

PATENT SPECIFICATION

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COMPLETE SPECIFICATION.

Electrical Circuits Comprising Field-Effect Transistors and Useful as Variable Reactance Circuits.

We, RADIO CORPORATION OF AMERICA, a Corporation organized under the laws of the State of Delaware, United States of America, of 30, Rockefeller Plaza, City and State of New York, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to electrical circuits comprising a field-effect transistor and useful as voltage responsive variable reactance circuits.

Voltage controlled variable reactance circuits have many uses in electronic apparatus. For example, such circuits may be used to control oscillators in the exciter or modulator portions of an FM transmitter in a manner to cause the frequency of the transmitter oscillator to deviate from a pre-selected centre frequency as a function of the amplitude and polarity of a modulating signal. Voltage controlled variable reactance circuits are also useful in frequency controlled oscillator circuits for super-heterodyne receivers, to control the frequency of operation of a local oscillator as a function of an automatic frequency control (AFC) voltage so that the receiver intermediate frequency (i-f) is maintained at the proper frequency.

According to the present invention, there is provided an electrical circuit comprising: a field-effect transistor having a substrate of semiconductor material, a gate electrode insulated from the substrate, and source and drain electrodes separated by a conductive path having a conductivity controllable as a function of a potential applied to the gate

electrode, said substrate forming with said source and drain electrodes respectively a pair of rectifying junctions: circuit means coupled with said source, drain and gate electrodes for conditioning said transistor to operate as an active device; and control means for applying a control signal to the substrate.

In accordance with an embodiment of the invention the source, gate and drain electrodes of the transistor may be connected for operation as an oscillator, the frequency of which is controlled as a function of a voltage applied to the substrate. By way of example, the oscillator may comprise the local oscillator of a signal receiver, and the voltage to the substrate may comprise a suitably derived automatic frequency control (AFC) voltage. Alternatively, the oscillator may comprise a portion of a modulator circuit in which the frequency of oscillations developed are altered as a function of a modulating signal applied to the substrate.

In accordance with another embodiment of the invention, the transistor may be connected as a tuned amplifier, the tuning of which is varied as a function voltage applied to the substrate.

Referring to the accompanying drawings:

Figure 1 is a diagrammatic view of a field-effect transistor of the type which may be used in circuits embodying the invention;

Figure 2 is a graph illustrating the drain voltage vs. drain current characteristics of the transistor shown in Figure 1 for various values of gate-bias voltage;

Figure 3 is a schematic circuit diagram of a frequency controlled oscillator circuit embodying the invention;

Figure 4 is a graph indicating the fre-

quency vs. the substrate voltage characteristic of the oscillator circuit shown in Figure 3.

Figure 5 is a graph indicating the relative oscillator output voltage with changes in the direct voltage applied to the substrate;

Figure 6 is a schematic circuit diagram of a frequency controlled oscillator circuit illustrating a modification of the circuit shown in Figure 3; and

Figure 7 is a schematic circuit diagram of a tuned amplifier circuit illustrating a further embodiment of the invention.

Referring particularly to Figure 1, an insulated gate field-effect transistors 21 which may be used with circuits embodying the invention includes a base or body 23 of semiconductor material. The base 23 may be either a single crystal or polycrystalline and may be of any one of the semiconductor materials used to prepare transistors in the semiconductor art. The transistor includes a conductive gate electrode 25 and a pair of electrodes 27 and 29 which may be interchangeably used as the source and drain electrodes. The gate electrode is separated from the body of the semiconductor material by an insulating oxide layer 31.

The transistor of Figure 1 may be prepared by processing the device in the following manner. A single crystal body of lightly doped P-type silicon of relatively high resistivity, such as 500 ohm-cm, has at least one surface cleaned, as by etching, to expose the body material. Heavily doped silicon dioxide is then deposited by any suitable means as a layer portion 33 on selected areas of the clean surface of the body 23. For example, a uniform layer of doped silicon dioxide may be deposited on the crystal body 23. The portion of the deposited layer which overlies the location where the insulating layer 31 is to be formed is then removed. The local removal of the deposited oxide may be effected, in any suitable manner, such as by a photo resist and acid etching technique. The thickness of the deposited oxide layer 33 is preferably between one and five microns.

The deposited silicon dioxide layer 33 contains a relatively high concentration of impurities (also referred to as dopant) which are N-type when present in silicon. Such impurities may for example be antimony, arsenic, or phosphor.

The body 23 is then placed in a furnace and heated to from 900 to 1100°C in a dry oxygen atmosphere and cooled. During the heating, the exposed surface portion of the silicon body 23 (under the later applied gate electrode 25) is converted to silicon dioxide. Such converted material is referred to as thermally grown silicon dioxide and comprises the oxide layer 31 as shown. The converted material 31 is essentially pure silicon dioxide and has a high resistivity of

10^{14} ohm-cm. A conducting channel 35 forms at the interface between the oxide layer 31 and a silicon body 23. During the same heating step, impurities from the deposited silicon dioxide layer 33 diffuse into the silicon as indicated at 37 and 39. The regions 37 and 39 are of low resistivity and provide a low resistance connection to the conducting channel 35.

Portions of the deposited oxide layer 33 are then removed to permit access to the diffused regions 37 and 39. Conductive electrodes are then selectively deposited on the diffused regions 37 and 39 to form the source and drain electrodes 27 and 29, and on the insulating layer 31 to form the gate electrode 25. The gate electrode 25 may be coextensive with the layer 31 of grown silicon dioxide, or may overlie only a portion of the conducting channel 35. If desired, the gate may be displaced laterally to a position closer to one of the source and drain regions 37 and 39.

In the embodiment described, the channel 35 is approximately 0.0005 inch dimension between the diffused areas 37 and 39 and is approximately 0.05 inch transversely thereto. The high resistivity layer 31 of silicon dioxide is approximately 2700 angstroms thick. Such a device has an input resistance of approximately 10^{14} ohms, as measured between source and gate electrodes.

Figure 2 is a family of curves 40—53 illustrating the drain voltage vs. drain current characteristic of the transistor of Figure 1 with different values of gate-to-source voltage. It will be noted that the curves 50—53 representative of high drain current and the curves 40—43 representative of relatively low drain current are relatively closely spaced, whereas the intermediate curves 43—50 are relatively uniformly spaced. The equal spacing of the curves for equal gate-to-source voltage increments is indicative of a linear operating region of the transistor.

The electrodes 27 and 29 may be interchangeably operated as source and drain electrodes. The one of the electrodes 27 and 29 to which an instantaneously positive voltage is applied relative to the other of the electrodes is considered to be the drain electrode, and the gate bias is referenced against the electrode operating as the source.

A feature of an insulated gate field-effect transistor is that the zero bias characteristic can be at any one of the curves 40—53 shown in Figure 2, with the curves above the zero bias curve representing positive bias voltage relative to the source, and the curves below the zero bias curve representing negative gate voltages relative to the source. The location of the zero bias curve may be selected by the control of the processing of the transistor during the manufacture. For example by controlling the time and/or temperature of the step of the process when



the silicon dioxide layer 31 is grown, the number of free charge carriers in the device can be controlled. The longer the transistor is baked, and the higher the temperature, in a dry oxygen atmosphere, the more the drain current for a given amount of drain voltage for zero bias between the source and gate electrodes. By way of example, to establish the curve 47 as the zero bias curve, during the step which produces the silicon dioxide layer 31 the transistor was baked for two hours at 900°C in an atmosphere of dry oxygen. If the temperature, or time of baking, or both are increased, the zero bias curve will correspond to one of the curves 48—53. By decreasing the time or temperature, or both, in the baking cycle, the zero bias curve will occur for lower values of drain current such as for example one of the curves 40—46.

In Figure 3 the oscillator circuit includes an insulated gate field-effect transistor 60 of the type described in Figures 1 and 2, and including gate, source and drain and substrate electrodes 61, 62, 63 and 64 respectively. Although not shown in Figure 1, the substrate electrode may be any ohmic connection to the substrate of the transistor. The drain electrode 63 is connected to the positive terminal of a suitable source of operating potential 65 (not shown) and is bypassed to ground for waves of the oscillator frequency through a capacitor 66. The source electrode 62 is isolated from ground by an oscillator frequency choke coil 67. A direct current (d-c) path is provided from the gate electrode 61 to ground through a resistor 68, and the gate electrode is coupled to an inductor 69 through a coupling capacitor 70.

The device 60 is connected in a grounded-drain Colpitts oscillator circuit configuration with the resonance frequency primarily established by the inductor 69 in parallel with the series combination of the gate-to-source and source-to-ground capacitances. The latter two capacitances are inter-electrode and distributed quantities and are not shown in the circuit diagram.

It has been found that the frequency of oscillation can be controlled as a function of the voltage applied to the substrate electrode 64. As shown in the graph of Figure 4, with a slightly negative voltage on the substrate electrode with respect to ground, the oscillator operates at its natural frequency established primarily by the inductor 69 and the gate-to-source and source-to-ground capacitances. As the substrate electrode 64 is driven further in the negative polarity direction relative to ground, the frequency of oscillation increases, and as the substrate electrode 64 is driven in the positive direction relative to ground, the frequency of oscillation decreases. The curves

of Figure 4 were derived with the capacitor 76 out of the circuit.

The mechanism by which this voltage responsive frequency change occurs is believed to result from the changes in bias on a pair of rectifying junctions which are created during the manufacture of the transistor. The interface of the source and drain regions with the substrate region forms a pair of rectifying junctions poled so that the substrate side of the junctions comprises the anodes and the source and drain sides of the junctions comprise the cathodes. These rectifying junctions are indicated schematically as diodes 71 and 72 in Figure 3.

It is to be understood that the poling of the diodes 71 and 72 is representative of a transistor of the type described in connection with Figures 1 and 2 wherein the substrate is of P-type material relative to the source and drain electrodes. However the transistor device can be fabricated where the substrate is of N-type material relative to the source and drain electrodes. In devices of the latter type the rectifying junctions would be oppositely poled so that the anode side of the rectifying junction appears at the source and drain electrodes, and the cathode side of these junctions appears at the substrate electrode. The description herein will be restricted to the type of device described in connection with Figures 1 and 2 wherein the substrate electrode is of P-type material relative to the source and drain electrodes.

With the substrate electrode 64 at d-c ground potential, the diode 71 is heavily reverse biased by the operating potential supply source 65. If the d-c voltage drop due to the oscillator frequency choke coil 67 and any source contact 62 resistance is neglected, the d-c voltage drop across the diode 72 is zero when the substrate electrode 64 is at ground potential. As a potential at the substrate electrode 64 is made more negative, both of the diodes 71 and 72 become more reversed biased, and the capacitance thereof decreases. Since the capacitances of the diodes 71 and 72 taken in series appears across the source-to-ground capacitance of oscillator frequency determining circuit, frequency of oscillation is increased.

In like manner, as a potential at the substrate electrode 64 is made more positive, the diode 72 becomes forwardly biased, the diode 71 becomes less reversed biased. Thus, the capacitance of the diode 71 increases and the diode 72 appears as a resistance. The net effect is to decrease the oscillator frequency. The voltage of the substrate electrode may be made progressively more positive until the diode 71 becomes forwardly biased at which time oscillation ceases.

It will be noted that the measured d-c voltage at the substrate electrode is slightly

negative when the oscillator is operating at its natural resonant frequency. This negative voltage result from self-rectification of the oscillator signal by the diodes 71 and 72, and is added to the control signal applied to the terminals 73 and 74.

As shown in Figure 5, the relative oscillator output voltage increases as the substrate voltage is made less negative. Hence the substrate voltage may also provide amplitude modulation of the oscillator output voltage. If desired, the amount of change in the amplitude of oscillator voltage may be reduced by the provision of additional feedback capacitance between the source electrode 62 and the gate electrode 61.

The frequency controlling voltage is applied to a pair of terminals 73 and 74, and through an oscillator frequency choke coil 75 to the substrate 64. By way of example, the frequency controlling voltage may comprise an automatic frequency control (AFC) voltage derived from a suitable source. An oscillator whose frequency is automatically controlled in this manner is useful as the heterodyne oscillator of a superheterodyne radio receiver. Alternatively, the frequency controlling voltage may comprise a suitable signal source for frequency modulating the developed oscillations, whereupon the circuit operates as a modulator. Still further, a switching signal providing a voltage of sufficient magnitude to forward bias both of the diodes 71 and 72 may be used to selectively switch the oscillator on and off and thereby provide a start-stop oscillation system.

If desired, the frequency characteristics of the circuit of Figure 3 may be modified by the addition of a reactance element, such as the capacitor 76, between the substrate electrode 64 and ground.

A modification of the oscillator circuit is shown in Figure 6. The circuit of Figure 6 is similar to that of Figure 3 in that the oscillator shown therein is a Colpitts oscillator operating with a drain electrode at ground potential for oscillator signals. The main difference in the circuits of Figures 3 and 6 is in the biasing of the substrate electrode. The source electrode 62¹ is raised off d-c ground potential by the addition of source biasing resistor 80 between the low signal potential side of the oscillator frequency choke 67¹ and ground. A variable resistor 81 is connected between the drain electrode 63¹ and the substrate electrode 64¹ to control the bias on the substrate. In the circuit of Figure 6, the diode 72¹ is forward biased and conducts current of a magnitude determined by the resistance of the resistors 80 and 81. The resultant voltage across the resistor 81 effectively appears across the diode 71¹ and controls its capacitance. It is the combina-

tion of the effective capacitance of the diode 71¹ and the effective resistance of the diode 72¹ which controls the frequency of oscillation in the circuit of Figure 6. As described above in connection with Figure 3, a suitable signal source or an AFC circuit may be used to replace the resistor 81, and the resistor 81 may represent the equivalent resistance of such a frequency controlling voltage source.

Figure 7 is a schematic circuit diagram of an amplifier circuit which includes an insulated gate field-effect semiconductor device 90 of the type described in connection with Figures 1 and 2. The device 90 includes a gate electrode 91 which is coupled through a coupling capacitor 92 to a source of signals to be amplified. The gate electrode 91 is also coupled over a lead marked AGC through a resistor 93 and a filter capacitor 94 to a source of gain controlling potential (not shown).

The semiconductor device 90 includes a source electrode 95 which is connected to ground through a resistor 96 paralleled by a signal bypass capacitor 97. A drain electrode 98 is coupled through a resonant circuit 99 and a resistor 100 to a source of potential +B. The resistor 100 is bypassed for signal frequencies by a capacitor 101. A tap 102 on the resistor 100 is coupled to the substrate electrode 103. A bypass capacitor 104 prevents signal energy from developing at the substrate electrode. Amplified signal energy may be extracted from the amplifier circuit at the output terminals 105.

For weak signals, the semiconductor device 90 conducts maximum current, and the voltage appearing at the tap 102 is least positive. The circuit parameters are selected so that the voltage at the tap 102 is less positive than the voltage at the source electrode 95. However it is to be understood that the circuit will operate in the manner to be described if the substrate electrode 103 is biased more positively than the source electrode 95.

Under the weak signal conditions the amplifier resonant output circuit 99 is tuned such as to provide peaking or maximum response to signals near the high frequency end of a predetermined signal pass band. As the signal level increases the AGC voltage applied to the gate electrode 91 tends to become more negative and reduces the current through the transistor 90. This, in turn causes the potential at the tap 102 of the resistor 100 to become more positive thereby driving substrate electrode 103 more positive. With the substrate electrode 103 more positive, the capacitance across the resonant circuit 99 is increased, thereby decreasing its resonant frequency to provide either an essentially flat frequency response characteristic over said predetermined signal pass band, or to change the maximum fre-



quency response to more nearly the centre of the band.

5 An amplifier of the general type described is useful as an i-f amplifier for intercarrier type television receivers to provide enhanced response to the video signal carrier when the average carrier level is weak.

10 Other types of control circuits may be employed. For example, a suitable control voltage circuit may be coupled directly to the substrate electrode for altering the tuning of the circuits coupled to the amplifier.

15 As described, circuits embodying the invention employ a single active circuit element which doubles as a voltage responsive reactance element. The control voltage is effective to control the active circuit reactance, while being isolated from the active circuit, thereby causing no undesirable interaction between the control voltage circuit and the active circuit.

WHAT WE CLAIM IS:—

25 1. An electrical circuit comprising: a field-effect transistor having a substrate of semiconductor material, a gate electrode insulated from the substrate, and source and drain electrodes separated by a conductive path having a conductivity controllable as a function of a potential applied to the gate electrode, said substrate forming with said source and drain electrodes respectively a pair of rectifying junctions; circuit means coupled with said source, drain and gate electrodes for conditioning said transistor to operate as an active device; and control means for applying a control signal to the substrate.

40 2. An electrical circuit according to Claim 1, wherein said circuit means includes a resonant circuit, and wherein the control signal varies the tuning of said resonant circuit.

3. An electrical circuit according to Claim 1 or Claim 2, wherein said circuit means is arranged to interconnect said source, drain and gate electrodes for sustaining oscillations, and wherein said control means controls the voltage of said substrate for adjusting the frequency of said oscillations. 45

50 4. An electrical circuit according to Claim 1 or Claim 2, wherein said circuit means is arranged to interconnect said source, drain and gate electrodes for sustaining oscillation, and wherein a source of signals is provided, and said control means connects said source of signals to said substrate for modulating the said oscillation. 55

60 5. An electrical circuit according to Claim 1 or Claim 2, wherein said circuit means is arranged to provide an amplified output in response to an applied signal, and wherein said control means applies a control voltage to said substrate to alter the frequency response characteristic of said amplified output. 65

70 6. An electrical circuit according to Claim 1 or Claim 2, including an automatic frequency control voltage source, and wherein said circuit means connects said source, drain and gate electrodes for oscillation, and said control means couples said automatic frequency control voltage source to said substrate to control the frequency of oscillation of the circuit. 75

7. An electrical circuit substantially as herein described with reference to Figure 3 or Figure 6 or Figure 7 of the accompanying drawings.

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