for example, generate a pulse with a constant width of 500 μsec, at repetition frequencies ranging from 10 to 1,000 Hz. The actual pulse width can be adjusted, on any particular range, over a 10 to 1 range, i.e., from 50 to 500 μsec.

In this quite simple circuit, Q2 and Q3 are wired as a monostable or one-shot multivibrator, with pulse width controlled by R9, R10 and C4. The multivibrator is triggered by positive-going pulses fed from R4 to Q3 base via C2 and D1. Thus, repetition frequency is controlled by the UJT, and pulse width by the multivibrator.

Different sets of C1–C2–C4 values are needed for each range of operation, but all three capacitors will usually be of equal value. The main point here is that the maximum period of the pulse must be less than the minimum period of the UJT cycle. Otherwise the pulse will not be ended by the time a new trigger pulse arrives, and stable operation will not be obtained.

Pulse outputs can be taken from either collector, the two outputs being opposite in phase.

Variable on/off-time pulse generator

This circuit (Fig. 7) generates a series of pulses in which the on and off times are independently controlled. Furthermore, each can be varied over a 100:1 range.

The circuit is similar to the square-wave generator of Fig. 4, Q2 and Q3 forming a bistable multivibrator that is triggered by positive-going pulses from R6. In the circuit of Fig. 7, however, two different C1 charging circuits (R1–R2 and R3–R4) are available, and the multivibrator operates diode gates that select the charging circuit that may be used at any particular moment.

Assume that when the power is turned on, Q2 is on and Q3 is off. Q2's collector is at zero volts, so D4 is forward-biased and D3 is thus back-biased. No charge current flows to C1 via R3–R4. Q3's collector is at near full positive supply potential, so D2 is back-biased. D1 is thus forward-biased and C1 charges via R1–R2 only. At the end of this timing cycle, the UJT fires and triggers the multivibrator, so Q2 switches off and Q3 switches on. D2 is forward-biased and D4 is back-biased, so R1–R2 are cut out of circuit and C1 charges via R3–R4 only. At the end of this new cycle, the circuit goes back to its original state.

C2 and C3 are of equal value and equal to $\frac{\text{C1}}{100}$, down to a minimum value of about 100 pF. When C1 is 0.1 μF, the on and off times of the output pulse can be individually controlled over the approximate range 500 μsec to 50 msec.

Variable frequency/M-S ratio generator

Figure 8's circuit generates a series of pulses in which both the mark/space (on time/off time) ratio and the frequency can be independently varied over a wide range. If, for example, the M–S ratio is set at 9 to 1, the operating frequency can be varied from, say, 10 to 1000 Hz without any resulting change in M–S ratio.

Similarly, if the operating frequency is set at, say, 100 Hz, the M–S ratio can be varied over the range 1 to 100 or 100 to 1 without any resulting change in operating frequency.

Both frequency and M–S ratio can be simultaneously varied, without interaction. This type of generator is used at the transmitter end of analog proportional two-channel remote-control systems, such as the "Galloping Ghost"—a radio control system.

In Fig. 8, Q2 and Q3 form a super-alpha-pair (Darlington pair) emitter follower, and permit a sawtooth output to be taken at low impedance from the R6–R7–R8 chain without affecting the operating frequency of Q1. This sawtooth is then

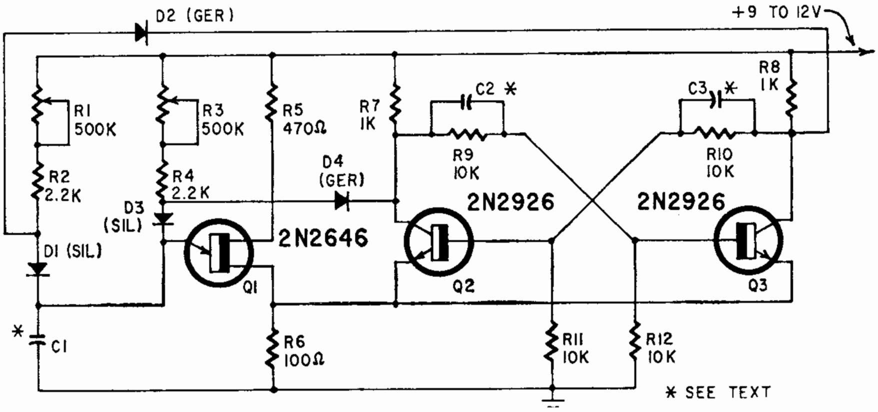


Fig. 7—Variable on/off-time pulse generator.

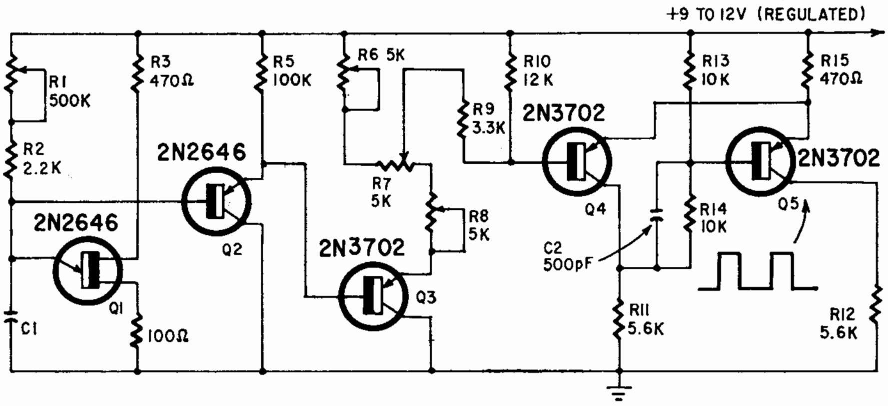


Fig. 8—Variable frequency, mark-space ratio generator.

fed, via R9, to the Schmitt trigger formed by Q4 and Q5. By adjusting R7 the Schmitt can be made to fire at different points on the sawtooth, and so generate different M–S pulse signals at Q5's (or Q4's) collector. R6 and R8 allow the maximum and minimum mark-space ratios to be preset. Different frequency ranges can be selected via C1—as in the case of all UJT circuits given in this article.

Radio control enthusiasts will have noticed that this circuit uses a total of five transistors, compared to the three used in some other pulsers. That's because this circuit is designed to give a total lack of channel interaction—an advantage you don't get with other less-complex circuits.

One-shot lamp/relay driver

For most lamp or relay sequential operations, where you want switching or delay times of only a few seconds, the unijunction offers no real advantage over conventional transistor circuits. It's only when you want very long sequential periods—ranging from tens of seconds up to several minutes—that the UJT is really useful. Fig. 9 shows just such an application.

This is a one-shot lamp or relay operator. The lamp is normally off, but as soon as you operate a pushbutton it comes on, and stays on for a preset period that can be adjusted from about 4 seconds to 8 minutes. At the end of that period, the lamp switches off and the circuit resets, ready for the next pushbutton operation that you select.

Q2 and Q3 form a bistable multivibrator in which Q2 is normally on and Q3 is off. Thus, Q2's collector is at zero volts, so D2 is forward-biased and D1 is back-biased. Capacitor C1 is prevented from charging via R1–R2. Q3's collector is at near full positive supply voltage, so no forward bias is applied to Q4, and the lamp is off. (R11–D3–R12 form a voltage divider, and insure that the small voltage at Q3's collector is not enough to turn transistor Q4 on.)

When start pushbutton S1 is momentarily operated, Q2's base is shorted to ground and the bistable multivibrator changes state. Q2 goes off, removing the forward bias from D2. C1 now takes on a charge via R1–R2–D1. Transistor Q3 goes on, drives Q4 hard (via D3–R12) and switches the lamp on. After a preset period, the UJT fires, and the positive-going pulse from R4 is fed to Q2's base via C2 and D4, turning Q2 back on and resetting the circuit to its original condition, with D2 forward-biased and the lamp off.

Only lamps or relays with operating currents less than 300 mA can be used in this circuit. Q4 can, however, be used to drive a power transistor to handle larger currents, so long as the collector current of Q4 is limited to less than 300 mA by a series resistor.

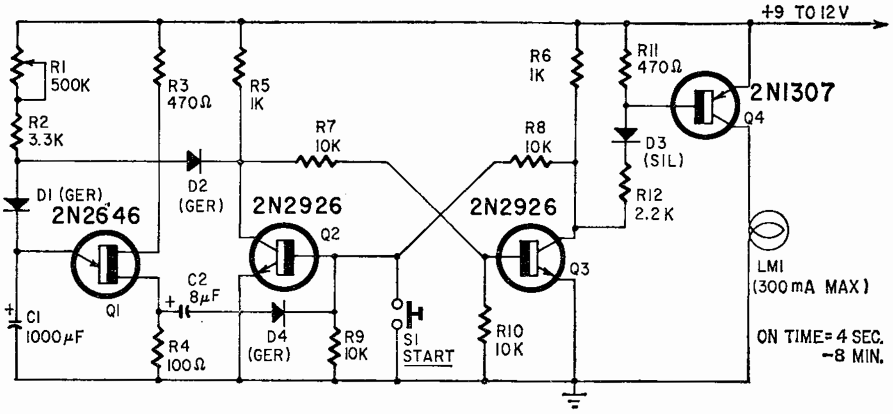


Fig. 9—One-shot lamp or relay driver.

Variable on/off-time lamp flasher

Another sequential UJT lamp-driving circuit is shown in Fig. 10. Here, the on and off times of the lamp can be individually varied over the approximate range of 4 seconds to 8 minutes (giving a maximum possible cycle period of 16 minutes). Operation is repetitive.

The circuit is like the one in Fig. 7, with the addition of the lamp-driving transistor stage given in Fig. 9. Maximum output current is again limited to about 300 mA. The on time of the lamp is controlled by potentiometer R3 and the off time is controlled by potentiometer R1.

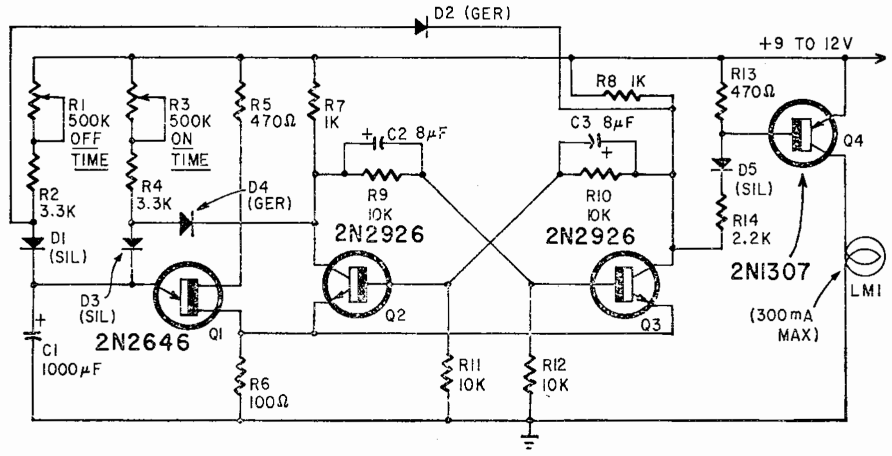


Fig. 10—Variable on/off-time lamp flasher.

Conclusions

If you decide to build any of these circuits, bear a couple of points in mind: Power supplies must be well filtered and reasonably stable. That doesn't mean they have to be fully regulated; it simply means that they may give trouble if they contain a lot of ac, or if you use batteries that are half dead. In most circuits, I've designed the UJT sections to cover a 100:1 frequency range. As a result, control may be coarse; if it's too coarse, wire a 10,000-ohm "fine" control in series with the main potentiometer. If you want a range less than 100:1, increase the value of the fixed series control resistor. **R-E**