Field Effect TRANSISTORS

PART TWO

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THE electrical characteristics and the theory of operation of f.e.t.s were considered last month; in this article some of the circuitry appropriate to f.e.t.s will be considered. It is not the purpose of the article to suggest that the f.e.t. is superior to the ordinary bipolar transistor, indeed arguments on the relative merits of various devices, like the valve transistor controversy that raged in the early days of transistors, are valueless without first clearly formulating a criterion of superiority.

If one adopts the criterion that the "best" device to use is the one that enables the desired circuit performance to be achieved with the minimum financial expenditure, the greater cost of f.e.t.s will usually favour the use of bipolar transistors, except in certain special circumstances, however, the price of commercially available f.e.t.s is falling so that they may eventually be used in preference to bipolar transistors.

F.E.T.s AS AMPLIFIERS

The f.e.t. like the bipolar transistor is a three terminal device and may be used as an amplifier in three different ways depending upon which of its terminals is made common to both input and output circuits.

The three amplifier configurations are called, common source, common gate and common drain analagous to common emitter, common base and common collector amplifiers respectively. The common gate circuit has a low input impedance and therefore offers no real advantages over bipolar transistor circuits, it will not be considered further.

Only junction gate f.e.t.s will be discussed here; insulated gate f.e.t.s are only just coming out of the development stage and are rather expensive.

COMMON SOURCE AMPLIFIER

A simple self-biased common source amplifier using a *p*-channel f.e.t. is illustrated in Fig. 10. An *n*-channel device would, of course, require a positive voltage supply rail. Readers familiar with valve circuits will notice the close resemblance to a common cathode valve amplifier.

Resistor R_s acts in a manner similar to the cathode resistor in a valve amplifier, source current flowing through R_s being used to produce the desired gate-source biasing voltage. R_s is bypassed by capacitor C_s to prevent degenerative feedback. The magnitude

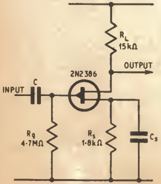

Fig. 10. Simple common source amplifier

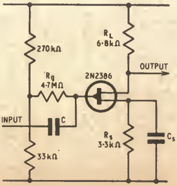

Fig. 11. Common source amplifier with bias

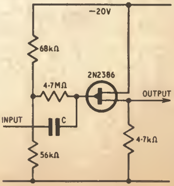

Fig. 12. Common drain amplifier

of the gate resistor (R_g) used should be such that the leakage current which flows through the reverse biased gate junction does not seriously affect the biasing at the highest working temperature.

A circuit giving greater stability of operating conditions is shown in Fig. 11, the method of bias stabilisation being similar to the technique used for stabilising common emitter amplifiers. This method of biasing is preferable for higher temperature working or for compensating for variations in f.e.t. characteristics.

Voltage gains of about 10 are typical for common source amplifiers and because of their high input impedance, the frequency response down to low frequencies may be obtained without the use of very large values of coupling capacitor (C).

Response at high frequencies is limited by a fall of input impedance and a consequent loading of any signal source feeding the amplifier. This is due to the capacitance that exists between gate and source (C_{gs}) and gate and drain (C_{gd}). These capacitances are quite small ($C_{gs} = 10$pF and $C_{gd} = 20$pF are typical values for currently available f.e.t.s), but the effective input capacitance of the amplifier due to C_{gd} is increased because the signal voltage at the drain is 180 degrees out of phase with the input voltage applied to the gate (the familiar Miller effect). The effective input capacitance is given by the equation

$$C_i = C_{gs} + C_{gd}(1 + A)$$

where A is the voltage gain of the amplifier. Substitution of typical values gives a value of about 230pF for the input capacitance. Thus at a frequency of 10kHz the input impedance will have fallen from its low frequency value of R_g to about 70 kilohms because of C_i. Input capacitance may be reduced at the expense of loss of gain by using smaller values of load resistance. If the load of a common source amplifier is reactive feedback through C_{gd} can cause instability if no neutralisation is used.

COMMON DRAIN AMPLIFIER OR SOURCE FOLLOWER

This amplifier is analogous to the valve cathode follower and the bipolar transistor emitter follower. It is not phase inverting and is characterised by a high input impedance, low output impedance, and voltage gain less than unity, it is very useful for impedance transformation when f.e.t.s are used with bipolar transistors.

An example of a common drain circuit is shown in Fig. 12. The effect of C_{gs} on the input capacitance is reduced in this type of circuit because the signal output voltage at the source varies in phase with the input signal applied to the gate. The effective input capacitance is, given by the equation $C_i = C_{gd} + C_{gs}(1 - A)$ and with A almost unity the input capacitance is not much greater than C_{gd}.

In order that the gain should approach unity the source resistance should be as large as possible. The relatively large voltage drop and power dissipation occasioned by the use of a large source resistance may be overcome by replacing it with a bipolar transistor as shown in Fig. 13. The effective source resistance is then the large dynamic resistance seen looking into the collector of this transistor. The quiescent current is set by the choice of the emitter resistance R_e.

AMPLIFIERS USING F.E.T.s WITH BIPOLAR TRANSISTORS

The outstanding low level characteristics of f.e.t.s are high input impedance and low noise, they are therefore

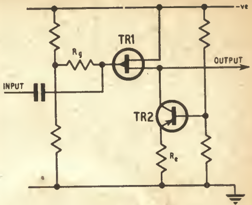

Fig. 13. Common drain amplifier using bipolar transistor instead of load resistor

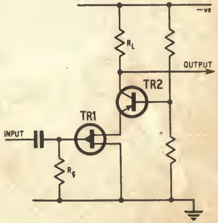

Fig. 14a. Common source amplifier driving a common base pnp transistor amplifier

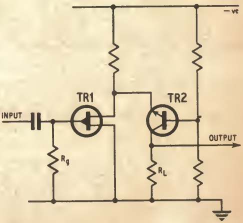

Fig. 14b. Common source amplifier driving a common base npn transistor amplifier

most useful at low level high impedance points in electronic circuits, for example, as a preamplifier for use with a high input impedance transducer. Once the impedance level has been reduced it is more economical to use conventional transistors for further amplification.

Many interesting compound connections of f.e.t.s and bipolar transistors are possible; some increase the bandwidth of the f.e.t. by reducing the effects of inter-electrode capacitance.

An f.e.t. common source or common drain stage may be used to drive any configuration of second stage making six possible circuit configurations. In Fig. 14 a common source amplifier is directly coupled to a common base amplifier, two versions of the circuit are shown. The voltage gain of the common source amplifier is small since it feeds the low input impedance of the common base amplifier. The low voltage gain gives a comparatively small effective input capacitance. The f.e.t. gives a very high current gain. If a large value resistance is used in the collector circuit of the bipolar transistor, high overall voltage and power gains are possible.

The circuit features a great amount of isolation between output and input making it suitable for use as a high frequency tuned amplifier if a tuned load is used instead of the load resistor. The breakdown voltage of currently available f.e.t.s is not large but quite large values of supply voltage can be used with the circuit of Fig. 14a. In this circuit the f.e.t. experiences only the voltage applied to the base of the bipolar transistor.

The effective input capacitance of a common drain amplifier, with gain close to unity, is little greater than C_{gd}, it may be reduced to an even smaller value using the type of circuit shown in Fig. 15.

In this circuit transistor TR3 drives the drain of the f.e.t. in phase with the signal applied to the gate, thus reducing the effective value of C_{gd}. The lower end of the gate resistor is also driven in phase with the signal applied to the gate, thus reducing the current through this resistance and increasing its effective magnitude.

Effective input impedances of many hundreds of megohms are possible; the input capacitance would be less than 1pF. Input capacitance is in fact usually determined by "strays". The circuit is basically a common drain amplifier, so its gain is less than unity.

Another type of compound connection with high effective input impedance, but which can have a voltage gain greater than unity, is shown in Fig. 16. It is sometimes referred to as a "bootstrapped source follower".

The drain of the f.e.t. drives the base of the *npn* transistor whose collector drives the source of the f.e.t. and the lower end of the gate resistor in phase with the input signal. With the component values shown the circuit was found to have a voltage gain of eight and a maximum signal output amplitude of 4 volts. Table 1 shows the input impedance for a wide frequency range.

F.E.T. MULTIVIBRATORS

Field effect transistors can be used in multivibrator circuits in a manner similar to bipolar transistors, but if high speed switching and high pulse frequencies are to be used bipolar transistors give better performance. However when repetitive waveforms and timing circuits having periods of several minutes are required the f.e.t. has a marked advantage.

The maximum timing resistance that can be used with a bipolar transistor is determined by the base current required by the transistor. Because of the high input impedance of an f.e.t. very high values can be used; long time constants can be obtained in monostable and astable circuits without the need for very large capacitance values.

A circuit for a free running multivibrator published by Semitron is shown in Fig. 17. It is said to have a frequency of one cycle per minute.

A field effect timer circuit using a monostable multivibrator is shown in Fig. 18. In the stable state of the circuit transistors TR1 and TR2 are both conducting;

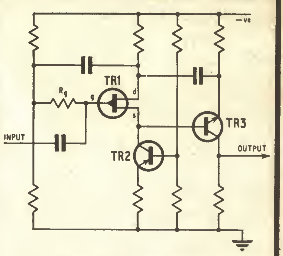

Fig. 15. High input impedance amplifier

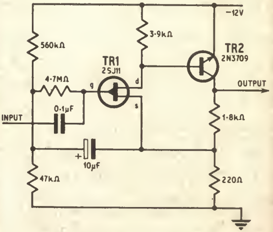

Fig. 16. Boot-strapped source follower

Table I. INPUT IMPEDANCE OF CIRCUIT IN FIG. 16

Frequency	5Hz	1kHz	5kHz	10kHz
Input impedance Z_I (MΩ)	26	26	19	8
Frequency	20kHz	40kHz	100kHz	
Input impedance Z_I (MΩ)	3·1	1·6	0·67	

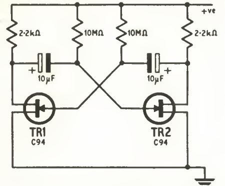

Fig. 17. Very low frequency free running multivibrator

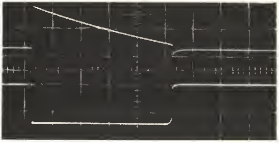

Fig. 19. Gate waveform (top) 5V/cm. TR2 collector (bottom) 5V/cm. Time 0·5 second per centimetre. (Refer to Fig. 18)

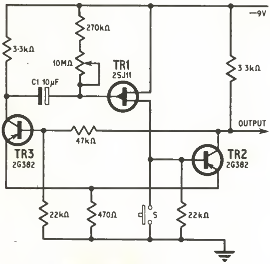

Fig. 18. Field effect timer circuit

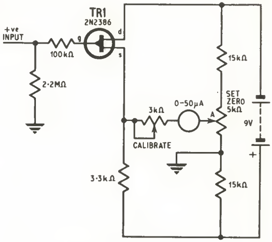

Fig. 20. Simple f.e.t. voltmeter

TR2 is saturated. Transistor TR3 is held cut off by the voltage across the 470 ohm emitter resistor and the potential divider connecting the collector of TR2 to the base of TR3. When the switch S1 is momentarily closed the current through TR2 stops and TR3 suddenly conducts. This causes a sudden change in TR3 collector voltage which is communicated to the gate of f.e.t. TR1 by the capacitor C. TR1 is cut off and this state is maintained until C discharges sufficiently to bring TR1 into conduction again when a regenerative action returns the circuit to its stable state. The waveforms at the gate of TR1 and at the collector of TR2 are shown in Fig. 19. The time delay is proportional to the time constant *CR*, with the values shown the delay is variable between 3 and 90 seconds.

F.E.T. VOLTMETER

The high input impedance of an f.e.t. may be utilised in the construction of high input resistance electronic voltmeters. The circuit of a simple f.e.t. voltmeter is shown in Fig. 20. With no input voltage applied the potentiometer VR1 is adjusted to bring the potential of the point A to the same potential as the source of the f.e.t. so that no current flows through the meter. The VR2 calibration control is adjusted to give full scale deflection of the meter when 0·5V is applied to the input. The basic sensitivity of the instrument is then 4·4 megohms per volt; it is a simple matter to make it read higher voltages by using a suitable input multiplier. The reading of the meter is very stable provided no violent fluctuations in temperature take place and the instrument is extremely useful for measuring direct voltages at high impedance points.

F.E.T.s AS VOLTAGE CONTROLLED RESISTORS

The drain characteristics of an f.e.t. in the non-pinched-off region (low values of drain voltage) are almost linear and their slope is dependent on the magnitude of the gate voltage. In this region the f.e.t. acts as a variable resistor; the gate voltage determines the resistance between source and drain. Interesting applications of an f.e.t. operated in this way are possible.

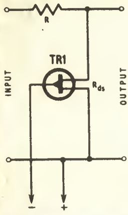

Fig. 21. Voltage controlled attenuator

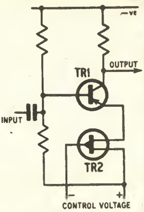

Fig. 22. Voltage operated gain control

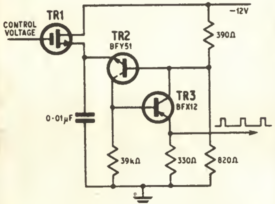

Fig. 23. Voltage to frequency converter

A simple voltage controlled attenuator is shown in Fig. 21. The attenuation ratio is given by

$$N = \frac{R_{ds}}{R + R_{ds}}$$

where R_{ds} is the source drain resistance. The range of attenuation obtainable is dependent on the range over which R_{ds} can be varied and this is a property of the particular f.e.t. in use.

In the circuit of Fig. 22 an f.e.t. is used as a voltage operated gain control. The f.e.t. is used as the emitter resistance of a common emitter amplifier introducing negative feedback. The amount of negative feedback and hence the gain of the amplifier is determined by the value of R_{ds}.

A Mullard circuit using an f.e.t. in a voltage-to-frequency converter is shown in Fig. 23. An insulated gate f.e.t. is used in this circuit although a junction gate f.e.t. could be used in the same way. The f.e.t. is used as the resistive element in a CR *npn-pnp* relaxation oscillator, changing the input voltage to the gate of the f.e.t. alters the effective timing resistor and varies the frequency of oscillation. ★