

PATENT SPECIFICATION

(11) 1 392 064

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- (21) Application No. 22786/72 (22) Filed 16 May 1972
 (31) Convention Application No. 145 407 (32) Filed 20 May 1971 in (19)
 (33) United States of America (US)
 (44) Complete Specification published 23 April 1975
 (51) INT CL² H03B 5/24 // 5/04
 (52) Index at acceptance
 H3T 1G3R 2C 2T3F 3N 4C 4D 4F 5E 5S



(54) OSCILLATORS USING INSULATED-GATE FIELD-EFFECT TRANSISTORS

(71) We, RCA CORPORATION, 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 10020, 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 is directed to oscillator circuits and more particularly to improved oscillator circuits using insulated-gate field-effect transistors. Oscillator circuits normally include an amplifying section and a feedback network. For oscillation to occur two criteria known as the Barkhausen criteria have to be met. These are: 1) that the gain (α) of the amplifying section multiplied by the attenuation ratio (β) of the feedback network to be equal to or greater than one ($\alpha\beta \geq 1$); and 2) that the phase shift around the loop be equal to $n \times 360^\circ$, where n is an integer equal to or greater than one. Normally, the amplifying section is designed to have a phase shift of approximately 180° , or an odd multiple thereof, and the feedback network in turn has a phase shift of 180° to provide the required 360° phase shift.

A problem present in most amplifying sections is that due to temperature variations and/or supply voltage variation the output impedance of the amplifying section changes causing a phase shift. Changes in the phase shift result in a change in the frequency of oscillation which, in some applications, may not be tolerable.

An example of a reference illustrating a possible amplifying circuit is United States patent No. 3,454,894 to Voorhoeve. The Voorhoeve reference is directed to means for stabilizing the drain electrode current of an insulated-gate field-effect transistor. The Voorhoeve reference shows the use of impedance means connected to the source electrode and an additional resistive network connected

to the substrate. The resistive network connected to the substrate biases the substrate at a potential intermediate the potential points (e.g. ground and $+V_s$) of the source of operating potential. Biasing the substrate at an intermediate point of potential renders the scheme unsuitable for integrated circuit applications where many transistors share the same substrate and must be at the same potential. Also, the resistive network of Voorhoeve dissipates power and is cumbersome. In applications such as watches where the circuit of the invention may have application, power dissipation and the simplicity of the circuit is of extreme importance. The circuit of Voorhoeve therefore has considerable disadvantages. Furthermore, the Voorhoeve reference does not suggest that it could be used to render more stable the frequency of oscillation of an oscillator circuit.

Other references also show a resistor connected to the substrate but then proceed to bypass the resistor with a capacitor. This eliminates the feedback which could be provided by the resistor throughout the dynamic range of operation. These references are broadly directed to amplifiers which does not necessarily mean that they would be suitable in oscillator circuits. Another prior art circuit of interest is disclosed in the February 3, 1969 issue of "Electronics" at page 80.

According to the present invention, an oscillator circuit comprises first and second insulated-gate field-effect transistors of opposite conductivity type each having a substrate and source and drain regions defining a conduction channel in its substrate. Each transistor also has a gate electrode for controlling conduction through its channel, the drain electrodes of the transistors being connected in common and to an output node, and the gate electrodes of the transistors being connected in common and to an input node. An approximately 180° phase-shift feedback network has an input terminal and an output terminal respectively connected to the output node and

[Price 33p]

the input node. The circuit has first and second terminals for a source of operating potential with relatively low impedance connections between the substrate of the first transistor and said first terminal and between the substrate of the second transistor and said second terminal. First substantial direct current impedance means connected between the source electrode of the first transistor and said first terminal, and second substantial direct current impedance means connected between the source electrode of the second transistor and said second terminal are provided for causing the source electrodes to be increasingly reverse-biased, with respect to their respective substrates, with increasing conduction through the channels of the respective transistors.

In the detailed description of the invention which follows, reference is made to the drawings attached to and forming a part of this specification and in which like reference characters denote like components; and

FIGURE 1 is a schematic diagram of an oscillator circuit embodying the invention; and

FIGURE 2 is a schematic diagram of another circuit embodying the invention.

Reference is now made to FIGURE 1 which shows an oscillator circuit which includes an amplifying section 2 and a feedback network 4. The amplifying section 2 includes a complementary-type inverter comprising P-type transistor 12 and N-type transistor 14 whose gates are connected to the amplifier's input node 16 and whose drains are connected to the amplifier's output node 18. The substrate 13 (indicated conventionally by the lead with the arrowhead) of transistor 12 is connected to terminal 20 and the source of transistor 12 is returned through resistor R_1 to terminal 20. A potential of $+V_{DD}$ volts may be applied to terminal 20. The substrate 15 of transistor 14 is connected to terminal 22 and the source of transistor 14 is returned through resistor R_2 to terminal 22. A negative potential, V_{SS} , which in this example is ground potential, may be applied to terminal 22.

A feedback resistor 30 is connected between nodes 16 and 18 of the inverter to establish the direct current (D.C.) bias level of the inverter. Resistor 30 should be large enough (normally greater than 10 megohms) so as not to appreciably affect the attenuation and phase of the feedback network 4. Resistor 30 sets the D.C. level so that the voltage at node 18 is substantially equal to the voltage at node 16. This point is typically at or near one-half

the supply voltage $\frac{V_{DD} - V_{SS}}{2}$ and is located

in the high gain region of the inverter transfer characteristic. For example, when V_{DD} is equal to +10 volts and V_{SS} is ground, the D.C.

level at nodes 16 and 18 is approximately equal to 5 volts.

A feedback network, 4, which determines the frequency of oscillation, is connected at its input terminal to node 18 and at its output terminal to node 16. The network, 4, includes a resistor R_3 connected between nodes 18 and 26, a capacitor C_1 connected between nodes 26 and terminal 22, a quartz crystal 24 connected between nodes 26 and 28, and a capacitor C_2 connected between node 28 and terminal 22. Node 28 which may be an output terminal of the network, is connected back to the input terminal (node 16) of the amplifying section.

As already mentioned, for sustained oscillation, the gain (α) of the amplifier multiplied by the attenuation (β) of the feedback network must be equal to or greater than one ($\alpha\beta \geq 1$).

For values of resistor 30 in the range of 10 megohms or more, and with $V_{DD} = 10$ volts, a one volt swing around the bias point (5 volts D.C.) produces approximately a full 10-volt output swing. Therefore, the gain (α) of the amplifier for the full swing is about 5. With the gain equal to 5, the attenuation ratio of the feedback network must be equal to or greater than 1/5 or 0.2.

The operation of the circuit is best understood by assuming, for example, a small falling signal (V_{IN}) applied to the input node 16 of the inverter 2. The inverter has an effective 180° phase shift between its input and output nodes and produces, in response to V_{IN} , a signal V_{O1} at its output node 18. The signal V_{O1} is a rising waveform of amplitude αV_{IN} which is inverted with respect to the input signal V_{IN} . The output of the inverter is then applied to the feedback circuit 4 which attenuates the signal by a factor β and phase shifts it an additional 180°. The output of the feedback network is then fed-back to the input node 16 of amplifier 2. The amplitude of the signal fed-back to the input node is equal to $(\alpha)(\beta)V_{IN}$ and is in phase with the exciting signal V_{IN} . This assumes that the total phase shift around the loop—the phase shift of the amplifier plus that of the feedback network—is equal to 360°.

If the product of $\alpha\beta$ is equal to 1, then the signal fed-back to the input node is equal to the exciting signal and the system is such that oscillations once initiated will be sustained. If the product of $\alpha\beta$ is greater than one, the feedback signal will be greater than the exciting signal and the circuit is such that oscillations always will be initiated. The circuit parameters are, therefore, normally selected so that $\alpha\beta$ is greater than 1.

The output impedance of the amplifying section is predominantly resistive and may be represented by a resistance R_O . Resistance R_O in series with resistor R_3 determines the input

resistance to the feedback network. Variations in R_0 cause a change in the phase shift around the loop. Changes in the phase shift are primary sources of error in the frequency of oscillation.

For example, with R_1 and R_2 short circuited (i.e., the source shorted to the substrate) and with V_{DD} varied from +3 volts to +4.5 volts, the output impedance of a typical complementary inverter was found to change from 5.6 kilohms to 2.01 kilohms and the frequency was found to vary from 262,095.9 HZ to 262,099.5 HZ. The frequency thus changed by approximately 13.6 parts per million (PPM) and the output impedance changed by 64 per cent.

Reverse biasing the sources with respect to the substrates by means of resistors R_1 and R_2 , as more fully explained below, minimizes the change in output impedance as a function of power supply variations and temperature changes. First, the source resistors R_1 and R_2 provide degenerative feedback to the amplifying stage. Secondly, connecting the sources to the substrate through the resistors R_1 and R_2 introduces an effect, known as the substrate bias effect, into the operation of the transistors. The degenerative feedback and the effect of substrate bias combine to render the output impedance of the amplifier (the impedance looking back into node 18) more constant.

For a given $+V_{DD}$ applied to terminal 20, a D.C. bias of approximately $\frac{+V_{DD}}{2}$ is

developed at the gates of the transistors causing a quiescent direct current (D.C.) of I_1 to flow through the current path comprising resistor R_1 the source-drain paths of transistors 12 and 14 and resistor R_2 . The potential at the source of transistor 12 is lower than the potential at the substrate 13 due to the voltage drop across resistor R_1 ($I_1 \times R_1$). Also, the potential at the source of transistor 14 is more positive than the potential at the substrate 15 due to the voltage drop across resistor R_2 ($I_1 \times R_2$). Since transistor 12 is a P-type transistor the source-to-substrate region will be reverse biased by the $I_1 \times R_1$ drop (the substrate is more positive than the source) and since transistor 14 is an N-type transistor the source-to-substrate region will also be reverse

biased by the $I_1 \times R_2$ drop (the source is more positive than the substrate. Now, a reverse bias between the source and substrate increases the impedance between the source and drain since it makes conduction there-between more difficult.

Assume now that the $+V_{DD}$ potential is increased by an increment ΔV . This causes the D.C. bias and the corresponding gate potential to increase by approximately $\frac{\Delta V}{2}$.

As a result, there is an increase in the gate-to-source potential of both P-type transistor 12 and N-type transistor 14. This tends to decrease the source-to-drain impedance of these transistors causing more current to flow in the source-drain paths. An increased current ($I_1 + \Delta I$) can now flow in the conduction path comprising resistors R_1 , R_2 and the source-drain paths of transistors 12 and 14.

However, the increased current (ΔI) increases the reverse bias between the sources of transistors 12 and 14 and their respective substrates. For, while the substrates 13 and 15 remain at points of fixed potential ($+V_{DD} + \Delta V$, and ground, respectively) the potential at the source of transistor 12 is decreased with respect to its substrate due to the increased current and the potential at the source of transistor 14 is increased with respect to its substrate due to the increased current. However, increasing the reverse bias between the source and the substrate increases the source-drain impedance which tends to decrease the current flow thereby offsetting the decrease in the output impedance due to the incremental increase in the operating potential.

Similarly, a decrease in the operating potential causes an increase in the output impedance which results in less current flow in the source-drain path. A decrease in current causes the source-to-substrate reverse bias to decrease which in turn lowers the source-to-drain impedance. Thus, in general, the substrate bias effect acts in a direction to minimize changes in the output impedance.

Measurements taken of the output impedance of a typical complementary amplifying stage for various values of source resistance at different values of power supply voltage are set forth in Table I below:

TABLE I

$R_1 = R_2$	$V_{DD} = 3V$	$V_{DD} = 4.5V$	Change in R_O and frequency
0 ohms	$R_O = 5.6 \text{ Kohms}$ $f = 262,095.9 \text{ HZ}$	$R_O = 2.01 \text{ Kohms}$ $f = 262,099.5 \text{ HZ}$	$\Delta R_O = 64\%$ $\Delta f = 13.6 \text{ PPM}$
5.1 Kohms	$R_O = 26.4 \text{ Kohms}$ $f = 262,091.1 \text{ HZ}$	$R_O = 18.2 \text{ Kohms}$ $f = 262,092.3 \text{ HZ}$	$\Delta R_O = 31\%$ $\Delta f = 4.6 \text{ PPM}$
10 Kohms	$R_O = 42.5 \text{ Kohms}$ $f = 262,090.2 \text{ HZ}$	$R_O = 32.6 \text{ Kohms}$ $f = 262,090.5 \text{ HZ}$	$\Delta R_O = 23\%$ $\Delta f = 1.15 \text{ PPM}$

5 An examination of the table shows that the output impedance varied by 23 per cent and the frequency by 1.15 part per millions with resistors R_1 and R_2 equal to 10K. This compares to a ΔR_O of 64 per cent and a Δf of 13.6 PPM when R_1 and R_2 are zero.

10 The addition of the resistors between the sources and the substrate thus minimize changes in the output impedance and results in greater frequency stability. In addition, the resistors decrease the power drain.

15 It has also been observed experimentally that the addition of resistors R_1 and R_2 in the source legs of the transistors minimize the effect of temperature on the output impedance. Thus, temperature compensation is achieved by connecting impedance means between the source and the substrate of the transistors.

20 In the circuit of FIGURE 1, the minimum starting voltage must be equal to or greater than the sum of the threshold voltages of the N-type transistor 14 and the P-type transistor 12. In those applications where the operating potential has a lower value than the sum of the threshold voltages the biasing scheme as shown in FIGURE 2 may be used.

25 Referring to FIGURE 2, a voltage divider network comprising resistors R_{10} and R_{11} is connected in series between $+V_{DD}$ terminal and node 18. A resistor R_{12} is connected at one end at the junction of resistors R_{10} and R_{11} and at the other end to the gates of the complementary pair of transistors 12 and 14. Transistors 12 and 14 are connected as before with a feedback network connected between output node 18 and the gates of the inverter.

30 This circuit can be made to oscillate so long as $+V_{DD}$ is greater than the threshold voltage of transistor 14. The ratio of R_{10} and R_{11} is a function of this threshold voltage. The particular ratio is selected such that the amplifier is biased in its high gain region.

35 With transistor 14 biased into conduction the circuit is self oscillating. A signal which is applied to the feedback network in turn

produces a signal to the gates of sufficient amplitude and of the correct phase to ensure oscillation at the desired frequency.

WHAT WE CLAIM IS:—

50 1. An oscillator circuit comprising: first and second insulated-gate field-effect transistors of opposite conductivity type, each transistor having a substrate and source and drain regions defining a conduction channel in its substrate and each transistor also having a gate electrode for controlling conduction through its channel, the drain electrodes of said transistors being connected in common and to an output node, and the gate electrodes of said transistors being connected in common and to an input node; an approximately 180° phase-shift feedback network having an input terminal and an output terminal respectively connected to said output node and said input node; first and second terminals for a source of operating potential; relatively low impedance connections between the substrate of the first transistor and said first terminal and between the substrate of the second transistor and said second terminal; and first substantial direct current impedance means connected between the source electrode of the first transistor and said first terminal and second substantial direct current impedance means connected between the source electrode of the second transistor and said second terminal, for causing said source electrodes to be increasingly reverse-biased, with respect to their respective substrates, with increasing conduction through the channels of the respective transistors.

75 2. An oscillator circuit as claimed in claim 1 wherein said feedback network includes a crystal.

80 3. An oscillator circuit as claimed in claim 1 or 2 wherein there is further included impedance means connected between the drains and gates of said transistors for establishing the direct current operating level of said transistors.

TABLE I

$R_1 = R_2$	$V_{DD} = 3V$	$V_{DD} = 4.5V$	Change in R_O and frequency
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The addition of the resistors between the sources and the substrate thus minimize changes in the output impedance and results in greater frequency stability. In addition, the resistors decrease the power drain.

It has also been observed experimentally that the addition of resistors R_1 and R_2 in the source legs of the transistors minimize the effect of temperature on the output impedance. Thus, temperature compensation is achieved by connecting impedance means between the source and the substrate of the transistors.

In the circuit of FIGURE 1, the minimum starting voltage must be equal to or greater than the sum of the threshold voltages of the N-type transistor 14 and the P-type transistor 12. In those applications where the operating potential has a lower value than the sum of the threshold voltages the biasing scheme as shown in FIGURE 2 may be used.

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2. An oscillator circuit as claimed in claim 1 wherein said feedback network includes a crystal.

3. An oscillator circuit as claimed in claim 1 or 2 wherein there is further included impedance means connected between the drains and gates of said transistors for establishing the direct current operating level of said transistors.



4. An oscillator circuit as claimed in claim 3 wherein said impedance means includes a resistive network connected between the output node and one of the first and second terminals and a biasing resistor connected between the gates of the transistors and a point on the resistive network. 10
5. An oscillator substantially as herein- before described with reference to Figure 1 or Figure 2 of the accompanying drawing.

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Printed for Her Majesty's Stationery Office by the Courier Press, Leamington Spa, 1975.
Published by the Patent Office, 25 Southampton Buildings, London, WC2A 1AY, from
which copies may be obtained.

