TRANSISTORS REPLACE FOUR-LAYER DEVICES

Economy, parameter control, packaging—these factors may dictate the substitution of a transistor model for a four-layer device.

WESLEY A. VINCENT, MOTOROLA, INC.

Variously named Shockley diode, reverse-blocking thyristor or silicon unilateral switch, the four-layer diode exhibits a V-I response that travels through a negative resistance region. This characteristic is explained easily by a transistor model that indicates that a similar device can be constructed with two transistors and a resistor.

The two transistors and a resistor may:

- Cost less than a four-layer semiconductor.
- Permit better parameter control.
- Be better adapted to a hybrid package since transistors now are available in chip form.

The transistor-resistor configuration gives the designer a wide range of switching voltage and holding currents. Further, the shunt resistors suppress the tendency toward premature switching from high di/dt to bulk rate effects. This concept is generally applied to the thyristor family, but can be extended to other devices such as the unijunction transistor (UJT)—simply add two resistors.

UJT Equivalent

Either circuit in **Fig. 1** represents the equivalent of a UJT. Neither appears to have any advantage over the other. Resistors R_{B1} and R_{B2} represent the interbase resistance and establish the peak point voltage. By proper selection, the designer can establish the required level for his needs.

Application

A p-base UJT relaxation oscillator is illustrated in **Fig. 2**. The oscillator frequency is determined by the

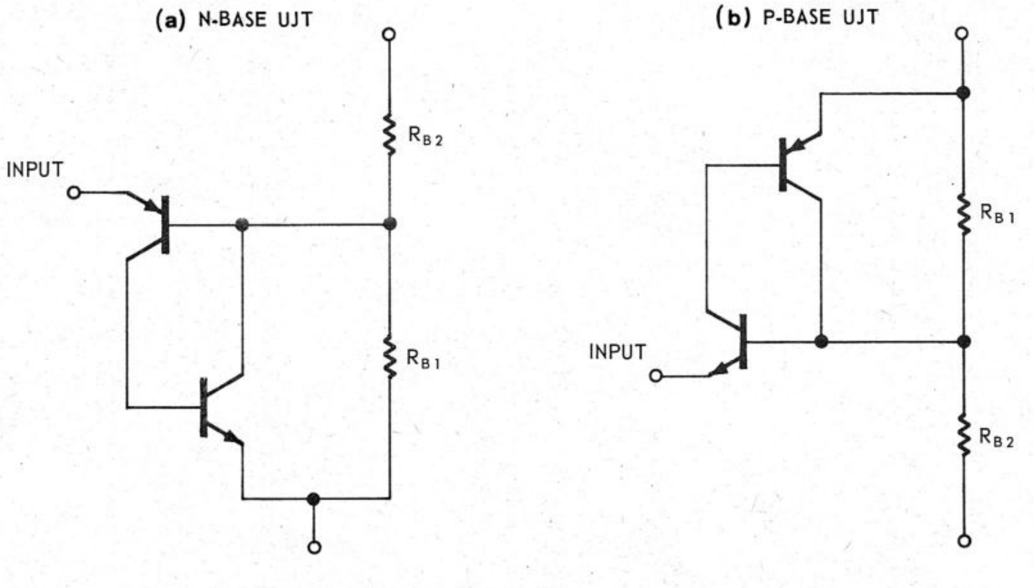

Fig. 1—**Transistor representation** for two types of UJT.

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FOR FREE 8-1/2 BY 11-INCH REPRINT OF THIS ARTICLE **CIRCLE NO. L62** time constant of R1 C1, and the discharge current through the emitter is limited by R2. Resistor R3 is selected for temperature compensation and develops a positive pulse at base-2 during operation.

Interbase resistance ratio (intrinsic standoff ratio) combined with emitter diode drop determine the firing point. Depending on the UJT construction, one of two mechanisms occurs during firing. In conventional "bar", "cube" or "planar" n-base UJT, the resistance between the emitter and base-1 is decreased by the carriers injected across the junction. This is known as conductivity modulation of the bulk silicon. In the recently introduced p-base UJT, the basic mechanism is because of the low-impedance pnpn, four-layer action.

In **Fig 2b**, the operation of the transistor equivalent is similar and depends on the pnpn performance for its regenerative action. Voltage divider R_{B1}, R_{B2}, R_2 and the base-emitter drop of Q2 establish the firing point. During firing, C1 is discharged through the low impedance of the transistor equivalent.

Test Results

Test results for a 1000-Hz oscillator using the transistor model are plotted in **Fig. 3**. The pnp and npn transistors are types 2N2907 and 2N2222, respectively, with an applied voltage of +10V, regulated. Similar results were obtained with other silicon transistors.

For the tests, frequency-determining components (R1 and C1) remained outside the temperature chamber or subject to room ambient temperature. Thus, all

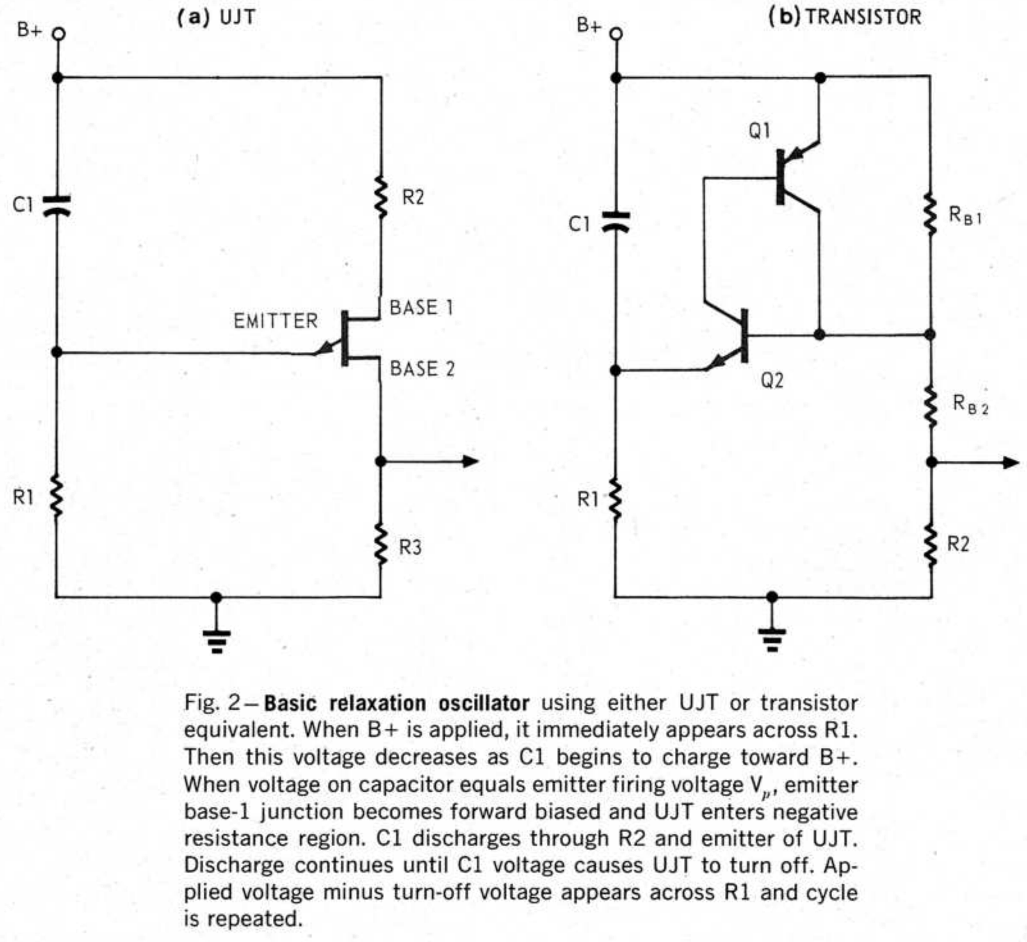
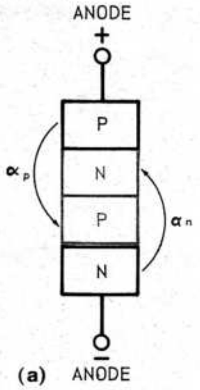
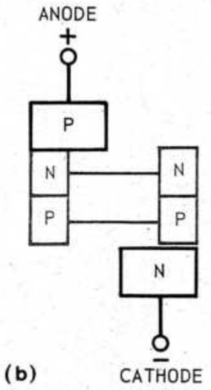
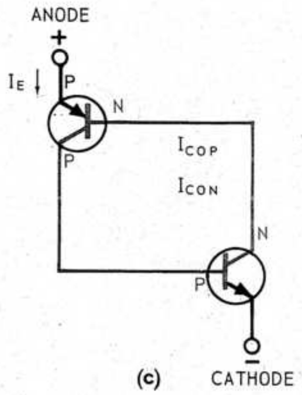


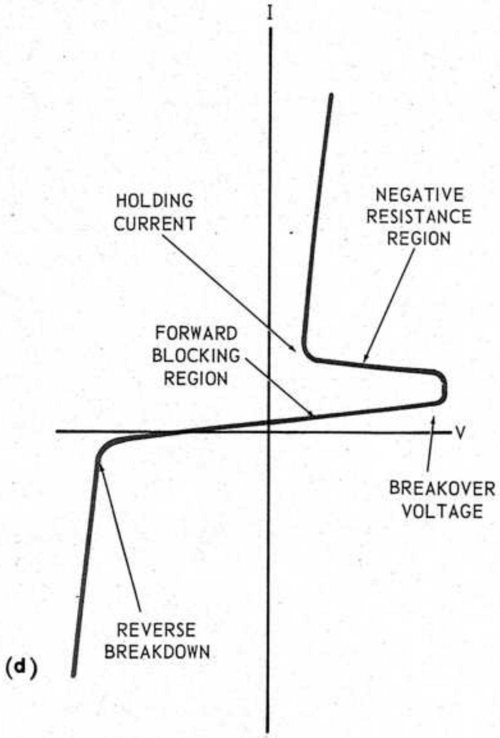
Fig. 2 – **Basic relaxation oscillator** using either UJT or transistor equivalent. When B+ is applied, it immediately appears across R1. Then this voltage decreases as C1 begins to charge toward B+. When voltage on capacitor equals emitter firing voltage V_p, emitter base-1 junction becomes forward biased and UJT enters negative resistance region. C1 discharges through R2 and emitter of UJT. Discharge continues until C1 voltage causes UJT to turn off. Applied voltage minus turn-off voltage appears across R1 and cycle is repeated.

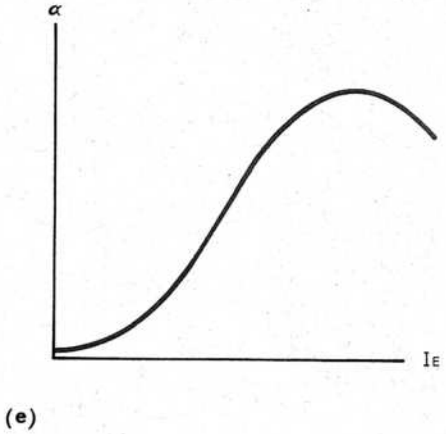
TRANSISTOR MODEL DEVELOPMENT OF FOUR-LAYER DIODE











Classical diagrams (**a**) to (**c**) show the evolution of a transistor version of four-layer diode. Unusual characteristic response curve (**d**) is caused by variability of multiplication factor, *M* and current gains α_p and α_n.

Mathematically, terminal current I_E may be expressed as:

$$I_E = \frac{I_{cop} + I_{con}}{1 - (M_p \propto_p + M_n \propto_n)} \qquad (1)$$

where p and n subscripts refer to pnp or npn devices and I_{co} represents collector-to-base leakage currents. Multiplication factor, M, accounts for carriers created by impact ionization in reverse-biased junction.

Practically, M_p and M_n can be assumed equal, designated as M. Leakages are combined and (1) becomes:

$$I_E = \frac{I_{co}}{1 - M(\propto_p + \propto_n)} \qquad (2)$$

At less than breakover voltage, only small leakage current flows. Current gain parameters are much less than 1, M is unity. As forward voltage is continually increased the condition occurs where $M(\propto_p + \propto_n) = 1$. Current then increases sharply over previous small leakage current. The voltage at this point is termed breakover voltage. *M* exceeds unity, since avalanche breakdown occurs in reverse-biased junction.

Interaction between *M*, $\propto_p$ and $\propto_n$ causes M to drop while current-dependent $\propto_p$ and $\propto_n$ rise as current increases. This causes forward bias across diode to fall off, giving rise to negative resistance region shown in (**d**).

Current continues to increase and voltage decreases until holes injected at anode of pnp equal the electrons injected at emitter of npn transistor. This condition results in saturation of the transistor model (forward-biased center junction of four-layer diode).

In reverse operating mode, four-layer diode or model appears as two reverse-biased diodes in series, passing small reverse current until breakdown occurs.

(Continued)

results for the equivalent UJT oscillator would be altered by the temperature characteristics of R1 and C1. Frequency change for all graphs were normalized for 25°C and expressed as a percent change. Above 25°C, the frequency increases in an approximate linear manner and below 25°C, it decreases in a nonlinear manner. In fact, the frequency decreases as much as 10 percent at −50°C.

Accuracy depends on the repeatability of the peak point voltage. Metal film resistors with low temperature coefficients were used, but the V_{BE} drop varies approximately −1.5 to 2.0 mV/°C. Any major temperature dependence of the peak point voltage is because of npn base-emitter diode. Temperature stability also depends on the turn-off voltage or roughly the voltage that exists at the minimum holding current.

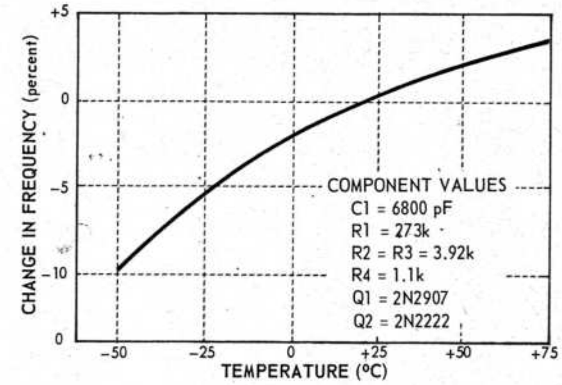


Fig. 3—**Test results** for a 1-kHz relaxation oscillator are plotted over −55 to +75°C temperature range. Listed component values were used with +10V, regulated, applied.

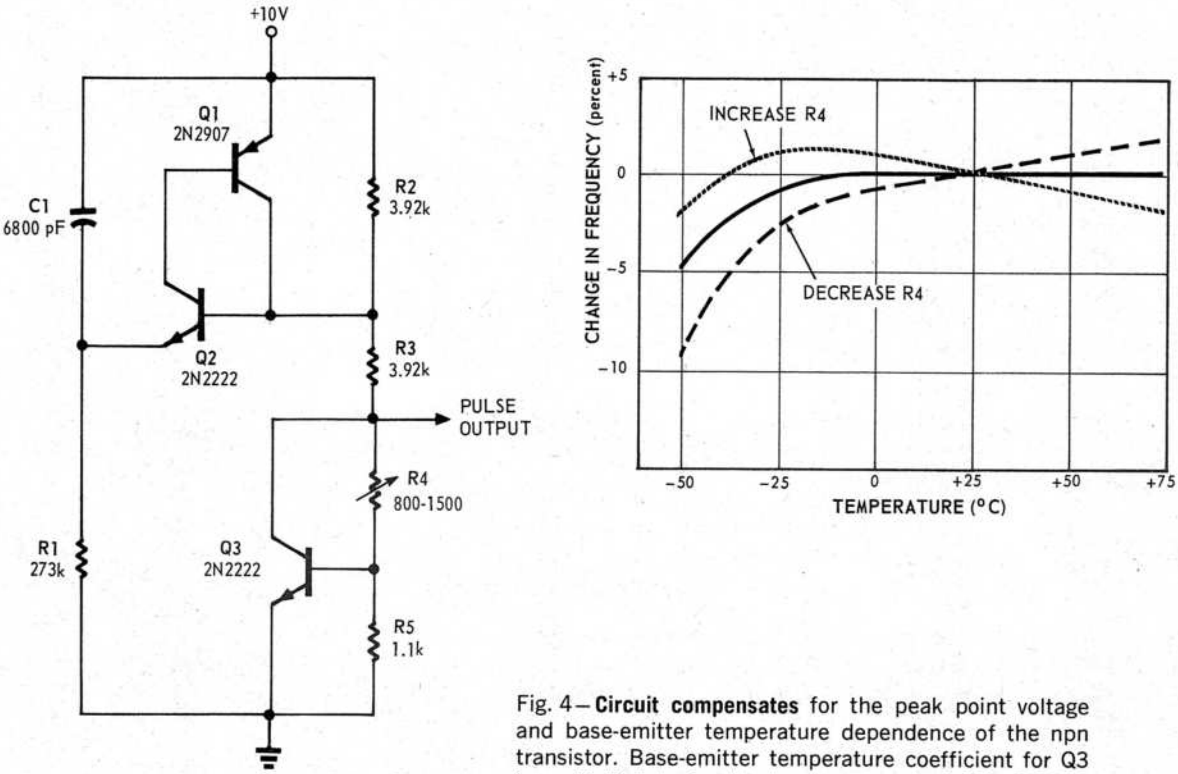
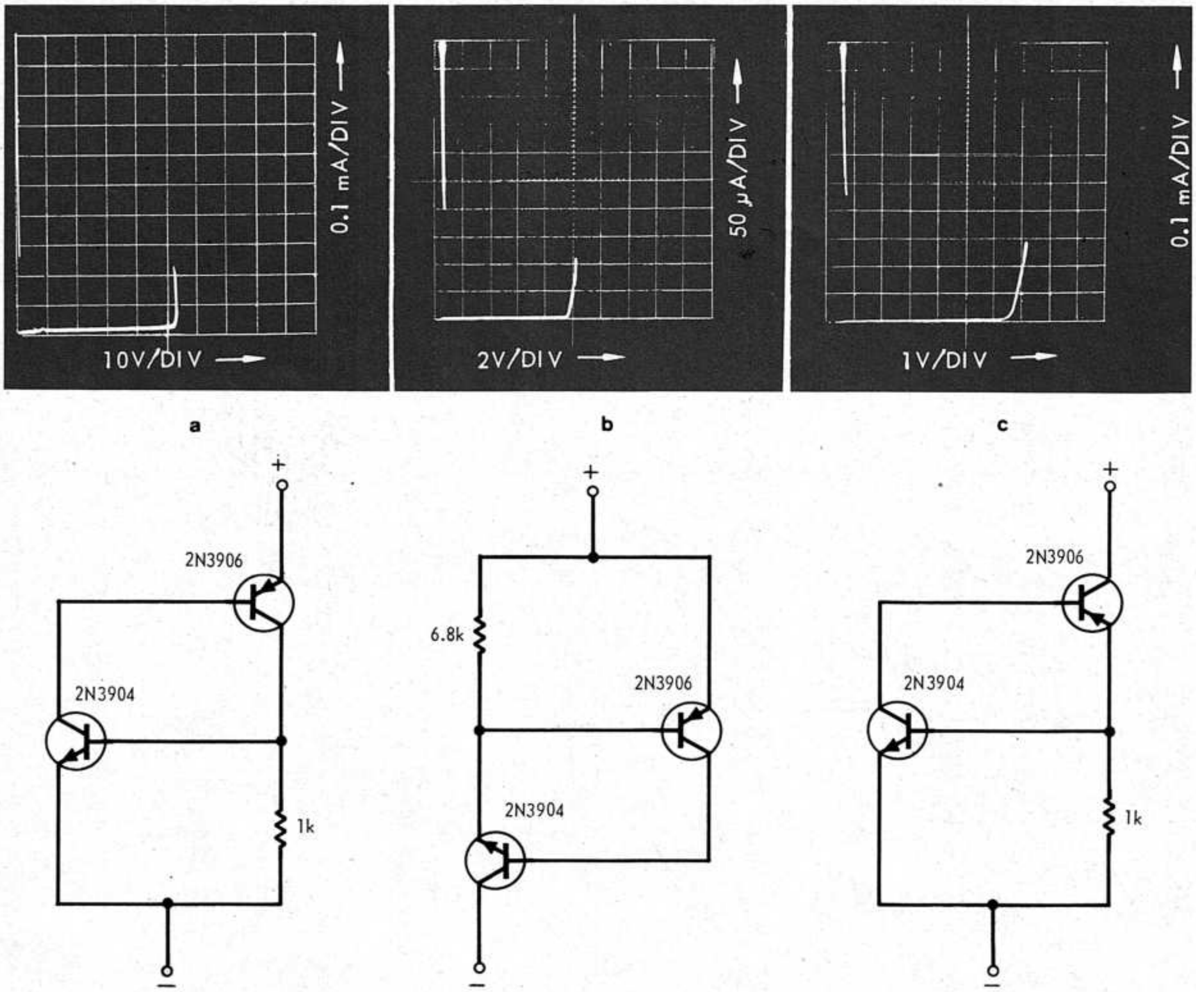


Fig. 4—**Circuit compensates** for the peak point voltage and base-emitter temperature dependence of the npn transistor. Base-emitter temperature coefficient for Q3 is multiplied by feedback arrangement of (R4+R5)/R5. Resistor R4 is used to select frequency stability. Graph illustrates typical test results.

THREE CONFIGURATIONS OF SIMULATED FOUR-LAYER DIODES



With the indicated connections, transistor current gain is much higher than that of four-layer diode. Breakover condition occurs at tenths of a volt. By shunting the emitter current path with a base-emitter resistor, very little injection takes place until the voltage across the shunt resistor begins to forward-bias the base-emitter junction. Shunt resistors can be placed across either pnp or npn transistor.

Forward V-I characteristics in (**a**) are for the circuit with the npn transistor shunted. Curves (**a**) and (**c**) are for two different 2N3906 transistors. BV_{ceo} is 55V (top), 65V (bottom). BV_{cer} of 2N3904 transistor is 120V. Breakover voltage of the pair is determined by the transistor with the lower breakdown parameter. Shunt resistors reduce base current gains and increase transistor breakdown voltage from BV_{ceo} to BV_{cer}, "o" designating open, "r" representing a resistive shunt.

Breakover voltage below BV_{ceo} is attained by operating either transistor in inverted mode, as in (**b**). Curve shows the result of inverting npn transistor, shunting base-emitter junction of pnp transistor, Even though α for an inverted transistor is severly reduced, it is still necessary to reduce the α of either the npn or pnp transistor with a shunt resistor. Here breakover voltage is determined by BV_{eco} of npn transistor, 10V. (A close approximation to breakover voltage is the more commonly specified BV_{ebo} voltage.)

A third four-layer diode equivalent is shown in (**c**), where the pnp transistor is inverted. Here the BV_{eco} voltage of pnp transistor determines the breakover point of the circuit, 6.5V.

Designers using proper transistor selection can synthesize four-layer diode breakover characteristics ranging from 5 to 100V or greater. Selecting suitable transistor current gains and shunt resistors, the holding current can be varied from a few μA to more than 20 mA.

(Continued)

***Transistors** (Cont'd)*

Temperature Compensation

One method for compensating the peak point voltage and base-emitter temperature dependence is shown in **Fig. 4**. The V_{BE} temperature coefficient of Q3 is multiplied by the feedback arrangement of (R4 + R5)/R5. Optimum frequency stability over the temperature range of interest is established with the variable resistor R4. Typical test results are plotted on the graph (**Fig. 4**). Varying within a few tenths of a percent from 0 to 75°C, the frequency equals or exceeds the stability of the temperature-compensated p-base UJT. Over the −50 to +75°C temperature range, the frequency stability can be adjusted to approximately ±1.5 percent—comparable to the n-base UJT oscillators.

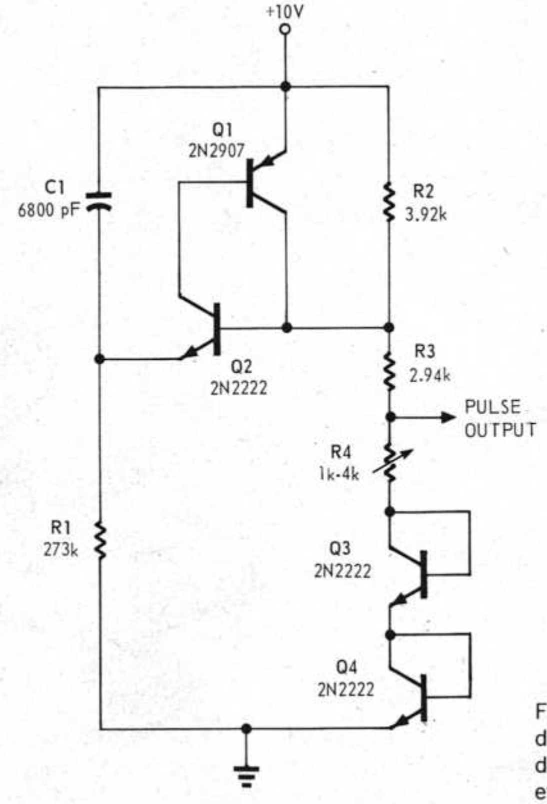
Another approach, illustrated in **Fig. 5** with test results, requires the addition of two diodes in the ground side of the biasing circuit. Since the compensation is scaled down by the voltage divider action of the biasing resistors, two diodes are necessary—thus, requiring one more V_{BE} characteristic to match. ▭

Databank

Mr. Vincent recommends these references:

1. "The Unijunction Transistor and Its Applications", by T. P. Sylan, Publication No. 90.10, General Electric Co., Syracuse, N.Y., 1965. This report is considered the "classic" application note for the unijunction. Contains both theory and applications.
2. "Complementary Unijunction Transistor", by W. R. Spofford, Publication No. 90.72, General Electric Co., Syracuse, N.Y., 1968. Discusses GE's complementary unijunction transistor, which is a planar, monolithic integrated circuit.
3. "Unijunction Transistor Timers and Oscillators", App Note 294, Motorola Semiconductor Products, Phoenix, Ariz.

Wes Vincent, a graduate of the University of Iowa, is an electronic engineer with Motorola's Government Electronics Div., Space Systems Lab. This article is based in part upon his work toward a Master's degree at Arizona State University. In addition, Wes teaches electronics at Mesa Community College.



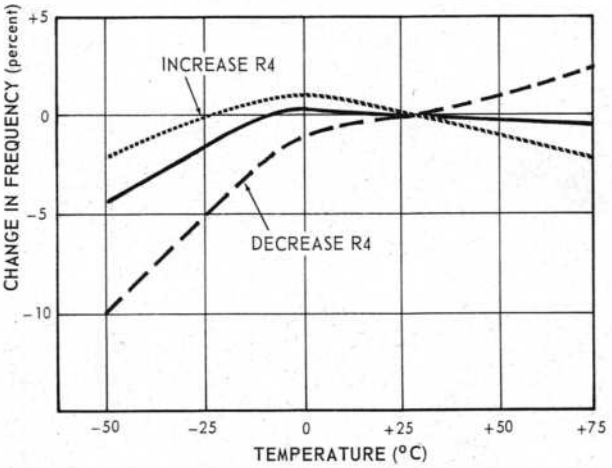


Fig. 5—**Temperature compensation** using two diodes. Two diodes are required because the compensation is scaled down by voltage divider action of biasing resistors. However, the two diode scheme requires the matching of one more base-emitter characteristic. Test results are plotted in the graph.

Engineer's notebook

Bipolar transistor pair simulates unijunction

by N. A. Shyne
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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:

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

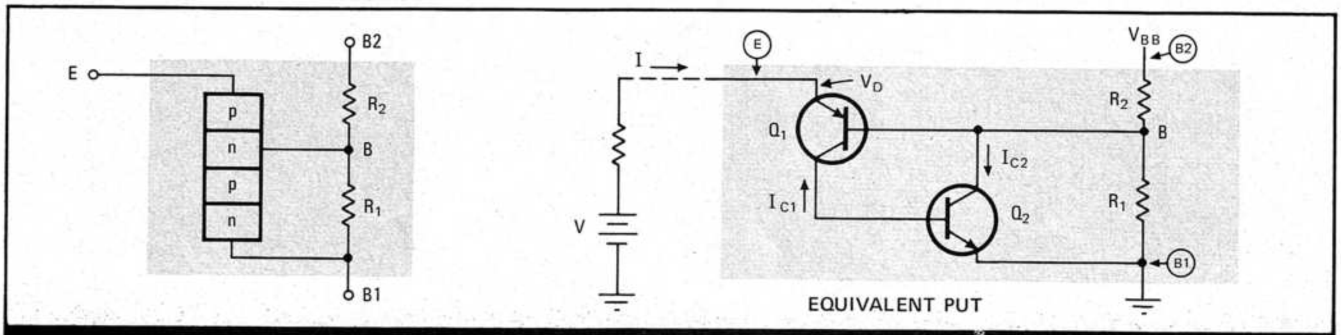
where V_D is the base-emitter voltage of transistor Q_1, both transistors will become saturated, and the PUT circuit will switch. When switching occurs, resistor R_1 is shorted out by transistor Q_2, and:

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

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 $\eta = 0.5$. A complementary (to the one shown) equivalent PUT can be made by just interchanging the positions of transistors Q_1 and Q_2. □

Program analyzes all-resistive dc circuits

by Mark Jong
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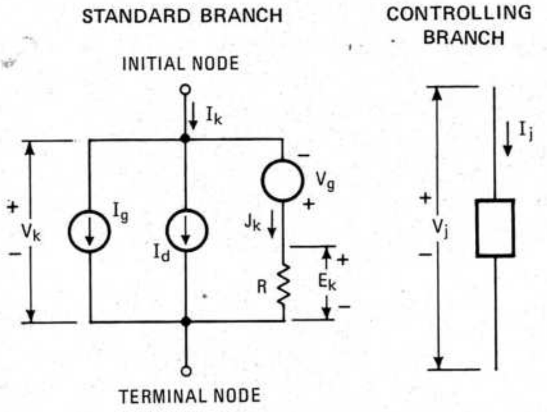
Networks that are strictly resistive can be analyzed easily and quickly for dc conditions with a brief but effective computer program written in Basic. The circuit to be analyzed can also contain active devices, provided those devices can be represented by only resistive elements and voltage-dependent sources.

The standard circuit branch allowed by the program is shown in Fig. 1, along with the program listing. Nodes may be numbered in any order with consecutive integers beginning with zero. (The program always assumes that node 0 is the reference node.) Branches may also be numbered in any order with consecutive integers, but this set of numbers must begin with the number one.

The program first asks to know the number of nodes minus one, and then it requests the number of branches. (A question mark is typed after each request.) The user responds by typing in the data requested each time and pressing the RETURN key on his terminal.

After this preliminary input data is obtained, the program asks for the branch data by typing a question mark each time for each branch. In response, the user types in the data for each branch in a specific order and



V_k, V_j = BRANCH VOLTAGES
I_k, I_j = BRANCH CURRENTS
E_k = ELEMENT VOLTAGE
J_k = ELEMENT CURRENT
V_g, I_g = INDEPENDENT SOURCES
$I_d = g_m \cdot V_j$ (VOLTAGE-CONTROLLED CURRENT SOURCE)

1. Dc circuit analysis. Computer program, which is written in Basic, is useful for a speedy dc analysis of small resistive networks. The definitions for a standard circuit branch and the program listing itself are given here. Dependent sources must be voltage-controlled.

```
100  DIM A[7,15],Y[15,15],E[15],I[15],
     J[15],V[15],S[15],W[15,7],U[15,7]
110  PRINT "NUMBER OF NODES - 1 =";
111  INPUT N
120  PRINT "NUMBER OF BRANCHES =";
121  INPUT B
130  MAT A=ZER[N,B]
140  MAT Y=ZER[B,B]
150  MAT E=ZER[B]
160  MAT I=ZER[B]
170  FOR K=1 TO B
180  INPUT B1,F1,T1,R,E[B1],I[B1],Y1,C1
190  IF F1=0 THEN 210
200  LET A[F1,B1]=1
210  IF T1=0 THEN 230
220  LET A[T1,B1]=-1
230  LET Y[B1,B1]=1/R
240  IF C1=0 THEN 260
250  LET Y[B1,C1]=Y1
260  NEXT K
270  MAT S=ZER[B]
275  MAT J=ZER[B]
280  FOR K=1 TO B
281  LET S[K]=Y[K,K]*E[K]
282  NEXT K
290  MAT S=I+S
295  MAT S=J-S
300  MAT W=ZER[B,N]
310  MAT W=TRN(A)
320  MAT U=ZER[B,N]
330  MAT U=Y*W
340  MAT W=ZER[N,N]
350  MAT W=A*U
360  MAT U=ZER[N,N]
370  MAT U=INV(W)
380  MAT V=ZER[N]
390  MAT V=A*S
400  MAT J=ZER[N]
410  MAT J=U*V
420  PRINT
430  PRINT "NODE"," VOLTAGE"
440  FOR K=1 TO N
450  PRINT K,J[K]
460  NEXT K
470  MAT V=ZER[B]
480  MAT W=ZER[B,N]
490  MAT W=TRN(A)
500  MAT V=W*J
510  MAT J=ZER[B]
520  MAT J=Y*V
530  MAT J=J-S
540  PRINT
550  PRINT "BRANCH"," VOLTAGE"," CURRENT"," POWER"
560  FOR K=1 TO B
570  PRINT K,V[K],J[K],V[K]*J[K]
580  NEXT K
590  MAT V=V+E
600  PRINT
610  PRINT "ELEMENT"," VOLTAGE"," CURRENT"," POWER"
620  FOR K=1 TO B
630  LET J[K]=Y[K,K]*V[K]
640  PRINT K,V[K],J[K],V[K]*J[K]
650  NEXT K
660  END
```

replace one unijunction transistor with two transistors

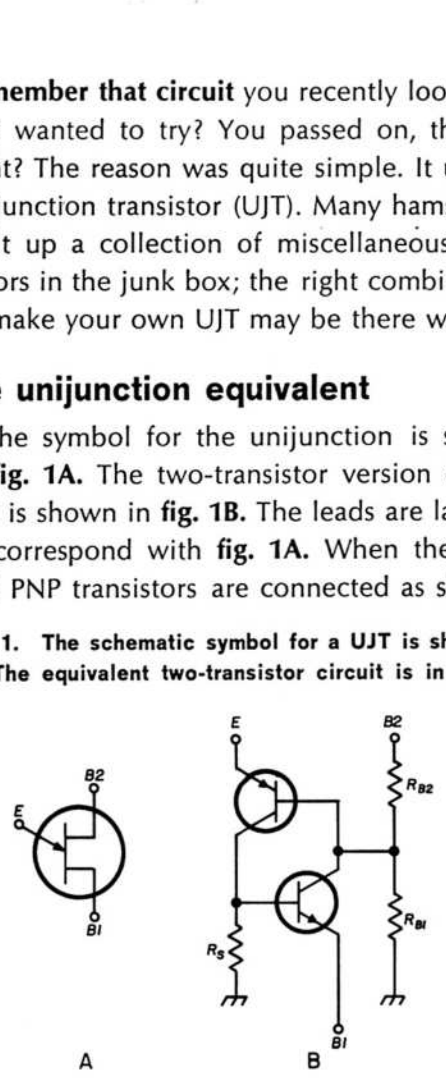
E. R. Davisson, K9VXL, RR #3, Columbus, Indiana 47201.

Remember that circuit you recently looked at and wanted to try? You passed on, though, right? The reason was quite simple. It used a unijunction transistor (UJT). Many hams have built up a collection of miscellaneous transistors in the junk box; the right combination to make your own UJT may be there waiting.

the unijunction equivalent

The symbol for the unijunction is shown in **fig. 1A.** The two-transistor version of the UJT is shown in **fig. 1B.** The leads are labeled to correspond with **fig. 1A.** When the NPN and PNP transistors are connected as shown, they effectively produce the equivalent internal construction of the UJT.

fig. 1. The schematic symbol for a UJT is shown in A. The equivalent two-transistor circuit is in B.



There is only one minor difference—it is necessary to add two resistors externally to the circuit to produce the equivalent resistance found between each base lead and the emitter of the UJT. These two resistors are labeled R_{B1} and R_{B2} in the diagram. Resistor R_S is added for stability; a value around 10k should be sufficient.

As a general rule, the values of the two resistors R_{B1} and R_{B2} may be determined by knowing only two characteristics about the UJT you're replacing; the **intrinsic stand-off ratio** and the **interbase** resistance. These two characteristics are related by the formula:

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$$

where η = intrinsic stand-off ratio
$R_{B1} + R_{B2}$ = equivalent interbase resistance

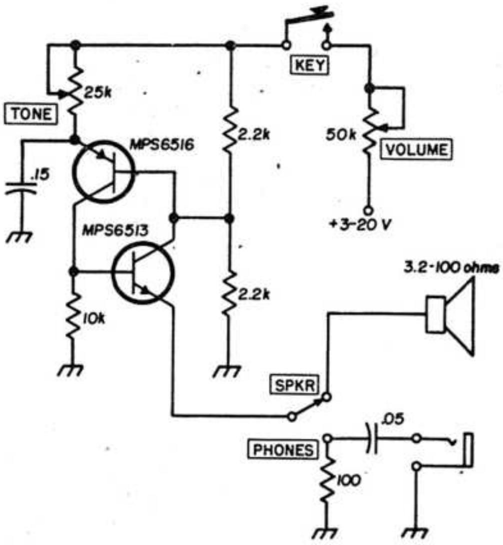
In unijunction transistors, the interbase resistance is typically between 5k and 10k ohms. The intrinsic standoff ratio of a common general-purpose UJT runs about 0.6. Using these values in the formula, you can quickly calculate that R_{B1} would have a value around 3k and R_{B2}, about 2k, to produce the equivalent of a general-purpose UJT.

In most applications, the actual values aren't critical and equal values of resistance could be used—such as 2.2k. This would produce an intrinsic stand-off ratio of 0.5 which is fine. If lower values of resistance are used, the circuit will draw more current and vice versa.

unijunction code-practice oscillator

Now for an actual application. A code-practice oscillator using the two-transistor UJT equivalent is shown in **fig. 2.** Both tone and volume controls have been provided as well as a choice between speaker or earphones.

fig. 2. Here is a relatively simple CPO using the two-transistor equivalent UJT.



In this circuit, a 3-volt supply voltage was sufficient, but you can use as high as 20 volts. The actual voltage will depend upon your transistors and the output level you desire.

In general, a little experimenting with two transistors (one NPN and one PNP) will let you duplicate the function performed by the UJT—generally at lower cost. The transistors shown in **fig. 2** are Motorola devices which are inexpensive and usable from audio through six meters: the latest price list shows the MPS 6513 at 57¢ and the MPS 6516 at 60¢. The price of these two transistors is in the ballpark of general-purpose UJT's, but with this approach, you may already have the UJT in your junk box.

Next time you start to bypass an article using a unijunction transistor, stop and think about how you could substitute two transistors and still have that same useful circuit.

reference

General Electric Transistor Manual, Seventh Edition, 1964, page 300.

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- a CW monitor with positive "RF" switch uses only 8" pickup antenna and NO connection to rig or key
- a code practice oscillator with adjustable tone & built in speaker
- high gain 4 transistor circuit powered by long life AA pencell
- 16 gauge aluminum cabinet in white & black epoxy finish, 3 1/2" by 2 3/8" by 1 1/4", weight 8 ounces
- 100% US made and guaranteed

12.95 (batt incl) ppd usa & can
send cert ck or m.o.
ny res add 5% tax

the James research company
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