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AN-6606
Simple VHF Analog Switches

Simple JFET switches like those in Figure 1 will toggle at rates to about 10 MHz and switch analog signals with frequencies to above 100 MHz. They accomplish this by resolving in the gate-driver design the contradictory performance goals that even the best switching transistors cannot meet.

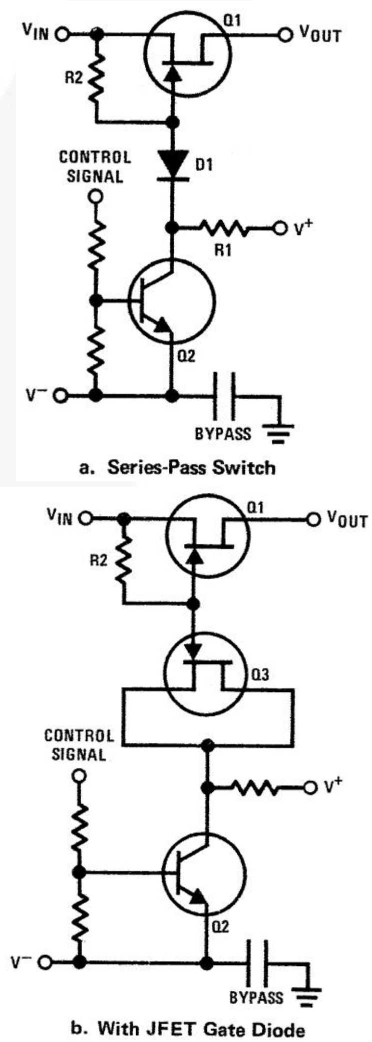
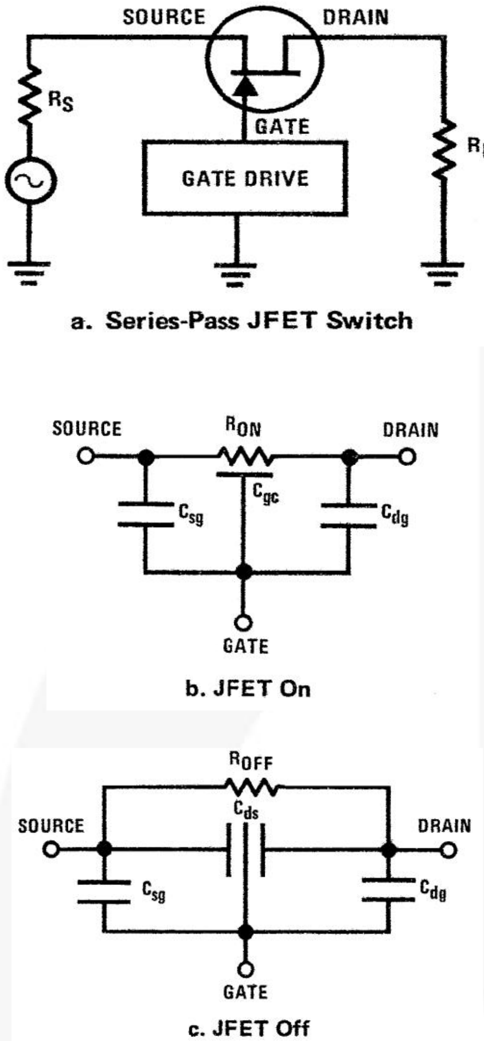


Figure 1. High-Frequency JFET Switching Circuits

To switch high-frequency signals, the JFET should have low ON impedance, rds(on) or R_{ON}, and low input capacitance, C_{iss}. The switch's RC time constant is established by these 2 parameters, and they also indicate the bandwidth capability. JFETs have been developed that come close to being ideal, but unfortunately the real-world nature of semiconductor devices makes it impossible to achieve optimum values of both parameters in the same device. Low R_{ON} calls for a physically large JFET. On the other hand, the very low capacitance needed for fast toggle rates implies small size.

At a casual glance, gate drive impedance does not appear very important. However, the JFET device conflict between R_{ON} and C_{iss} may be overcome by using the proper gate driver. The drive circuit should have low impedance when the JFET is turned OFF and high impedance when the JFET is turned ON. The low-impedance path is needed to prevent analog-signal feed-through and the high impedance to minimize signal attenuation through the driver while the JFET is conducting. A well-designed driver can do both.

The relationships among JFET and driver characteristics can be sorted out with the help of Figure 2, which shows a typical series-pass switch and the equivalent circuits of the JFET in its ON and OFF conditions. A JFET operates best as a series-pass switch when the ON condition allows R_{ON} and shunt capacitance to be low, and series-pass capacitance to be high. But in the OFF condition, it should exhibit low series-pass capacitance and high series-pass resistance (R_{OFF}). The JFET will have these characteristics when properly matched to the driver.



C_{dg} = drain-gate capacitance
C_{gc} = gate-channel distributed capacitance
C_{sg} = source-gate capacitance
C_{ds} = drain-source capacitance
R_{ON} = ON impedance
R_{OFF} = OFF impedance

Figure 2. Series Pass Switch and JFET Equivalent Circuits

Getting down to a low R_{ON} when the gate is turned ON is no problem. A JFET such as the 2N4391 has a maximum RON of 30 ohms (see rds(on) in Table 1). However, the parallel capacitance in the signal path can become fairly high - about 15 pF when drain, source and gate have the same potential ($V_{DS} = V_{GS} = 0$). The simple answer to this dilemma is to drive the gate with high AC impedance when the switch is closed. The shunt capacitance will be in series with high impedance. Virtually all of the signal will then go through the JFET, the path of least resistance, rather than through the gate-to-ground connection.

Next problem; when the switch is OFF, high-frequency attenuation is the name of the game. It is depended upon to prevent the signal at the input from reaching the output. The JFET channel is, for all practical purposes, an open circuit because R_{OFF} of a quality JFET is over 10^{12} ohms although this decreases as frequency goes up. However, capacitive feed-through is the most significant route across the switch. From Figure 2c.

$$C_{FEEDTHROUGH} = C_{ds} + \frac{C_{sg}C_{dg}}{C_{sg} + C_{dg}}$$

Feed-through capacitance can be significant if the gate is not operated at AC ground. Minimizing the right-hand term by operating the gate at AC ground allows C_{ds} to become the pacing factor. If the gate is grounded, C_{ds} will be approximately 0.2 pF. In other words, the effective R_{OFF} of the switch depends directly on circuit design, not the JFET.

Now to put these principles to work; the best high-frequency switch is an N-channel JFET. Its gate should be biased positive from a high-impedance source for turn-on and biased negative through a low-impedance path for turn-off. Driving the switch ON through an RF choke sounds tempting, but it would be difficult to avoid resonances and oscillation bursts during some switching conditions. DC resistances could be increased to equal or exceed R_S in parallel with R_L, but then the toggle rate would be kept down by the very high drive impedance.

We prefer the circuits in Figure 1, which are fairly fast and not tricky. When NPN transistor Q2 is in saturation, Q1 is biased OFF through a low-impedance path. The diode is slightly forward-biased and exhibits high capacitance. When Q2 turns OFF, D1's cathode is driven positive by R1. Now the diode is reverse-biased and exhibits high impedance and low capacitance. The charge that was stored on D1 discharges into the gate of Q1, allowing the JFET to be turned ON. Because there is no good discharge path available to the charge stored on Q1's gate, the gate will "follow" any signal swing in the analog input voltage. Adding R2 will ensure that the gate follows the signal even during DC conditions. Remember, however, that the R2/C_{sg} time constant will effect switching time and gate-source signal tracking.

Don't expect just any diode to work well; D1's capacitance is critical and should match that of the JFET ($C_{D1} = C_{Q1}$). One good way of making sure that the JFET and the diode are well mated is to use the same type of JFET for both. The gate lead is one electrode of the diode and the drain and source leads are simply tied together to form the other electrode. The circuit in Figure 1b was optimized in this way.

Excellent high-frequency series switches can be made with 2N4091, 2N4092 and 2N4093 JFETs. RC time constants are short because of their low rds(on) and capacitance, and leakage is low. The 2N4391, 2N4392 and 2N4393 series is even better, having only 100 pA leakage and lower C_{iss}. Even though' the 2N4416 is classed as an RF amplifier, it is also listed in Table (1) to illustrate that many of our other JFETs can solve special switching problems. This one does well in circuits requiring very low capacitance and leakage. Although the R_{ON} of an RF transistor is not specified, it can be estimated as rds(on) ≈ 0.85/Yfs, which is typically 170 ohm for the 2N4416.

TABLE I. JFETs for High-Frequency Analog Signal Switching

TYPE NO.	BV_{GSS} OR BV_{DGO} (MAX)	I_{GSS} (MAX)	C_{iss} (MAX)	C_{rss} OR C_{DGO} (MAX)	$r_{ds(on)}$ (MAX)	t_{on} (MAX)	t_{off} (MAX)
2N4091	40V	0.2 nA	16 pF	5 pF	30Ω	25 ns	40 ns
2N4092	40V	0.2 nA	16 pF	5 pF	50Ω	35 ns	60 ns
2N4093	40V	0.2 nA	16 pF	5 pF	80Ω	60 ns	80 ns
2N4391	40V	0.1 nA	14 pF	3.5 pF	30Ω	15 ns	20 ns
2N4392	40V	0.1 nA	14 pF	3.5 pF	60Ω	15 ns	35 ns
2N4393	40V	0.1 nA	14 pF	3.5 pF	100Ω	15 ns	50 ns
2N4416	30V	0.1 nA	4 pF	0.8 pF	170Ω*		
2N4416A	35V	0.1 nA	4 pF	0.8 pF	170Ω*		

*This value is not specified in RF amplifier JFETs; 170Ω is typical

Author: *Mike Turner, Feb 1977, FET Brief 1*

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