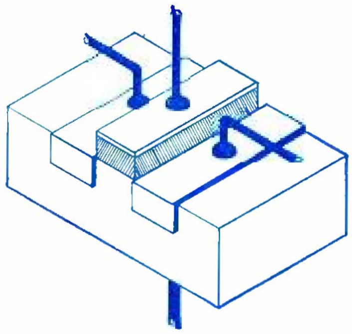


The Insulated Gate Transistor

By DONALD E. LANCASTER

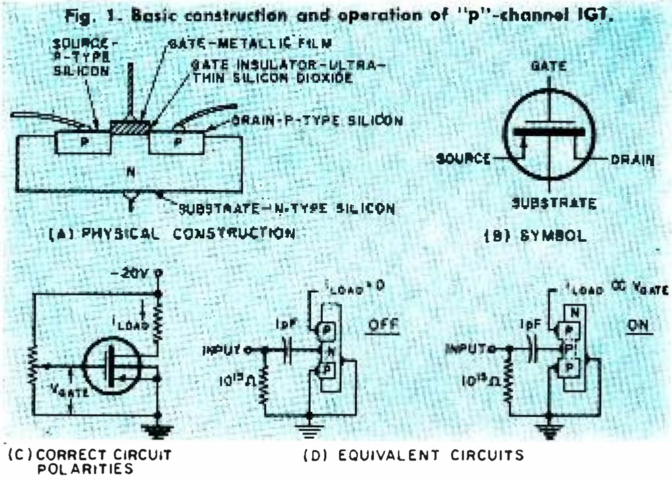
This new semiconductor, also called MOSFET, IGFET, or MOST, has an input impedance much higher than most vacuum tubes, simple geometry leading to inexpensive fabrication, high current gain, and very small size.

THERE is a new type of semiconductor with such remarkable properties that it promises to advance the electronic art as significantly as did the junction transistor itself. This is the *insulated gate transistor* (IGT), with an input impedance much higher than most vacuum tubes, a simple geometry inherently cheaper to fabricate than a junction transistor, essentially infinite current gain, and extremely small size.

Various designations for the device include the IGFET (insulated gate field-effect transistor), the MOSFET (metal-oxide silicon or semiconductor field-effect transistor), and the MOST (metal-oxide silicon or semiconductor transistor). All these devices are similar and simply represent the different nomenclature each company has chosen for its particular device. The IGT is *not* an ordinary junction field-effect device since it differs significantly in operating principle, biasing, and performance from the ordinary junction FET.

The most prominent feature of all IGT's is the fantastic input impedance which is typically 10^{15} ohms. The addition of leads and a glass header drops this to a mere 10^{13} ohms (that is 10 million megohms!). Considering surface conduction, ions, and grid current in vacuum tubes, this input impedance is much higher than any but special electrometer tubes. As an example, a 2-picofarad capacitor has enough charge to keep an IGT running at constant output current for several hours. This extreme input impedance opens new vistas for electronic circuits, particularly in ultra-sensitive electronic instruments; timing, monitoring, and holding circuits; and various types of logic circuitry.

Fig. 1. Basic construction and operation of "p"-channel IGT.



Operating Principles

An IGT consists of three terminals, the *drain*, the *source*, and the *gate*. Between the gate and the rest of the transistor is a nearly perfect insulator of ultra-thin silicon dioxide (typical thickness = 1500 Å). This is the key to the extremely high input impedance of the IGT. A voltage applied to the gate of an IGT allows a current to flow between source and drain. Any change in input voltage is reflected as a change in output current.

Fig. 1 shows a typical IGT and the bias polarities required. The device consists of an *n*-type substrate into which two identical *p*-regions have been diffused. Contact is made to these two *p*-regions, forming the source and drain terminals. Between the two *p*-regions, a capacitor is formed out of the *n*-type substrate, the silicon-dioxide insulator, and a metallic gate terminal.

We connect the source and the substrate to ground and bias the drain negatively, perhaps by −20 volts. In the absence of a negative gate voltage, no current will flow between source and drain because of the *n* substrate which forms a reverse-biased junction and prevents conduction.

Suppose a negative voltage is applied to the gate terminal. This places a negative charge on the gate terminal end of the gate capacitor. Consequently, a *positive* charge must be built up on the substrate end of the gate capacitor. The substrate started out as *n*-type material. The presence of the positive charge makes the material less and less *n*-type, until there is more positive charge available than there are excess electrons in the *n*-type material. At this instant, a portion of the substrate changes from an *n*-type to a *p*-type, forming a *p*-*p*-*p* junction or simply a connection of all *p* material between source and drain.

Down to a certain threshold level, perhaps less than −5 volts, the input gate voltage has little effect and very little output current flows (Fig. 1D). At inputs more negative than the threshold voltage, the output current between drain and source is a linear function of the negative gate voltage. The threshold level is that point at which a portion of the substrate switches from *n*- to *p*-type.

This type of operation is called "enhancement mode" for

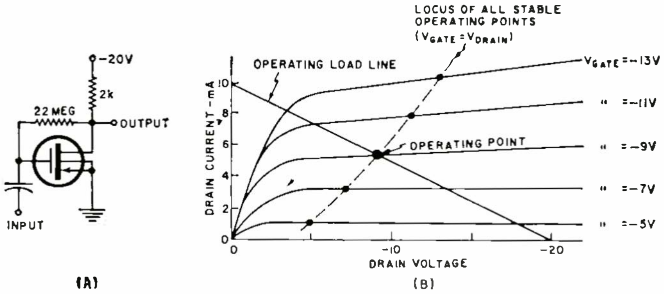


Fig. 2. Single resistor biasing of IGT. Since no gate current is drawn in the absence of an input, there is no drop across the 22-megohm biasing resistor, and the gate voltage equals the drain voltage. A stable operating point may be chosen on the curves anywhere the gate voltage equals the drain voltage. The bias point is stable because a slight increase in negative gate voltage produces an increase in source-drain current and decreases the drain voltage. This, in turn, decreases the gate voltage, returning to a stable operating point. Similarly, a slight decrease in gate voltage decreases drain current, increasing the drain and gate voltages, and returning the IGT to a stable point. By proper choice of load resistance, temperature drift of gate-to-source voltage can be made negligible. In this figure, operating point is chosen where $V_{gate} = V_{drain} = -9$ V. Using a −20 V supply, we can construct load line between operating point and supply axis. This intersects current axis at 10 mA, dictating load resistance of 2000 ohms.

no output current flows unless a large enough input voltage is present. As the gate voltage rises and falls, the charge on the gate-to-substrate capacitor changes in proportion which, in turn, causes a proportional change in output current. Notice that no gate current is ever drawn. All the input voltage has to do is charge up or discharge a nearly perfect capacitor having a capacitance as low as 0.2 picofarad.

Some interesting features of the IGT should now become apparent. There is only one diffusion required to simultaneously put down both *p* regions into the *n* substrate, compared with a minimum of two diffusions required for any junction device. Thus, fewer steps are required to build an IGT, making it inherently cheaper than junction devices. In one specific instance, 130 processing steps are required for a junction-type device, while only 38 are required for a similar IGT device.

The IGT can be made quite small. Typical designs require only two square mils for an IGT whose equivalent junction device would take up forty-eight mils. In this example, 24 IGT's can, in theory, be put in the space of a single conventional transistor.

In the "on" (conducting) state, the IGT essentially consists only of *p*-type material. There are no semiconductor junctions, and no offset voltage is produced. The IGT will easily switch signals as low as 1 microvolt without any offset problem. The applied polarity doesn't really matter as long as the gate is biased negatively with respect to the substrate. Because of this, the IGT is bipolar and can accommodate either polarity of output current.

Most devices are symmetrical and it makes no difference which lead is called the source and which the drain.

The type of IGT we are describing and using in all the diagrams is called a *p-channel* device because in the "on" state the equivalent circuit is a single bar of *p*-material. Just as we have *p-n-p* and *n-p-n* junction transistors, *n*-channel IGT's which operate from opposite polarities are available.

Biasing Considerations

Only a single resistor is needed to bias an IGT compared with several resistors and an electrolytic capacitor frequently used for an ordinary junction transistor. Further, by the correct choice of operating current, the biasing may be made largely independent of temperature. Fig. 2 shows how a biasing resistor is added from drain to gate. This resistor may be any value as long as it is small compared to 10^{13} ohms, and is chosen to be large enough to not significantly load the input signal. A value of 22 megohms is typical.

Amelco Semiconductor
1300 Terra Bella Ave.
Mountain View, Calif.

Crystalonics Inc.
147 Sherman Street
Cambridge, Mass. 02140

Fairchild Semiconductor
313 Fairchild Drive
Mountain View, Calif.

General Instruments
Semiconductor Products
600 West John Street
Hicksville, New York

General Microelectronics Inc.
2920 San Ysidro Way
Santa Clara, Calif.

KMC Semiconductor Corp.
Parker Road, RD #2
Long Valley, N.J. 07853

Motorola Semiconductor
Box 955
Phoenix, Arizona 85001

Radio Corporation of America
Electronic Components and Devices
Harrison, New Jersey

Raytheon Company
Semiconductor Div.
350 Ellis Street
Mountain View, Calif.

Siliconix Incorporated
1140 West Evelyn Ave.
Sunnyvale, Calif.

Texas Instruments Inc.
P.O. Box 5012
Dallas 22, Texas

TRW Semiconductors Inc.
14520 Aviation Blvd.
Lawndale, Calif.

Union Carbide Corporation
365 Middlefield Road
Mountain View, Calif.

Table 1. Directory of insulated gate transistor manufacturers.

For a given gate voltage, the IGT allows a certain current to flow. If this current produces a drain voltage equal to the gate voltage required for that current, the bias point is stable. If not, the IGT quickly shifts to the correct bias point. Optimum values of bias and load depend upon the IGT. They are determined in exactly the same way as operating load lines of a pentode are determined, as detailed in Fig. 2.

IGT's have voltage gains from 1 to 15 or more. These figures are bound to improve with newer devices. The optimum load resistor for an IGT is usually between 1 and 20,000 ohms. When a lower output impedance is needed, the IGT may be cascaded with an ordinary emitter-follower, as in Fig. 3A. The voltage gain of this circuit is around five, while the current gain is around one million as the input impedance is 22 megohms and the output impedance is around 22 ohms. The resultant power gain under optimum conditions is 5,000,000—quite a respectable figure for a two-stage amplifier.

Today, the IGT is available in three forms, a single device in a TO-5 or TO-18 can, matched pairs on the same substrate

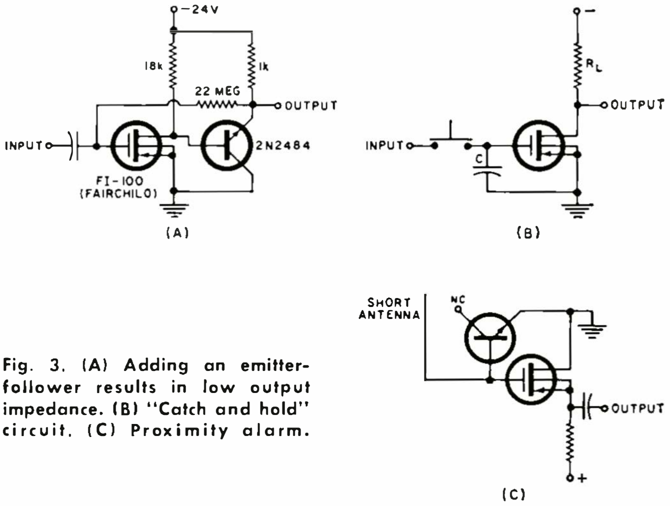
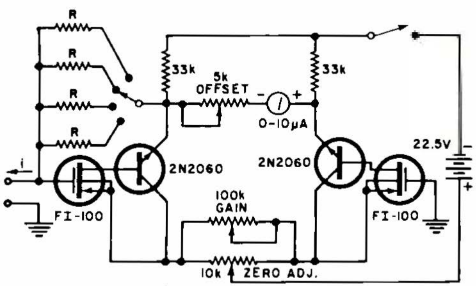


Fig. 3. (A) Adding an emitter-follower results in low output impedance. (B) "Catch and hold" circuit. (C) Proximity alarm.



i FULL SCALE	R
0-1μA	100k
0-100nA	1MEG
0-10nA	10MEG
0-1nA	100MEG
0-100pA	1000MEG
0-10pA	10kMEG
0-1pA	100kMEG

TRANSISTORS AND IGT'S MUST BE MATCHED PAIRS

Fig. 4. Circuit of extremely sensitive d.c. picoammeter.

in a similar package, or as the active elements in completely integrated circuits. Prices for a single unit range from $4 to $20, depending upon the manufacturer and the performance specs. The pricing trend is downward and much less expensive IGT's should be readily available within a very few months.

Table 1 lists a number of IGT manufacturers. Data sheets, application notes, and prices are available from most of these sources upon written requests on company letterhead.

Applications

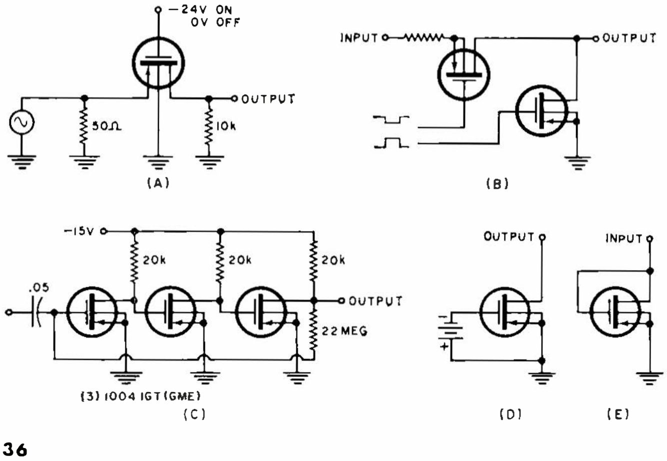
The IGT applications fall naturally into two groups, those using integrated circuits and those using discrete devices. Using IGT's as the basic transistor in integrated circuits has many interesting advantages, especially the small size, low current operation, and ease of manufacture.

Two problems always of interest in logic circuits are the "fan in" and the "fan out" of each logic element, be it gate, a flip-flop, a register, or an inverter. The fan in is simply the number of inputs available to a circuit. When using IGT's, multiple inputs are easily obtained in small space by paralleling as many IGT's together as there are inputs. Fan out is the number of circuits a given element can drive. With the extremely high input impedance of the IGT, a single device can drive hundreds, or even thousands, of similar circuits. This is a most significant advantage of the IGT in computer and logic circuitry.

Some integrated-circuit units are already available using IGT's. One is a shift register that counts to 21 and uses over 100 IGT devices. A second shift register counts to 100 and contains 612 IGT's. Both units fit easily inside a TO-5 can. We can soon expect to see entire IGT *systems* integrated into single large substrates, such as complete counting chains of flip-flops, decade counters with internal decoding, binary adders, entire logic circuits, and others.

Turning to the discrete-component applications, Fig. 3B shows an IGT with a capacitor between gate and source. An input signal momentarily applied will charge the capacitor to some value, producing some output current. Removing the input signal leaves the charge on the capacitor and so does the 10^{13} ohm leakage path through the IGT. The IGT will "remember" the magnitude of the input voltage and produce the same output current for days after the signal has gone. This is called a "box car" or a "catch and hold" circuit, useful for sampling and averaging out a varying waveform, or catching a brief impulse and keeping its value long enough so that it may be easily measured. Even with no external capacitor, the internal gate-to-substrate capacitance, usually 0.2 to 10 picofarads, will hold the value of the input signal for several hours after the signal has disappeared.

Fig. 5. (A) R.f. switch. (B) Series-shunt chopper. (C) Audio amplifier. (D) Constant-current source. (E) Constant-R load.



Timing and delay circuits are an obvious extension of the basic hold circuit. A resistor from a reference voltage is used to charge a capacitor whose voltage is IGT monitored. When the capacitor voltage reaches the turn-on voltage of the IGT, an output is produced, and the timer reset. Precision saw-tooth and ramp voltages are generated in the same manner, with the IGT output being a low-impedance "copy" of the charge voltage on the capacitor without any loading effects.

Fig. 3C shows a proximity detector. Here a high-quality silicon transistor is used as the biasing resistance for the IGT. This provides a very high input impedance, yet protects the IGT should the gate actually be touched. The gate terminal of the IGT is extended to include a small antenna. A moving hand brought near the antenna will change the capacitance to ground without altering the charge present. This lowers the IGT gate voltage and produces a change in output current which is easily monitored. Only a slight amount of additional capacitance is required. For an IGT with a 1-picofarad gate-to-source capacitance, only 0.1 picofarad of additional capacitance will produce a 10% change in the output current. This makes the circuit extremely sensitive.

An interesting proximity application is alarms. Unlike practically all other alarm circuits, no energy is transmitted and there is no light beam, ultrasonic signal, or other detectable energy available that can either reveal the location of the alarm or even the fact that an alarm is present at all.

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HANDLING PRECAUTIONS FOR IGT DEVICES

The extremely high input impedance of the IGT is a two-edged sword, for a careless moment in handling can result in immediate and permanent damage to the component.

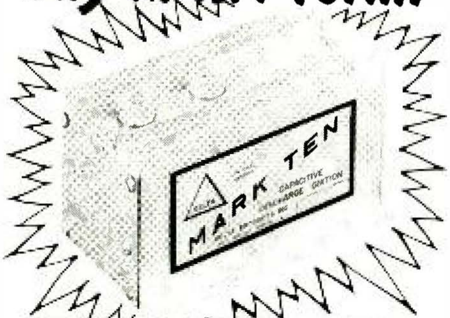
The culprit is static electricity which can easily build up several hundred volts of potential on the gate and puncture the silicon dioxide insulator between gate and substrate. As an example, the insertion of an IGT into a block of Styrofoam will almost certainly ruin the device as this generates over 200 volts of static electricity.

Engineers and technicians working with IGT's should strictly adhere to the following precautions:

1. The IGT comes with all four leads shorted together. Do not untwist the leads until ready for use.
2. Before untwisting the leads, wrap a layer or two of aluminum foil or fine wire securely around all four of the leads directly at the can.
3. Ground the tip of the soldering iron to the substrate lead before soldering the gate lead in place. Do not use a soldering gun.
4. Do not remove the aluminum foil or fine wire until all four leads are secure.

Once the circuit is permanently connected to the IGT, there is no further danger, as the input and biasing components will protect the IGT.

If sockets are used, always hold the IGT by the can and contact first the substrate lead and then the remaining three. Do not release the IGT until it is in the socket.



Insulated Gate Transistor

(*Continued from page 36*)

The IGT may be used for extremely sensitive ammeters and for high-impedance electronic voltmeters. Fig. 4 shows an electronic ammeter with a full-scale sensitivity of 1 picoampere (10^{-12} ampere). The current drawn at the input produces a voltage drop across the biasing resistor which, in turn, shifts the operating point of the left IGT. This is differentially compared to a second IGT matched to the first. The resulting current unbalance is then monitored on an ordinary sensitive 0-10 d.c. microammeter. The input biasing resistor determines the full-scale sensitivity. The values shown produce a range of meter sensitivities from 0-1 picoampere to 0-1 μA.

IGT voltmeters work in the same manner as vacuum-tube voltmeters except they need not be connected to the nearest a.c. socket and will easily measure voltage differences well above or below ground. This combines the accuracy and non-loading of a v.t.v.m. with the convenience of a conventional v.o.m. Fancier circuitry allows peak-reading voltmeters, averaging voltmeters, and true r.m.s. voltmeters, all of which are considerably less complicated than conventional designs.

Switches and Choppers

Fig. 5A shows an IGT r.f. switch, useful from d.c. to several megacycles. It can handle up to a volt of peak-to-peak signal. Since there is no offset voltage, there is no distortion of the controlled signal, and the control and the signal remain completely isolated.

An effective method of d.c. amplification is to chop up a d.c. signal into a series of pulses whose amplitude is proportional to the d.c. voltage. These pulses are very easy to amplify in an ordinary a.c. amplifier with no gain stability or drift problems. A rectifier and filter at the output then recovers the d.c. signal, amplified many times. The difficulty is that the chopping switch is far from perfect. Mechanical devices have limited speeds, contact noise, dwell time, and bounce; semiconductor junction devices have offset voltage; tubes are unipolar and have a poor "on" resistance. The IGT has none of these disadvantages and is well suited for chopper applications. Fig. 5B is typical—a series-shunt chopper that alternately connects the output to ground or the input signal.

Many conventional circuits can benefit from conversion to IGT's. For instance, Fig. 5C shows an IGT voltage amplifier with a voltage gain of 2500, a 22-megohm input impedance, and a 5-Hz to 60-kHz frequency response. Note the absence of any large capacitors, particularly emitter bypass electrolytics, and the simple biasing. This sort of circuit lends itself readily to integration.

The high input impedance comes in handy in monostable and astable multivibrators where significantly smaller values of capacitance can be used to obtain the same delay times. When used as level detectors, voltage comparators, or Schmitt triggers, there is no loading of the input signal. Another area for the IGT is the sine-wave oscillator. Very pure waveforms may be easily obtained using an IGT and a phase-shift network in a Wien-bridge configuration.

For two final applications, consider Figs. 5D and 5E. If we apply a constant voltage to an IGT gate, a constant current results. The IGT can then be used as a constant-current source in exactly the same way a zener diode is used as a voltage source. This is useful for current regulation, circuit protection, and for generating linear ramp waveforms. On the other hand, if an IGT is biased in the normal manner with no input signal, it behaves like a constant-resistance device which, for low-level signals, is electrically variable. The uses for automatic gain control, electronic multiplication, modulation, and demodulation, are obvious.

A more subtle application lies within integrated circuits. It makes no difference in cost how many transistors go on a certain substrate, for they are simply more holes in the various masks. Thus, it pays to use IGT's instead of load resistors in integrated circuits. Not only are they smaller than conventional deposited resistors, but they eliminate the extra steps necessary to fabricate conventional resistors. ▲

Editor's Note: As pointed out in this article, because of the extremely high input impedance inherent in the IGT, permanent damage to the component can result in the event of a careless moment of mishandling. To remove the possibility of such damage, the General Instruments Corp. *is manufacturing a line of IGT's having a built-in zener diode between the gate and the substrate. This zener protects the gate from any accidental voltage damage, however, it reduces the input impedance of the IGT to the order of 10^{10} ohms.*