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(54) **REFERENCE CURRENT GENERATION SYSTEM AND METHOD**

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(57) **ABSTRACT**

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As disclosed herein, systems and methods are provided for generating and distributing a plurality of reference currents on an integrated circuit. In a particular embodiment, an integrated circuit is disclosed which includes a reference current generator adapted to generate a plurality of reference currents. Such circuit includes an operational amplifier coupled to receive, at a first polarity input, a reference voltage, and a first transistor Q1 having a biasing input coupled to an output of the operational amplifier. The first transistor also has an output coupled to a fixed potential through a first resistor R1, and the output of the first transistor Q1 is further coupled as feedback to a second polarity input of the operational amplifier. One or more second transistors Qi are provided in the circuit, each of which has a biasing input coupled to the output of the operational amplifier, and an output coupled to the fixed potential through a respective second resistor Ri. In order to conserve chip area and power, the outputs of the second transistors Qi are not coupled as feedback to the operational amplifier. By the action of the operational amplifier, bias is maintained on the first transistor Q1 and each of the second transistors Qi for each to conduct a reference current I_{si}.

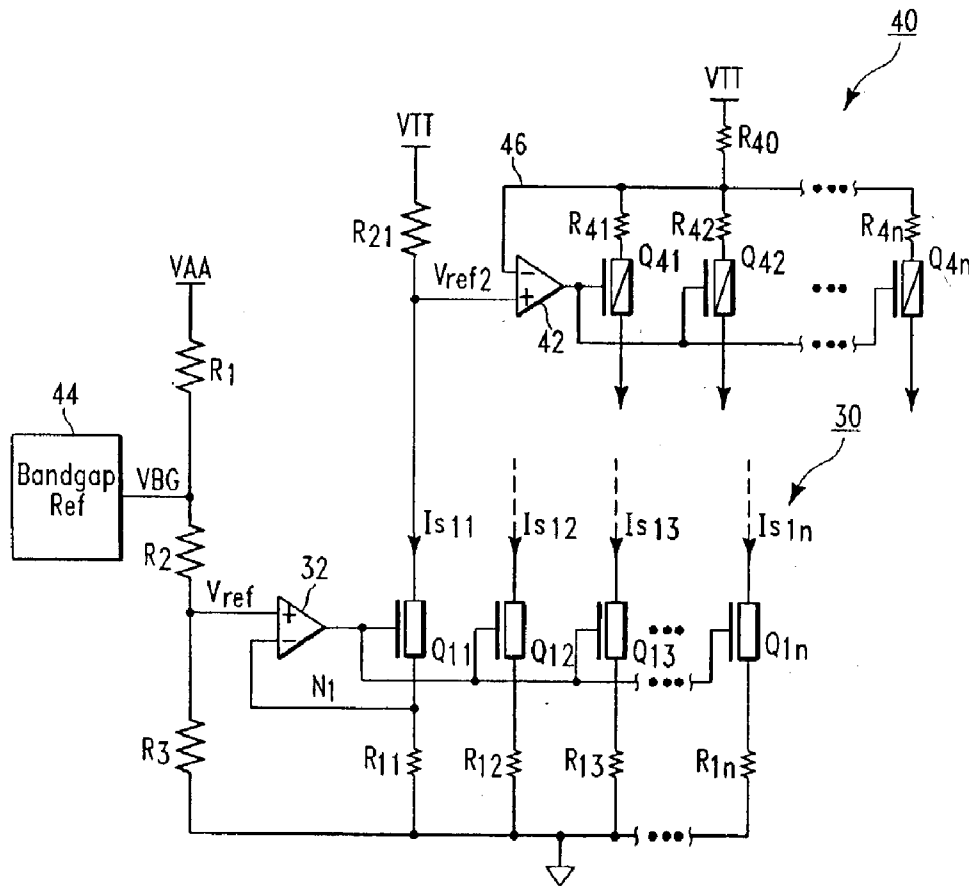
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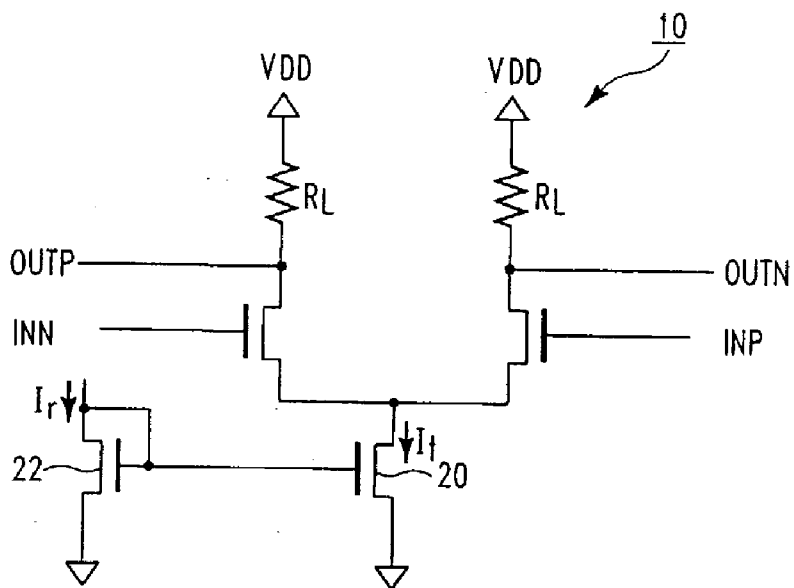


FIG. 1 Prior Art

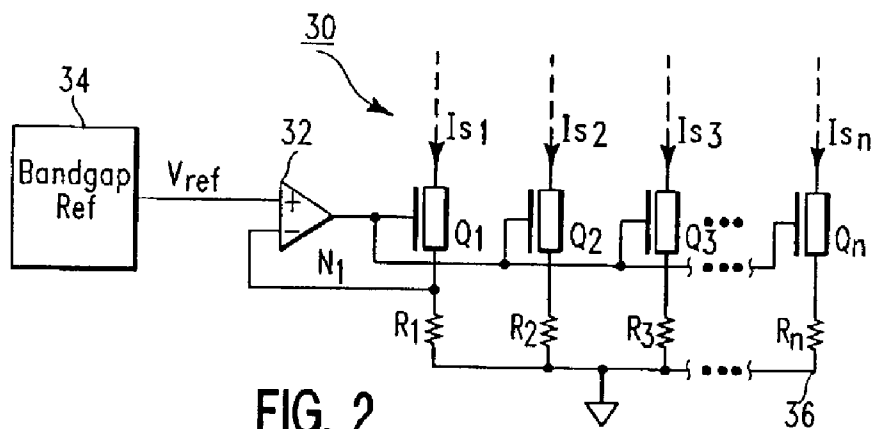


FIG. 2

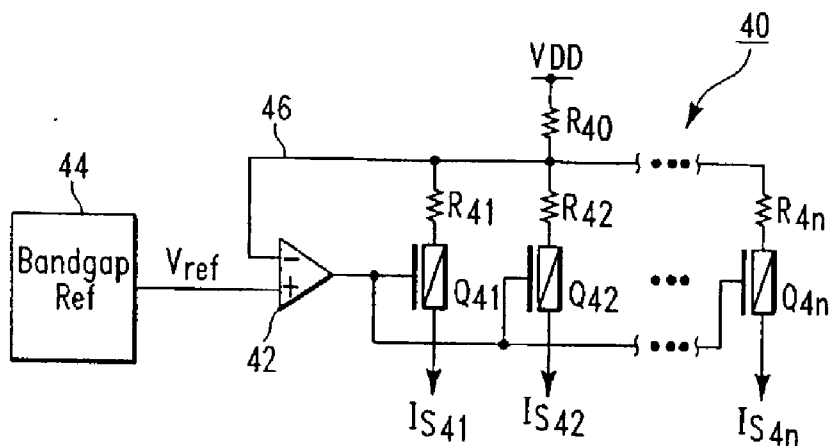


FIG. 3

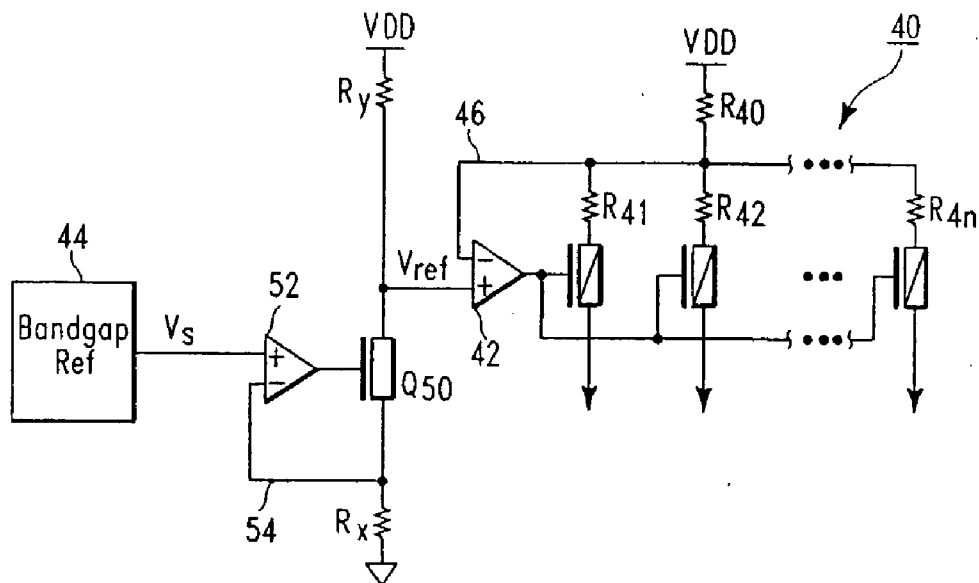


FIG. 4

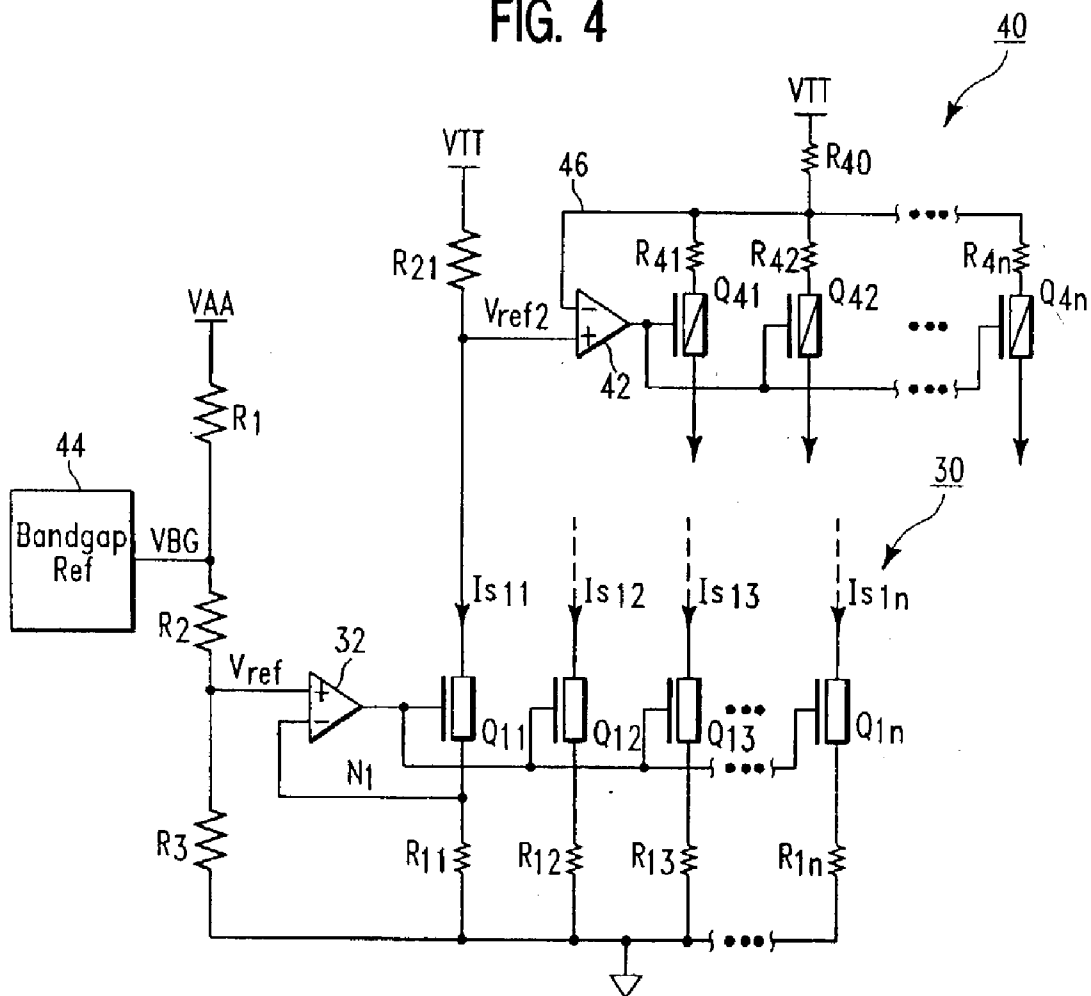


FIG. 5

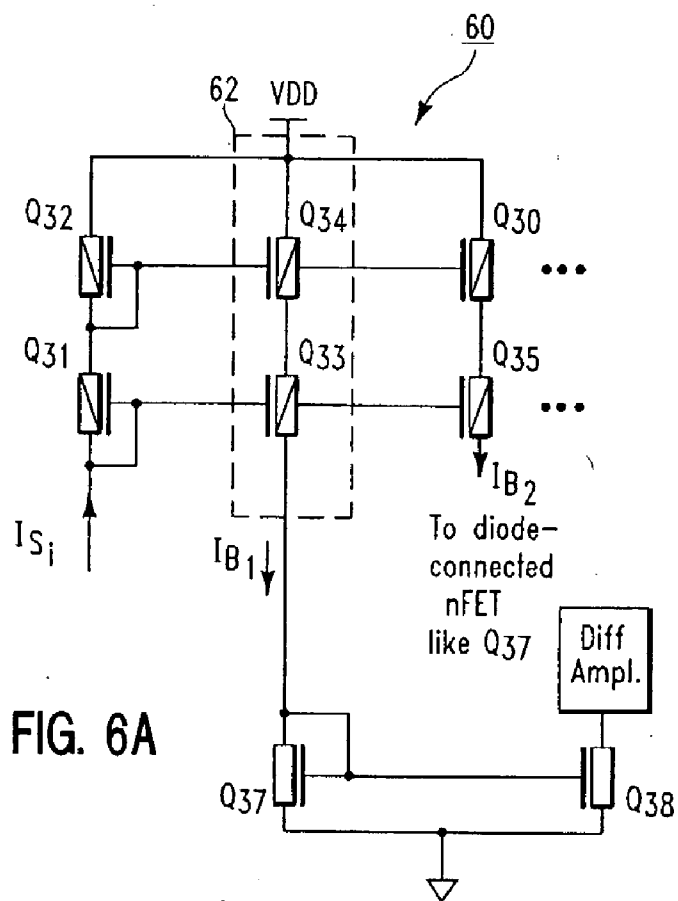


FIG. 6A

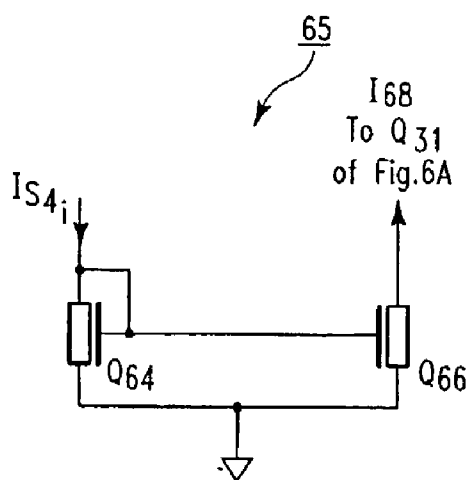


FIG. 6B

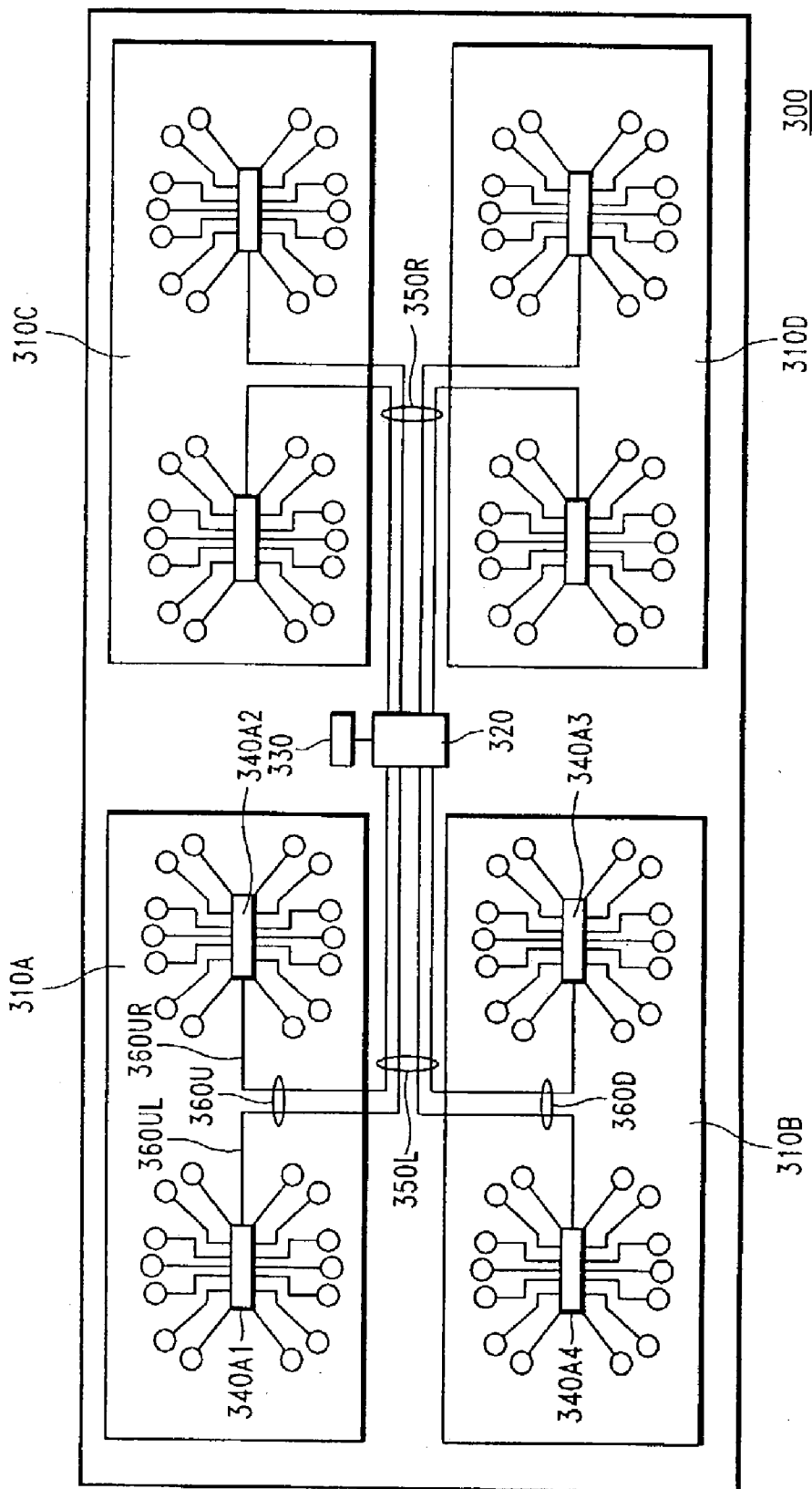


FIG. 6C

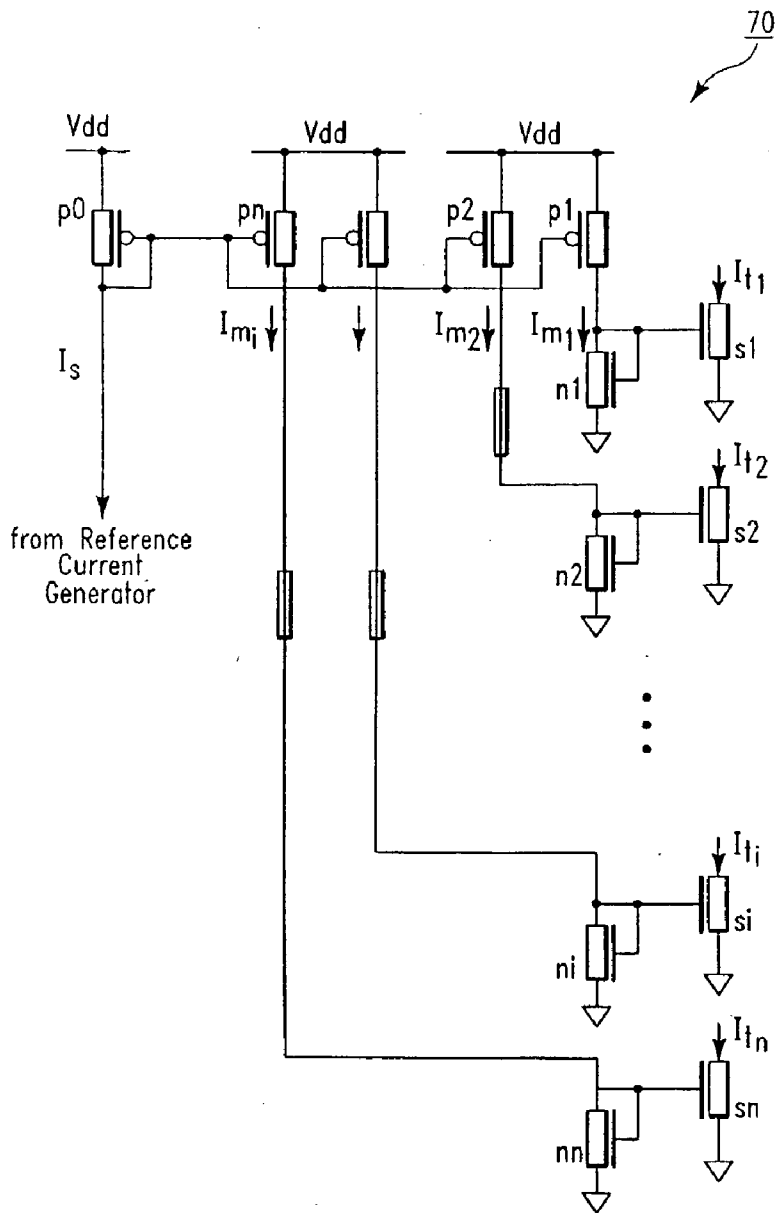


FIG. 7A Prior Art

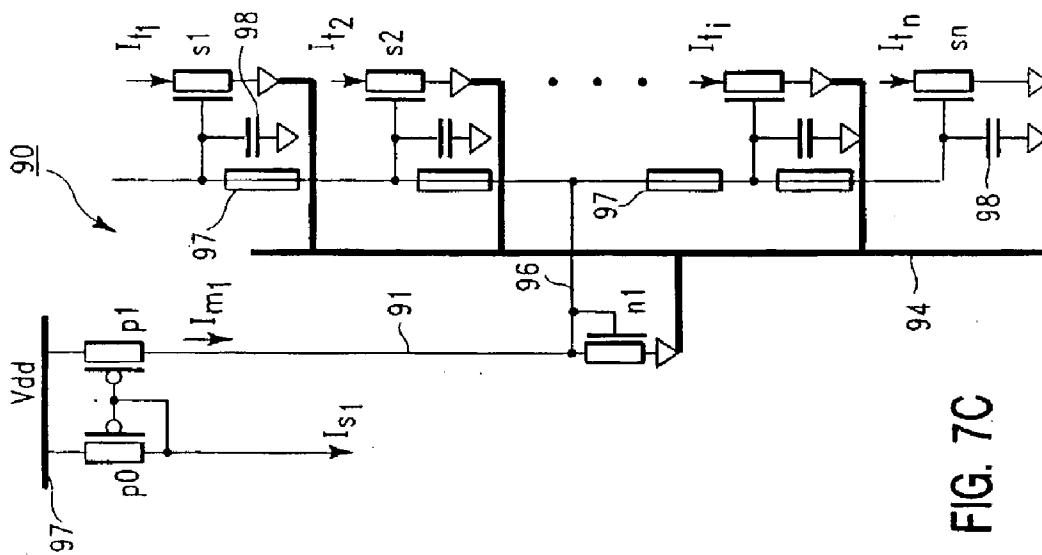


FIG. 7C

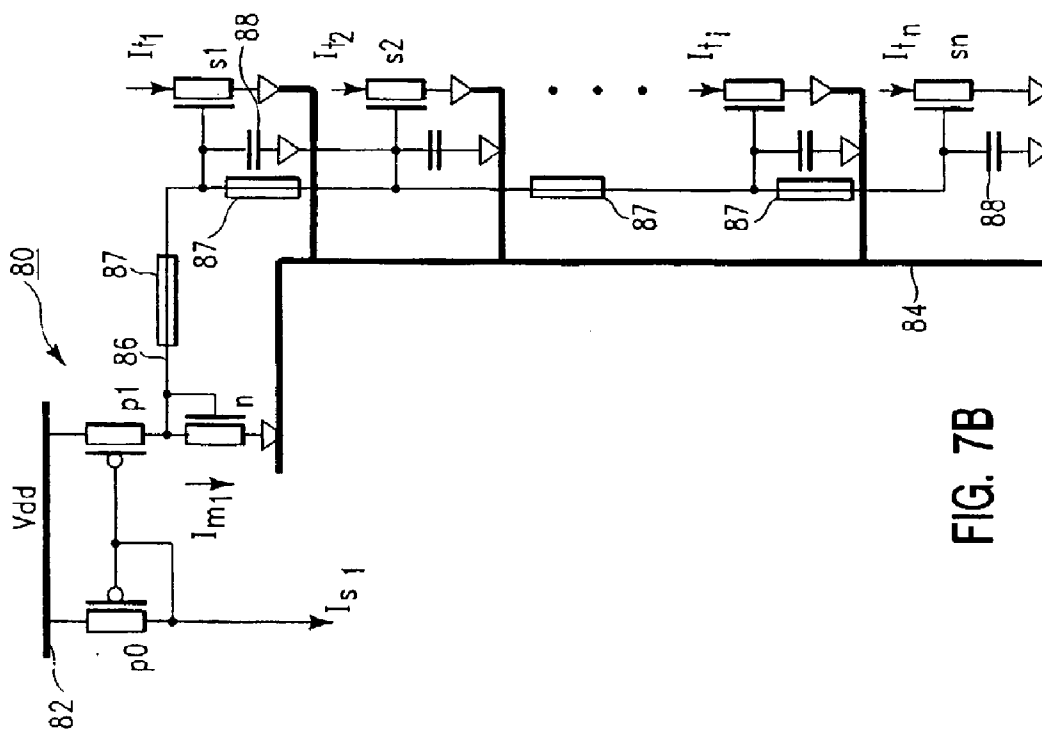


FIG. 7B

REFERENCE CURRENT GENERATION SYSTEM AND METHOD

BACKGROUND OF INVENTION

[0001] Integrated circuits, whether digital or analog in form, require reference currents. A reference current is a current source generated by the integrated circuit for the purpose of operating devices of the integrated circuit in a manner that minimizes the effects of variation in power supply, temperature, and fabrication process at a particular location within the integrated circuit. For example, a high speed differential amplifier used in an off-chip driver of a communication circuit needs a reference current to drive signals with required fixed amplitude onto a signal line towards a remote receiver, despite variations which occur in power supply, temperature, resistance values and fabrication process relative to particular locations of the chip.

[0002] As shown in **FIG. 1**, an exemplary high speed differential amplifier **10** drives differential outputs **OUTP** and **OUTN** based on the voltages of input signals **INN** and **INP** presented thereto. The differential amplifier **10** includes a "tail" transistor **20** which is coupled in mirror configuration to a first transistor **22** such that the tail transistor **20** generates a tail current I_t which is proportional to the reference current I_r through the first transistor **22**. The tail current I_t is used to pull down one of the outputs **OUTP** or **OUTN** as a voltage drop across one of the on-chip load resistors **RL** by the quantity $I_t R_L$, based on the inputs **INN** and **INP** presented to the differential amplifier. When an output **OUTP** or **OUTN** is pulled down in use, the voltage drop across the corresponding one of the on-chip load resistors **RL** is required to be of fixed amplitude. Since the values of the on-chip load resistors **RL** vary with temperature and the fabrication process conditions, it will be understood that the reference current I_r , from which the tail current is mirrored, must not be constant, but rather must vary in a way to compensate for such temperature and process-related variations in resistance.

[0003] On the other hand, some circuits, which do not use on-chip resistors as load elements, are also required to provide output signals of fixed amplitude. For example, many different configurations of differential amplifiers are available which include transistors rather than resistors as load elements. In such cases, a reference current is needed which does not vary according to changes in an on-chip resistance, but rather, is independent from the variability of on-chip resistances.

[0004] Other problems of existing reference current generators are the chip area and power consumed by the placement of multiple independent reference current generators at different locations on a chip, such reference current generators including many elements that are duplicative. In addition, variations in the fabrication processing at such different chip locations may result in local variations in the generated reference currents. Therefore, a reference current generator system is desired which reduces demands on chip area and power consumption by eliminating duplicative elements and which provides uniform reference currents.

[0005] It would further be desirable for a reference current generator system to centrally generate a plurality of reference currents, and then distribute the reference currents to a

plurality of different locations on a chip where a set of local reference currents are regenerated from the distributed reference currents and then used.

SUMMARY OF INVENTION

[0006] Accordingly, as disclosed herein, systems and methods are provided for generating and distributing a plurality of reference currents to different locations on an integrated circuit. According to a first aspect of the invention, an integrated circuit is provided which includes a reference current generator adapted to generate a plurality of reference currents. Such circuit includes an operational amplifier coupled to receive, at a first polarity input, a reference voltage, and a first transistor **Q1** having a biasing input coupled to an output of the operational amplifier. The first transistor also has an output coupled to a fixed potential through a first resistor **R1**, and the output of the first transistor is further coupled as feedback to a second polarity input of the operational amplifier. One or more second transistors Q_i are provided in the circuit, each of which has a biasing input coupled to the output of the operational amplifier, and an output coupled to the fixed potential through a respective second resistor **R_i**. However, the outputs of the second transistors Q_i are not coupled as feedback to the operational amplifier. By the action of the operational amplifier, bias is maintained on the first transistor **Q1** and each of the second transistors Q_i for each to conduct a reference current I_{si} .

[0007] According to another aspect of the invention, a method of generating and distributing a plurality of reference currents to multiple locations of said integrated circuit is provided. Such method includes centrally generating a plurality of reference currents using a centrally located stable reference voltage and a plurality of generator transistors Q_i , each transistor having an output coupled to a fixed potential through a resistor. The centrally generated reference currents are then distributed to different locations of the integrated circuit, and then a plurality of local reference currents are regenerated locally, through current mirroring, in different locations of the integrated circuit from each of the centrally generated reference currents

BRIEF DESCRIPTION OF DRAWINGS

[0008] **FIG. 1** is a schematic diagram illustrating a prior art differential amplifier.

[0009] **FIG. 2** is a block and schematic diagram illustrating a first preferred embodiment of a reference current generator.

[0010] **FIG. 3** is a block and schematic diagram illustrating a second preferred embodiment of a reference current generator.

[0011] **FIG. 4** is a block and schematic diagram illustrating a modified second embodiment of a reference current generator.

[0012] **FIG. 5** is a block and schematic diagram illustrating an embodiment in which a second reference current generator is coupled in tandem to a first reference current generator.

[0013] **FIGS. 6A through 6C** are diagrams illustrating aspects of reference current distribution systems.

[0014] FIG. 7A is a schematic diagram illustrating a prior art circuit for mirroring and distributing a reference current to a plurality of end use circuits.

[0015] FIGS. 7B and 7C are schematic diagrams illustrating improved circuit embodiments for mirroring and distributing a reference current to a plurality of end use circuits.

DETAILED DESCRIPTION

[0016] A first preferred embodiment of a reference current generator 30 is illustrated in FIG. 2. In this embodiment, reference currents are generated which change with variations in the resistance of on-chip resistors, in such way as to compensate for variations in the resistance of load resistors in the end use circuit (e.g. differential amplifier) where the reference current is used. As shown in FIG. 2, an operational amplifier 32 is coupled to receive, at a positive input, a stable reference voltage V_{ref} , for example, from a bandgap reference generator 34. A bandgap reference generator generates a constant voltage output which is independent of power supply, temperature and process variations.

[0017] An insulated gate field effect transistor (IGFET) Q1, preferably of n-type (an NFET), but permissibly of p-type (a PFET), has a gate to which the output of the operational amplifier 32 is coupled as a biasing input. The output node N1 from the source of the transistor Q1 is coupled to a resistor R1, which in turn, is coupled to a fixed potential 36, such as ground. Preferably, resistor R1 and resistors R2, R3, . . . Rn are on-chip resistors which vary in resistance as to temperature and process conditions, including their directional orientation on the chip, so as to compensate for similar variations in resistance of other on-chip resistors to which the reference currents are applied in end use circuits. However, as an alternative, it may be desirable to place the resistors R1, R2, R3 . . . Rn off the chip to limit such variations in resistance and to save chip area, when it is not needed to generate currents that compensate for variations in the resistance in end use circuits.

[0018] The output N1 of transistor Q1 is further coupled as feedback to the negative input of the operational amplifier 32. In such way, operational amplifier 32 maintains transistor Q1 biased to conduct a reference current I_{s1} which varies with the resistance of a resistor R1, such variations as may occur with temperature and the fabrication process, for example. The output of operational amplifier 32 is also coupled as biasing inputs to the gates of one or more second transistors Q2, Q3, . . . Qn, being NFETs, when the first transistor Q1 is an NFET, and being PFETs when the first transistor Q1 is a PFET. Each of the second transistors Qi has an output, for example, the source when the transistor is an NFET, which is coupled to a corresponding resistor Ri, which in turn, is coupled to the fixed potential, e.g. ground. When the second transistors Qi are PFETs, the output of each PFET Qi, from the drain, is coupled to a corresponding resistor Ri, which in turn, is coupled to the fixed potential, e.g. ground. The resistance values of all the resistors R1, R2, R3, . . . Rn are preferably set equal so as to bias the transistors Q1, Q2, Q3, . . . Qn each to conduct a reference current I_{si} in the same amplitude as each other, but permitting, however, some statistically acceptable variation. The operational amplifier 32 maintains each second transistor Qi biased to conduct a reference current I_{si} .

[0019] However, unlike the output N1 of the first transistor Q1, an important feature of this embodiment is that the outputs of the second transistors Qi are not coupled as feedback to the operational amplifier 32, helping to make possible high output impedance while conserving chip area. High output impedance is important in order to provide stable reference current outputs, good noise rejection, and to reduce the effects of power supply variations. As will be understood, by not coupling the outputs of all transistors to the operational amplifier, the output impedance of each branch of the generator through a transistor Qi can be maintained higher than otherwise. If the outputs of all transistors were coupled as feedback to the operational amplifier 32, then all of those outputs would be at the same potential, and a parallel current path would exist through resistors R1, R2, R3, . . . Rn to ground, reducing the output impedance of each branch by 1/n times. Low output impedance is undesirable as it can result in high power consumption and impedance mismatch between the output of the reference current generator and the end use circuit (e.g. differential signal amplifier) which uses the reference current. Without this important feature of the embodiment, to achieve the required output impedance, it would be necessary to increase the size of each resistor by n times to nR_i , or to construct separate reference current generators, each one having a bandgap reference generator and generating just one reference current. Such alternatives are undesirable as each one of them requires much greater chip area to implement.

[0020] In operation, a reference voltage V_{ref} is provided as a positive input to operational amplifier 32 from a stable voltage source such as a bandgap reference generator 34. The operational amplifier 32 produces an output that biases the gate of the first transistor Q1 to conduct a reference current I_{s1} . Since the output N1 of the first transistor is coupled to the negative input of the operational amplifier 32 as feedback thereto, the action of the operational amplifier 32 maintains the output N1 at the reference voltage V_{ref} . The amount of current through resistor R1 is therefore determined to be V_{ref}/R_1 , and the amount of the reference current I_{s1} through Q1 is the same.

[0021] A second embodiment of a reference current generator is illustrated in FIG. 3. In this embodiment, a plurality of reference currents I_{s41} , I_{s42} , . . . I_{s4n} are generated which are substantially independent of the resistances of resistors R41, R42, . . . R4n which are used in the respective branches of the reference current generator. In this embodiment, as in the first embodiment, a reference voltage from a bandgap reference generator 44 is provided to the positive input of the operational amplifier 42. The output of the operational amplifier is provided to the gates of a plurality of transistors Q41, Q42, . . . Q4n as biasing inputs thereto. Feedback to the negative input of the operational amplifier 42 is provided from a node 46 to which all branch resistors R41, R42, . . . R4n and resistor R40 are coupled. By the action of the operational amplifier 42, node 46 will be held at the reference voltage, and the current through resistor R40 is $(1/R_{40})(V_{DD} - V_{ref})$. Since the values of resistors R41, R42, . . . R4n, which may be located either on the chip or off the chip, are also the same or nearly the same, it will be understood that the quantity of the reference current I_{si} through each branch of the reference current generator 40 is

$(1/n)(1/R_{40})(V_{DD}-V_{ref})$, n being the number of branches, i.e. the number of reference currents output from the reference current generator 40.

[0022] In this embodiment, the value of the reference currents I_{s41} , I_{s42} , . . . I_{s4n} depends mainly on the resistance value of R_{40} , which is preferably located off of the chip such that its resistance is well controlled (typically within a tolerance of plus or minus one percent). On the other hand, resistors R_{41} , R_{42} , . . . R_{4n} are used principally to bias transistors Q_{41} , Q_{42} , . . . Q_{4n} for high output impedance and have little effect on the value of each reference current.

[0023] Transistors Q_{41} , Q_{42} , . . . Q_{4n} are preferably all of the same size, characteristics, and type. In a preferred embodiment, transistors Q_{41} , Q_{42} , . . . Q_{4n} are selected to be p-type insulated gate field effect transistors (PFETs), especially for the purpose of reducing power consumption, since the use of PFETs here permits the supply voltage and reference voltage to be set for low power consumption. For example, good results can be achieved while conserving power when PFET transistors are used and the supply voltage V_{DD} is set at a level only slightly higher than the reference voltage V_{ref} (e.g., 100 mV higher). However, n-type insulated gate field effect transistors (NFETs) can be used for Q_{41} , Q_{42} , . . . Q_{4n} instead of PFETs if the design permits a greater voltage difference between the supply voltage V_{DD} and the reference voltage V_{ref} .

[0024] It will be understood that, in the second embodiment, although reference currents I_{si} are generated which are substantially free from the effects of variations in resistance values of the circuit, the reference currents are still very much affected by fluctuation in the supply voltage V_{DD} . Accordingly, in a third embodiment, as shown in FIG. 4, an addition is made to the circuit to make the reference current values independent from the supply voltage V_{DD} . In this embodiment, V_{ref} , rather than being provided directly from a bandgap reference generator 44, as in the second embodiment, is now provided as an output of a transistor Q_{50} , which is coupled as feedback to an added operational amplifier 52. The added operational amplifier 52 receives a stable voltage input V_s from a bandgap reference generator 44.

[0025] As shown in FIG. 4, transistor Q_{50} is preferably an NFET; however, a PFET transistor can be used instead of an NFET under appropriate biasing conditions. The source of NFET transistor Q_{50} is coupled at node 54 to operational amplifier 52. By the action of the operational amplifier 52, node 54 is maintained at the stable voltage V_s . A resistor R_x is placed between node 54 and a fixed potential such as ground. Consequently, the current flow from node 54 to ground is equal to V_s/R_x . From the output (drain) of transistor Q_{50} a reference voltage V_{ref} is supplied as input to operational amplifier 42. As V_{ref} is determined by the resistive voltage drop due to the current through R_y , V_{ref} is equal to $V_{DD}-(R_y)(V_s/R_x)$, or expressed differently, $V_{ref}=V_{DD}-V_s(R_y/R_x)$. It will be further understood that node 46 is held at this voltage $V_{DD}-V_s(R_y/R_x)$, and that each generated reference current I_{s41} , I_{s42} , I_{s4n} is equal to $(1/n)(1/R_{40})(V_{DD}-(V_{DD}-V_s(R_y/R_x)))$; that is, $I_{si}=(1/n)(1/R_{40})(V_s(R_y/R_x))$, which is independent of the supply voltage V_{DD} . Moreover, when an off the chip, fixed value resistor is used as R_{40} , it will be understood that each

reference current I_{s4i} remains essentially constant despite temperature variation, because the resistance of R_{40} is fixed and that the ratio R_y/R_x of the resistances tends to cancel out any variations which may occur.

[0026] A further reference current generator embodiment is shown in FIG. 5. In this embodiment, a second reference current generator 40, of the type shown in FIG. 3, is operated in tandem with a first reference current generator 30, of the type shown in FIG. 2. The second reference current generator 40 is operated by a second reference voltage input V_{ref2} which is determined by a voltage drop due to a reference current I_{s11} across a resistor R_{21} coupled to the supply voltage V_{TT} , the reference current I_{s11} supplied from the first reference current generator 30. In this manner, which is different from the embodiments of FIGS. 2 and 3, there is no need for reference the second reference current generator 40 to a voltage input directly from a bandgap reference generator 44. Thus, the need for an additional bandgap reference generator 44 is eliminated, thereby permitting power and chip area to be conserved.

[0027] Another difference in this embodiment from those of FIGS. 2 and 3 relates to the way that the first reference voltage input V_{ref} is generated and provided to the operational amplifier 32. As shown in FIG. 5, a bandgap reference voltage V_{BG} is output from the bandgap reference generator 44. However, in this case, the supply voltage V_{AA} to the bandgap reference generator 44 is selected independently from the supply voltage V_{TT} provided to the first and second reference current generators 30 and 40. In such manner, the supply voltage V_{AA} can be made higher than the supply voltage V_{TT} to the first and second reference current generators 30 and 40, so as to enable better performance and better immunity to fluctuations in the supply voltage V_{AA} . It will be understood that the reference voltage V_{ref} provided to operational amplifier 32 is divided down from the bandgap reference voltage V_{BG} by resistors R_2 , and R_3 , such that the reference voltage $V_{ref}=(V_{BG})(R_3/(R_2+R_3))$, a quantity which should remain substantially constant despite changes in conditions, since the resistances of R_2 and R_3 are all expected to vary in the same direction. Because the bandgap reference voltage V_{BG} is now divided prior to input to the reference current generator 30, the supply voltage V_{TT} can also be lowered independently of the bandgap reference voltage V_{BG} , for conserving power, for example.

[0028] Since node N_1 of reference current generator 30 is held at V_{ref} , then the reference current I_{s11} is determined to be V_{ref}/R_{11} ; that is, $I_{s11}=(1/R_{11})(V_{BG})(R_3/(R_2+R_3))$.

[0029] This quantity, like the reference currents I_{si} of the embodiment of FIG. 2, is dependent upon the value of the resistor (R_{11}) that is coupled to the output of the transistor (Q_{11}). Therefore, the reference current I_{s11} (as well as reference currents I_{s12} , I_{s13} , . . . I_{s1n}) are available to compensate for variations in the resistances of circuits that use them.

[0030] It will be understood that even though a resistance dependent reference current I_{s11} is used to generate a second reference voltage V_{ref2} input to the second reference current generator 40, the second reference voltage V_{ref2} is substantially independent from variations in resistance. The second reference voltage V_{ref2} is determined by $V_{ref2}=V_{TT}(R_{21})(I_{s11})$; that is, using the above equation for I_{s11} , $V_{ref2}=(R_{21}/R_{11})(V_{BG})(R_3/(R_2+R_3))$.

[0031] FIG. 6A illustrates a local regenerating circuit 60 for mirroring and distributing a received reference current I_{si} (such as from the reference current generator 30 of FIG. 2) as a plurality of local regenerated reference currents I_{B1} , I_{B2} , etc. As shown in FIG. 6A, a reference current I_{si} is input to the drain of a diode-connected PFET Q31, which is preferably series connected to a second diode-connected PFET Q32, coupled to a voltage supply VDD. Pairs of series-connected PFET transistors Q33 and Q34, coupled to PFETs Q31 and Q32 in a current mirror configuration, are preferably sized a multiple of the sizes of the transistors Q31 and Q32 coupled to them so that the mirrored currents I_{B1} , I_{B2} , etc. that are a multiple of the incoming reference current I_{si} . In a first branch 62 of the local regenerating circuit 60, the incoming reference current I_{si} is mirrored by a PFET Q33 having its gate tied to the gate of diode-connected PFET Q31. PFET Q34 also mirrors the incoming reference current I_{si} , Q34 also having its gate tied to the gate of PFET Q32. The series connection of PFETs Q33 and Q34 in the branch 62 helps to assure the accuracy and stability of the mirrored current. Preferably, all of the PFETs of the local regenerating circuit 60 are located close to each other, rather than in different areas of the chip, such that all of them have the same or very little variation in threshold voltage and a variation in the supply voltage will not affect the quantity of the locally regenerated reference current I_{Bi} . If the supply voltage does vary for these closely located PFETs, the gate source voltage V_{sg} of all the PFETs will vary in the same way at the same time, such that the effect upon operation in the circuit 60 will be minimal.

[0032] It will be understood that the local regenerating circuit of FIG. 6A is not arranged to permit direct use of the reference current outputs I_{s41} , I_{s42} , etc. of the embodiment of FIG. 3. FIG. 6B illustrates a circuit 65 which allows such a reference current I_{s4i} to be converted into a suitable input current for use in the local regenerating circuit 60 of FIG. 6A. As shown in FIG. 6B, a reference current I_{s4i} is input to the drain of a diode-connected NFET Q64, having a gate tied to the gate of a mirroring NFET Q66, which has the same type as NFET Q64, but which may preferably be longer than NFET Q66 in order to mirror an output current that is a multiple of the incoming reference current I_{s4i} . Both NFET Q64 and NFET Q66 preferably have their sources coupled to ground, as shown. By such arrangement, a converted reference current 168 is output for use in the local regenerating circuit 60 of FIG. 6A.

[0033] FIG. 6C illustrates a network system 300 for generating and distributing reference currents over a plurality of areas of an integrated circuit. As shown in FIG. 6C, a reference current generator 320, coupled to a bandgap reference voltage generator 330, is located in the system 300 between a plurality of areas on the IC, shown exemplarily as quadrants 310A-310D, so as to provide a reference current on a wire, for example the wire 360UL, to a local regenerating circuit, for example circuit 340A1 coupled to the wire 360UL. Collectively, the four wires of the left group 350L provide one reference current each to the four local regenerating circuits 340A1-340A4 that lie to the left of the central reference current generator 320. Similarly, the four wires of the right group 350R provide one reference current to each of the local regenerating circuits in each of the areas 310C and 310D.

[0034] Several advantages are achieved through the network system 300 of this embodiment. First, since reference currents are generated centrally and then distributed and locally regenerated in other parts of the chip, the variation that may occur between independently generated reference currents in different areas of the chip is eliminated. In addition, since reference currents, rather than reference voltages, are transferred from one part of the chip to another, the transferred reference currents are less likely to be affected by noise disturbance across areas of the chip than is the case with voltages. In the network system 300, voltages are transferred between devices only in localized areas of the chip that are served by a locally regenerated reference current from a local regenerating circuit, e.g. circuit 340A1. Second, only one reference current generator 320 and only one bandgap reference generator 330 are required for the network system 300. This is an advantage over chips in which reference currents are independently generated in several parts of the chip, thus requiring multiple reference current generators and bandgap reference generators. The reduction in the number of reference current generators and bandgap reference generators, both of which require relatively high power consumption and large area, leads to savings of power and chip area.

[0035] FIG. 7A illustrates a prior art local current mirroring circuit 70 for mirroring an incoming reference current I_s from a diode-connected PFET p_0 , by a plurality of PFET mirror devices p_1, p_2, \dots, p_n , to a plurality of mirrored currents $I_{m1}, I_{m2}, \dots, I_{mn}$. As in the foregoing embodiment described relative to FIG. 6A, the quantity of the mirrored current I_{m1} depends on the size of the PFET mirror device, e.g. p_1 , relative to the size of the diode-connected PFET p_0 to which it is connected. The mirrored currents $I_{m1}, I_{m2}, \dots, I_{mn}$, in turn, are mirrored from a plurality of diode-connected NFETs n_1, n_2, \dots, n_n by having gate bias inputs coupled to a plurality of corresponding NFET tail transistors s_1, s_2, \dots, s_n , to generate a plurality of "tail" currents $I_{t1}, I_{t2}, \dots, I_{tn}$.

[0036] In this circuit 70, all of the PFETs p_0, p_1, \dots, p_n are located close to each other so as to reduce the possibility of variation in their threshold voltages, or disturbance due to a variation in the supply voltage VDD. The diode-connected NFETs n_1, n_2, \dots, n_n are located close to the respective tail devices s_1, s_2, \dots, s_n to which they are connected such that they too vary little in threshold voltage and are little affected by noise imparted from ground at the particular location since the both the diode-connected device n_1 and the tail device s_1 will be affected in the same way at that time. In this way, the prior art circuit 70 of FIG. 7A provides a high quality current transfer characteristic which is relatively immune to noise disturbance.

[0037] However, the circuit 70 of FIG. 7A consumes much power and chip area. It would be desirable to reduce the number of transistors therein while still maintaining good noise immunity, in order to reduce the consumption of power and chip area. Accordingly, local current mirroring circuits 80 and 90 are shown in FIGS. 7B and 7C which address these concerns. In these embodiments, unlike that shown in FIG. 7A, a reference voltage, rather than a plurality of mirror currents, transfers the bias between an NFET n_1 coupled to receive a mirrored current I_{m1} and a plurality of tail devices s_1, s_2, \dots, s_n . By doing so, the number of PFET mirror transistors p_1, p_2, \dots and diode-

connected NFET devices $n1, n2, \dots$ of these embodiments are reduced from one PFET and one NFET for every tail device $s1$, as shown in **FIG. 7A**, to only one PFET and only one NFET per each group of many tail devices $s1, s2, \dots sn$. However, because of the greater potential for noise disturbance when a voltage is transferred from on chip location to another, rather than a current, certain other modifications are necessary to preserve good noise immunity.

[0038] In the embodiment **80** shown in **FIG. 7B**, the connection to and quality of the voltage supply VDD are enhanced locally where contacted by the diode-connected PFET $p0$ and the PFET mirror device $p1$. In addition, the connection to and quality of the ground line **84** are enhanced where contacted by NFET $n1$ and the tail devices $s1, \dots sn$. The incoming reference current I_{s1} is mirrored from PFET $p0$ to PFET $p1$ and the mirrored current 1 ml is then driven through the diode-connected NFET $n1$ to ground to generate a reference voltage on line **86**. The reference voltage line **86**, connected to the gates of the tail devices $s1, s2, \dots sn$, then allows the current 1 ml to be mirrored from NFET $n1$ to a plurality of tail devices $s1, s2, \dots sn$, such as may each be coupled to a differential amplifier, as shown in **FIG. 1**, for example. Since the tail devices may not all be in the same location, filtering is added to reduce possible noise disturbance. Such filtering is accomplished, for example, by insertion of a plurality of resistive elements **87** along the reference voltage line **86** and placing capacitors **88** at the input to the tail devices $s1, s2, \dots sn$, etc., between the reference voltage line **86** and ground.

[0039] In the embodiment **90** shown in **FIG. 7C**, as in the embodiment shown in **FIG. 7B**, the connection to and quality of the voltage supply VDD **92** are enhanced locally where contacted by the diode-connected PFET $p0$ and the PFET mirror device $p1$, and the connection to and steadiness of the ground line **94** are enhanced where contacted by NFET $n1$ and the tail devices $s1, \dots sn$. As in **FIG. 7B**, the incoming reference current I_{s1} is mirrored from PFET $p0$ to PFET $p1$. The mirrored current 1 ml is then driven along a wire **91** from the location near the PFET mirror device $p1$ to a location of the diode-connected NFET $n1$ which is central to the NFET tail devices $s1, s2, \dots sn$. At that location, the mirrored current 1 ml is then driven through the diode-connected NFET $n1$ to ground to generate a reference voltage on line **96**. The reference voltage line **96**, connected to the gates of the tail devices $s1, s2, \dots sn$, then transfers the bias locally for the current 1 ml to be mirrored from NFET $n1$ to a plurality of tail devices $s1, s2, \dots sn$. Since the tail devices may not all be in the same location, filtering is added to reduce possible noise disturbance along the reference voltage line **96**. Such filtering is accomplished, for example, by insertion of a plurality of resistive elements **97**, each one adjacent to each tail device $s1, \dots sn$, etc. along the reference voltage line **96**, and placing capacitors **98** at the input of each tail devices $s1, s2, \dots sn$, etc. between the reference voltage line **96** and ground **94**.

[0040] In the foregoing described manner, in the circuit embodiments shown in **FIGS. 7B and 7C**, the number of PFET mirror transistors and corresponding diode-connected NFET transistors are reduced from one PFET and one NFET per every tail device $s1, s2, \dots sn$, to only one PFET and only one NFET per each group of many tail devices $s1, s2, \dots sn$. This, in turn, reduces the power and chip area that

each circuit embodiment **80** or **90** requires, while still maintaining adequate noise immunity through use of enhanced connections to the voltage supply and ground and adding filtering to the reference voltage line **86** or **96** which transfers the bias signal to each of a plurality of attached tail devices $s1, s2, \dots sn$.

[0041] While the invention has been described with respect to certain preferred embodiments thereof, those skilled in the art will understand the many modifications and enhancements that can be made without departing from the true scope and spirit of the appended claims.

1. An integrated circuit including a reference current generator adapted to generate a plurality of reference currents, comprising:

an operational amplifier coupled to receive, at a first polarity input, a reference voltage;

a first transistor **Q1** having a biasing input coupled to an output of said operational amplifier and an output coupled to a fixed potential through a first resistor **R1**, said output of said first transistor **Q1** further being coupled as feedback to a second polarity input of said operational amplifier;

one or more second transistors Q_i , each having a biasing input coupled to said output of said operational amplifier and an output coupled to said fixed potential through a respective second resistor R_i , said outputs of said one or more second transistors Q_i not being coupled as feedback to said operational amplifier;

wherein said operational amplifier maintains bias on each said first transistor **Q1** and each said second transistor Q_i for each to conduct a reference current I_{s1} .

2. The integrated circuit of claim 1 wherein said fixed potential is ground.

3. The integrated circuit of claim 1 wherein said reference voltage is referenced to output of a bandgap reference generator.

4. The integrated circuit of claim 3 wherein said reference voltage is provided as an undivided bandgap voltage reference to said first polarity input of said operational amplifier.

5. The integrated circuit of claim 3 wherein said reference voltage is provided as a resistively divided bandgap voltage reference to said first polarity input of said operational amplifier.

6. The integrated circuit of claim 1 wherein said first transistor and each of said second transistors comprise insulated gate field effect transistors (IGFETs) and said biasing inputs of said first transistor and said second transistors comprise gates of said IGFETs.

7. The integrated circuit of claim 6 wherein said first transistor and each of said second transistors further comprise n-type IGFETs.

8. The integrated circuit of claim 1 further comprising a local reference current regenerating circuit for receiving a reference current and locally regenerating one or more local reference currents from each said received reference current, said local reference current regenerating circuit comprising:

a pair of end-to-end coupled, diode-connected transistors coupled between a voltage supply and a received reference current; and

one or more pairs of end-to-end coupled mirror transistors, each mirror transistor having a biasing input coupled to a respective biasing input of a corresponding one of said end-to-end coupled, diode-connected transistors, such that each pair of said mirror transistors is adapted to locally regenerate a local reference current from said received reference current.

9. The integrated circuit of claim 8 further comprising an end use current source generator adapted to generate an end use current source, said end use current source generator comprising

a second diode-connected transistor coupled to said local reference current, and

a second mirror transistor having a biasing input coupled to a biasing input of said second diode-connected transistor, such that said second mirror transistor is adapted to generate said end use current source.

10. The integrated circuit of claim 9 wherein said end use current source is coupled to a differential amplifier as an operating current thereof.

11. The integrated circuit of claim 1 further comprising a second reference current generator coupled to receive a second reference voltage input from a line conducting a reference current I_{si} output from said reference current generator, said second reference current generator being adapted to generate a plurality of second reference currents.

12. The integrated circuit of claim 11 wherein said reference voltage input to said second reference current generator is generated from a voltage drop due to said reference current I_{si} across a resistor placed between a supply voltage V_{TT} and said input to said second reference current generator.

13. The integrated circuit of claim 12 wherein said reference voltage input to said reference current generator is output from a bandgap reference generator having a voltage supply V_{AA} having a higher voltage than said supply voltage V_{TT} .

14. The integrated circuit of claim 13 wherein said second reference current generator includes

an operational amplifier coupled to receive, at a first polarity input, said second reference voltage;

a plurality of transistors $Q_1 \dots Q_n$, n being the total number, each transistor having a biasing input coupled to an output of said operational amplifier and each transistor Q_i further being coupled through a respective first resistor R_i to a common node, said common node being coupled through a second resistor R_0 to a fixed potential;

wherein a voltage of said common node is further coupled as feedback to a second polarity input of said operational amplifier, and

wherein said operational amplifier is adapted to maintain bias on each said transistor Q_i to each conduct a respective reference current I_{sj} .

15. A system including a reference current generator according to claim 1 for generating and distributing a plurality of reference currents to multiple locations of an integrated circuit, comprising:

a plurality of wires adapted to conduct said reference currents I_{si} output from said reference current generator to remote locations of said integrated circuit; and

a plurality of local reference current generators receiving said reference currents Q_i in said remote locations and adapted to regenerate local reference currents I_{sj} from said reference currents I_{si} .

16. An integrated circuit including a reference current generator adapted to generate a plurality of reference currents, comprising:

an operational amplifier coupled to receive, at a first polarity input, a reference voltage;

a plurality of transistors $Q_1 \dots Q_n$, n being the total number, each transistor Q_i having a biasing input coupled to an output of said operational amplifier and each transistor Q_i further being coupled through a respective first resistor R_i to a common node, said common node being coupled through a second resistor R_0 to a fixed potential,

wherein a voltage of said common node is further coupled as feedback to a second polarity input of said operational amplifier, and

wherein said operational amplifier is adapted to maintain bias on each said transistor Q_i to each conduct a respective reference current I_{si} .

17. The integrated circuit of claim 16 wherein said second resistor R_0 is located external to said integrated circuit and has resistance which varies little with operating conditions.

18. The integrated circuit of claim 17 wherein said fixed potential is a supply voltage V_{DD} , and said reference current I_{si} through a given said transistor Q_i is determined by the equation: $I_{si} = (1/n)(1/R_0)(V_{DD} - V_{ref})$, wherein V_{ref} denotes said reference voltage.

19. The integrated circuit of claim 16 wherein said reference voltage is referenced to output of a bandgap reference generator.

20. The integrated circuit of claim 19 further including a voltage reference circuit adapted to output said reference voltage (V_{ref}) as a difference from a supply voltage V_{DD} and a constant m multiplied by a stable voltage V_s , such that said reference voltage V_{ref} is a function of $V_{DD} - mV_s$ and said reference current I_{si} output from each said transistor Q_i is independent from said supply voltage V_{DD} , as determined by the equation: $I_{si} = (1/n)(1/R_0)(mV_s)$.

21. The integrated circuit of claim 20 wherein said voltage reference circuit includes

an operational amplifier coupled to receive a stable voltage V_s at a first polarity input,

a reference circuit transistor having a biasing input coupled to an output of said operational amplifier, and a first voltage output coupled as feedback to a second polarity input of said operational amplifier such that, in operation, said first voltage output is maintained at said stable voltage V_s , and further having a second voltage output coupled to provide said reference voltage V_{ref} to an input of said operational amplifier of said reference current generator;

a first resistor R_x coupled between said first voltage output of said reference circuit transistor and a fixed potential; and

a second resistor R_y coupled between said second voltage output of said reference circuit transistor and a supply voltage,

whereby said reference voltage is provided to said reference current generating circuit as $VDD (Ry/Rx)Vs$.

22. The integrated circuit of claim 21 wherein said stable voltage Vs is referenced to an output of a bandgap reference generator.

23. The integrated circuit of claim 21 wherein said fixed potential is ground.

24. A system including a reference current generator according to claim 16 for generating and distributing a plurality of reference currents to multiple locations of an integrated circuit, comprising

a plurality of wires adapted to conduct said reference currents I_{si} output from said reference current generator to remote locations of said integrated circuit; and

a plurality of local reference current generators receiving said reference currents Q_i in said remote locations and adapted to regenerate local reference currents I_{sj} from said reference currents I_{si} .

25. A method of generating and distributing a plurality of reference currents to multiple locations of said integrated circuit, comprising:

centrally generating a plurality of reference currents using a centrally located stable reference voltage and a plurality of generator transistors Q_i , each having an output coupled to a fixed potential through a resistor;

distributing said centrally generated reference currents to different locations of said integrated circuit; and

locally regenerating, through current mirroring, a plurality of local reference currents in said different locations from each said centrally generated reference current.

26. A method of locally regenerating a plurality of reference currents from a remotely generated reference current, comprising:

locally regenerating a first reference current from a remotely generated reference current through a mirror transistor having a biasing input coupled to a biasing input of a diode-connected receiving transistor being coupled to conduct said remotely generated reference current;

applying said first reference current to a biasing input of a diode-connected transfer device to locally generate a reference voltage; and

applying said locally generated reference voltage to biasing inputs of a plurality of second transistors to locally regenerate a plurality of second reference currents.

27. The method of claim 26 further comprising filtering said locally generated reference voltage prior to applying said locally generated reference voltage to said biasing inputs.

28. The method of claim 27 wherein said filtering is performed by RC (resistor and capacitor) elements placed along a line by which said locally generated reference voltage is carried.

29. The method of claim 26 further comprising locating said single diode-connected transfer device closer to and central to said plurality of second transistors.

30. The method of claim 26 further comprising providing locally enhanced connections to power supply and to ground to said receiving transistor, said mirror transistor, said transfer device and said plurality of second transistors.

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