



PATENT SPECIFICATION

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COMPLETE SPECIFICATION

DRAWINGS ATTACHED

Circuit Arrangements Utilising Thermal Feedback Utilizing

We, TEXAS INSTRUMENTS INCORPORATED, of 13500 North Central Expressway, Dallas, Texas, United States of America, a corporation organized and existing under the Laws of the State of Delaware, 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 circuit arrangements utilizing thermal effects in various components, and has particular application in DC stabilization of an amplifier circuit or thermal stabilization of a semiconductor device by thermal negative feedback.

One of the most significant trends in electronics is in the miniaturization of components and circuits. It is now possible to incorporate entire functional blocks such as amplifiers or multivibrators into one or more small semiconductor wafers which may be mounted in an extremely small package. The close spacing and integral connections between elements in such a functional block produces inherent interaction between thermal and electrical characteristics of the components. While this interaction ordinarily degrades performance, it can be utilized to advantage in some instances, as will be seen by this invention. Transistors and diodes for these miniature circuits are formed by the usual techniques, but resistors and capacitors are quite different from the commonly-used components in that they must be formed in or on the semiconductor material. It has been difficult to provide large-value capacitors and resistors for integrated circuits due to the size limitations, and so the low frequency or DC characteristics of the circuits have been compromised to some extent.

In a high gain AC amplifier, for example, the operating or bias point is ordinarily stabilized by DC feedback, requiring large capacitors or inductors in a filter. Without this DC negative feedback, the amplifier would have as large a DC gain as it had AC gain. The operating point would shift severely with temperature, cutting off or saturating the last stage of a high gain amplifier. Also, it would be exceedingly hard to bias the amplifier in a linear range even at a constant temperature without DC negative feedback, since this would require very careful selection and matching of components. The fact that large value capacitors and inductors are not readily available in integrated circuit form makes the construction of a stabilized high gain amplifier quite difficult.

Since the characteristics of semiconductor devices are quite dependent upon temperature, it is highly desirable to maintain an integrated circuit device at a constant temperature. This must be done by means which are compatible in size, power requirements, etc., with the functional blocks.

The present invention is an electrical circuit utilizing thermal-electrical interactions for controlling electrical or thermal quantities comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, electrically isolated from one another in the semiconductor material, and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said electrical circuit elements generating heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.

[Price 4s. 6d.]



The present invention is also an electrical circuit utilizing thermal-electrical interactions for controlling electrical or thermal quantities comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, electrically isolated from one another in the semiconductor material and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said electrical circuit elements comprising an elongated portion of said semiconductor wafer bounded by a PN junction and generating heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements comprising at least one PN junction in said semiconductor wafer terminating at said one surface of said semiconductor wafer and being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.

The present invention is also a DC stabilized amplifier circuit having low frequency negative feedback between its input and output comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, and electrically isolated from one another in the semiconductor material, said electrical circuit elements including one or more transistors having its or their PN junctions terminating at said one surface of said semiconductor wafer and one or more resistors comprising elongated sections of said semiconductor wafer, said circuit elements being electrically coupled to one another to form said DC stabilized amplifier circuit, one of said electrical circuit elements generating heat in response to the electrical output signal of said DC stabilized amplifier circuit, and another of said electrical circuit elements being thermally coupled to said one of said electrical circuit elements through said semiconductor wafer and being responsive to said heat generated through said semiconductor wafer for controlling said electrical output signal.

Embodiments of the invention will now be described by way of example, with reference to the accompanying drawings, wherein:

Fig. 1 is a schematic diagram of an amplifier circuit in accordance with this invention;

Fig. 2 is a pictorial view of a transistor mounted on a semiconductor resistor as used in the circuit of Fig. 1;

Fig. 3 is a schematic diagram of a circuit which may be used in semiconductor network form to provide a temperature-stabilized substrate in accordance with another embodiment of this invention;

Fig. 4 is a pictorial view of the circuit of

Fig. 3 in integrated circuit form;

Fig. 5 is a sectional view of the integrated circuit of Fig. 4 taken along the line 5-5; and

Fig. 6 is a sectional view of the integrated circuit of Fig. 4 taken along the line 6-6.

With reference to Fig. 1, a high gain amplifier is illustrated which is particularly well adapted for utilizing the thermal feedback concept of this invention. An input terminal 10 which may be coupled to a low-level AC signal source, is connected to the base of a transistor 11 in a first amplifying stage. The collector of this transistor 11 is connected to a positive voltage supply line 12 through a load resistor 13, while the emitter is connected to a negative voltage supply line 14 through an emitter resistor 15. The base of the transistor 11 is connected to ground through a suitable bias resistor 16 so that this stage will be operating in an acceptable linear range of the transistor's characteristic. A signal applied to the input terminal 10 will appear in an amplified form on the collector of the transistor 11, and this amplified signal is coupled through a Zener diode 17 to the base of a transistor 18 in a second amplifying stage. The Zener diode is used as a coupling element in lieu of a capacitor since the diode is easier to fabricate in integrated circuit form. The reverse voltage drop across this diode 17 reduces the relatively high DC level on the collector of the first stage to an acceptable level for base bias on the second stage. The emitter of the transistor 18 is directly connected to the negative supply line 14, while the collector is connected through a load resistor 19 to the positive line 12. This second stage also functions as an amplifier, and signals applied to the base of the transistor 18 appear in further amplified form on an output terminal 20.

Since DC coupling is used in the amplifier circuit of Fig. 1, a slight change in the level of the input, or of the operating point of the transistor 11, may drive the transistor 18 into saturation or cutoff. Accordingly, negative feedback for DC and very low frequencies is provided by mounting or positioning the transistor 11 in thermal contact with the resistor 19. Another transistor 21, connected differentially with the transistor 11, is mounted in thermal contact with a resistor 22 to provide a reference. The transistor 21 is biased at a selected point by a resistor 23 connected from the base to ground. The resistor 23 may well have the same value as the resistor 16 to provide a balanced circuit.

In operation, if the resistor 19 draws too much current, due to saturation of the transistor 18, this will heat the transistor 11, reducing its base-emitter voltage for a con-

stant current. However, the transistor 11 will draw more current due to the increased temperature, and the transistor 21 will draw correspondingly less, since these transistors are connected differentially or have a common emitter resistor. This increased current in the resistor 13 will lower the base bias on the transistor 18 and reduce the current in the latter, effecting negative DC feedback. In a like manner, if the transistor 18 is driven to cutoff, its collector current will decrease and the resistor 19 will cool, reducing the collector current in the transistor 11 and causing an increase in the bias on the transistor 18 so that it will be driven out of cutoff. The resistor 22, not being affected by signal or output current, will be maintained at a temperature dependent upon the supply voltage and will heat the transistor 21 accordingly, acting as a standard. If the transistors 11 and 21 are balanced or matched, the circuit will maintain a steady-state bias point where the temperature of the resistor 19 is equal to the temperature of the resistor 22. If these resistors 19 and 22 are equal and thermally symmetrical, the circuit may provide a steady-state bias point with the output at ground potential.

The circuit of Fig. 1 will pass AC from the input 10 to the output 20 at full gain since the thermal inertia or capacity of the resistors 19 and 22 will not allow the temperature to follow the AC signal. The maximum in feedback results when the change in temperature of the resistors per unit change in power is high.

In semiconductor network or integrated circuit applications, the resistors 19 and 22 may well take the form of elongated bars of monocrystalline silicon, or elongated paths in silicon wafers defined by P-N junctions. In Fig. 2, in order better to understand the present invention, the transistor 11 is mounted on the semiconductor bar which forms the resistor 19. This transistor comprises a wafer 25 of silicon, the major bulk of which provides the collector region. The wafer is mounted on, but electrically insulated from, the resistor bar 19 by means of a cement such as solder glass. The wafer 25 may provide a mesa-type transistor, as illustrated, and base and emitter leads are attached to base and emitter stripes 26 and 27 on the top surface of the mesa. A collector contact 28 is also made on the top surface of the wafer 25, spaced from the mesa. The transistor 21 also would be physically mounted on the resistor 22 by cementing the semiconductor wafer which forms this transistor to the semiconductor bar which forms the resistor in a manner similar to Fig. 2. However, in accordance with the present invention, a resistor and its associated transistor are formed in the same wafer of monocrystalline silicon, electrically

separated from one another by P-N junctions. The transistors obviously could be of other configuration, such as double-diffused planar. The feature of interest here is merely that the two components be in intimate, heat conducting relation, but electrically insulated.

Referring now to Fig. 3, a circuit is illustrated which uses thermal negative feedback to provide a stabilized temperature for a semiconductor network substrate. This circuit would be fabricated with the two transistors in intimate, heat conducting relationship as provided by the semiconductor network of Fig. 4, for example. A first transistor 30 is employed having a base 31, an emitter 32 and a collector 33. The base 31 is biased at a point such that initially the transistor is slightly below cutoff. For a silicon transistor this would be about 0.4 volts. This bias is provided by a large resistor 34 and a much smaller resistor 35 connected as a voltage divider across positive and negative supply lines 36 and 37. The collector 33 is connected to the line 36 through a resistor 38, while the emitter 32 is directly connected to the negative line 37, providing a grounded-emitter amplifier stage. The collector of the first transistor is further connected by a conductor 39 to the base of second transistor 40. This transistor likewise includes a base 41, an emitter 42 and a collector 43, with the collector and emitter being directly connected to the positive and negative lines 36 and 37 by conductors 44 and 45, respectively. Thermal feedback is provided between the region adjacent the collector of the transistor 40 and the body of the transistor 30 by fabricating both transistors in a single silicon wafer 50 as seen in Fig. 4 and described in more detail below.

In operation, the second transistor in the circuit of Fig. 3 will be initially biased for heavy conduction with base-emitter current flowing through the resistor 38 and the conductor 39. Conduction of this transistor 40 will tend to heat the silicon wafer 50 in the region of the collector 43 due to power dissipation, primarily near the collector-base junction. Heat in the area of the collector 43 will be transmitted through the silicon wafer to the transistor 30, and will cause a reduction in the base-emitter voltage necessary to switch on the transistor 30. The voltage on the base 31 is maintained constant by the voltage divider, so when the temperature of the transistor 30 reaches a point where the fixed base voltage is adequate to turn it on, collector current will begin to flow. This will reduce the voltage on the line 39, decreasing the base-emitter bias current for the transistor 40. Collector current will therefore decrease in the transistor 40, reducing its collector dissipation

and the heat fed back to the transistor 30. The circuit will tend to stabilize at an operating point, perhaps 125°C., where the temperature of the wafer 50 is at some value such that the transistor 30 is biased slightly into the conducting region and the transistor 40 is conducting fairly heavily.

A diode 51 is also provided in the wafer 50 so that the stable temperature of the substrate may be used to provide a stable voltage reference. The diode 51 may be connected externally to a current source and biased in the reverse direction past the Zener breakdown point. The voltage across the diode will be constant, since the temperature of the semiconductor material making up the diode is relatively constant. Of course, other components could be used as the reference element, a Zener diode being shown as an example.

With reference to Fig. 4, and the sectional views thereof in Figs. 5 and 6, the entire temperature stabilization circuit may be fabricated in planar form by using conventional procedures with oxide masking. The transistors 30 and 40 are of the triple-diffused N-P-N type, with the collectors, bases and emitters being formed by successive diffusion steps into the P-type wafer 50 in the named order. The Zener diode 51 would be of the same configuration as a transistor, but only the base and emitter regions would be used as the active portion, what would be a collector in a transistor serving here to electrically isolate the diode from the remainder of the circuit. The resistors are shown to be fabricated in the same wafer 50 as the transistors and diode, but could be in a separate wafer. The resistors are elongated P-type diffused regions formed simultaneously with the base regions of the transistors. The resistors are isolated from one another and from the remainder of the circuit by N-type regions formed at the same time as the collectors of the transistors. Interconnections between various elements of the circuit can be made as shown by leads which are thermocompression bonded to deposited contacts on the appropriate regions of the semiconductor material. Obviously, connections could be made by evaporating appropriate patterns of aluminum on top of the silicon oxide coating which is left on the wafer after the diffusions. The wafer 50 is mounted by a cement such as solder glass onto a heat-insulating plate 52 which may be a ceramic wafer. This serves to hold the power required for operation of the circuit to a minimum. The assembly would be packaged in any suitable manner.

WHAT WE CLAIM IS:—

1. An electrical circuit utilizing thermal-electrical interactions for controlling electrical or thermal quantities comprising a semi-

conductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, electrically isolated from one another in the semiconductor material, and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said electrical circuit elements generating heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.

2. An electrical circuit according to claim 1, wherein said electrical circuit is an amplifier having an input and output, said one of said electrical circuit elements is in the output of said amplifier and said another one of said electrical circuit elements is in the input of said amplifier and low frequency negative feedback is provided through said thermal coupling in order to DC stabilize said amplifier.

3. An electrical circuit according to claim 1, wherein the electrical output of said another of said electrical circuit elements controls said electrical signal and maintains the temperature throughout said semiconductor wafer substantially constant.

4. An electrical circuit utilizing thermal-electrical interactions for controlling electrical or thermal quantities comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, electrically isolated from one another in the semiconductor material and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said electrical circuit elements comprising an elongated portion of said semiconductor wafer bounded by a PN junction and generating heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements comprising at least one PN junction in said semiconductor wafer terminating at said one surface of said semiconductor wafer and being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.

5. An electrical circuit according to claim 4, wherein said electrical circuit is an amplifier having an input and output, said one of said electrical elements is in the output of said amplifier and said another one of said electrical circuit elements is in the input of said amplifier and low frequency negative feedback is provided through said thermal coupling in order to DC stabilize said amplifier.

6. An electrical circuit utilizing thermal-



and the heat fed back to the transistor 30. The circuit will tend to stabilize at an operating point, perhaps 125°C., where the temperature of the wafer 50 is at some value such that the transistor 30 is biased slightly into the conducting region and the transistor 40 is conducting fairly heavily.

A diode 51 is also provided in the wafer 50 so that the stable temperature of the substrate may be used to provide a stable voltage reference. The diode 51 may be connected externally to a current source and biased in the reverse direction past the Zener breakdown point. The voltage across the diode will be constant, since the temperature of the semiconductor material making up the diode is relatively constant. Of course, other components could be used as the reference element, a Zener diode being shown as an example.

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WHAT WE CLAIM IS:—

1. An electrical circuit utilizing thermal-electrical interactions for controlling electrical or thermal quantities comprising a semi-

conductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, electrically isolated from one another in the semiconductor material, and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said electrical circuit elements generating heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.

2. An electrical circuit according to claim 1, wherein said electrical circuit is an amplifier having an input and output, said one of said electrical circuit elements is in the output of said amplifier and said another one of said electrical circuit elements is in the input of said amplifier and low frequency negative feedback is provided through said thermal coupling in order to DC stabilize said amplifier.

3. An electrical circuit according to claim 1, wherein the electrical output of said another of said electrical circuit elements controls said electrical signal and maintains the temperature throughout said semiconductor wafer substantially constant.

4. An electrical circuit utilizing thermal-electrical interactions for controlling electrical or thermal quantities comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one surface of said wafer, electrically isolated from one another in the semiconductor material and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said electrical circuit elements comprising an elongated portion of said semiconductor wafer bounded by a PN junction and generating heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements comprising at least one PN junction in said semiconductor wafer terminating at said one surface of said semiconductor wafer and being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.

5. An electrical circuit according to claim 4, wherein said electrical circuit is an amplifier having an input and output, said one of said electrical elements is in the output of said amplifier and said another one of said electrical circuit elements is in the input of said amplifier and low frequency negative feedback is provided through said thermal coupling in order to DC stabilize said amplifier.

6. An electrical circuit utilizing thermal-



electrical interactions for controlling electrical or thermal quantities comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one surface
 5 of said wafer, electrically isolated from one another in the semiconductor material and thermally coupled to one another through said semiconductor wafer, said circuit elements being electrically coupled to one another in said electrical circuit, one of said
 10 electrical circuit elements comprising at least one PN junction in said semiconductor wafer terminating at said one surface of said semiconductor wafer and generating
 15 heat in response to an electrical signal in said electrical circuit, and another of said electrical circuit elements comprising at least one PN junction in said semiconductor wafer terminating at said one surface of
 20 said semiconductor wafer and being responsive to said heat generated through said semiconductor wafer for controlling said electrical signal.
 7. An electrical circuit according to
 25 claim 6, wherein the electrical output of said another of said electrical circuit elements controls said electrical signal and maintains the temperature throughout said semiconductor wafer substantially constant.
 30 8. A DC stabilized amplifier circuit having low frequency negative feedback between its input and output comprising a semiconductor wafer having a plurality of electrical circuit elements adjacent one sur-

face of said wafer, and electrically isolated 35 from one another in the semiconductor material, said electrical circuit elements including one or more transistors having its or their PN junctions terminating at said one surface of said semiconductor wafer and
 40 one or more resistors comprising elongated sections of said semiconductor wafer, said circuit elements being electrically coupled to one another to form said DC stabilized amplifier circuit, one of said electrical circuit elements generating heat in response to
 45 the electrical output signal of said DC stabilized amplifier circuit, and another of said electrical circuit elements being thermally coupled to said one of said electrical circuit elements through said semiconductor
 50 wafer and being responsive to said heat generated through said semiconductor wafer for controlling said electrical output signal.

9. An electrical circuit according to any preceding claim, including a heat-insulating plate fastened to the opposite surface of
 55 said semiconductor wafer.

10. An electrical circuit substantially as herein described with references to Figures 60 4-6 of the accompanying drawings.

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