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Current sensing by using aging sense transistor

Abstract

A current sense circuit that allows for accurate sensing of a power current that flows through a power transistor as the power transistor ages. The circuit includes the power transistor, a sense transistor and a pull-up component. The control nodes of the power transistor and the sense transistor are connected, causing the power transistor and sense transistor to be on or off simultaneously. The pull-up component is connected between the input node of the power transistor and the input node of the sense transistor. When power is provided to the pull-up component, and when each of the power transistor and sense transistor are off, the pull-up component forces a voltage present at the sense transistor input node to be approximately equal to a voltage present at the power transistor input node, causing the sense and power transistors to age together.

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References Cited

U.S. PATENT DOCUMENTS

Patent No.	Issued Date	Patentee Name	U.S. Cl.	CPC
4553084	12/1984	Wrathall	N/A	N/A
10014851	12/2017	Chauhan	N/A	H03K 17/687
11411562	12/2021	Tranca	N/A	H03K 19/094
2012/0161733	12/2011	Hua	323/282	G05F 1/565
2016/0087622	12/2015	Kaeriyama	327/109	H03K 17/0828
2017/0201251	12/2016	Chandrasekaran	N/A	H03K 17/6871
2019/0097525	12/2018	Nakao	N/A	H02M 3/33515
2019/0260376	12/2018	Zuniga et al.	N/A	N/A

FOREIGN PATENT DOCUMENTS

Patent No.	Application Date	Country	CPC
2024189603	12/2023	WO	N/A

OTHER PUBLICATIONS

European Search Report Received for Application No. / Patent No. (24177328.2-1001) on Oct. 22, 2024. 11 Pages. cited by applicant

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Background/Summary

BACKGROUND

(1) Electronic circuits typically include transistors, which function as electronic switches that regulate or control current flow in portions of the circuit. One type of transistor is a field-effect transistor in which a voltage is applied to a gate terminal to turn the transistor on and off. A semiconductor channel region is disposed between the drain terminal and the source terminal. When the transistor is on, current flows through the semiconductor channel region between the source terminal and the drain terminal. When the transistor is off, lesser or no current flows through the semiconductor channel region between the source terminal and the drain terminal. The gate terminal is disposed over the semiconductor channel region between the source terminal and the drain terminal. Voltage on the gate terminal generates a field that affects whether the semiconductor channel region conducts current-hence the term “field-effect transistor”.

(2) Nevertheless, there are other types of transistors. In each transistor, current flows from an input node to an output node through a channel when the transistor is turned on by applying a sufficient voltage to a control node. For instance, in a field-effect transistor, the control node would be the gate terminal, the input node would be one of the source or drain terminals, and the output node would be the other of the source or drain terminals.

(3) Typical transistors are used for amplifying and switching purposes in electronic circuits. On the other hand, power transistors are used to convey more substantial current, have higher voltage ratings, and may more typically be used in power supplies, battery charging, and the like. Power transistors can typically operate with currents greater than 1 amp to as much as a hundred amps or even greater. Power transistors may convey power greater than 1 watt to as many as hundreds of watts or even greater.

(4) The subject matter claimed herein is not limited to embodiments that solve any disadvantages or that operate only in environments such as those described above. Rather, this background is only provided to illustrate one example technology area where some embodiments described herein may be practiced.

SUMMARY OF THE INVENTION

(5) This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to be used as an aid in determining the scope of the claimed subject matter.

(6) Embodiments described herein relate to a current sense circuit that allows for accurate sensing of a power current that flows through a power transistor as the power transistor ages. The circuit includes the power transistor and a sense transistor. The power transistor and the sense transistor each include a control node (e.g., a gate terminal if a field-effect transistor), an input node (e.g., a drain terminal if a field-effect transistor) from which current flows, and an output node (e.g., a source terminal if a field-effect transistor) to which current flows. The control nodes of the power transistor and the sense transistor are connected. Because the control nodes of the power transistor and the sense transistor are connected, both the power transistor and sense transistor are likely to be on or off at the same time.

(7) When the current sense circuit is on (i.e., when the power transistor and sense transistor are each on), a power current is passed through the power transistor, and a sense current is passed through the sense transistor. The power current may be very large and thus may be difficult to measure directly. The sense current may be much smaller than, but proportional to, the power current. Thus, the sense current can be more easily measured, and a signal representing the power current may be generated using the proportionality between the sense current and the power current.

(8) When transistors are turned off, there is typically some voltage drop between the input node and the output node of that transistor. Power transistors may be used to handle hundreds of volts. Thus, while a power transistor is off, the voltage drop between the input node and the output node of the power transistor may also be hundreds of volts. Power transistors are susceptible to “aging” over time due to high electric fields caused by such large voltage drops. When a power transistor experiences aging, it may have an increase in internal resistance while the power transistor is on. This causes the power transistor to be less efficient at passing current and causes an increase in power lost due to heat.

(9) Over time, the power transistor may experience more aging than its accompanying sense transistor, particularly if the power transistor and the sense transistor are not exposed to the same large voltage drop while off. Thus, over time, the sense current measured through the sense transistor may no longer accurately reflect the proportional power current passing through the power transistor. Accordingly, the sense current may no longer be used to accurately generate a signal representing the power current.

(10) To solve this issue, the current sense circuit also includes a pull-up component. The pull-up component is connected between the input node of the power transistor and the input node of the sense transistor. When power is provided to the pull-up component, and when each of the power transistor and sense transistor is off, the pull-up component forces (or is configured to force) a voltage present at the sense transistor input node to be approximately equal to (or at least more towards) a voltage present at the power transistor input node. Thus, each of the power transistor and sense transistor are exposed to approximately the same voltage drop while off. Accordingly, each of the power transistor and sense transistor may experience aging at a similar rate, and over time, may both have a proportional increase in internal resistance while on. Thus, after the power transistor has aged significantly, its accompanying sense transistor has also aged proportionally, and the sense current passing through the sense transistor may still be used to accurately generate a signal representing the power current passing through the power transistor.
(11) Additional features and advantages will be set forth in the description which follows, and in part will be obvious from the description, or may be learned by the practice of the teachings herein. Features and advantages of the invention may be realized and obtained by means of the instruments and combinations particularly pointed out in the appended claims. Features of the present invention will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth hereinafter.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) In order to describe the manner in which the advantages and features of the systems and methods described herein can be obtained, a more particular description of the embodiments briefly described above will be rendered by reference to specific embodiments thereof which are illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the systems and methods described herein, and are not therefore to be considered to be limiting of their scope, certain systems and methods will be described and explained with additional specificity and detail through the use of the accompanying drawings in which:
(2) FIG. **1** illustrates a current sense circuit in which the principles described herein may be practiced, in which a sense transistor is aged more proportionate to a power transistor by forcing some pull up of the input voltage of the sense transistor when the sense transistor is off.
(3) FIG. **2** illustrates an example current sense circuit that is an example of the current sense circuit of FIG. **1**;
(4) FIG. **3** illustrates an example current sense circuit that is an example of the current sense circuit of FIG. **2**, but in which the transistors are field-effect transistors and the pull-up component is a diode-connected field-effect transistor; and
(5) FIG. **4** illustrates a feedback component, which is an example of the feedback component of FIG. **3**.
DETAILED DESCRIPTION
(6) Embodiments described herein relate to a current sense circuit that allows for accurate sensing of a power current that flows through a power transistor as the power transistor ages. The circuit includes the power transistor and a sense transistor. The power transistor and the sense transistor each include a control node (e.g., a gate terminal if a field-effect transistor), an input node (e.g., a drain terminal if a field-effect transistor) from which current flows, and an output node (e.g., a source terminal if a field-effect transistor) to which current flows. The control nodes of the power transistor and the sense transistor are connected, and the output nodes of the power transistor and sense transistor are connected. Because the control nodes of the power transistor and the sense transistor are connected, both the power transistor and sense transistor are likely to be on or off at

the same time.
(7) When the current sense circuit is on (i.e., when the power transistor and sense transistor are each on), a power current is passed through the power transistor, and a sense current is passed through the sense transistor. The power current may be very large and thus may be difficult to measure directly. The sense current may be much smaller than, but proportional to, the power current. Thus, the sense current can be more easily measured, and a signal representing the power current may be generated using the proportionality between the sense current and the power current.
(8) When transistors are turned off, there is typically some voltage drop between the input node and the output node of that transistor. Power transistors may be used to handle hundreds of volts. Thus, while a power transistor is off, the voltage drop between the input node and the output node of the power transistor may also be hundreds of volts. Power transistors are susceptible to “aging” over time due to high electric fields caused by such large voltage drops. When a power transistor experiences aging, it may have an increase in internal resistance while the power transistor is on. This causes the power transistor to be less efficient at passing current and causes an increase in power lost due to heat.
(9) Over time, the power transistor may experience more aging than its accompanying sense transistor, particularly if the power transistor and the sense transistor are not exposed to the same large voltage drop while off. Thus, over time, the sense current measured through the sense transistor may no longer accurately reflect the proportional power current passing through the power transistor. Accordingly, the sense current may no longer be used to accurately generate a signal representing the power current.
(10) To solve this issue, the current sense circuit also includes a pull-up component. The pull-up component is connected between the input node of the power transistor and the input node of the sense transistor. When power is provided to the pull-up component, and when each of the power transistor and sense transistor is off, the pull-up component forces (or is configured to force) a voltage present at the sense transistor input node to be approximately equal to (or at least more towards) a voltage present at the power transistor input node. Thus, each of the power transistor and sense transistor are exposed to approximately the same voltage drop while off. Accordingly, each of the power transistor and sense transistor may experience aging at a similar rate, and over time, may both have a proportional increase in internal resistance while on. Thus, after the power transistor has aged significantly, its accompanying sense transistor has also aged proportionally, and the sense current passing through the sense transistor may still be used to accurately generate a signal representing the power current passing through the power transistor.
(11) FIG. **1** illustrates a current sense circuit **100** in which the principles described herein may be practiced. The current sense circuit **100** is just one embodiment of the principles described herein. The current sense circuit **100** includes a power transistor **110**, a sense transistor **120** and a pull-up component **130**. The pull-up component **130** will be described further below. The power transistor **110** is larger than the sense transistor **120**. The size of a transistor may be defined by the total cross-sectional area through which current can flow, referred to as “current flow area” herein. As an example, for a field-effect transistor, the size of the transistor may be characterized by gate width.
(12) The principles described herein are not limited to what the relative size is between the transistors. However, in some embodiments, the ratio of the current flow area of the power transistor **110** over the current flow area of the sense transistor **120** is 500 or more. Further, in some embodiments, the power transistor **110** and the sense transistor **120** may be gallium-nitride field-effect transistors. However, the principles described herein are not limited to the types of the transistors **110** and **120**, although it is preferred that the transistors **110** and **120** are the same type, or even constructed in the same epitaxial stack. Nevertheless, to represent that the principles described herein are not restricted to the transistors **110** and **120** being of the same type, the power transistor **110** and the sense transistor **120** are represented symbolically using trapezoidal boxes.

Trapezoidal boxes are also used in FIG. **2** to represent transistors where the transistor may be of any type. As an example, transistors represented as trapezoids in each of FIGS. **1** and **2** may be gallium nitride transistors, high-electron mobility field-effect transistors, or any other type of transistor.

(13) The power transistor **110** includes a control node **111** that controls whether current flows from an input node **112** of the power transistor **110** to an output node **113** of the power transistor **110**. The sense transistor **120** also has a control node **121** that controls whether current flows from an input node **122** of the sense transistor **120** to an output node **123** of the sense transistor **120**. The control node **111** of the power transistor **110** and the control node **121** of the sense transistor **120** are connected together. The on-off state of each of the power transistor **110** and the sense transistor **120** are controlled by whether a voltage V.sub.C applied to the control node **111** and the control node **121** is high or low. Furthermore, the output node **113** of the power transistor **110** and the output node **123** of the sense transistor **120** are connected together. In some embodiments, the connected output nodes **113** and **123** are grounded, or may be connected to a reference voltage node. In any case, the output nodes **113** and **123** are connected to a circuit current sink **142** that is capable of sinking current.

(14) In operation, while the current sense circuit **100** is on (herein referred to as an “ON state”), the control voltage V.sub.C applied to the connected control nodes **111** and **121** is in one state (e.g., a high state) that causes the power transistor **110** and the sense transistor **120** to conduct current. In this ON state, the power transistor **110** passes an amount of power current that is sourced by a circuit current source **141**. The current that passes in this ON state from the circuit current source **141** through the power transistor **110** and to the circuit current sink **142** is referred to herein and in the drawings as current I.sub.Power. In contrast, when the current sense circuit **100** is off (herein referred to as an “OFF state”), each of the power transistor **110** and the sense transistor **120** is off. The embodiments described herein more accurately determine the power current I.sub.Power as the power transistor **110** ages. The ON state will now be described in detail.

(15) While the current sense circuit **100** is in this ON state, the sense transistor **120** passes a sense current I.sub.Sense. The sense current I.sub.Sense is sourced from circuit current source **143** and passes through the sense transistor **120** to the circuit current sink **142**. For instance, perhaps the pull-up component **130** operates to allow sense current I.sub.Sense to pass from the circuit current source **141** to the sense transistor **120**. However, in an embodiment described below, the circuit current source **143** is a separate current source as compared to the circuit current source **141**.

(16) In some embodiments, the power current I.sub.Power is largely proportional to the sense current I.sub.Sense, even across a wide variety of operating conditions, the sense current I.sub.Sense being much smaller than the power current I.sub.Power. Thus, a signal representing the sense current I.sub.Sense can be used to generate a signal representing the power current I.sub.Power. The reason that the sense current I.sub.Sense is proportional to the power current I.sub.Power in the ON state is that the sense transistor **120** is an approximate replica of the power transistor **110**, except for the current flow area of the power transistor **110** being N times larger than the current flow area of the sense transistor **120**. For example, the sense transistor **120** may be a miniaturized replica of the power transistor **110** when the active region of both are fabricated using the same epitaxial stack, except with the active area being N times larger for the power transistor **110**. Thus, the on-resistance of the sense transistor **120** is N times that of the power transistor **110**.

(17) Furthermore, in the ON state, the control voltage V.sub.C applied to the control nodes **111** and **121** is the same, and the output voltage present at the output nodes **113** and **123** is also the same. Accordingly, if the voltage applied at the input nodes **112** and **122** can be made at least proportional to each other (even if not the same), the sense current I.sub.Sense will be proportional to the power current I.sub.Power with a certain constant of proportionality. This constant of proportionality will remain approximately the same over time provided that the ratio of the on-resistance of the sense transistor **120** over the on-resistance of the power transistor **110** remains the same.

(18) As previously expressed, the on-resistance of a transistor may increase as the transistor ages, as will now be explained. For context, the current sensing circuit **100** may be implemented into a large power system requiring hundreds of volts. That is, while the power transistor **110** is off, the power transistor **110** may be required to handle a voltage difference of hundreds of volts between its input node **112** and output node **113**. Such large voltage drops may cause the power transistor **110** to degrade over time and become less efficient due to an increase in on-resistance. This increase results in more power lost due to heat and a larger voltage drop over the power transistor **110** while on. This phenomenon is referred to as aging.
(19) As previously mentioned, if the ratio of the on-resistance of the sense transistor **120** over the on-resistance of the power transistor **110** remains the same, the constant of proportionality between the sense current I.sub.Sense and the power current I.sub.Power should remain the same. The principles described herein aim to at least partially accomplish this by pulling up the voltage at the input node **122** of the sense transistor **120** when the current sense circuit **100** is operating in the OFF state.
(20) The embodiments described herein promote aging of the sense transistor **120** at closer to the same rate as the power transistor **110** is aging. That is, the principles described herein encourage the on-resistance of the sense transistor **120** to increase in better proportion to what the power transistor **110** is undergoing. This is accomplished by forcing the sense transistor **120** to sustain a voltage difference in the OFF state that is larger than what the sense transistor **120** would otherwise experience in the absence of pulling up its input voltage. For example, to force the sense transistor **120** to undergo the same voltage drop in the OFF state as the power transistor **110** is undergoing in the OFF state, the input voltage of the sense transistor **120** should be the same as the input voltage of the power transistor **110** in the OFF state.
(21) To accomplish this, the pull-up component **130** is connected between the input node **112** of the power transistor **110** and the input node **122** of the sense transistor **120**. In operation, when the current sense circuit **100** is in the OFF state, each of the power transistor **110** and the sense transistor **120** is off, and the pull-up component **130** forces a voltage V.sub.INSenseOFF present at the input node **122** of the sense transistor **120** to be approximately equal to a voltage V.sub.INPowerOFF present at the input node **112** of the power transistor **110**. In other words, the pull-up component **130** “pulls up” the voltage V.sub.INSenseOFF to be approximately the same as the voltage V.sub.INPowerOFF, hence the term “pull-up component”. For example, while the current sense circuit **100** is in the OFF state, the voltage V.sub.INPowerOFF at the input node **112** of the power transistor **110** may be 650 volts. In this scenario, the pull-up component **130** may force the voltage V.sub.INSenseOFF at the input node **122** of the sense transistor **120** to also be approximately 650 volts.
(22) Accordingly, while the current sense circuit **100** is in the OFF state, both of the power transistor **110** and the sense transistor **120** experience approximately the same voltage difference. Thus, over time, the power transistor **110** and the sense transistor **120** should age more similarly, and the ratio of power current I.sub.Power to sense current I.sub.Sense should remain approximately constant. In this manner, even after aging, the signal representing the sense current I.sub.Sense may still be used with the same proportionality to accurately generate the signal representing the power current I.sub.Power.
(23) However, in some embodiments, the pull-up component **130** may only force the voltage V.sub.INSenseOFF at the input node **122** of the sense transistor **120** to be some fraction of the voltage V.sub.INPowerOFF present at the input node **112** of the power transistor **110**. As an example, that fraction might be twenty percent or more, fifty percent or more, or eighty percent or more. This would still be beneficial because, even though the sense transistor **120** would age slower than the power transistor **110**, the signal representing the sense current I.sub.Sense could still be used to accurately generate (within a margin of error) the signal representing the power current I.sub.Power for a longer period of time compared to if the sense transistor **120** did not age

at all, or at least did not age with the assistance of the pull-up component **130**.

(24) FIG. **2** illustrates an example current sense circuit **200** that is an example of the current sense circuit **100** of FIG. **1**. Specifically, the power transistor **210**, the first sense transistor **220**, the pull-up component **230**, the circuit current source **241** and the circuit current sink **242** are respective examples of the power transistor **110**, the first sense transistor **120**, the pull-up component **130**, the circuit current source **141** and the circuit current sink **142** of FIG. **1**. However, the current sense circuit **200** further includes a second sense transistor **250**, a feedback component **260** and a feedback component shield transistor **270**, which collectively act as an example of the circuit current source **143** of FIG. **1**, as will be described further below.

(25) A control node **251** of the second sense transistor **250** and a control node **271** of the feedback component shield transistor **270** are connected to each other, as well as to the control nodes of each of the power transistor **210** and the first sense transistor **220**. An input node **252** of the second sense transistor **250** is connected to the input node of the first sense transistor **220**. The pull-up component **230** is connected between the input node of the power transistor **210** and the connected input node **252** of the second sense transistor **250**. An input node **272** of the feedback component shield transistor **270** is connected to the input node of the power transistor **210**. The feedback component **260** is connected between an output node **253** of the second sense transistor **250** and an output node **273** of the feedback component shield transistor **270**.

(26) The operation of the current sense circuit **200** will now be described. While the current sense circuit **200** is in its ON state, each of the power transistor **210**, first sense transistor **220**, second sense transistor **250**, and feedback component shield transistor **270** are on. Additionally, while the current sense circuit **200** is in its ON state, the pull-up component **230** may act as an open circuit, as will be explained later. Furthermore, while in this ON state, the power current I.sub.Power passes through the power transistor **210**. The power transistor **210** has a small amount of on-resistance, resulting in a small voltage V.sub.INPowerON being present at the input node of the power transistor **210**. Since the feedback component shield transistor **270** is on, this small voltage V.sub.INPowerON is input into the feedback component **260**. The feedback component **260** provides a feedback component output voltage to the output node **253** of the second sense transistor **250**. The feedback component output voltage is proportional to the voltage V.sub.INPowerON present at the input node of the power transistor **210**.

(27) In this ON state, the first sense transistor **220** and the second sense transistor **250** are on (with some on resistance) and coupled in series between the output of the feedback component and the circuit current sink **242** (which may be ground). Thus, the application of the feedback component output voltage from the feedback component **260** causes the sense current I.sub.Sense to be passed through the second sense transistor **250** and the first sense transistor **220**. The current sense current I.sub.Sense is proportional to the power current I.sub.Power because the on-resistance of the series combination of the first second transistor **220** and the second sense transistor **250** is proportion to the on-resistance of the power transistor (for reason described below), and also because the feedback component output voltage is proportional to the input voltage V.sub.INPowerON present at the input node of the power transistor **210**.

(28) The on-resistances are approximately proportional for reasons now described. The second sense transistor **250** is an approximate replica of the power transistor **210**, except for the current flow area of the power transistor **210** being M times larger than the current flow area of the second sense transistor **250**. For example, the second sense transistor **250**, similar to the first sense transistor **220**, may be a miniaturized replica of the power transistor **210** when the active regions of both transistors are fabricated using the same epitaxial stack, except the current flow area being M times larger for the power transistor **210**. Recall that the first sense transistor **220** is an approximate replica of the power transistor **210**, except for the current flow area of the power transistor **210** being N times larger than the current flow area of the first sense transistor **220**.

(29) In the case of the first sense transistor **220** and the second sense transistor **250** having the same

current flow area, M would be equal to N. This being the case, the on-resistance of the first sense transistor **220** is N times that of the power transistor **210**, and the on-resistance of the second sense transistor **250** is M times that of the power transistor **210**. The series resistance of the first sense transistor **220** and the second sense transistor **250** would thus M+N times that of the power transistor **210**. Since M and N are each constants, this means that the on-resistance of the power transistor **210** is proportional to the combined on-resistances of the first sense transistor **220** and the second sense transistor **250**. Thus, in the ON state, the sense current I.sub.Sense is approximately proportional to the power current I.sub.Power, allowing for accurate generation of the signal representing the power current I.sub.Power.

(30) While the current sense circuit **200** is in its OFF state, the aim is to cause the sense transistors **220** and **250** to age approximately equal to (but at least proportional to) the aging that the power transistor **210** undergoes in the OFF state. In the OFF state, each of the power transistor **210**, first sense transistor **220**, second sense transistor **250** and feedback component shield transistor **270** are off. Further, while the current sense circuit **200** is in the OFF state, the pull-up component **230** forces the voltage V.sub.INSenseOFF present at the input node of the first sense transistor **220** and the input node **252** of the second sense transistor **250** to be approximately equal to the voltage V.sub.INPowerOFF present at the input node of the power transistor **210**.

(31) Further, because the feedback component shield transistor **270** is off, the voltage received at the input to the feedback component **260** quickly degrades to be zero volts. At that point, the feedback component **260** also outputs zero volts. Therefore, the voltage at the output node **253** of the second sense transistor **250** is approximately zero volts. Likewise, in the scenario of circuit current sink **242** being grounded, the voltage at the output nodes of the power transistor **210** and the first sense transistor **220** is also approximately zero volts. Accordingly, while the current sense circuit **200** is in the OFF state, each of the power transistor **210**, first sense transistor **220** and second sense transistor **250** experience approximately the same large voltage drop, and thus age at approximately the same rate.

(32) Therefore, even though the power transistor **210** ages, the first sense transistor **220** and the second transistor **250** also age approximately equally. Specifically, the percentage increase in the on-resistances of each of the first sense transistor **220** and the second sense transistor **250** is approximately equal to the percentage increase in the on-resistance of the power transistor **210**. Accordingly, the proportionality between the power current I.sub.Power and the sense current I.sub.Sense will also remain relatively constant. Thus, throughout a longer period of aging, the current sense circuit **200** may be used to generate an accurate representation of the power current power current I.sub.Power.

(33) In some embodiments, each of these transistors **210**, **220**, **250** and **270** may be the same type of transistor, even if not constructed from the same epitaxial stack. As the principles described herein are not limited to the types of the transistors **210**, **220**, **250** and **270**, the transistor, these transistors are each also represented symbolically using trapezoidal boxes. However, in a more specific embodiment, the transistors may be field-effect transistors. FIG. **3** illustrates such an embodiment.

(34) FIG. **3** illustrates an example current sense circuit **300** that is an example of the current sense circuit **200** of FIG. **2**. However, in FIG. **3**, each of the transistors **310**, **320**, **350** and **370** are examples of the respective transistors **210**, **220**, **250** and **270** in a case in which the transistor are each field-effect transistors. Each of the control nodes, input nodes, and output nodes of the transistors are respective gate terminals, drain terminals, and source terminals of the field-effect transistors.

(35) Furthermore, a pull-up component field-effect transistor **330** is illustrated as an example of the pull-up component **230** of FIG. **2**. The pull-up field effect transistor **330** is connected in diode-configuration, allowing current to flow downward, but not upward. A control node **331** and an output node **333** of the pull-up component field-effect transistor **330** are connected to the input

node of the power field-effect transistor **310**. An input node **332** of the pull-up component field-effect transistor **330** is connected to the input node of the first sense field-effect transistor **320** and to the input node of the second field-effect transistor **350**.

(36) Similar to the feedback component **260** of FIG. **2**, the feedback component **360** of FIG. **3** is configured to, when provided with a voltage via the feedback component field-effect transistor **370**, pass the sense current I.sub.Sense through the second sense field-effect transistor **350** and the first sense field-effect transistor **320**. In order to perform such a function, the feedback component **360** may, for example, comprise an operational amplifier, or the like. FIG. **4** illustrates such an example.

(37) FIG. **4** illustrates a feedback component **400**, which is an example of the feedback component **360** of FIG. **3**. The feedback component **400** includes an operational amplifier **410**. The operational amplifier **410** has a positive input node **411**, a negative input node **412** and an output node **413**. The positive input node **411** may be connected to the output node of the feedback component shield field-effect transistor **370** of FIG. **3**. The output node **413** of the operational amplifier **410** is connected to the negative input node **412** of the operational amplifier **410**, thus creating a negative feedback loop that causes the output voltage present at the output node **413** to be approximately equal to the input voltage present at the positive input node **411**. The output node **413** of the operational amplifier **410** may be connected to the output node of the second sense field-effect transistor **350** of FIG. **3**.

(38) The operational amplifier **410** may optionally be constructed on a separate integrated chip, and not on the same semiconductor substrate as the transistors **310**, **320**, **330**, **350** and **370** of FIG. **3**. Incidentally, if the operational amplifier **410** is constructed on a separate silicon integrated chip, the operational amplifier **410** would likely not be able to withstand the same high voltages that the transistors **310**, **320**, **350** and **370** of FIG. **3** could withstand as, for example, gallium-nitride field-effect transistors. Accordingly, an advantage of the current sense circuit **300** of FIG. **3** is its ability to use the feedback component shield field-effect transistor **370** and the second sense field-effect transistor **350** to isolate (i.e., to “shield”) the feedback component **360** (or the operational amplifier **410** of FIG. **4**). In this manner, the feedback component **360** is not exposed to the high voltages at the input nodes of the power field-effect transistor **310** and the first sense field-effect transistor **320** while the current sense circuit **300** is in its OFF state.

(39) Accordingly, what has been described is a current sense circuit that allows for accurate sensing of a power current that flows through a power transistor as the power transistor ages.

(40) Literal Support Section

(41) Clause 1. A current sense circuit comprising: a power transistor having a power transistor control node that controls whether current flows from a power transistor input node to a power transistor output node; a sense transistor having a sense transistor control node that controls whether current flows from a sense transistor input node to a sense transistor output node, the sense transistor control node connected to the power transistor control node; and a pull-up component connected between the power transistor input node and the sense transistor input node, the pull-up component being structured such that, when power is provided to the pull-up component and when the power transistor and the sense transistor are off, the pull-up component is structured to cause a sense transistor input node voltage at the sense transistor input node to be at least half of a power transistor input node voltage at the power transistor input node.

(42) Clause 2. The current sense circuit according to Clause 1, the sense transistor being a first sense transistor, the sense transistor control node being a first sense transistor control node, the sense transistor input node being a first sense transistor input node, the sense transistor output node being a first sense transistor output node, the current sense circuit further comprising: a second sense transistor having a second sense transistor control node that controls whether current flows from a second sense transistor input node to a second sense transistor output node, the second sense transistor control node connected to the power transistor control node and to the first sense transistor control node, the second sense transistor input node connected to the first sense transistor

input node.
(43) Clause 3. The current sense circuit according to Clause 2, further comprising: a feedback component connected between the power transistor input node and the second sense transistor output node, the feedback component being configured to, when each of the power transistor, first sense transistor and second sense transistor are on, generate a sense current that flows through the second sense transistor and first sense transistor, the sense current being a function of a power current flowing through the power transistor.
(44) Clause 4. The current sense circuit according to Clause 3, wherein the feedback component comprises an operational amplifier including a first operational amplifier input node, a second operational amplifier input node, and an operational amplifier output node, the second operational amplifier input node connected to the second sense transistor output node, the operational amplifier output node also connected to the second sense transistor output node.
(45) Clause 5. The current sense circuit according to claim **4**, the current sense circuit further comprising a feedback component shield transistor having a feedback component shield transistor control node that controls whether current flows from a feedback component shield transistor input node to a feedback component shield transistor output node, the feedback component shield transistor input node connected to the power transistor input node, the feedback component shield transistor output node connected to the first operational amplifier input node.
(46) Clause 6. The current sense circuit according to Clause 3, wherein the feedback component is included in a silicon integrated chip.
(47) Clause 7. The current sense circuit according to Clause 3, the function being a proportional function.
(48) Clause 8. The current sense circuit according to Clause 7, the proportional function being an approximately proportional function.
(49) Clause 9. The current sense circuit according to Clause 2, wherein each of the power transistor, the first sense transistor and the second sense transistor are gallium nitride transistors.
(50) Clause 10. The current sense circuit according to Clause 2, wherein each of the power transistor, the first sense transistor and the second sense transistor are high-electron mobility transistors.
(51) Clause 11. The current sense circuit according to Clause 2, wherein the pull-up component comprises a pull-up transistor that has a pull-up transistor control node that controls whether current flows from a pull-up transistor input node to a pull-up transistor output node, the pull-up transistor output node connected to the power transistor input node, the pull-up transistor control node also connected to the power transistor input node, and the pull-up transistor input node connected to the first sense transistor input node and the second sense transistor input node.
(52) Clause 12. The current sense circuit according to Clause 1, wherein each of the power transistor and the sense transistor are gallium nitride transistors.
(53) Clause 13. The current sense circuit according to Clause 1, wherein each of the power transistor and the sense transistor are field-effect transistors.
(54) Clause 14. The current sense circuit according to Clause 1, wherein the pull-up component is a pull-up transistor that has a pull-up transistor control node that controls whether current flows from a pull-up transistor input node to a pull-up transistor output node, the pull-up transistor output node connected to the power transistor input node, the pull-up transistor control node also connected to the power transistor input node, and the pull-up transistor input node connected to the sense transistor input node.
(55) Clause 15. The current sense circuit according to Clause 1, the power transistor and the sense transistor each having active regions formed from a same epitaxial stack.
(56) Clause 16. The current sense circuit according to Clause 15, herein a size ratio of a current flow area of the power transistor over a current flow area of the sense transistor is 500 or more.
(57) Clause 17. The current sense circuit according to Clause 1, herein a size ratio of a current flow

area of the power transistor over a current flow area of the sense transistor is 500 or more.

(58) Clause 18. A current sense circuit comprising: a power transistor having a power transistor control node that controls whether current flows from a power transistor input node to a power transistor output node; a sense transistor having a sense transistor control node that controls whether current flows from a sense transistor input node to a sense transistor output node, the sense transistor control node connected to the power transistor control node; and a pull-up component connected between the power transistor input node and the sense transistor input node, the pull-up component being structured such that, when power is provided to the pull-up component and when the power transistor and the sense transistor are off, the pull-up component is structured to cause a sense transistor input node voltage at the sense transistor input node to be at least twenty percent of a power transistor input node voltage at the power transistor input node.

(59) Clause 19. The current sense circuit in accordance with Clause 18, wherein the pull-up component is structured to cause the sense transistor input node voltage at the sense transistor input node to be at least half of the power transistor input node voltage at the power transistor input node.

(60) Clause 20. The current sense circuit in accordance with Clause 18, wherein the pull-up component is structured to cause the sense transistor input node voltage at the sense transistor input node to be at least eighty percent of the power transistor input node voltage at the power transistor input node.

(61) Although the subject matter has been described in language specific to structural features and/or methodological acts, it is to be understood that the subject matter defined in the appended claims is not necessarily limited to the described features or acts described above, or the order of the acts described above. Rather, the described features and acts are disclosed as example forms of implementing the claims.

(62) The present disclosure may be embodied in other specific forms without departing from its essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

(63) When introducing elements in the appended claims, the articles “a,” “an,” “the,” and “said” are intended to mean there are one or more of the elements. The terms “comprising,” “including,” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements.

Claims

1. A current sense circuit comprising: a power transistor having a power transistor control node that controls whether current flows from a power transistor input node to a power transistor output node; a sense transistor having a sense transistor control node that controls whether current flows from a sense transistor input node to a sense transistor output node, the sense transistor control node connected to the power transistor control node, the power transistor and the sense transistor each having active regions formed from a same epitaxial stack; and a pull-up component connected between the power transistor input node and the sense transistor input node, the pull-up component being structured such that, when power is provided to the pull-up component and when the power transistor and the sense transistor are off, the pull-up component is structured to cause a sense transistor input node voltage at the sense transistor input node to be at least half of a power transistor input node voltage at the power transistor input node.

2. The current sense circuit according to claim 1, the sense transistor being a first sense transistor, the sense transistor control node being a first sense transistor control node, the sense transistor input node being a first sense transistor input node, the sense transistor output node being a first sense transistor output node, the current sense circuit further comprising: a second sense transistor having a second sense transistor control node that controls whether current flows from a second

sense transistor input node to a second sense transistor output node, the second sense transistor control node connected to the power transistor control node and to the first sense transistor control node, the second sense transistor input node connected to the first sense transistor input node.
3. The current sense circuit according to claim 2, further comprising: a feedback component connected between the power transistor input node and the second sense transistor output node, the feedback component being configured to, when each of the power transistor, first sense transistor and second sense transistor are on, generate a sense current that flows through the second sense transistor and first sense transistor, the sense current being a function of a power current flowing through the power transistor.
4. The current sense circuit according to claim 3, wherein the feedback component comprises an operational amplifier including a first operational amplifier input node, a second operational amplifier input node, and an operational amplifier output node, the second operational amplifier input node connected to the second sense transistor output node, the operational amplifier output node also connected to the second sense transistor output node.
5. The current sense circuit according to claim 4, the current sense circuit further comprising a feedback component shield transistor having a feedback component shield transistor control node that controls whether current flows from a feedback component shield transistor input node to a feedback component shield transistor output node, the feedback component shield transistor input node connected to the power transistor input node, the feedback component shield transistor output node connected to the first operational amplifier input node.
6. The current sense circuit according to claim 3, wherein the feedback component is included in a silicon integrated chip.
7. The current sense circuit according to claim 3, the function being a proportional function.
8. The current sense circuit according to claim 7, the proportional function being an approximately proportional function.
9. The current sense circuit according to claim 2, wherein each of the power transistor, the first sense transistor and the second sense transistor are gallium nitride transistors.
10. The current sense circuit according to claim 2, wherein each of the power transistor, the first sense transistor and the second sense transistor are high-electron mobility transistors.
11. The current sense circuit according to claim 2, wherein the pull-up component comprises a pull-up transistor that has a pull-up transistor control node that controls whether current flows from a pull-up transistor input node to a pull-up transistor output node, the pull-up transistor output node connected to the power transistor input node, the pull-up transistor control node also connected to the power transistor input node, and the pull-up transistor input node connected to the first sense transistor input node and the second sense transistor input node.
12. The current sense circuit according to claim 1, wherein each of the power transistor and the sense transistor are gallium nitride transistors.
13. The current sense circuit according to claim 1, wherein each of the power transistor and the sense transistor are field-effect transistors.
14. The current sense circuit according to claim 1, wherein the pull-up component is a pull-up transistor that has a pull-up transistor control node that controls whether current flows from a pull-up transistor input node to a pull-up transistor output node, the pull-up transistor output node connected to the power transistor input node, the pull-up transistor control node also connected to the power transistor input node, and the pull-up transistor input node connected to the sense transistor input node.
15. The current sense circuit according to claim 1, wherein a size ratio of a current flow area of the power transistor over a current flow area of the sense transistor is 500 or more.
16. A current sense circuit comprising: a power transistor having a power transistor control node that controls whether current flows from a power transistor input node to a power transistor output node; a sense transistor having a sense transistor control node that controls whether current flows

from a sense transistor input node to a sense transistor output node, the sense transistor control node connected to the power transistor control node, the power transistor and the sense transistor each having active regions formed from a same epitaxial stack; and a pull-up component connected between the power transistor input node and the sense transistor input node, the pull-up component being structured such that, when power is provided to the pull-up component and when the power transistor and the sense transistor are off, the pull-up component is structured to cause a sense transistor input node voltage at the sense transistor input node to be at least twenty percent of a power transistor input node voltage at the power transistor input node.

17. The current sense circuit in accordance with claim 16, wherein the pull-up component is structured to cause the sense transistor input node voltage at the sense transistor input node to be at least eighty percent of the power transistor input node voltage at the power transistor input node.

18. A current sense circuit comprising: a power transistor having a power transistor control node that controls whether current flows from a power transistor input node to a power transistor output node; a sense transistor having a sense transistor control node that controls whether current flows from a sense transistor input node to a sense transistor output node, the sense transistor control node connected to the power transistor control node; and a pull-up component connected between the power transistor input node and the sense transistor input node, the pull-up component being structured such that, when power is provided to the pull-up component and when the power transistor and the sense transistor are off, the pull-up component is structured to cause a sense transistor input node voltage at the sense transistor input node to be at least half of a power transistor input node voltage at the power transistor input node wherein the pull-up component is a pull-up transistor that has a pull-up transistor control node that controls whether current flows from a pull-up transistor input node to a pull-up transistor output node, the pull-up transistor output node connected to the power transistor input node, the pull-up transistor control node also connected to the power transistor input node, and the pull-up transistor input node connected to the sense transistor input node.

19. The current sense circuit according to claim 18, wherein a size ratio of a current flow area of the power transistor over a current flow area of the sense transistor is 500 or more.