A GUARDED INSULATED GATE FIELD EFFECT ELECTROMETER

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Summary

An investigation has been made of a new type of insulated gate field effect transistor (IGFET), in which the gate lead is brought through the header in a guarded configuration. Measurements of gate leakage current with the drain connected to the source on this guarded IGFET show that its gate leakage current is less than 1/10 that of the conventional device, demonstrating that most of the leakage in an IGFET is across the header. When the guarded IGFET is operated in the active region, it is possible to set the operating conditions such that the gate leakage current cannot be measured on the best vibrating reed electrometers. Models of the guarded IGFET which explain the effect of bias on gate leakage current are presented. Others have shown that the IGFET, under proper bias, exhibits a zero temperature coefficient. It is shown how to simultaneously satisfy the bias conditions for minimum gate leakage current and zero temperature coefficient, as well as eliminate drift with time. Biased in this manner, a single guarded IGFET electrometer, which can be battery operated, was built. Its current sensitivity is better than 10^{-17} amperes.

Introduction

Extensive use has been made of the vacuum tube for instruments which measure small currents. However, due to grid current, the measuring capability of these instruments is limited to about 10^{-14} amperes. Below this, the vibrating reed electrometer which employs modulation techniques[1] can detect currents in the 10^{-17} ampere region. Since the insulated gate field effect transistor (IGFET) has inherently high impedance, it is attractive as a replacement for the vacuum tube.[2,3] The major limiting effect on the current sensitivity of an IGFET electrometer is gate leakage current and to a lesser extent, drift.

With the objective of minimizing the effects of gate leakage and drift, an investigation was undertaken to determine the extent of these factors. During initial tests, it became apparent that leakage across the header was masking the measurement of the gate leakage current. Therefore, several IGFETs were obtained in which the gate lead is brought through the header in a guarded configuration. The gate leakage current of both the standard IGFET and the guarded device (GIGFET) was studied over a range of operating conditions. Drift as a function of time and temperature was investigated for its effect on current sensitivity.

As a result of this investigation, criteria were developed which made it possible to design a charge measuring circuit that uses a single GIGFET input and exhibits a current sensitivity of better than 10^{-17} amperes.

Leakage Characteristics

IGFET

A P-channel enhancement mode (normally off) IGFET (2N3610) having four leads--gate, source, drain, and outer case, and a substrate tied internally to the source was used for this investigation. It was mounted on a teflon slab in a shielded enclosure with a special fitting that allowed coupling to a Cary Model 31 Vibrating Reed Electrometer (Figure 1). The case lead was connected to the low side of the Vibrating Reed Electrometer, which acts as a guard terminal. The leakage current was studied under different bias conditions.

For the first test, data were obtained with the drain to source voltage (V_{DS}) set at zero and the gate to source voltage (V_{GS}) varied. A plot of this data is shown in Figure 2. It is linear for gate voltages less than 16 volts and breaks sharply upward for gate voltages greater than 16 volts. Since tests conducted on the GIGFET do not display this linear region, it is believed that the current in the linear region is due to header leakage paths. The same data are plotted in Figure 3 as the logarithm of the leakage current versus the square root of the gate voltage. The straight line for gate to source voltages (V_{GS}) greater than 16 volts indicates that Schottky emission is probably present.[4] However, further experiments would be necessary to prove its presence conclusively.

For the second test, the gate leakage current (I_G) was measured with a fixed gate to source potential, V_{GS}, and a variable drain to source voltage, V_{DS}. The data obtained are shown in Table I.

TABLE I

IGFET Gate Leakage

V_{GS} (volts)	V_{DS} (volts)	$I_G \times 10^{-17}$ (amps)
-9.4	0	70
-9.4	-9.4	18
-9.4	-17.4	0*

* Within the measuring limits of the Vibrating Reed Electrometer

In Table I, as V_{DS} approaches $2V_{GS}$, the gate leakage current approaches zero. This reduction is caused by the header leakage paths (R_{GD}, R_{GS}) shown in Figure 4. Since the drain and source leads are symmetrically located with respect to the gate lead, R_{GD} is approximately equal to R_{GS}. Thus, for V_{DS} equal to twice V_{GS}, the current in R_{GD} is equal and opposite to the current in R_{GS}. Under this condition, the net input current due to header leakage paths is zero.

GIGFET

While it is possible to reduce header leakage, it is more effective to eliminate it by bringing the gate lead through the header in a guarded configuration. The guarded IGFET (GIGFET) shown in Figure 5 was made on special order by General Micro-Electronics Inc. using their standard IGFET chip, but with the substrate connected to the outer case.

The GIGFET was first tested with the drain, source, and substrate tied together. The guard lead of the GIGFET was connected to the guard terminal of the Vibrating Reed Electrometer. Below a gate voltage of 10 volts, the gate leakage current was not measurable. A plot of the logarithm of the gate leakage current versus the square root of the gate voltage for gate voltages greater than 10 volts is shown in Figure 6. Once again the straight line obtained in Figure 6 is probably due to Schottky emission. The gate leakage current of the GIGFET is well below the gate leakage current of the IGFET. This reduction in gate leakage current is due to the elimination of header leakage paths by the guard conductor.

Tests were performed with both drain to source and gate to source potentials applied and with the substrate connected to the source. Since the leakage currents could not be measured below a gate voltage of 10 volts, a gate to source voltage of 16 1/2 volts was used. The results obtained are shown in Table II.

TABLE II

GIGFET Gate Leakage

V_{GS} (volts)	V_{DS} (volts)	$I_G \times 10^{-17}$ (amps)
-16 1/2	0	33
-16 1/2	-3	22
-16 1/2	-4 1/2	14

As with the IGFET, the gate leakage current of the GIGFET decreases with increasing drain voltage. To explain this reduction, the model shown in Figure 7 is proposed. In this model, the channel resistance is the sum of R_{D1} and R_{D2} while the silicon dioxide insulator has been lumped into resistor, R_L. The gate leakage current for the model is given by

$$I_G = \frac{V_{RL}}{R_L} = \frac{-V_{GS} + \frac{V_{DS}\,(R_{D2})}{R_{D1} + R_{D2}}}{R_L} \qquad (1)$$

This indicates that for a fixed gate to source voltage the gate leakage current, I_G, decreases as V_{DS} is increased from zero.

IGFET and GIGFET

The leakage tests conducted show that the IGFET should be biased at a drain voltage equal to twice the gate voltage to obtain the minimum gate leakage current. Based on the model in Figure 7 (assuming $R_{D1} = R_{D2}$) and the data in Table II, it appears that the GIGFET should be biased the same way as the IGFET to obtain minimum gate leakage current. The tests conducted on the GIGFET show that the gate leakage current decreases as the drain to source voltage increases. Due to the limit in sensitivity of the vibrating reed electrometer, these tests did not establish the exact ratio between gate to source and drain to source voltage for a minimum gate leakage current in the GIGFET.

Drift Characteristics

Drift vs. Temperature

The initial temperature tests performed on the IGFET, at a drain current of 1 mA and a drain to source voltage of -15 volts, showed that the drain current had a negative temperature coefficient of 3.6 μA, per °C from -7°C to 49°C.

However, depending on bias conditions, the IGFET can exhibit negative, positive, or zero temperature coefficients.[5, 6] The presence of surface states produces a positive drain current temperature coefficient while channel mobility causes a negative drain current temperature coefficient. With the proper level of drain current, a zero temperature coefficient is achieved.

The devices tested by Zuleg[6] had a zero temperature coefficient at a drain current of 1.8 mA, while those tested by Heinman and Miller[5] had a zero temperature coefficient at a drain current of 70 μA. The drain current at which a zero temperature coefficient is achieved depends on the doping of the particular device.

Tests were conducted on the GIGFET to establish the drain current necessary for a zero temperature coefficient. These tests indicated that the units had a zero temperature coefficient from -18°C to 66°C when biased for drain currents less than 100 μA. However, the drain current was not stable with time.

Drift vs. Time

The stability of the IGFET has been investigated extensively.[7-11] The cause of the instability has been attributed to mobile ions in the insulating layer. To determine if the observed drift with time was due to mobile ions in the silicon dioxide insulator, several devices were biased with $V_{GS} = V_{GD} = -15$ volts and then heated at a temperature of 100°C for 18 hours. After heating, the devices were stored at room temperature with the bias voltage maintained. If any mobile ions were present, the combined effect of bias and high temperature would quickly sweep them in the direction of the applied field. Storing the devices with the bias maintained prevents these ions from diffusing into the bulk of the silicon dioxide insulator. The units tested after this treatment showed no drift with time and exhibited a zero temperature coefficient at a drain current of 95 μA.

To further ascertain the presence of mobile ions in the silicon dioxide layer, an IGFET was biased with $V_{GS} = V_{GD} = -15V$ and heated for a few hours at 100°C. With this negative bias maintained, the IGFET was then quickly cooled to room temperature. The turn-on characteristic of the IGFET was then recorded with $V_{DS} = -15$ volts and is shown in Figure 8, Curve A. This procedure was then repeated for a positive gate bias. The result is shown in Curve B of Figure 8. Since this device requires negative gate potential for a flow of drain current, when the turn-on characteristic is that shown by Curve B it will shift to that shown by Curve A. At room temperature, this shift takes several days.

Drift and Mobile Ions

It is believed[7,9] that there is a fixed positively charged layer very near the oxide-silicon interface as shown in Figure 9 (reproduced from ref. 9). These charges are immobile, and their number does not change. Mobile positive ions may also be present within the oxide layer, due to contamination, and can move under the influence of electric fields.

If the mobile ions are all concentrated next to the metal electrode, they induce their image charge entirely in the metal and have no effect on the silicon. This corresponds to Curve A in Figure 8. If a positive bias is applied to the metal for a period of time, the mobile ions will be driven over to the oxide-silicon interface. This process takes only a few minutes at 200°C but can take several days at room temperature. At the interface, they induce their negative image charge in the silicon. This corresponds to Curve B. Now, if a negative bias is applied to the metal electrode for some time, the mobile charges will again be drawn back to the metal plate and the turn-on characteristic will return to Curve A.

The mobile ions, therefore, make the turn-on characteristic unstable while drifting through the insulating layer. It is believed that sodium ions are the main contaminant in the oxide and it would take only a two part per million concentration of sodium in the oxide layer to cause a 10 volt change in the turn-on characteristic.

If the device is stored without applied potentials, it would be expected that the positive ions would slowly diffuse throughout the bulk of the silicon dioxide insulator. Thus, when voltages are applied, a turn-on characteristic similar to Curve C in Figure 8 would be initially observed. The negative gate bias required to turn the device on results in a shift to Curve A. After use, the removal of the gate potential results in partial or complete diffusion of the mobile ions throughout the insulator. The drain current must be kept constant to maintain the zero temperature coefficient. It is possible in a practical circuit to achieve this by insuring that a negative gate to source bias is always present so that the mobile ions do not drift. This keeps the turn-on characteristic at Curve A.

GIGFET Circuit

Previous electrometer circuits employing IGFETs[2,3] have been based on a balanced configuration requiring two devices. If both IGFETs have similar characteristics, then the output is temperature insensitive; however, in practice, no two devices are identical. Since the gate leakage current of the GIGFET can be adjusted to essentially zero and the drain current independently adjusted for a zero temperature coefficient, it was possible to design a temperature insensitive and minimal leakage circuit with a single device. The use of a single device eliminates the noise contributed by the IGFET introduced for balance.

The circuit (Figure 10a) uses the output of the GIGFET as the input for the battery powered operational amplifier (Philbrick Model P18Q). The offset voltage, V_o, is equal and opposite to the voltage drop across the 12 kilohm load resulting in a quiescent voltage of zero applied to the operational amplifier. Since batteries do not have adequate stability for the offset, V_o, and gate bias, V_G, potentials, a battery powered low drain regulator circuit must be used (Figure 10b). The temperature compensated Zener diode, D_1, is supplied by a constant current from the field effect diode, I.

With a 12 kilohm load, the voltage gain through the GIGFET is -1. The operational amplifier is connected so that its open loop gain is +1000. Thus, the change in IGFET bias to produce the maximum voltage output is essentially zero. A 10 picofarad capacitor, C, is returned from the output to the gate as the charge integrating element. The change in output voltage, Δe_{out}, is related to input current, I_{in}, by the capacitance, C, in farads, and the elapsed time, Δt, in seconds. The equation is

$$I_{in} = -C\,\frac{\Delta e_{out}}{\Delta t} \quad \text{amperes.} \tag{2}$$

The feedback connection permits the guard to be maintained at the gate potential thus eliminating header leakage effects. A gate to source potential of 7 volts gives a drain current of 95 μA which was the current necessary for the zero temperature coefficient. The drain to source potential, initially set for twice V_{GS} (i.e., V_d = 7 volts) to minimize the gate leakage current as based on the assumption that R_{D1} equals R_{D2} in Figure 7, caused the output voltage to change indicating that the net input current was not zero. It was found that a drain to source voltage of 9.1 volts gave optimum results, that is, minimum change in output voltage.

The circuit was calibrated by introducing 25×10^{-17} amperes from an ionization chamber in a background radiation flux and caused the output voltage to change by 90 mV in one hour. Drift runs were then taken with the input of the circuit capped while the output voltage was recorded by a 100 mV strip-chart recorder. The drift in output voltage over a five day period corresponded to an input current of 3×10^{-19} amperes. During this time, diurnal variations were observed. However, the worst drift over any three hours was less than 10^{-17} amperes.

It is believed that during the drift tests, the GIGFET was not biased for zero gate leakage current, but rather that the gate leakage current of the GIGFET was cancelling another current. The other current, because of the appreciable volume of the air capacitor was probably an ionization current induced by background radiation. To test this hypothesis, the background radiation was increased by placing a small radioactive source near the capacitor. This increased the ionization current causing an increase in the output voltage. By reducing the drain to source voltage from 9.1 volts to 8.4 volts, the output voltage did not change indicating the restoration of a balanced condition. Therefore, decreasing the drain to source voltage increased the gate leakage current by an amount equal and opposite to the increase in ionization current. This is consistent with Equation 1 derived from Figure 7 which also shows that the gate leakage current increases with decreasing drain to source voltage.

Cancellation of the ionization current by the GIGFET gate leakage current limits the current sensitivity of the circuit. If the ionization current is reduced, by shielding or using a vacuum capacitor, the GIGFET gate leakage current can be correspondingly reduced resulting in improved sensitivity.

Conclusions

The gate leakage current of an IGFET was reduced by using a guard on the gate lead and proper selection of the drain to source voltage. Through maintenance of a constant gate potential such that the drain current was 95 μA, drift with temperature and time was minimized. This made possible the design of an extremely sensitive electrometer using a single guarded IGFET, biased for both minimum gate leakage current and zero temperature coefficient.

The sensitivity of this GIGFET circuit is comparable to that of the vibrating reed electrometer. However, even better current sensitivity is possible by reducing the ionization effect in the capacitor.

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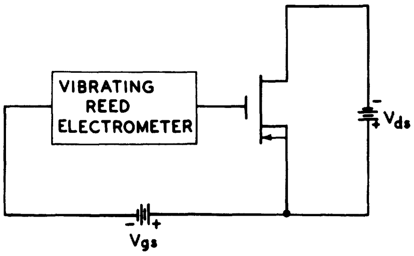


CIRCUIT FOR MEASURING GATE LEAKAGE CURRENT

Fig. 1. Vibrating Reed Electrometer measures IGFET gate leakage current using various drain to source, V_{DS}, and gate to source, V_{GS}, potentials.

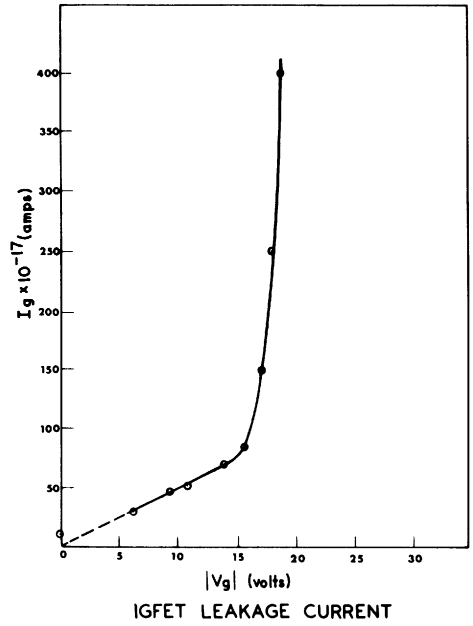


Fig. 2. Linear plot of leakage current, I_G, vs. gate voltage, V_G, for IGFET. The straight line below 16 volts extrapolated to the origin represents header leakage; the curve above 16 volts indicates Schottky emission.

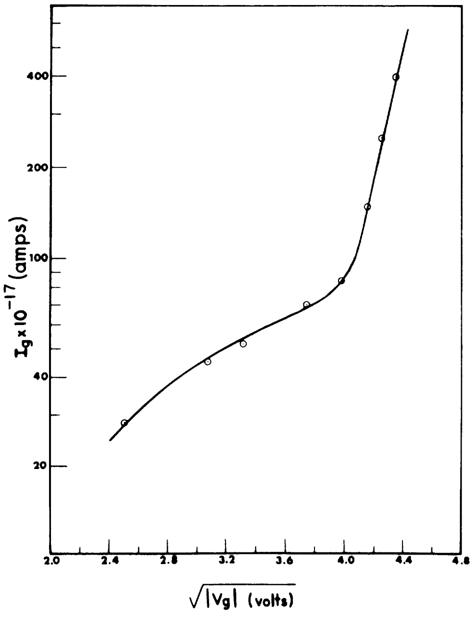


Fig. 3. Log plot of gate leakage current, I_G, vs. square root of gate voltage for IGFET. The straight line above 16 volts (4.0) clearly indicates the presence of Schottky emission.

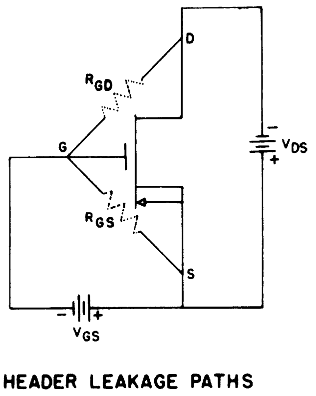


Fig. 4. The resistor representation of IGFET header leakage paths, R_{GD} and R_{GS}, shows the reduction in gate leakage current as the drain to source voltage, V_{DS}, is increased.

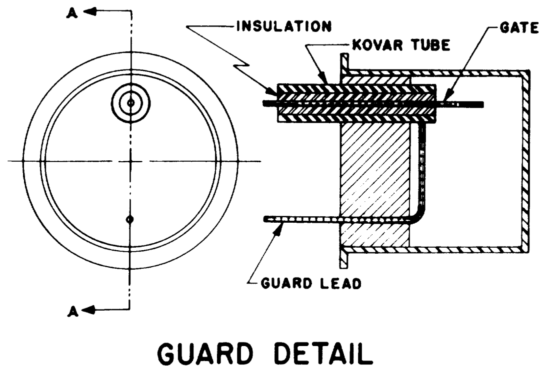


Fig. 5. Cross sectional view of a guarded insulated gate field effect transistor (GIGFET).

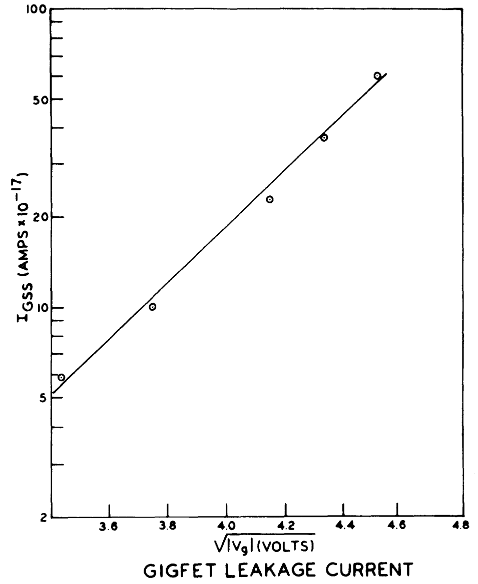


Fig. 6. Log plot of gate leakage current vs. square root of gate voltage for GIGFET. The straight line indicates Schottky emission and the elimination of header leakage paths.

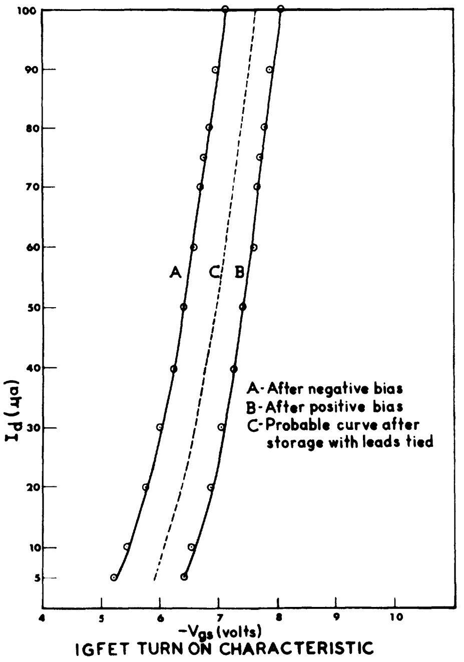


Fig. 8. The turn-on characteristics for the IGFET (or GIGFET) show the shift caused by mobile ions in the silicon dioxide insulator.

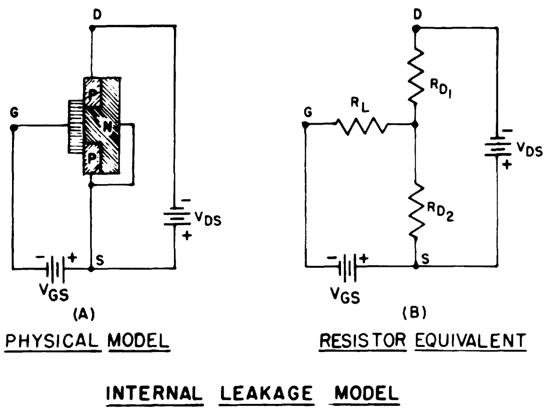


Fig. 7. The equivalent circuit, B, of the GIGFET, A, shows the reduction in gate leakage current as the drain to source voltage, V_{DS}, is increased. The channel is represented by the resistors R_{D1} and R_{D2}; the silicon dioxide insulator is represented by the resistor R_L.

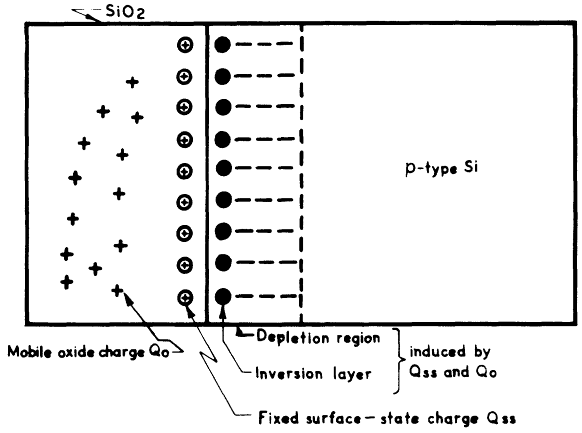
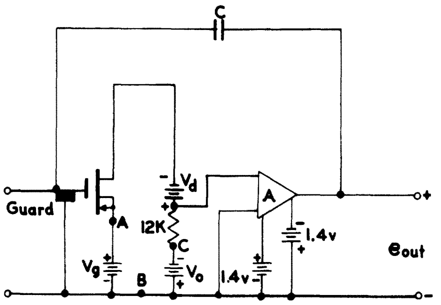
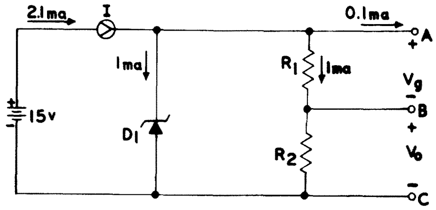


Fig. 9. Model of the silicon-dioxide-silicon system.



BATTERY OPERATED ELECTROMETER



CIRCUIT FOR V_g AND V_o SUPPLIES

Fig. 10(a). GIGFET electrometer. The amplifier, A, is battery powered. (b). This circuit supplies V_g and V_o for the GIGFET electrometer.