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(54) **LOW DROPOUT VOLTAGE REGULATOR**

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(57) **ABSTRACT**

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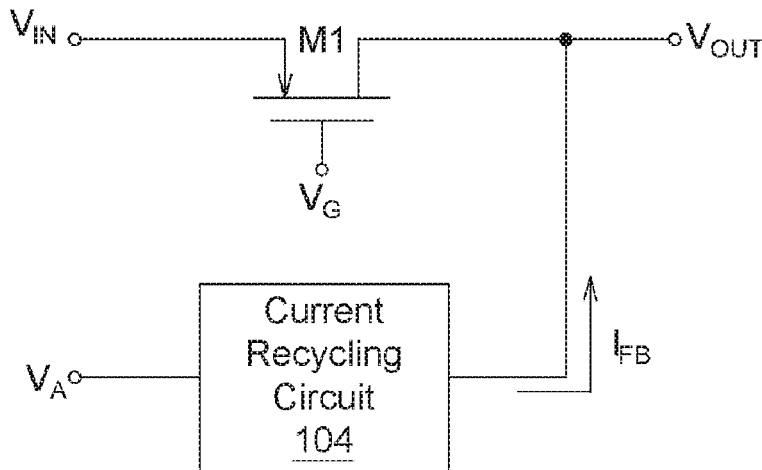
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A low dropout voltage regulator for generating an output regulated voltage is provided. The low dropout voltage regulator includes a first transistor and a current recycling circuit. The first transistor has a first terminal for receiving an input supply voltage, a second terminal for generating the output regulated voltage, and a control terminal for receiving a control voltage. The current recycling circuit is configured to drain a feeding current to the second terminal of the first transistor in response to a first signal having feedback information of the output regulated voltage.



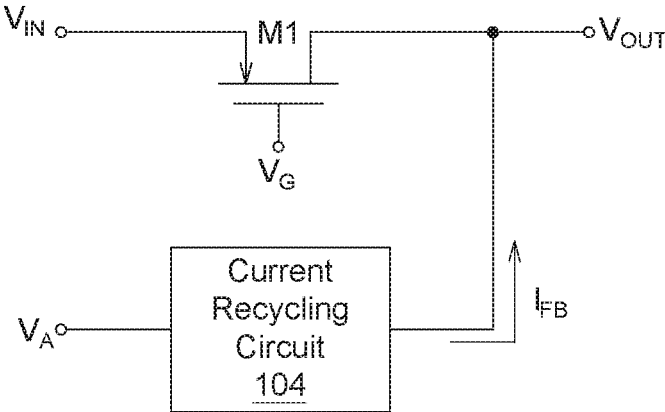


FIG. 1

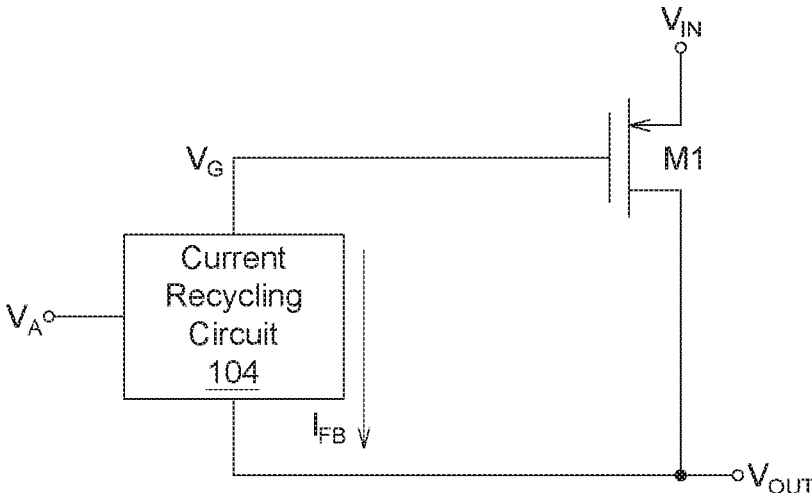


FIG. 2

12

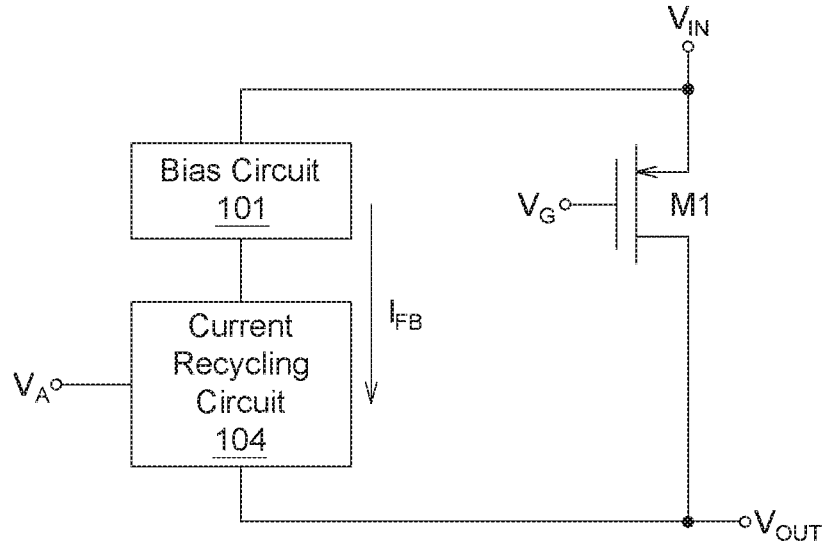


FIG. 3

13

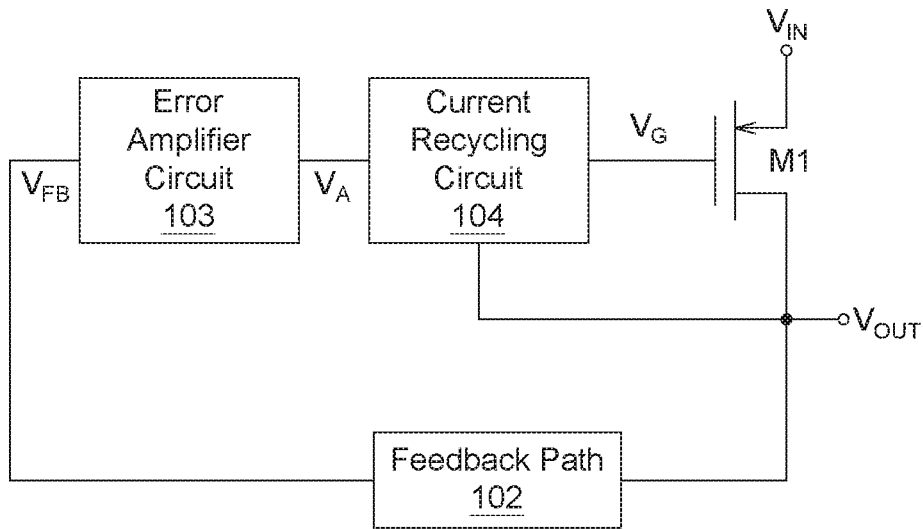


FIG. 4

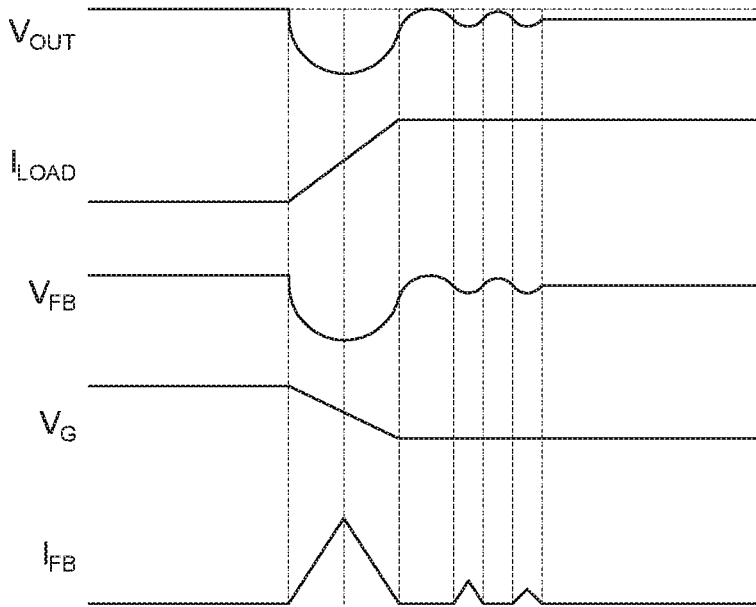


FIG. 5

LOW DROPOUT VOLTAGE REGULATOR

[0001] This application claims the benefit of U.S. provisional application Ser. No. 62/416,736, filed Nov. 3, 2016, the subject matter of which is incorporated herein by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to a voltage regulator, and more particularly to a power saving voltage regulator.

BACKGROUND OF THE INVENTION

[0003] A low dropout regulator (LDO) is a DC linear voltage regulator that can regulate the output voltage even when the supply voltage is very close to the output voltage. The advantages of an LDO include the absence of switching noise, smaller device size, and greater design simplicity. However, a quiescent current, also known as ground current or supply current, is drawn by the LDO in order to control the internal circuitry for proper operation. The quiescent current may lead to excessive power dissipation if the LDO is applied to a high transient current load in a low supply voltage environment. In this regard, there is a need for designing an LDO with low power consumption.

SUMMARY OF THE INVENTION

[0004] The disclosure is directed to a low dropout voltage regulator. One of the advantages of the proposed low dropout voltage regulator is reduced power consumption.

[0005] According to one embodiment, a low dropout voltage regulator for generating an output regulated voltage is provided. The low dropout voltage regulator includes a first transistor and a current recycling circuit. The first transistor has a first terminal for receiving an input supply voltage, a second terminal for generating the output regulated voltage, and a control terminal for receiving a control voltage. The current recycling circuit is configured to drain a feeding current to the second terminal of the first transistor in response to a first signal having feedback information of the output regulated voltage.

[0006] Numerous objects, features and advantages of the present invention will be readily apparent upon a reading of the following detailed description of embodiments of the present invention when taken in conjunction with the accompanying drawings. However, the drawings employed herein are for the purpose of descriptions and should not be regarded as limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The above objects and advantages of the present invention will become more readily apparent to those ordinarily skilled in the art after reviewing the following detailed description and accompanying drawings, in which:

[0008] FIG. 1 illustrates a block diagram of a low dropout voltage regulator according to an embodiment of the invention.

[0009] FIG. 2 illustrates a block diagram of a low dropout voltage regulator according to another embodiment of the invention.

[0010] FIG. 3 illustrates a block diagram of a low dropout voltage regulator including a bias circuit according to an embodiment of the invention.

[0011] FIG. 4 illustrates a block diagram of a low dropout voltage regulator including an error amplifier circuit according to an embodiment of the invention.

[0012] FIG. 5 illustrates a signal waveform of the low dropout voltage regulator shown in FIG. 4.

[0013] FIG. 6 illustrates a circuit schematic of a low dropout voltage regulator according to an embodiment of the invention.

[0014] In the following detailed description, for purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the disclosed embodiments. It will be apparent, however, that one or more embodiments may be practiced without these specific details. In other instances, well-known structures and devices are schematically shown in order to simplify the drawing.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

[0015] FIG. 1 illustrates a block diagram of a low dropout voltage regulator **10** according to an embodiment of the invention. The low dropout voltage regulator **10** includes a first transistor **M1**, a feedback path **102**, and a current recycling circuit **104**. The first transistor **M1** has a first terminal for receiving an input supply voltage V_{IN} , a second terminal for generating the output regulated voltage V_{OUT} , and a control terminal for receiving a control voltage V_G . The current recycling circuit **104** is configured to drain a feeding current I_{FB} in response to a first signal V_A . The first signal V_A has feedback information of the output regulated voltage V_{OUT} . For example, there is an electrically coupled path between the output voltage regulated voltage V_{OUT} and the first signal V_A . In one embodiment, the first signal V_A is positively correlated with the output voltage regulated voltage V_{OUT} . In another embodiment, the first signal V_A is negatively correlated with the output voltage regulated voltage V_{OUT} .

[0016] The first transistor **M1** may be a power metal oxide semiconductor field effect transistor (MOSFET). In the example shown in FIG. 1, the first transistor **M1** is a p-channel MOSFET (PMOS). In other embodiments, the first transistor **M1** may also be other types of transistors, such as n-channel MOSFET (NMOS), bipolar junction transistor (BJT), junction gate field effect transistor (JFET), and so on. Using PMOS transistor as the first transistor **M1** may be suitable for low supply voltage applications. For example, the input supply voltage V_{IN} is 1.8V, and the output regulated voltage V_{OUT} is about 1V. In the following description, PMOS transistor will be used as an example for the first transistor **M1**. However, the invention is not limited thereto.

[0017] The first terminal of the first transistor **M1** is the source terminal of the PMOS transistor, the second terminal of the first transistor **M1** is the drain terminal of the PMOS transistor, and the control terminal of the first transistor **M1** is the gate terminal of the PMOS transistor. If the first transistor **M1** is an NMOS transistor, the first terminal, the second terminal, and the control terminal are the drain terminal, the source terminal, and the gate terminal of the NMOS transistor, respectively. If the first transistor **M1** is a PNP BJT, the first terminal, the second terminal, and the control terminal are the emitter terminal, the collector terminal, and the base terminal of the PNP BJT, respectively.

[0018] FIG. 2 illustrates a block diagram of a low dropout voltage regulator **11** according to another embodiment of the invention. In this embodiment, the current recycling circuit **104** is coupled between the control terminal and the second terminal of the first transistor M1. In one embodiment, the current recycling circuit **104** is configured to provide the control voltage V_G in response to the output regulated voltage V_{OUT} . The second terminal of the first transistor M1 may be coupled to a load device, which draws load current I_{LOAD} during operation. For example, when the load current I_{LOAD} increases, the output regulated voltage V_{OUT} decreases temporarily. The first signal V_A reflects the decreased output regulated voltage V_{OUT} , and then the current recycling circuit **104** decreases the control voltage V_G correspondingly, such that the first transistor M1 is turned on, effectively decreasing the internal resistance of the first transistor M1. Therefore the output regulated voltage V_{OUT} increases. In this way the output regulated voltage V_{OUT} be kept as a stable regulated voltage.

[0019] The size of the first transistor M1 is usually large in order to provide sufficient driving capability. The first transistor M1 may have large parasitic capacitance, and thus there may be a large amount of charge stored in the first transistor M1. In the embodiment shown in FIG. 2, the current recycling circuit **104** is configured to drain a feeding current I_{FB} from the control terminal of the first transistor M1 to the second terminal of the first transistor M1. As such, charge accumulated at the control terminal of the first transistor M1 (due to the bulky power MOS) can be drained to the output regulated voltage V_{OUT} for power efficiency. In other words, energy is directly provided to the output regulated voltage V_{OUT} . The feeding current I_{FB} flows directly to the second terminal of the first transistor M1, rather than flows to the ground node, thus preventing unnecessary power dissipation.

[0020] FIG. 3 illustrates a block diagram of a low dropout voltage regulator **12** including a bias circuit according to an embodiment of the invention. In this embodiment, the low dropout voltage regulator **12** includes a bias circuit **101** for the current recycling circuit **104**. The bias circuit **101** may be configured to establish proper operating conditions, such as voltage and current, for the current recycling circuit **104**. In the embodiment shown in FIG. 3, the bias circuit **101** is coupled to the first terminal of the first transistor M1. In some other embodiments, the bias circuit **101** may also be coupled to the control terminal of the first transistor M1. The bias circuit **101** generally carries a large amount of current. The current recycling circuit **104** is configured to drain the feeding current I_{FB} from the bias circuit **101** to the second terminal of the first transistor M1. As such, energy flows from the bias circuit **101** directly to the output regulated voltage V_{OUT} , rather than flows to the ground node, thus preventing unnecessary power dissipation. Note that the embodiments shown in FIG. 2 and FIG. 3 may also be combined. For example, both the current recycling circuit **104** and the bias circuit **101** may be coupled to the control terminal of the first transistor M1.

[0021] FIG. 4 illustrates a block diagram of a low dropout voltage regulator **13** including an error amplifier circuit according to an embodiment of the invention. In this embodiment the low dropout voltage regulator **13** further includes a feedback path **102** and an error amplifier circuit **103**. The feedback path **102** provides a feedback voltage V_{FB} in response to the output regulated voltage V_{OUT} . The

error amplifier circuit **103** is configured to amplify a voltage difference between the feedback voltage V_{FB} and a reference voltage V_{REF} to generate the first signal V_A .

[0022] There may be several implementations for the feedback path **102**. In one embodiment, the feedback voltage V_{FB} is substantially equal to the output regulated voltage V_{OUT} via the feedback path **102**. In another embodiment, the feedback path **102** may include a voltage divider, such that the feedback voltage V_{FB} is a fraction of the output regulated voltage V_{OUT} . In still another embodiment, the feedback path **102** may include a coupling capacitor, such that the output regulated voltage V_{OUT} information can be promptly passed to the error amplifier circuit **103** that receives the feedback voltage V_{FB} .

[0023] FIG. 5 illustrates a signal waveform of the low dropout voltage regulator shown in FIG. 4. When the load current I_{LOAD} increases (a transient caused by the load device coupled to the second terminal of the first transistor M1), the output regulated voltage V_{OUT} drops, and the voltage level of the feedback voltage V_{FB} drops in turn. The first signal V_A reflects the decreasing of the feedback voltage V_{FB} . The current recycling circuit **104** is configured to decrease the control voltage V_G when the output regulated voltage V_{OUT} decreases. Consequently, the output regulated voltage V_{OUT} increases back to be close to its initial level.

[0024] As shown in FIG. 5, when the control voltage V_G starts decreasing, the feeding current I_{FB} increases, providing energy to the output regulated voltage V_{OUT} . A fast transient loop is formed by the current recycling circuit **104** to shorten the response time. The current recycling circuit **104** coupled between the control voltage V_G and the output regulated voltage V_{OUT} constitutes the shortest path in the low dropout voltage regulator **10**.

[0025] In the embodiments provided above, the current recycling circuit **104** is configured to increase the feeding current I_{FB} when the output regulated voltage V_{OUT} decreases. Because the feeding current I_{FB} flows directly to the output node of the low dropout voltage regulator **10**, rather than flows to the ground node, the power consumption can be reduced. In addition, because the shortest path is introduced by the current recycling circuit **104**, the response time of the low dropout voltage regulator **10** can also be reduced.

[0026] There may be several different implementations regarding the current recycling circuit **104**. In one embodiment, the current recycling circuit **104** may be a buffer circuit coupled between the first signal V_A and the first transistor M1. Any available architecture for the buffer circuit may be applied to the current recycling circuit **104**.

[0027] FIG. 6 illustrates an example circuit schematic of a low dropout voltage regulator **14** according to an embodiment of the invention. In this embodiment, the current recycling circuit **104** includes a second transistor M2. The second transistor M2 is a PMOS transistor. In another embodiment, the second transistor M2 may be a different type of transistor. Also, the current recycling circuit **104** may include other transistors and components in addition to the second transistor M2. For example, the current recycling circuit **104** may also include additional passive devices, multiple cascade or cascode connected transistors, and so on. In the embodiment shown in FIG. 4, the second transistor M2 is the only element in the current recycling circuit **104**. A single transistor implementation for the current

recycling circuit **104** has the advantage of low hardware area, simplified circuit design, and low path delay.

[0028] FIG. 6 shows an example buffer impedance attenuation (BIA) low dropout voltage regulator (LDO). The BIA LDO has the advantage of better stability at fast transient due to its one-pole system in bandwidth. FIG. 6 shows a BIA LDO having the current recycling circuit **104** as described in the embodiments shown in FIG. 1-FIG. 4.

[0029] In this embodiment, the second transistor M2 (PMOS in this example) has a first terminal (source terminal) directly coupled to the control terminal of the first transistor M1, a second terminal (drain terminal) directly coupled to the second terminal of the first transistor M1, and a control terminal (gate terminal) for receiving the first signal V_A . The bias circuit **101** shown in FIG. 3 may include a third transistor M3 shown in FIG. 6. The third transistor M3 is coupled to the first terminal and the control terminal of the first transistor M1. In this embodiment, the output regulated voltage V_{OUT} is fed back through a coupling capacitor C_C . The feedback voltage V_{FB} (at the gate of the transistor M11) may be equal to or a fraction of the output regulated voltage V_{OUT} . The error amplifier circuit **103** shown in FIG. 4 may include the transistors M4-M11 shown in FIG. 6. The error amplifier circuit **103** is configured to amplify the voltage difference between the feedback voltage V_{FB} and the reference voltage V_{REF} (which may be provided by a bandgap reference circuit) to generate the first signal V_A . The transistors M3 and M12 are used for biasing a reference current to the BIA LDO shown in FIG. 6.

[0030] In this embodiment, the feeding current I_{FB} may come from two sources, including the third transistor M3 and the charge stored at the gate of the first transistor M1. For example, when the output regulated voltage V_{OUT} decreases, the second transistor M2 drains the feeding current I_{FB} from the third transistor M3 and/or the control terminal of the first transistor M1 to the second terminal of the first transistor M1. The second transistor M2 constitutes the shortest path in the regulator circuit to enhance the response time.

[0031] Because the second transistor M2 is not directly coupled to the ground node GND (which has the most negative voltage level in the circuit), all the feeding current I_{FB} is drained to the output regulated voltage V_{OUT} . The feeding current I_{FB} does not flow to the ground node GND, and thus the quiescent current (I_Q) of the regulator circuit can be reduced, resulting in less power consumption.

[0032] The control voltage V_G decreases when the output regulated voltage V_{OUT} decreases. Because of the shortest path introduced by the second transistor M2, when the output regulated voltage V_{OUT} starts bouncing back due to the first transistor M1 being turned on, the increased output regulated voltage V_{OUT} quickly prevents the control voltage V_G from decreasing or makes the control voltage V_G increase as well. According to the circuit structure shown in FIG. 6, the energy stored at the control terminal of the first transistor M1 has nowhere else to go when the output regulated voltage V_{OUT} boosts, and thus the control voltage V_G stops decreasing. The control voltage V_G then turns off the first transistor M1, preventing the output regulated voltage V_{OUT} from overshooting (exceeding the target regulated voltage). In other words, the low dropout voltage regulator **14** can prevent overshoot inherently by introducing the current recycling circuit **104**.

[0033] According to the embodiments described above, by adopting a current recycling circuit in the low dropout voltage regulator, a fast response time can be achieved. In addition, the quiescent current of the regulator circuit can be reduced, resulting in less power consumption. Moreover, the proposed low dropout voltage regulator can prevent overshoot inherently, resulting in a more stable output regulated voltage.

[0034] While the invention has been described in terms of what is presently considered to be the most practical and preferred embodiments, it is to be understood that the invention needs not be limited to the disclosed embodiment. On the contrary, it is intended to cover various modifications and similar arrangements included within the spirit and scope of the appended claims which are to be accorded with the broadest interpretation so as to encompass all such modifications and similar structures.

What is claimed is:

1. A low dropout voltage regulator for generating an output regulated voltage, the low dropout voltage regulator comprising:

a first transistor, having a first terminal for receiving an input supply voltage, a second terminal for generating the output regulated voltage, and a control terminal for receiving a control voltage; and

a current recycling circuit, configured to drain a feeding current to the second terminal of the first transistor in response to a first signal having feedback information of the output regulated voltage.

2. The low dropout voltage regulator of claim 1, wherein the current recycling circuit is coupled between the control terminal and the second terminal of the first transistor.

3. The low dropout voltage regulator of claim 2, wherein the current recycling circuit is configured to provide the control voltage in response to the output regulated voltage.

4. The low dropout voltage regulator of claim 1, further comprising a bias circuit for the current recycling circuit, wherein the current recycling circuit is configured to drain the feeding current from the bias circuit to the second terminal of the first transistor.

5. The low dropout voltage regulator of claim 1, further comprising:

a feedback path, for providing a feedback voltage in response to the output regulated voltage; and

an error amplifier circuit, for amplifying a voltage difference between the feedback voltage and a reference voltage to generate the first signal.

6. The low dropout voltage regulator of claim 1, wherein the current recycling circuit is configured to increase the feeding current when the output regulated voltage decreases.

7. The low dropout voltage regulator of claim 1, wherein the current recycling circuit is a buffer circuit.

8. The low dropout voltage regulator of claim 1, wherein the current recycling circuit comprises a second transistor.

9. The low dropout voltage regulator of claim 8, wherein the second transistor has a first terminal directly coupled to the control terminal of the first transistor, a second terminal directly coupled to the second terminal of the first transistor, and a control terminal for receiving the first signal.

10. The low dropout voltage regulator of claim 8, wherein the first transistor and the second transistor are PMOS transistors.

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