The present invention relates to a novel and inventive compound device structure, enabling a charge-based approach that takes advantage of sub-threshold operation, for designing analog CMOS circuits. In particular, the present invention relates to a solid state device based on a complementary pair of n-type and p-type current field-effect transistors, each of which has two control ports, namely a low impedance port and gate control port, while a conventional solid state device has one control port, namely gate control port. This novel solid state device provides various improvement over the conventional devices.
COMPLEMENTARY CURRENT FIELD-EFFECT TRANSISTOR DEVICES AND AMPLIFIERS

CROSS-REFERENCE TO RELATED APPLICATIONS
Not Applicable.

BACKGROUND OF THE INVENTION

Field of the Invention
The present invention relates to a novel and inventive compound device structure, enabling a charge-based approach that takes advantage of sub-threshold operation, for designing analog CMOS circuits.

Description of Related Art
The new millennium brings with it a demand for connectivity that is expanding at an extremely rapid pace. By the end of year 2015, the number of global network connections will exceed two times the world population and it is estimated that in 2020 more than 30 billion devices will be wirelessly connected to the cloud forming the Internet of Things (or “IoT”). Enabling this new era are the revolutionary developments in mobile computing and wireless communication that have arisen over the last two decades. Following Moore’s Law, development of highly-integrated and cost-effective silicon complementary metal oxide semiconductor (CMOS) devices allowed incorporation of digital and analog system elements, such as bulky Analog-to-Digital converters or transceivers, into a more cost effective single chip solution.

In the last few years, however, while digital circuits have largely followed the predicted path and benefited from the scaling of CMOS technology into ultra-deep submicron (sub-μm), analog circuits have not been enabled to follow the same trend, and may never be enabled without a paradigm shift in analog design. Analog and radio frequency (or “RF”) designers still struggle to discover how to make high-performance integrated circuits (or “ICs”) for ultra-deep sub-μm feature sizes without losing the benefits of shrinking size; including reduced power, compact footprint, and higher operational frequencies. Truly a paradigm shift is needed to break through the established science of analog design to meet the system on chip (SoC) demands of the new millennium.
Prior Art:

The core building block of analog circuits is the amplifier. Discrete component amplifiers are free to use resistors, capacitors, inductors, transformers, and non-linear elements as well as various types of transistors. Unwanted parasitics between various components are normally negligible. However, in order to build amplifiers within an integrated circuit, the normal analog circuit components are not readily available, and often take special IC process extensions to obtain these circuit elements if at all. The parasitics on integrated circuit amplifiers are severe due to their close proximity and being coupled together through the silicon wafer they are integrated into. Moore’s law IC process advancements are focused on digital, microprocessor, and memory process development. It takes a generation (~18 months) or two to extend the IC process to incorporate analog components, thus analog functionality is generally not included on the latest process single chip systems. These “mixed-mode” IC processes are less available, vendor dependent, and more expensive as well as being highly subject to parametric variation. It takes substantial engineering to include sparse analog functionality on any IC which becomes specific to its IC vendor and process node. Because analog circuitry is carefully and specifically designed or arranged for each process node, such analog circuitry is highly non-portable. Eliminating this limitation, analog circuit design engineers are becoming scarce and are slowly retiring without adequate replacements.

Operational Amplifiers (or OpAmps) are the fundamental IC analog gain block necessary to process analog information. OpAmps make use of a very highly matched pair of transistors to form a differential pair of transistors at the voltage inputs. Matching is a parameter that is readily available on an integrated circuit, but to approach the required level of matching, many considerations are used: like centroid layout, multiple large devices, well isolation, and physical layout techniques among many other considerations. Large area matched sets of transistors are also used for current mirrors and load devices. OpAmps require current sources for biasing. OpAmps further require resistor and capacitor (or RC) compensation poles to prevent oscillation. Resistors are essential for the “R” and the value of the RC time constant is relatively precise. Too big value for a resistor would make the amplifier too slow and too small results in oscillation. Constant “bias” currents add to the power consumed. In general, these bias currents want to be larger than the peak currents required during full signal operation.
As IC processes are shrunk, the threshold voltages remain somewhat constant. This is because the metal-oxide-semiconductor (or MOS) threshold cutoff curve does not change with shrinking of the IC processes and the total chip OFF leakage current must be kept small enough to not impact the full-chip power supply leakage. The threshold and saturation voltage tends to take up the entire power supply voltage, not leaving enough room for analog voltage swings. To accommodate this lack of signal swing voltage, OpAmps were given multiple sets of current mirrors, further complicating their design, while consuming more power and using additional physical layout area. This patent introduces amplifier designs that operate even better as power supply voltages are shrunk far below 1 volt.

Prior art CMOS integrated circuit amplifiers are based on several analog or mixed-mode IC process extensions which are not available on all-digital IC processes. Primarily matched pairs of transistors are used as a differential inputs and current mirrors. These analog FET transistors must be long, as depicted in Figure 1q, to provide the necessary high output resistance, and also must be wide in order to support the necessary current that is mirrored between them. For example, conduction channel 13q which is operable by the gate terminal 17q must have a sufficient length or distance between the source terminal 14q and the drain terminal 19q on the body/substrate 16q. Bias currents, which are normally larger than the peak analog signal currents, must be generated and maintained. Resistors and large area capacitors are normally required to create references and stabilize the amplifiers. Because of parametric sensitivity, these designs are not very portable between IC processes or vendors. They are redesigned for each IC process node and are very specifically tailored to their various applications. Due to their bulkiness amplifiers are normally the limiting speed element of an IC system. What is needed is a scalable design that uses logic-only IC processes components, is process parameter tolerant, consumes a small area, uses relatively low power, and operates at voltages significantly below 1 volt. This is the subject of the present invention.

The conventional MOS amplifier gain formation is an input voltage driving a trans-conductance (g_m) which converts the input voltage into an output current. This output current then drives an output load which is normally the output of a current source for the purpose of establishing a high load resistance. This high resistance load converts the output current back into an output voltage. The resulting amplifier voltage gain is $g_m \times R_{load}$. The equivalent output load resistance is actually the parallel combination of the load current source transistor and the amplifier output transistors. In order to keep this equivalent load resistance high, and the voltage gain high, these parallel transistors must be very long, but to drive enough
current, these transistors must be very wide to carry sufficient current also, thus very large transistors are necessary. It also might be noted that the load resistance the amplifier output drives is also an additional parallel resistance that reduces the voltage gain. It should also be noted that a load capacitance interacts with the amplifiers output resistance, modifying the AC performance characteristics. What is actually needed is exactly the opposite of the present analog amplifier operating principles of very small voltage-input to high-impedance current-output ($g_m$); which the present invention is about: very small current-input to low-impedance voltage-output ($r_m$). Figure 1a is a transistor level schematic diagram of a high-quality MOS IC OpAmp as a baseline reference (Gray, Paul R. et al., “Analysis and Design of Analog Integrated Circuits,” 5th edition, John Wiley & Son Ltd, at pg. 484) which is used for comparison in the description of the amplifiers illustrated herein.

The baseline comparisons are (all made in a 180nm IC process) in the form of performance plots as in: a Bode Gain-Phase plot Figure 1b, when $V_{dd} = 1.8$ Volts and $R_{cmp} = 700$ ohms. Wherever possible all the axis scales for each of these three comparison plots are kept the same. A 180nm process was selected for comparison of all the comparative examples in this specification because conventional prior art amplifiers work best and have had the most usage to mature the analog mixed-mode IC process extensions offered as required for conventional analog. Also as the IC process is shrunk and the power supply voltage is decreased, this is where the implementations of the present invention become highly beneficial.

Normally MOS amplifiers operate within a square-law form due to the strong-inversion MOS transistor square-law characteristics; these are not very well defined or predictably stable to the degree that analog circuits need. Exponential-law operation, like bipolar transistors operation is higher gain, stable, and well defined. At very weak operating conditions, MOS transistors convert to exponential operation, but they are too slow to be of very much use. Furthermore, the “moderate-inversion” transition between these two operating mode provide non-linearities that lower the quality of analog MOS circuits. At the threshold voltage, where MOS transistors operate around, is where 50% of the current is square-law and the other 50% is exponential. This is the definition of threshold voltage in the latest MOS simulation equations. Full exponential MOS operation at high speed would provide higher gain that is predictable, stable, and well defined. This patent is about fast amplifiers that operate in the exponential mode but not in weak-inversion; instead a supersaturated mode is introduced.
To understand the prior art, let’s begin with a discussion of weak vs. strong-inversion (Enz, Christian C. et al., “Charge-based MOS Transistor Modeling – The EKV model for low-power and RF IC Design, John Wiley & Son Ltd., 2006). Referring to Figures 1e and 1f, weak-inversion is the range where most designers would consider the transistor to be OFF:

- Weak conduction channel inversion 13e occurs when the Gate 17e on the body/substrate 16e is operated below its threshold voltage $V_{\text{threshold}}$ 17f in Figure 1f with channel ionization 13e characterized by a thin surface layer;
- Source 14e to Drain 19e voltage 19f is small (typically less than 100 mV);
- For weak-inversion, the gate G 17e is typically operated by gate voltage supply 12e at a low potential (~300mV);
- This creates a channel surface conduction layer 13e, of uniform depth from source S 14e to drain D 19e;
- Since there is essentially zero voltage gradient along the channel 13e (~no electric field), any current between drain D 19e and source S 14e is primarily supported by diffusion;
- Increased gate voltage Vgs 12e at the gate G 17e increases the thickness of the conduction layer 13e below the gate 17e, thus allowing more charge to diffuse along the channel 13e;
- The conductivity of this surface layer is exponentially related to the gate voltage Vgs 12e at the gate G 17e;
- This exponential relationship holds over as many as 6 decades of dynamic analog signal range for the drain channel current;
- The channel appears as a moderately high value resistor for its channel current (many 100’s of K-Ohms);
- The resulting uniform conduction channel depth promotes higher exponential gain but at a severe speed penalty due to low current density; and
- This weak-inversion conduction is reflected in a near zero operating point 13f in Figure 1f.

Strong conduction channel inversion occurs when the gate voltage Vgs 12g at the Gate 17g on the body / substrate 16g is operated above its threshold voltage 17h (referring to Figures 1g and 1h) with channel ionization characterized by a graduated conduction channel, deeper near the Source 14g and shallow near at the Drain 19g;
- Strong conduction channel inversion 15g and 15h occurs when the Drain 19g to Source 14g voltage 19h is larger than the threshold V_{threshold} 17h in Figure 1h (typically in excess of 400mV);
- The Gate 17g is operated above its threshold voltage V_{threshold} 17h in Figure 1h;
- In strong-inversion 18g, the Drain 19g voltage is typically operated above the Gate 17g voltage which results in a pinched-off conduction channel 15g near the Drain 19g;
- This pinched-off channel at 15g gives rise to high output impedance at the Drain 19g and can be observed as the thick flat part 18h of the operating characteristic plot Figure 1h;
- As the Drain 19g voltage V_d is changed, the pinched-off region 15g changes length, but its thin conduction layer is retained, keeping the output impedance high;
- Due to the Gate 17g to channel 15g voltage and the electric field along the conduction channel path (Drain 19g to Source 14g), the conduction channel 15g is forced deeper at the Source 14g and tapers to near pinch-off at the Drain 19g;
- The resulting conduction layer behaves with a Square-law response to the gate voltage at the Gate 17g;
- In strong-inversion, dynamic range of channel current is limited to about 2 or 3 decades; the channel must drop into weak-inversion for additional dynamic range;
- This strong-inversion conduction channel 15g appears as an adjustable current source (high value resistor); and
- The wedge shape of the conduction channel 15g provides high speed from high current density, but requires the carriers to transit the channel and velocity saturation is reached limiting the speed or cutoff frequency of the transistor; and
- This is reflected as the operating point 15h in Figure 1h which is along its bolded line 18h.

Figure 1e, shows the channel development under weak-inversion conditions. The conduction channel has a relatively even distribution of carriers over its entire length and
width. Note that the conduction layer 13e depth of the entire channel is the same as the pinch-off area 15g on the right channel side (or near the drain 19g) of Figure 1g. The output drain voltage Vd loaded on the drain D 19e by bias current, I_{bias} Ld19e. This thin conduction layer 13e contributes a significant amount of noise because the channel current travels along the surface where defect traps are concentrated. The Gate 17e to channel voltage Vg in Figure 1e has a strong (exponential) effect on the density of carriers in this conduction layer 13e.

Figure 1f shows a plot which has an exponential relationship of drain current I_d to drain voltage V_{ds} using a fixed gate voltage V_g. It is to be noted that the drain voltage V_{ds} must be limited to a small value (on the order of 100 mV) in order to stay in weak-inversion.

Figure 1g shows channel 15g ionization under strong-inversion conditions. In strong-inversion, there is an output drain voltage V_d loaded on the Drain 19g by an output load: I_{bias} Ld19g. This load presents a lower potential difference between Gate 17g and Drain 19g end of the conduction channel 15g than the potential difference between the Gate 17g and Source 14g end of the conduction channel, resulting in a tapered conduction channel 15g. The conduction channel thins down to a minimum as it approaches the drain providing a high output resistance. This output resistance is primarily defined by the thin channel cross-sectional area. As the drain voltage is varied, this thin pinched-off length of the channel changes, but not so much its cross-sectional area. This leads to a high output resistance, in that Drain 19g output resistance variation with drain voltage is relatively small, yielding a high output resistance. This high resistance is required in conventional g_m analog MOS circuit design. In this pinched-off channel region, the carriers approach their velocity saturation, thus limiting their transit time along the channel. This is called “channel length modulation” (the flat part of the channel 15g), resulting in pinch-off near the drain diffusion where the channel reaches a thin layer at 15g. The pinch-off region, where the carriers are forced to the top of the channel, imparts significant noise by means of surface defect carrier traps. The higher the drain voltage V_d, the longer the pinch-off region and thus the higher the contributed noise (Rahul, Sarapeshkar, “Ultra Low Power Bioelectronics-Fundamentals, Biomedical Applications, and Bio Inspired Systems”, ISBN9780521857277, and Lee, Thomas “The Design of CMOS Radio-Frequency Integrated Circuits”, 2nd Ed, Cambridge ISBN-13 978-0521835398), thus is desired to keep this voltage low for low noise contribution to the channel current. Other effects such as velocity saturation and hot electron jumping over to the gate oxide are noted around this thin saturated region, thus it would be highly desirable to minimize this region by lower voltage and semiconductor doping profiles.
Figure 1h shows a characteristic plot which approaches a “constant current” relationship between drain current $I_d$ and drain voltage $V_{ds}$ with a fixed Gate voltage $V_g$ on the gate G. It is to be noted that the drain voltage $V_{ds}$ spans a much larger range of nearly the power supply voltage $V_{dd}$, while maintaining the same current.

A two-finger CMOS inverter is illustrated in Figures 1i, 1j, 1k, 1m, and 1n. A logic inverter possesses several desirable properties:

- They exist in all logic IC processes
- are the most common and fundamental building block
- highly scalable
- process parameter drift tolerant
- small
- high speed
- high output drive for varying capacitive loads
- arguably the highest gain of a complementary pair of MOS transistors
- low power
- easily used

A basic two finger inverter schematic of the prior art is depicted in Figure 1i. For example, $V_{in}$ 10i of the basis two finger inverter 100 is connected to the gate terminals of NFET 101 and PFET 102. The source terminal of NFET 101 is connected to negative power voltage, and the source terminal of PFET 102 is connected to positive power voltage. The drains of NFET 101 and PFET 102 are connected together to form an output 19i. A generic physical layout is illustrated in Figure 1k in parallel with another inverter schematic diagram in Figure 1j which has been stretched out and aligned alongside the physical layout to correlate the inverter schematic Figure 1j to the physical layout structure Figure 1k. Artistic liberty was used to clearly relate these two figures. Actual physical layout would be in accordance of the design rules and practices of the IC process it is designed for. Figure 1m is a 3-D sketch of the physical layout. Figure 1n shows a cross-section view of the physical layout as indicated Section AA in Figure 1m. The two finger inverter 100 includes a common gate terminal 10j/10k/10m/10n, and output 19j/19k/19m/19n connected to drain terminal D- 11j/11k/11m/11n and D+ 12j/12k/12m/12n. As can be seen in Figures 1k to 1n, the drain D- 11k/11m/11n is displaced between the source terminals, S- s13k/s13m/s13n and s15k/s15m/s15n, while the drain D+ 12k/12m/12n is displaced between the source terminals, S+ s16k/s16m/s16n and s14k/s14m/s14n. The pull down transistor channel 13k/13m/13n is in parallel with 15k/15m/15n, while the other pull down transistor channel 14k/14m/14n is in
parallel with 16k/16m/16n. The poly transistor control gate 17k/17m/17n is in communication with the gate terminal 10k/10m/10n. Drain diffusions 12n are shown in Figure 1n. The charge distribution in the drain channels 13n, 15n, 14n, and 16n are shown in Figure 1n. This charge distribution is illustrated for the voltage where the logic is in the middle or most active part of its state change. This charge distribution is an extension of the charge distribution in Figure 1g. These inverter figures are closely related to the present invention as the basis for making minor alterations that do not require any IC process modification as will be developed below.

Figure 1p illustrates a prior art MOS structure that turns out to actually emulate a combination of both modes of operation; strong-inversion Figure 1g, 1h with enhanced weak-inversion-like properties of Figure 1e, 1f. This structure is inherent in a 2-finger inverter as shown twice in the Figure 1k physical layout abstraction. For reasons that will be developed, this structure will be named an iFET (MOSFET with a current input terminal = i) where the MOS structure is employed for the present invention.

Although similar MOS structures appear in prior art, no significant exploitation of many of its unique properties are known or published. In addition, proper biasing remains as a problem(s) for its operation(s). A deeper understanding of the internal mechanisms resulted in discovery of many desirable applications (enabling superior operation at deep-sub-micron scale), including an approach to proper biasing that takes advantage of natural equilibrium. This natural equilibrium is the result of a “PTAT”/”CTAT” (proportional to absolute temperature / complement to absolute temperature) known as a “Band-Gap” voltage reference mechanism, again functional at deep-sub-micron scale.

Some references show a MOS field effect device includes a body / substrate 16p, the source terminal 14p and drain terminal 19p on the body 16p. The gate terminal 17p is placed between the source terminal 14p and the drain terminal 19p for controlling conductivity therebetween. The device further includes two identical regions 13p and 15p of like “conductivity type” separated by a diffusion region 11p (designated as Z for Low Impedance in the prior art) as shown in Figure 1p. Non-patent literature, Pain, Bedabrata et al., “Low-power low-noise analog circuits for on-focal-plane signal processing of infrared sensors”, the Jet Propulsion Laboratory, California Institute of Technology, and the Defense Advanced Research Projects Agency and the National Aeronautics and Space Administration; and Baker, Jacob et al., “High Speed Op-amp Design: Compensation and Topologies for Two and Three Stage Design”, Boise State University, for example, shows such a structure. However, these references do not exploit any opportunities as shown in this present invention,
especially when complementary devices like this are combined into a single composite device structure as will be explained in this invention. Such configurations have been called self-cascading or split-length devices. The two conduction regions of such a configuration are arranged between source and a drain diffusions and have both a high impedance common gate connection and a low impedance Z connection to the mid channel region. This low impedance mid channel control input/output Z, when exploited as outlined in this document, enables an entirely new set of analog design methods and capabilities.

Although a cascode amplifier can be found in prior art, the prior art does not contain a complementary pair of cascode transistors connected as a totem-pole. With this simple compound device structure, feedback from the output to the input can be used to self-bias the resulting inverter into its linear mode. As mentioned above in association with Figure 1a, the biasing of an amplifier by means of current mirrors has always been problematic; however, the novel and inventive self-biasing structure of the present invention addresses such an issue. Advantages of the configuration of the present invention (referred to as a complementary iFET or CiFET) are many, including, but not limited to:

- Gain of the single stage is maximum when the output is at the midpoint (self-bias point);
- The gain of a single CiFET stage is high (typically approaching 100), therefore, while the final output may swing close to the rails, its input remains near the midpoint where the gain is high.
- When used in a series chain of CiFET devices, all earlier stages operate with their inputs and outputs near the mid-point (“sweet-spot”) where the gain is maximized;
- Slew rate and symmetry are maximized where the channel current is highest (near the mid-point);
- Noise is minimized where the channel current is highest (near the mid-point); and
- Parasitic effects are negligible where the voltage swing is small.

When the gate input signal moves in one direction, the output moves in the inverse direction. For example; a positive input yields a negative output, not so much because the N-channel device is turned on harder, but rather because the P-channel device is being turned off. A Thevenin/Norton analysis perspective shows that the current through the P and N devices must be exactly the same, because there is nowhere else for drain current in one
transistor to go except through the drain of the complementary transistor; however the voltage drop across those devices does not have to be equal, but must sum to the power supply voltage. Due to the super-saturated source channel, these voltages are tied together exponentially. This is even more evident at low power supply voltages where the voltage gain peaks due to the conduction channels being forced into a diffusion mode of operation similar to weak-inversion. This means that the gate-to-source voltage is precisely defined by the same and only drain current going through both transistors. Exponentials have the unique transparent physical property like as with a time constant, or “half-life;” It does not matter where a value is at a given point of time, a time constant later the value will be a fixed percentage closer to the final value. This is a “minds-eye” illustration of the primary contributor to output movement in response to input change. This same current balance of gate-to-source operating voltages also indicates why the “sweet-spot” in the self-biased amplifier is so repeatable. In effect it is used as a differential pair-like reference point to the amplifier input signal.

Briefly stated, the operation of the conventional CMOS amplifier of Figure 1a is as follows:

In operation, differential analog input voltages are applied to Input + 10a and Input − 11a of a precisely matched pair of transistors Q1a and Q2a respectively. Any mismatch in these two transistors appears as a DC voltage added to the differential input. If there is 1 millivolt of mismatch, which is very hard to meet in CMOS, and the amplifier has a gain of 1000, the output voltage error will be 1 volt. In newer IC process nodes, power supplies are already limited to less than a volt. Exotic double centroid physical layout with multiple identical transistors arranged in diametrical opposition and everything else possible symmetrically possible are needed in the physical layout of the differential pair to minimize the offset voltage.

These amplifiers function by steering and mirroring bias currents from a current source 12a between their transistors. All the bias currents have to be larger than the peak signal deviations and these currents always flow. These currents also have to be large enough to drive the internal capacitive load of the amplifier’s internal transistors plus interconnect, not to mention the output drive current which comprises the capacitive load at the maximum bandwidth frequency or slew rate.

The first bias current mirror input transistor is a transistor Q8a which is “diode connected” in that its gate and drain are tied together and bias at a threshold voltage below the top power supply rail. This bias voltage is applied to the gates of two transistors Q5a,
Q7a additional positive rail based current mirrors that have to be matched to a lesser degree. In order to progressively increase the mirrored currents from the bias current mirror input transistor Q8a to the differential current feed transistor Q5a to the output pull-up current transistor Q7a, the transistors Q5a and Q7a are actually multiple instances connected in parallel. A double for the transistor Q5a and an eight (8) times for the transistor Q7a are typical choices for these multiples.

The differential pair of the transistors Q1a, Q2a is used to split the bias current to the transistor Q5a equally at the zero differential voltage input where the amplifier strives for. To achieve a voltage gain in analog designs, a positive drive current is balanced against a negative drive current. The differential pair of transistors Q1a, Q2a achieves this by mirroring transistor Q3a of the outputs back to the other leg of transistor Q4a, making current opposition with the transistor Q2a. Voltage gain is $g_m \times R_L$ where $R_L$ is the parallel combination of the output impedance of the transistors Q4a and Q2a. For analog MOSFET transistors to present a high impedance on their output, they need to be very long because the depletion width due to drain voltage modifies the conduction channel length near the drain terminal. This is called “channel length modulation” which is similar to the bipolar “Early voltage” named by Jim Early of Fairchild Semiconductor during the early bipolar days. For this high output impedance requirement, the transistor Q4a must be long, and it also must be equally wide to preserve its gain setting the basic transistor sizing of the amplifier. This size must be set equal for the transistors Q3a and Q6a, except the transistor Q6a must also include the multiple used for the transistors Q5a to Q7a along with a factor of two to make up for the split of current by the differential pair. In equilibrium, the gate voltage on the transistor Q6a wants to be the same as the gate voltage on the transistors Q3a, Q4a looking like a pseudo-current mirror arrangement at the bottom power supply rail.

There are still many other linear amplifier circuit design considerations beyond these basic principles like stability considerations by compensation resistance or $R_{comp}$ 15a and compensation capacitance or $C_{comp}$ 16a and power supply noise rejection. As can easily be envisioned, the design of analog circuits in an IC is quite involved, process parameter dependent, and not very portable between IC processes.

The resulting linearity of these amplifiers are also limited due to different non-linear characteristics between the gain device and the load device (pull-up and pull-down) which cannot cancel each other out. The CiFET device structure, which is the present invention to be explained later in this specification, loads itself with the same device structure, except that
the combination obtains its complementary nature through the use of opposite semiconductor diffusion types which inherently and precisely mimic any non-linear characteristics with the opposite sign to cancel each other’s linearity deviations out. CMOS inverters get their opposing drive through the opposite semiconductor diffusion type, thus are a good foundation to base linearity on. This is because the same current is carried through one transistor is also passed through the complementary device. Inversion is obtained through opposite diffusions.

It is to be noted that during the transition from vacuum tubes to bipolar transistors the industry underwent a major paradigm shift, learning to think in terms of current rather than voltage. With the advent of FETs & MOSFETs the pendulum swing is back toward thinking in terms of voltage, but much knowledge has been lost or forgotten. Herein is contained the rediscovery of some old ideas as well as some new ones, all applied to the up-coming “current” state of the art. It is believed that the inherent simplicity of the present invention speaks to their applicability and completeness.

A first issue may be that there is always a need for a little analog functionality, yet nearly all analog performance metrics of a MOS transistor are remarkably poor as compared to that of a Bipolar transistor. The industry has made MOS devices serve by employing extensive “work-around.” Conventional analog design is constrained by one or more of the followings:

- Power supply voltages sufficient to bias the stacked thresholds, and transistors large enough to supply the necessary low output impedance, or high output impedance for gain and linearity.
- Process extensions (unavailable at deep sub-μm scale) to function at all, let alone with the enhanced performance, demonstrated herein.
- Resistors, inductors, and large capacitors are mostly non-existent for analog designs in newer IC processes.

In contrast, bipolar transistors can be made to have high gain (β), wider bandwidth, wider dynamic range (many decades, from near the rails down to the noise floor), better matching (required in differential pairs), and band-gap references. Junction FETs, which operate with sub-surface channel conduction below the surface defects, have lower noise than bipolar transistors. Likewise the iFET super-saturated source channel operates primarily below the defects at the channel surface underneath the gate oxide.

MOS designs are poorer in the above areas but have their own extreme advantages, including, but not limited to:
✓ MOS devices are small
✓ highly scalable
✓ high speed
✓ low power
✓ ultra-dense / high functionality systems on a chip, where Bipolar designs cannot go (deep sub-μm scale).

Accordingly, building analog circuits on an IC has always been problematic. Engineering around poorly performing analog components has been the overriding objective for analog IC designers since analog circuits have been integrated. This drove the need for digital signal processing with algorithm development yielding digital magic.

Today the real-world of analog circuit design signals still needs to be converted, on both the front and back end of signal processing systems. This need has become a road-block at deep sub-μm scale.

Another problem may be that solid-state amplifiers have been notoriously non-linear since their inception. To make them linear, increased open loop gain (with levels significantly higher than is ultimately needed) is traded for control over actual circuit gain and linearity through the use of a closed loop (feedback). A closed loop amplifier requires negative feedback. Most amplifier stages are inverting, providing the necessary negative feedback. A single stage, with a closed loop, is stable (does not oscillate). Increased loop gain requires that stages be added such that there are always an odd number of stages (sign is negative), to provide the necessary negative feedback. While a single stage amplifier is inherently stable, three stages and most definitely five stages are unstable (they always oscillate).

The problem then is how to properly compensate a multi-stage closed loop amplifier while maintaining a reasonable gain-bandwidth product. This is particularly difficult at deep-sub-micron scale where circuit stages must be simple in their design. The severely limited power supply voltages preclude the use of conventional analog design approaches. Additionally, it is desirable to avoid reliance upon analog extensions but rather to accomplish the necessary analog functions using all digital parts, to improve yields and decrease costs. Using all digital parts allows analog functions at process nodes that do not yet have analog extensions, and may never have them.

There is a long felt needs for low-cost / high-performance systems on a single chip to realize, affordable high-volume devices such as the Internet of things, smart-sensors, and other ubiquitous devices.
SUMMARY OF THE INVENTION

The present invention relates to a novel and inventive compound device structure, enabling a charge-based approach that takes advantage of exponential relationships of a super-saturated source channel described in relation to Figures 2a, 2b and 2e to 2m below which possesses sub-threshold like operation when used for analog CMOS circuit designs. The sub-threshold like operation offers current input to voltage output trans-impedance functionality with interesting properties.

Through incorporating this compound device structure 200 as shown in Figure 2m into an inverter, the present invention is an evolution of an ordinary CMOS inverter. It provides extremely high precision, speed, linearity, low voltage operation, low noise, and a compact physical layout, using an all-digital IC process that naturally extends into deep sub-μm IC process nodes. In addition to the expected digital inverter function, several classes of analog circuits are facilitated: a voltage input to voltage output amplifier, a current input to voltage output amplifier, an analog adder, an analog multiplier, a spectrally-pure sine-wave multi-phase oscillator controlled through an adjustable delay circuit, and a Voltage or Current reference source which includes temperature measurement or temperature independence. It is envisioned that the present invention may open up the possibility of integrated analog signal processing at logic speed, thus enabling the continuation of microprocessor capability according to Moore’s law. Take special note that analog functionality is realized, in a digital IC process, using a single optimized digital logic circuit cell.

A preferred embodiment of the present invention 300 provides for a stacked pair of transistors with a common gate 301, mirrored with a complementary pair of stacked transistors 302 Figures 3a, 3b, 3c, 3d, 3e (like a digital inverter 100 in Figures 1i, 1j, 1k, 1m, 1n), with feedback from its own output to establish an optimum bias point. This configuration offers additional trans-impedance control inputs that respond to current rather than voltage and so provides an ideal connection for symmetrical roll-off compensation in a multi-stage amplifier. This embodiment also provides extreme linearity as well as a low impedance voltage output that is essentially insensitive to capacitive loading. Drawing inspiration from the past, concepts developed for the chopper stabilized amplifier are rediscovered and may be applied to lend an element of gain, accuracy, and stability uncommon in the industry.

According to one aspect of the present invention, a CiFET amplifier is provided, which is a basic Analog-in-DIGITAL building block. It is impractical to try to construct analog systems at small scale using the same system design techniques that have been
previously applied at larger scales. The power supply voltage is too low to provide a
dynamic range needed to swing analog voltages, and the required analog IC process
extensions are not available. In the newest ultra-deep sub-μm processes, long and wide
transistors are not available, often all the all the individual transistors must be identical in
size. The solution is to convert analog signals to digital as early as possible and take
advantage of digital signal processing techniques that are available today. To accomplish this
it is necessary to have a reliable, precision front-end and that requires a high-precision
amplifier. The techniques in this specification point to such a solution.

According to another aspect of the present invention, it takes advantage of the Doping
Profile and Ratioing. Not everything in optimizing a circuit has to do with the circuits’
electrical configuration. Proper device sizing and especially coarsely adjusting the size
relationship between complementary transistors provides considerable performance benefits.
As will be developed in this specification, the CiFET, being a compound device structure,
offers extensive opportunity to establish impedance matching and gain control through proper
ratio of the physical device parameters. Other important characteristics, like noise, speed,
and power, can be tailored through careful specification of the physical construction and
doping of the transistors, rather than relying solely on circuit configuration.

According to yet another aspect of the present invention, certain noise advantages are
provided. In the end, it comes down to signal-to-noise ratio. Low power supply voltage
requirements in ultra-deep-sub-μm IC processes limit the maximum signal swing to a much
smaller number than most analog designers are used to. So with a smaller signal, the low-
noise techniques embodied herein must be employed in order to maintain the desired signal to
noise ratio or perhaps even improve the ratio.

Simply stated, the CiFET device starts with a common 2-finger inverter and re-wires
the inverter’s parallel transistor connections to series, making these intermediate series
transistor connections available to spawn a supplementary pair of input/output terminals.
These new terminals (referred to as iPorts) are observed to be particularly sensitive to charge
transfer (or current) and exhibit ultra-linear analog trans-impedance (input current to output
voltage) response, among many other interesting analog properties observed. In a manner
similar to an inverter, the output can handle varying high capacitive loads with minor
degradation – highly desirable for analog portability. The sizing and rationing of the
individual transistor conductance can be roughly optimized to enhance various analog
performance metrics.
Traditionally analog MOS circuits convert input voltage to output current ($g_m$), which is then turned back into a voltage by means of an opposing high impedance load; high impedance is needed in order to obtain voltage gain. This results in vastly different gain path verses load path which is made up of nonlinear structures. Thus, a mismatch in output pull-down and pull-up signals come from fundamentally different circuits in order to obtain the signal polarity inversion needed to drive the output up or down. This not only restricts the linearity of the amplification, but the dynamic output swing, and takes appreciable power causing substantial design effort to create at best with poor portable and flawed performance among many other things.

On the other hand, as in a CMOS inverter, the CiFET derives its opposing load by means of opposite diffusion types, not different types of circuits. Both the pull-up and the pull-down circuits are not only the equivalent, but they pass the same current when equilibrium is reached, thus matched circuits passing the same current cancel out nonlinearities leading to minimum distortion over extreme ranges of operation. As in CMOS logic, opposing signals come from opposite diffusion types. In addition the CiFET operates with opposing exponential equalities that enable interesting mathematical operations that are valid over an exciting wide range.

**BRIEF DESCRIPTION OF FIGURES:**

Figure 1a illustrates a high quality CMOS OpAmp prior art transistor schematic from a prominent textbook “Analysis and Design of Analog Integrated Circuits,” 5th Ed, by Gray, Hurst Lewis and Meyer, p484 as a prior art amplifier for comparison;

Figures 1b to 1d are a baseline set of representative performance plots illustrating frequency domain performance and power supply dependency of the prior art OpAmp of Figure 1a;

Figures 1e and 1g show cross-sectional views of prior art MOSFET channel construction weak-inversion and strong-inversion, respectively, and Figures 1f and 1h show plots showing exponential relationship between drain current and drain voltage when weak-inversion and when strong-inversion, respectively;

Figure 1i shows schematic diagram of a prior art 2-finger inverter;

Figures 1j and 1k show physical layout abstractions of the 2-finger inverters shown in Figure 1i;
Figure 1m shows a three (3) dimensional perspective view of the 2-finger inverter of Figure 1i;

Figure 1n shows cross-sectional view at Section AA shown in Figure 1m;

Figure 1p shows a physical layout of a prior art split channel MOS transistor;

Figure 1q shows a three (3) dimensional perspective view of a prior art linear MOS field-effect transistor;

Figure 2a illustrates a three (3) dimensional prospective view of a MOS field-effect transistor (or iFET) with a new mid-channel bi-directional current port (iPort) of the present invention;

Figure 2b illustrates a cross-sectional view of iFET of the present invention with visualized channel charge distributions;

Figure 2c shows a graph of drain voltage $V_{dc}$ and drain current $I_d$ when there is no iPort injection current, while Figure 2d shows another graph when max iPort injection current is provided;

Figure 2e illustrates how the new iPort current terminal replaces half of a differential pair in an iFET amplifier of the present invention;

Figures 2f to 2L illustrate channel ionization and trans-impedance characterization of the iFET along with suggested schematic symbols;

Figure 2m illustrates a schematic diagram of a trans-impedance iFET amplifier of the present invention;

Figure 3a illustrates a schematic diagram of complimentary pair of iFETs of the present invention;

Figure 3b and 3c illustrate a physical layout abstraction of the complementary iFET (or CiFET) compound device shown in Figure 3a;

Figure 3d shows a three (3) dimensional perspective view of the CiFET compound device shown in Figure 3a;

Figure 3e illustrates cross-sectional view at Section AA of Figure 3d;

Figure 3f and 3g illustrate a CiFET operational modeling and a suggested schematic symbol therefor;

Figures 3h to 3k illustrate various CiFET compound device transfer characteristics and properties of the present invention; and

Figure 3L illustrates the availability of self-biased reference voltage terminals;

Figure 3n illustrates the wide range and linearity of the PTAT temperature measurement characteristics of the PTAT self-biased reference terminal of Figure 3L;
Figure 3m to 3w are representative performance plots of the CiFET compound device illustrations of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

A MOS structure referred to herein as an iFET, where the letter “i” refers to a current and “FET” refers to a Field Effect Transistor, is the enabling element of several high performance and novel designs of the present invention. The present invention is based on the addition of a direct connection to a mid-point in a Field Effect Transistor (or FET) channel and the realization that this is a low impedance port (current port, or herein referred to as “iPort”) having trans-impedance current input to voltage output gain properties realized by providing a bidirectional current sink/source mid-channel with a very low input impedance at a low saturation voltage, and additionally connecting reciprocal iFETs pairs of opposite “conductivity type” or polarity type (P-type & N-type) interconnected to take advantage of their complementary nature to operate as a team and with symmetry to self-bias near the midpoint between power supplies. In addition, the relative conductance of the first and second channels of the iFETs can be adjusted (threshold choice, relative sizing, and doping profiles) to tailor the gain, speed, quiescent current and input impedance of such an complementary iFET (or CiFET) compound device of the present invention.

The iFET, with its iPort provides an uncommon and unexpected solution to the compensation problem, and then continues to provide new or alternative solutions to other old problems, exceeding industry expectations. The advantages of operating circuits in “weak-inversion” have long been known but, so also have the problems. The CiFET enables circuits to exploit the high gain and wider dynamic range available in “weak-inversion,” without sacrificing superior speed performance. The CiFET compound device provides a standard active IC gain device that is superior to ordinary analog MOSETs making digital ICs host analog functionality. It is not a tradeoff.

The following is a list of some of the unusual aspects of a CiFET based circuit, including, but not limited to:

- Operates at low power supply voltage;
- High gain;
- Extremely linear;
- Very high speed (wide band);
- Self-Biasing;
- Low noise;
• Quick recovery (DC);
• Uses all digital parts and processes;
• iPorts respond to charge (things in nature are charge based) rather than Volts across a Resistance; and
• iPort has wide dynamic range with constant gain in an open loop.

Referring to Figures 2a and 2b, according to a preferred embodiment of the present invention, an iFET 200, is shown which is comprised of substrate 26a or 26b, source terminal 24a or 24b, and drain terminal 29a or 29b, defining therebetween two channels 23a and 25a, or 23b and 25b on the substrate 26a or 26b, respectively. Typically the first (source channel 23a, or 23b) is connected to the power supply (not shown) while the second (drain channel 25a, or 25b) connects to the load (not shown in Figure 2a). The substrate 26a or 26b is N- or P-type. The two channels, source and drain channels 23a and 25a, or 23b and 25b, respectively, are connected to each other as shown in Figures 2a, and 2b, at the iPort control terminal 21a or 21b, and the channels 23a and 25a, or 23b and 25b, share a common gate control terminal 27a or 27b, respectively. The source channel portion of the gate control terminal s27a/s27b is capacitively coupled to the source channel 23a/23b; while the drain channel portion of the gate control terminal d27a/d27b is capacitively coupled to the drain channel 25a/25b. This configuration means that the iFET 200 has more than one control input terminal.

The gate control terminal 27a or 27b operates like a conventional MOSFET insulated gate, with its high input impedance and a characteristic trans-conductance (g_m) transfer function. Typical values of (g_m) for a small-signal MOSFET transistor are 1 to 30 millisiemens (1 millisiemen = 1/1K-ohm) each, a measure of trans-conductance.

The iPort control terminal 21a or 21b is low impedance with respect to the source terminal 24a or 24b, and has a transfer function that looks more like beta (β) of a bipolar transistor, but is actually trans-resistance (or r_m), or more generally, especially at high frequencies, trans-impedance, measured in K-ohms, where the output voltage is a consequence of an input current. Typical resistance values (or values of r_m) for a small-signal iFET transistor 200 are 50KΩ to 1MΩ, a measure of trans-resistance. Current input to voltage output (trans-impedance) is the basis for the assertion that 1μA in will yield an output of 100mV (or a gain of 100,000:1) at a large signal level, or 1pA in will yield an output of 100 nanoV (or a gain of 100,000:1) in an LNA (both results from the same circuit).
These values have been shown to remain true for a single minimum sized CiFET, with inputs from 1 pico-ampere to 10 micro-ampere, using the same circuit in simulation and limited device measurements. In 180 nm CMOS construction the noise floor limits measurements below about 10 pico amps. iFETS can be constructed with different length to width proportions with very predictably differing results.

High gain, uncharacteristic or surprising results differing from the state of the art designs, is the result of the “weak-inversion” like exponential characteristics of the source channel 23b of the iFET 200 operating in a highly ionized super-saturation mode 28b.

Speed in this super-saturated source channel 23b is not limited by the transit time of carriers along the source channel 23b, but the high concentration of ionized charge carriers in the active channel only have to push the surrounding charge a little as charge is either added or removed from the source channel 23b by means of the iPort control terminal 21b, resulting in a diffusion current which is defined by exponential relationship as has been realized when a MOSFET is operated in weak-inversion. This is in contrast to an electric field causing the charge to transit the channel, which is a square-law function of the gate control voltage. In this configuration, speed is faster than logic built from the same fundamental transistors and unhampere by the “weak-inversion” stage that has higher gains like bipolar transistors. As opposed to bipolar transistors, control current can go either in or out of the iPort control terminal 21b as well as operate with no iPort current, which is useful for creating a self-bias operating point.

In a self-biased CiFET all of the channels are operated with a higher than normal gate to channel voltage and a lower than normal voltage gradient along the channel. This provides lower noise which is facilitated by the self-biasing approach. The potential at drain terminal 29a or 29b is the same as potential at the gate control terminal 27a or 27b, greatly reducing the pinch-off effect found in conventional analog circuit designs.

The iFET 200, because of the common gate connection over the source channel 23a/23b and drain channel 25a/25b, a higher than conventionally applied voltage is placed on the source channel gate control terminal s27a/s27b (or SG) with respect to the source terminal 24a/24b and source channel 23a/23b when compared to the gate voltage 17e used for weak-inversion 13e of Figure 1e and 1f. This higher than expected voltage 22b Figure 2b is responsible for a much thicker (lower resistance highly ionized) conduction layer 28b, allowing the mainstream of carriers to avoid the traps in the surface of the crystal lattice just under the gate s27b, hence – much lower noise similar to the manner in which a junction field effect transistor (or j-FET) conduction channel is located below the surface.
Trans-resistance (r_m) is the “dual” of trans-conductance (g_m). When looking up trans-resistance, most of the references are to inductors and capacitors, suggesting that the iFET may be useful in synthesizing inductors. Thus ultra-pure sine-wave oscillators can be made from CiFET stages that do not use inductors.

The iFET works in the following ways: A low noise amplifier requires a low impedance channel. A low impedance channel is low in voltage gain but high in current gain. To establish voltage gain, a second stage, operating as a current to voltage converter, is required. A cascoded pair (one on top of the other) of transistors provides such a configuration. Biasing requirements for a cascoded pair preclude its use at low voltage unless a convenient solution for the biasing problem is found. The CiFET device structure provides the solution to this problem through self-biasing of a complementary pair. The impedance of the source channel 23b can be designed to accommodate the impedance of the particular signal source driving it (see later section on ratio).

Regarding FETs in general, carriers are attracted to the surface by the gate field, a low gate voltage creates a thin surface-layer on the channel (where the conductivity takes place) while a higher gate voltage creates a thicker under-layer. The thin layer of carriers is impeded by the non-uniform surface defects resulting in electrical noise, while a thicker layer of carriers finds a smoother path below the surface, thus reducing total electrical noise. This indicates that higher gate voltage translates to lower noise.

Referring to Figure 2b, in the iFET 200 the electric field created by the gate voltage Vg 22b on the gate control terminal 27b causes carriers to rise from the substrate 26b into the source channel 23b region converting the semiconductor material to an ionized conductor with a relatively large number of carriers per volume which is identified as “super-saturation” 28b, thus establishing a high level of conductivity.

Injection current 20b introduced into the iPort control terminal 21b increases the diffused charge density (number of carriers per volume) throughout the source channel 23b, thus making the source channel 23b even more conductive. The rate of conductivity change is exponential, similar to that found in “weak-inversion.” This exponential rate of conductivity change is due to the low voltage gradient along the source channel 23b (source terminal 24b to iPort control terminal 21b voltage gradient).

The iFET exponential relationship between source channel 23b charge 28b and gate voltage 25b provides access to exponential / logarithmic functionality, where the addition of two logarithmic functions is equivalent to multiplication when an antilog is applied. A
reversing antilog or exponential operation recovers the analog output through the opposing complementary CiFET loading device structure. This complement is obtained through opposing diffusion types, similar to CMOS logic, instead of some other transistor linear circuit configuration. Such exponential relationship may be used for various low noise amplifier applications as well as many analog mathematical operations. The exponential relationship is also responsible for the wider dynamic range of these CiFET circuits.

Again, referring to the source region in Figure 2b, removing charge from the gate control terminal 27b or/and iPort control terminal 21b (number of carriers per volume) results in reduced conductivity of the semiconductor material in the source channel 23b. In this respect, the iPort control terminal 21b-to-source terminal 24b connection operates in a manner similar to the base-region of a bipolar transistor (which is exponential): the more control current to the iPort control terminal 21b, the more the device conductivity (g_m or 1/r_m). In addition to the base current operation of a bipolar transistor, the iPort works symmetrically around zero injection current in either direction, thus it possesses true bidirectional operation for four quadrant operations.

The drain channel 25b of the iFET 200 operates more like a conventional FET, in that the thickness of the drain channel 25b is greater near the iPort control terminal 21b (same thickness as the source channel 23b) and tapers as it reaches its diffusion region around the drain terminal 29b (the decreasing voltage differential between drain channel 25b and gate control terminal 27b diminishes the gate 27b to channel 25b field) establishing the output resistance of the transistor as set by the gate voltage V_g. The tapered decreasing channel 25b depth near the drain 29b is from the lower gate 27b to drain 29b voltage which decreases the number of carriers that are ionized up from the semiconductor body 26b below into the conduction channel 25b. When loaded with a complementary iFET, the resulting CiFET device Figure 3e is biased at a lower gate 27b to drain 29b voltage (close to the voltage found on the gate), decreases the drain channel output resistance (thicker channel 25b at the drain diffusion). This lower drain channel resistance results in lower noise and a high output drive capability to establish the desired drain voltage at the drain 29b regardless of the capacitive load.

A thick source conduction channel 23b within the iFET 200, operating at a low voltage gradient along this channel, has a low voltage gain but it has a high power gain as a result of the low input impedance which efficiently accepts input signal energy from the iPort in the form of input current. This source channel also contributes a very minimal noise.
The conduction region 25b around the drain terminal 29b, operating at a higher voltage along its conduction channel 25b, provides the desired voltage gain with a minimal noise contribution when operated with the drain voltage being the same as the gate voltage Vg 27b. This voltage equality is contributed by a unique biasing construct of the CiFET Figure 3e, to be explained hereinafter.

Figure 2b further shows iFET channel charge distributions, according to the present invention, with their operating points 23c, 25c, and 23d, 25d graphed for a zero iPort injection current Figure 2c and for a maximum positive iPort injection current Figure 2d respectively. Vertical lines from Vt at 27c/27d represent threshold voltage in Figures 2c and 2d. This threshold voltage is the dividing line between weak inversion and strong inversion. At threshold voltage 50% of the channel current is diffusion driven and 50% is driven by the electric field along the channel, thus below threshold voltage 27c/27d the channel current is becoming predominately diffusion driven which possesses exponential characteristics. In super-saturation, the channel is essentially all diffusion driven, thus exponential characteristics define the channel carrier conduction or channel conductance. With zero iPort injection current at 20b in Figure 2b, as shown in Figure 2c, bias current at 1a produces the bias point output at 25c with voltage Vd 29c as it is measured at the drain terminal 29b, along with an iPort 21b voltage at its bias current 1a point 23c.

Figure 2d illustrates how a small amount of iPort current 20d impressively changes the drain channel output voltage to a point at 25d: With a maximum positive iPort 20b injection current, the ΔId bias current from 23d to 20d produces the Vd output voltage at 29d (seen at the drain terminal 29b), along with an essentially constant iPort 21b voltage at its bias point 23d. The iPort voltage remained basically constant while the drain voltage changed by nearly half of the power supply voltage, thus input current changes the output voltage, demonstrating a trans-impedance transfer function. This trans-impedance output voltage 29b, 29c, 29d changes as if the input current is flowing through the trans-impedance rm resistance, while it is actually flowing into the super-saturated source channel, which has an input resistance that is much lower. The source channel is a current to exponential voltage (at the iPort) converter and the drain channel provides the anti-log conversion back to form the output drain voltage, while providing all the drive required for various capacitive loads.

The iFET 200 of the present invention can be viewed as a differential amplifier (or long tailed pair), as shown in Figure 2e, where drain channel 25e converts the “−Voltage” input to the “Voltage Derived Current” and the iPort “+Current” input is a current (rather
than a voltage). The source channel 23e converts "Bias" from negative power voltage Vss 24e. A balance is still required between the current input 21e and the voltage derived current from the drain channel 25e, with the difference being presented as a voltage change on the output terminal 29e. While this output suffers from some non-linear transfer characteristics, the use of an adaptive load with a complementary non-linearity compensates, resulting in an ultra-linear transfer function and can be viewed as a "black box" as shown in Figure 2g.

Figure 2h shows series transistor channel arrangement in the iFET, illustrating the current-voltage arrangements of the two channels 23h and 25h which corresponds to 23b and 25b of Figure 2b, produces voltage V_{out} at 29h. With zero iPort 21h injection current, the current through the drain channel 25h is constrained to be the exact same current that passes through the source channel 23h. Without leakages or an iPort current, there is nowhere else for the current to go except through the series path of these two channels. If the two series transistors in Figure 2h are sized equally, their gate to channel control voltages want to be the same. That is V_{g2} 27h wants to be the same as V_{g1} in Figure 2h, thus forcing the iPort voltage V_i at iPort 21h to be the same voltage as the source voltage V_s at the source 24h. This restraint ideally forces low impedance at the iPort input terminated with zero volts to the source. By altering the relative conductance ratio of these two channels, the input impedance and termination voltage can be set. Since both transistor channels are made together and adjacent to each other, the input impedance and termination voltage are a very fixed and consistent pair of parameters, similar to matching of a differential pair of transistors. Their bandgap relationship configuration is a PTAT for the N channel iFET (Vittoz, Eric A. et al., "A Low-Voltage CMOS Bandgap Reference", IEEE Journal of Solid-State Circuits, Vol. SC-14, No. 3, June 1979, at page 573 to 577) and a CTAT reference for a P channel iFET (Anvesha A, et al., "A Sub-1V 32nA Process, Voltage and Temperature Invariant Voltage Reference Circuit", 2013 26th International Conference on VLSI Design and the 12th International Conference on Embedded Systems, IEEE Computer Society, 2013).

Figure 2i illustrates a slightly higher level circuit prospective of the iFET operation, which exemplifies a trans-resistance transfer function. Here an input current to a virtual PTAT reference voltage provides an output voltage change that is multiplied by the trans-resistance r_m and strongly buffered. This trans-resistance r_m gain ratio is typically in the range of 50K to 2Meg.

Figure 2j is a behavioral schematic of the iFET operational model which illustrates the iFET behavioral relationship in a more detailed schematic. The I_{inj} current into the iPort
sees a low $R_m$ to a PTAT voltage above $V_s$ at the iPort input. At the output this $I_{inj}$ current input becomes a voltage that has a magnitude that looks like it went through a high resistor $r_m$, but is sourced at the output $V_{out}$ with a low impedance variable output voltage source. This low impedance can equally drive highly varying capacitive loads as normally encountered in integrated circuit instantiations. This functionality is depicted with Figure 2g at the “black box” level where a current input produces an $r_m$ times higher $V_{out}$. This black box depiction of a trans-resistance amplifier is the dual of the normal MOS amplifier depicted in Figure 2f where an input voltage produces an output current that is the input voltage multiplied by $g_m$. It is highly desirable to provide a voltage output instead of a current output that must be turned back into a voltage by running this current into a load resistance. The load significantly effects the voltage in the $g_m$ amplification black box while it does not in the $r_m$ black box amplifier.

Figures 2k and 2l are suggested schematic symbol for the iFET device.

Figure 2m captures yet another application of the iFET 200, which provides a methodology of obtaining a voltage output from a bi-directional current input on the iPort. This follows a trans-impedance $r_m$ transfer-function which is precisely defined over an extremely wide dynamic range Figure 3h. At this iPort terminal 21m, a bi-directional input current into an iFET 23m provides a proportionally large voltage change on the output 29m which is biased with a load current 28m. This operates through the weak-inversion like exponential characteristic of the iFET source channel 23b as shown in Figure 2b by altering the amount of charge in the super-saturated 28b source channel of the iFET 200. The gate is provided with bias voltage, $V_{bias}$ 27m. This trans-impedance $r_m$ transfer-function is set by the relative conductance ratio of the iFET source channel 23b to drain channel 25b as plotted in Figure 3i. Here the conductance ratio is plotted along the-axis and the trans-resistance $r_m$ or more generally, the trans-impedance is plotted up the right axis. This plot 3i also plots the directly related iPort input resistance on the left axis.

**Non-Inverting nature**

Regarding the iPort control terminal 21b as shown in Figure 2b, in the case of an N-channel device, a positive current 20b on the iPort control terminal 21b, such an input displaces the current coming in through the upper channel 25b, causing the drain (output) connection 29b to move in a positive direction – thus the non-Inverting nature of the iPort 21b input.
Interestingly, unlike other semiconductor devices, a negative current $20b$ can be extracted from the iPort $21b$, causing a drain (output) $29b$ shift in the negative direction.

**Proper bias**

An iFET $200$ (as shown in Figures $2a$, $2b$) has both gates $27a$, $27b$ connected together and requires a proper bias voltage $22b$ on the gate $27a$, $27b$ to establish the desired operating point.

**Symmetry**

A P-channel device can be constructed and behaves in a similar fashion to its N-channel counterpart.

It should be emphasized that while the gate input $27a$, $27b$ is inverted with respect to the drain, the iPort $21a$, $21b$ is NOT inverted in EITHER the PiFET or NiFET devices diffusion types with respect to their output drains.

**The “Rule-of-Thumb” view:**

Referring to Figure $2d$ or $2j$, the operation of the iFET transistor is extremely simple to think about; not much more than Ohm’s law is needed, and it can be seen as followings:

- A small $+$ or $-$ current input on the iPort results in a voltage out that is “$K$” times larger, but with the same sign as the input.

1. “$K$” does not change over an enormous dynamic range of operation.
2. “$K$” is on the order of 100,000, defined as trans-resistance ($r_m$) and can be viewed as a simple functional block shown in Figure $2g$. $r_m$ units are ohms which is $V_{out}/I_{in}$. $r_m$ of Figure $2g$ represents the transfer function of the iPort control terminal of an iFET in accordance with the present invention.
3. The $r_m$ block in Figure $2g$ is the “dual” of the $g_m$ block in Figure $2f$, which defines the normal MOSFET transfer function. Accordingly, current and voltage have been interchanged, and thus $r_m$ as shown in Figure $2g$ can be viewed as a simple resistance in ohms, while $g_m$ as shown in Figure $2f$ is conductance in units of 1/ohms.

The $r_m$ circuit of Figure $2g$ has low impedance on both the input and output while the $g_m$ circuit of Figure $2f$ has high impedance on both the input and output. The benefits of the $r_m$ iFET circuit of Figure $2g$ are essentially zero voltage swing at the input and all the output
current drive required to establish the output voltage, yielding parasitic capacitance insensitivity on both the input and output, thus very high speed. The resulting $R_m$ circuit of Figure 2g through 2j is essentially constant with frequency and operates with much lower power supply voltages than the $g_m$ circuit of Figure 2f, in that the trans-impedance $R_m$ iFET device’s operation is basically not threshold voltage limited. The power supply voltage does not stop at the sum of threshold voltages or a threshold voltage and a saturation voltage as in prior art analog circuits, but functions well below 600mv and operates usefully down to a millivolt of power supply voltage. Gain typically hits its maximum in the range of 600mv to 1.0 volt of power supply voltage. Clearly not threshold voltage limited. Many of the iFET benefits are worth the trouble of re-thinking the approach to analog MOS circuit design.

The useful power gain is partially realized as current gain. Although MOS circuits are perceived as voltage mode circuits, analog MOS circuits work much better as current or charge controlled circuits. After all MOS transistors operate on the instantaneous charge in their channels and do so with great precision as seen throughout this specification.

- The iPort input terminates in a non-varying, low value resistance (typically 50Ω-50kΩ depending on design). The circuit allows matching an antenna impedance for maximum power transfer into the iPort input.
- The output is a voltage source with a low driving impedance, providing the load with whatever current is required to establish the desired voltage with precision.

Additional iFET observations of the present invention are as follows:

- $R_m$ does not change over the entire operating range from near clipping, all the way down to the noise floor. AC performance of an iFET is FLAT from DC to faster than logic speed. Analog voltages only move a little while logic has to get unstuck from one rail and go all the way to the other power supply rail.
- The iPort control terminal, being a current input, is free of voltage derived parasitic effects because the iPort control terminal has very minimal voltage change.
- Figure 3k shows the input termination voltage at iPort control terminal from ½ mv to about 100mv, depending on the iFET ratio (or input impedance), from its respective power supply rail, allowing a high compliance voltage from the other rail to bias the input such as desirable for transducer or some other input circuit.
- The iPort termination voltages are either a PTAT or a CTAT (proportional to absolute temperature or the complementary to absolute temperature) bandgap reference depending on the N or P semiconductor diffusion type respectively.
• The output in the complementary CiFET configuration swings around the self-bias midway voltage ("sweet-spot") between the power supply rails, where it is free of power supply induced noise. Power supply induced noise cancels with this "sweet-spot" as the analog-zero reference.

• The advantages of operating circuits in “weak-inversion” have long been known but, so also have the problems. The iFET enables circuits to exploit the high gain and wide dynamic range available in “weak-inversion,” without sacrificing superior speed performance.

• In the “Behavioral Model” Figure 2j the iPort current is converted to a voltage by a resistance ($r_m$), whose value determines the gain. This "trans-resistance" ($r_m$) is established by the ratio of the “drain channel” to “source channel” conductance, and remains constant throughout the entire operational range. Simulation has shown this resistance ($r_m$) to typically be in the range of 100,000Ω, set by the relative channel sizing. $r_m$ is the dual of $g_m$, but with more control.
  a. The output is a low-impedance source follower that can deliver its voltage with all the necessary transient current to drive the next circuit and capacitive load to get there.
  b. The input is a constant low resistance termination (related to $r_m$ but much lower) with a constant termination voltage of about 100mV from the respective power supply rail. This offset voltage is a “bandgap” reference, established by the ratio of the “drain channel” to “source channel” conductance.

The CiFET Amplifier is the Basic Analog-in-DIGITAL Building Block:

The complementary nature of a CMOS inverter of Figure 1i is of interest for processing analog signals. If the inverter output is tied back to its input, it self-biases near the midpoint of power supply voltage. Care, of course, must be taken to size the individual transistors weakly enough as to not exceed what the IC process can handle, such as maximum current the contacts are rated for in both their AC and DC ratings. Local temperature rise is also a consideration, but self-biasing combats temperature degradation.

When sized with similar pull-up conductance to pull-down conductance, the self-bias point is nicely centralized between the power supplies where noise from both the positive and negative power supplies tend to cancel. The variation in process parameters will move this midpoint voltage around a bit, but it is always relative the transistor conductance ratios. At
this midpoint, the gain is arguably at the maximum available for the pair of transistors used. In addition, the pull-up performance is equal to the pull-down conductance yielding symmetric DC, AC, and transient response in either direction. The effective threshold voltages cancel each other out in that the circuit always works at its best. The AC bandwidth performance of this conventional inverter is extremely wide as compared to any analog circuit configuration as illustrated in the Bode Plot of AC Gain and Phase in Figure 3u. You get the most bang for the least amount of parasitic loading. For the 180nm IC process used as a comparison baseline, the 3db gain is about 1.2 GHz with a phase shift of about 45 degrees from DC. One would be hard pressed to run equivalent low power logic at 1GHz in the 180nm reference technology using a minimum power logic family.

A primary limiting factor to the use of a logic inverter for an analog voltage amplifier is that the logic inverter has only about 25db or 18x of voltage gain available with a single inverter stage, as illustrated in the standardized Bode gain-phase plot of Figure 3u. The required minimum analog voltage gain has to be at least 80db or 10,000x. The voltage gain defines how well the analog output signals reach their desired amplitude.

Closed loop analog voltage amplifiers require inverting gain so that the output feedback can move the input back to a virtual ground input voltage. Without the amplifier being inverting, the positive feedback would result in a latched output, like a flip-flop when the feedback loop is closed. Using a series of say three inverters is virtually impossible to stabilize with any frequency response left over in a closed loop application, which is essential for practical analog amplifiers.

While a single iFET has interesting characteristics on its own, a complementary pair of iFETs prove to be much more beneficial. The resulting device is arguably the highest possible power gain and widest bandwidth use of FETs possible. Figure 3a is the schematic diagram of such a complementary pair of iFETs herein named CiFET for complementary current input field effect transistors. This is the core of the present invention.

Figures 3b and 3c structurally relate the CiFET transistor 300 schematic diagram of Figure 3b to the adjacent physical layout abstraction of Figure 3c. The NiPort 31b of the NiFET transistor 301 in Figure 3b relates to the NiPort 31c in the physical layout abstraction of Figure 3c. The PiPort 32b of the PiFET transistor 302 relates to PiPort 32c in Figure 3c. The reference numbers cross relate the transistor schematic to the physical layout. Likewise, these reference numerals also cross reference to the 3-dimensional sketch of Figure 3d and the cross section AA view of Figure 3e. This set of CiFET Figures 3a through 3e and their cross-reference relationship is a reflection of the prior art 2-finger inverter of Figures 1i to 1n.
Essentially, the two pairs of opposite diffusion type transistors 101 and 102 in the inverter device structure 100 Figure 1m, and again in Figure 1n, are each connected in parallel: 13m in parallel with 15m as well as 14m in parallel with 16m for the 2-finger inverter 100. These two pairs of parallel transistors are also connected to the output terminal 19m with the cross-hatched metal connection 18m, or equivalently shaded portion 18k in Figure 1k or 18n bold wire in Figure 1n.

These same two pairs of transistors 33d, 35d (or 33e, 35e) and 34d, 36d (34e, 36e) are connected in series in Figure 3d and 3e in order to form their respective iFET device structures 301 and 302 thus forming the CiFET device structure 300 with their respective iPort control terminals Ni, Pi access using the intermediate diffusions 31d, 32d. Just a metal mask modification from the connections 18k, 18m, 18n in Figures 1k, 1m, 1n to the connections 38d, 38e in Figures 3d and 3e, respectively, yields unprecedented analog performance as is presented in the remaining figures of this present invention. Thus CiFET designs are completely compatible, and portable, to any IC process of which all possess their most fundamental logic inverter; while being a radical improvement from the state of the art in high gain, high precision, and small scale primitive analog building blocks. The complementary pairs of iFETs are built entirely from logic components, without analog extensions, while enabling scaling and portability. Both the footprint and the power consumption per gain/bandwidth are drastically reduced from the present state of the art, while retaining superior noise performance.

Referring to Figure 3a, the complementary pair of iFETs (or CiFET) 300 comprises P-type iFET (or PiFET) 302 and N-type iFET (or NiFET) 301, comprising input terminal 30a connected to both the gate control terminal of PiFET 302 and the gate control terminal of NiFET 301, function as the common gate terminal 30a. CiFET 300 receives power, Power+ (or positive supply voltage) and Power- (or negative supply voltage), where Power- is connected to the source terminal of NiFET 301 and Power+ is connected to the source terminal of PiFET 302. Each of PiFET 302 and NiFET 301 comprises iPort control terminal (31a and 32a) for receiving injection current. The drain terminal of PiFET 302 and NiFET 301 are combined to provide output 39a.

Referring to Figure 3d (or Figures 3c, 3e), the CiFET 300 comprising PiFET 302 and NiFET 301, laid out on the substrate (or body B+ and B- respectively) like a mirror image along well border shown therein. PiFET 302 comprises source terminal S+ s34d (or s34c, s34e), drain terminal D+ d36d (or d36c, d36e), and iPort control terminal Pi, defining source + channel 34d (or 34c, 34e) Between the source terminal S+ and the iPort control terminal Pi.
diffusion region 32d (or 32c, 32e, or 32b in Figure 3b), and drain + channel 36d (or 36c, 36e) between the drain terminal D+ and the iPort control terminal Pi diffusion region 32d (or 32c, 32e, or 32b in Figure 3b); NiFET 301 also comprises source terminal S- s33d (or s33c, s33e), drain terminal D- d35d (or d35c, d35e), and iPort control terminal Ni, defining source - channel 33d (or 33c, 33e) between source - terminal S- s33d (or s33c, s33e) and the iPort control terminal Ni diffusion region 31d (or 31c, 31e, or 31b in Figure 3b), and drain - channel 35d (or 35c, 35e) between drain - terminal D- d35d (or d35c, d35e) and the iPort control terminal Ni diffusion region 31d (or 31c, 31e, or 31b in Figure 3b). CiFET 300 further comprises a common gate terminal 30d (or 30c, 30e, or 30b in Figure 3b) over source + channel 34d (or 34c, 34e), drain + channel 36d (or 36c, 36e), source - channel 33d (or 33c, 33e), and drain - channel 35d (or 35c, 35e). Accordingly, the common gate terminal 30d (or 30a, 30b, 30c, 30e) is electrically coupled to the iPort control terminals Pi and Ni.

In many analog circuits, biasing is a problem. Using fFETs in complementary pairs 301 and 302 as shown in Figure 3d allows them to “self-bias” when the drain output 39d (or 39a, 39b, 39c, 39e) is connected to the gate input 30d (or 30a, 30b, 30c, 30e), thus eliminating drift problems and additionally, the amplifier finds the maximum gain point on its operating curve. This self-bias connection is illustrated in Figures 3f and 3g as 38f, 38g and also in Figure 3l as “Bias” for an analog zero reference.

In the “Behavioral Model” of CiFET of the present invention as shown in Figure 3f, the currents I_m at the iPort control terminals 31f and 32f are converted to a voltage by trans-resistance (r_m), whose value determines the gain. This “trans-resistance” (r_m) is established by the ratio of the “drain channel” to “source channel” conductance, and remains constant throughout the entire operational range. Simulation has shown this resistance (r_m) to typically be in the range of 100,000Ω, set by the relative channel sizing. r_m in Ω is the dual of g_m (1/Ω).

The output V_output 39f is a low-impedance source follower that can deliver its voltage with all the necessary current to drive the next circuit and any capacitive loading in between. The common gate input terminals 30f/30g represent the common gate input terminals 30a/30b/30c/30d/30e of their previous related Figures 3a/3b/3c/3d/3e. The CiFET structurally differs only in the output 39a/39b/39c/39d/39e metal connection 38c/38d/38e from that of the two finger inverter of Figures 1i/1j/1k/1m/1n output 19i/19j/19k/19m/19n metal hookup 18k/18m/18n. The CiFET is only a metal connection difference from the two-finger inverter, and can be further optimized by adjusting the individual transistor
conductance for the intended CiFET purpose. Only a couple of optimizations are required for most purposes.

The input is a constant low resistance termination (related to \( r_m \) but much lower) with a constant offset voltage of about 100mv from the respective power supply rail. This offset voltage is a PTAT / CTAT “bandgap” reference, established by the ratio of the “drain channel” to “source channel” conductance.

A standard CiFET compound device cell can be physically constructed and used like a logic cell for designing analog. Normally this is the only active circuit component needed for analog circuits. Like a transistor, but the CiFET cell does everything needed for an active component.

Now, referring to Figure 3g, \( V_{\text{input}} \) is connected to the gate terminals of NiFET and PiFET. Positive power voltage (Power +) is connected the source terminal of PiFET, while negative power voltage (Power -) is connected to the source terminal of NiFET. NiFET provides the channel 33g and PiFET provides the channel 34g. NiFET further comprises NiPort 31g; while PiFET compros PiPort 32g. Drain terminals of NiFET and PiFET are connected together to form \( V_{\text{output}} \). Self-Bias path 38g is provided from \( V_{\text{output}} \) to \( V_{\text{input}} \) for repeatability.

How then is the proper bias voltage produced? The simplest way of generating the bias voltage is to use iFETs in complementary pairs 301 and 302, creating an inverting device 300 as shown in Figure 3d and 3L, and then using the output 39d to provide negative feedback “Bias” connection in Figure 3L to the input 30d. The CiFET as a compound device will “self-bias” at a point approximately midway between the power supplies, where the gain is maximized and the speed or slew rate is symmetrically poised for its most rapid changes. At this self-bias voltage point, the current through all of the complementary iFET channels 33d, 35d, 36d, 34d is exactly the same current, thus equal. There is no other DC current path for the PiFET 302 drain d36d to go through except into the NiFET 301 drain d35d, and thus a specific set of gate to channel voltages within the CiFET conduction channels are established for this equality of currents (or conductivity). Also since both iFETs 301 and 302 have the same current, the pull-up ability is exactly equal to the pull-down ability, which defines the maximum slew rate bias point.

Since the complementary pair 300 of iFETs 301 and 302 is self-biased, any parametric factors are auto-compensated for changes in operating environment. Because of inherent matching between adjacent parts on an IC, the bias generator can be used to bias
other iFETs nearby. The real-time self-biasing circuit corrects for parametric changes (in various forms).

Each of the transistors in an inverter of the present invention acts as a “dynamic” load for its complement, allowing the gate voltage to be significantly higher than the traditional bias point of an analog circuit gate. With the complementary iFET compound device’s higher than normal gate voltage, the source and drain conduction channels are deep, yielding lower noise.

The dominant noise source in a traditional analog circuit is primarily related to the “pinch-off” region near the drain 19g of the conduction channel 15g illustrated in Figure 1g. The length of this pinch-off region is effected by the magnitude of the drain to source voltage. Biasing the Drain 19g, 29b Figures 1g, 2b (or output) at the same voltage as the gate 17g, 27b (zero differential) causes the drain conduction channel to avoid the channel pinch-off (shallow channel) phenomena usually encountered in analog circuits. Another way of stating this is: a transistor gets noisier as the drain approaches its design maximum voltage, the self-biased inverter operates its transistors at half the design maximum voltage and the gate is at the same voltage as the drain (zero differential), therefore the self-biased inverter is much quieter. With lower drain voltage, the ionized conduction channel carriers diffused down away from the surface carrier traps which are just below their gate.

The operation of the CiFET amplifier differs from the operation of a conventional analog amplifier, with its current mirror loads, in that:

The “Source” channel, as illustrated in the individual iFET Figure 2b, has an extremely small (~100mv) voltage from source terminal 24b to iPort control terminal 21b while the gate terminal 27b is at ~½ Vsupply when complementary diffusion type iFETS 301, 302 are combined into a single CiFET device structure 300 Figure 3d. This puts the iFET Source channel 23b, 33d, 34d into “Super-Saturation” 28b, a condition similar to weak-inversion 18e Figure 1e but with high gate overdrive. Gate overdrive results in an unusually thick conduction layer 23b and along with a low source 24b to iPort 21b voltage resulting in that conduction layer 23b remaining thick and deep all the way along the channel. Notice the differences in the thickness between the weak-inversion 18e conduction channel 13e in Figure 1e and the super-saturated 28b conduction channel 23b in Figure 2b. This thick channel difference is why the iFET operates so well. It takes the desired exponential property of the conduction channel found in weak-inversion 18e and fixes its high resistance limitation to a very low resistance conduction channel, with the same exponential properties – a long wished for FET transistor performance metric.
The “Drain” channel 25b operates with its Drain terminal 29b at ~½ Vmax, greatly reducing the pinch-off (and DIBBL) effect. This reduced pinch-off condition is further enhanced by the fact that the “Gate terminal” 27b is operated at ~½ Vsupply (same as ½ Vmax), meaning no potential difference between the Drain 29b and the Gate 27b. Notice the difference in the thickness between the drain conduction channel 15g in Figure 1g and that of 25b in Figure 2b.

Another important aspect of the iFET and CiFET compound device is its ~constant voltage low impedance current input 20b Figure 2b that frees it from the speed robing effects of parasitic capacitance. With current input, the input voltage remains nearly constant, thus parasitic capacitance has little effect on input signal level changes.

This subtle but significant difference is one of the enabling features that makes weak-inversion like exponential response work and gives the complementary iFET amplifier its linear response, superior low noise, wider dynamic range, and speed advantages.

MOSFETs do not make particularly good amplifiers compared to equivalent bipolar circuits. They have limited gain, they are noisy, and their high impedance makes them slow. Process parameters are also soft, so that matching a differential input is difficult, unlike bipolar. Bipolar Diff-Amps are developed to the point where the input offset is pretty good, but the move to CMOS never really delivered as good a solution.

It has long been known that superior gain and wide dynamic range performance can be obtained from CMOS operated in weak-inversion. But complications arising from high impedance, due to impractically low currents and high output resistance, preclude taking advantage of the superior gain (equivalent to that of bipolar transistors), dynamic range (exceeding that of bipolar transistors), and logarithmic performance (allowing numerous decades of amplification) that are characteristic of weak-inversion. However, the CiFET conduction channels circumvent these high-impedance limitations of weak-inversion due to the CiFET’s deep conduction channels 33d, 36d, 33e, 36e Figures 3d, 3e respectively. The CiFET is a low-impedance device that also incorporates the noise benefits of majority carriers in a deep channel found in junction-FETs to the MOSFET. Improved signal to noise ratios are essential for analog system operation with sub 1volt power supplies of ultra-deep sub-μm IC systems. When signals are reduced, the noise must at least be proportionally reduced to maintain the signal to ratio. System performance is all about s/n ratio in the end.

While a MOSFET in weak-inversion, working into a current source load, delivers a logarithmic transfer function, the same MOSFET working into an anti-log load cancels the logarithmic nonlinearity, yielding a precisely linear transfer function. The CiFET amplifier is
such a circuit, i.e.: log input, antilog load, yielding perfectly linear, wide dynamic range, low noise, and high speed performance. The low noise is a consequence of the biasing, where the source channel gate potential is unusually high and the potential across the source channel itself is maintained at near zero volts while the voltage across the drain channel is minimized. The drain channel is a level shifter, maintaining a very low voltage on the source channel while delivering high amplitude signal swings at the output with all the output drive to charge any capacitive load. The CiFET is a trans-impedance amplifier Figures 2g through 2j and 3f, which is a low-impedance device. The prior art trans-conductance amplifiers Figure 2f are high-impedance devices. Low-impedance devices generally have low noise, while high-impedance devices have high noise.

A 3-stage CiFET voltage amplifier delivers an open loop voltage gain of $>1$ million or $10^6$ which is 120db and equivalent to 20 bits of digital accuracy, while still maintaining unity gain closed loop stability over its multi-GHz bandwidth. At power supply voltages below 1 volt gains can easily be around 100 million or $10^5$ which is 160db and equivalent to 27 bits of digital accuracy, while still maintaining unity gain closed-loop stability over its GHz bandwidth, which is obviously limited by the noise floor. It is all about signal to noise. Gain increases as power supply voltage is dropped well below a volt. At a power supply voltage of only 10 millivolts, CiFET current input amplifiers operate with 10db gain and closed-loop bandwidth over 1KHz, and can operate at power supply voltages as low as 1.0 millivolt with reasonable performance. Clearly, the CiFET amplifiers are not slaved to the threshold voltage stacking that prior art amplifiers are.

**Taking Advantage of the Doping Profile and Ratioing:**

Traditionally engineers have avoided using digital logic in an analog configuration because it was believed to be unacceptably nonlinear and was difficult to bias and impossible to stabilize. Digital logic also sacrifices drive symmetry for compactness. Restoring the symmetry through proper device ratioing ($\sim 3:1$ p:n width to $\sim 4:1$ on smaller IC processes) improves linearity, increases noise immunity, and maximizes dynamic range. Self-biasing solves the bias problem.

Noise figures can be particularly optimized on front end amplifiers through proper ratioing. The iFET’s electrical characteristics can be enhanced by modifying the combined and relative conductance of the source and drain channels, without modifying the available IC process (without analog extensions). When all the transistors must be the same size as in the newest IC processes, multiple transistors can be wired together to achieve the desired
iFET rationing, as course resolution works fine. There are several approaches to realizing this optimization (adjusting length, width, and threshold among others).

Nearly any source and drain channel size will make a functional iFET, but varying the individual iFET channel size, both relative and cumulative, increases the iFET performance depending on the objective.

Fundamentally:

- Lower iPort input impedance is obtained via a lower source channel current density (wider source channel) as compared to the drain channel.
- Higher output voltage gain is obtained via higher source channel current density (narrower source channel) as compared to the drain channel.
- Proportionally sizing the CiFET channel interrelationships optimizes various performance metrics. Gain and symmetry are maximized when the P-channel iFET conductance to N-channel iFET conductance is equalized, thus balancing the CiFET complementary conductance. Equalizing conductance adjusts the self-bias voltage near the midpoint of the power supply voltage. This provides a symmetrical dynamic analog signal range and serves a convenient analog ground or zero reference, permitting “four quadrant” mathematical operations. Experience with deep sub-μm IC processes place the P-channel iFET to be around 3 to 4 times wider than N-channel iFET, as fixed by length or width ratios of the iFET channels.
- The CiFET performance is minimally affected by ambient and IC process parameter variation because of self-biasing to an optimum mid-point, regardless of conditions.
- The power verses speed tradeoff is controlled by the cumulative sum of all of the channel conductances used to set the idle current through the complementary iFET amplifier. This establishes the output slew rate (or output drive capability).
- Care must be exercised so as to not exceed both DC and transient current limitations of the biased CiFET structure. Current rating for the contacts and metal widths must be considered in determining the self-bias current and physical layout care must be considered so as to not be prone to premature failure. Local heating should also be considered.
- Since any logic inverter would work, it is not necessary to even make this optimization, but it is a performance booster.
To be clear, the conductance of the iFET channels are a function of the individual channel width and lengths, as well as their thresholds and doping profiles. Each of the iFET channels can have individually selected sizes and/or threshold relationships to the other related channels.

While iFET amplifiers can be constructed with minimum sized devices which do provide ample current at the output for very fast response and high accuracy, as stated above, care must be exercised so that the complementary iFET amplifier does not pass too much current, subjecting it to mechanical failure. The physical layout requires enough contacts and metal for the required DC and transient currents.

**Performance Description:**

Figures 3h to 3t exemplify performance of the CiFET device structure.

Figure 3h is a transfer function plot of the CiFET device over an extreme range of ±1 pico-amp to ±5 micro-amps of input current into either iPort, yielding a ± 100 nano-volt to ±500 milli-volt output on the vertical scale. In order to cover the range, both axis are log scale.

- The CiFET is ratioed to provide a $r_m$ gain of 100K;
- Gain remains constant over the entire range;
- Transfer function is precisely linear;
- Plus and minus precisely overlay each other;
- Either iPort input/output precisely overlays the other;
- Input current can be zero;
- Output voltage swings around the midscale AC zero reference voltage,

Figure 3i shows how the iFET channel conductance ratio defines the trans-resistance (also known as trans-impedance indicating the same AC relationship) $r_m$ to set the CiFET device gain in which input current producing an output voltage. The iFET Ratio is along the horizontal axis as the ratio of width/length of the source channel divided by the width/length of the drain channel. The gain factor or trans-resistance is the right vertical axis in the units of $\Omega$s using a log scale to cover the 3 decade range of values from about 1 K$\Omega$ to 1 meg$\Omega$.

Also note that the iPort input resistance on the left vertical scale of the graph shown in Figure 3i provides a precisely overlaying plot with a reduced set of values by the ratio shown on the following Figure 3j, which is related to the peak voltage gain of the CiFET device. In other words, $R_m$ times the CiFET voltage gain yields the trans-resistance $r_m$. 
The following Figure 3k of this CiFET property set plots the iPort termination voltage over the same iFET ratio on the horizontal scale. Again, the complementary iPorts overlay each other. The scales are aligned with a match of the CiFET ratios. In reality, the N channel iPort termination voltage is a PTAT bandgap reference which has its voltage set by the iFET channel ratio relationship. The p Channel iPort is a precise complement CTAT bandgap voltage reference. When these two voltage references are added the temperature effect of the PTAT cancels the temperature dependence of the CTAT yielding temperature independent reference. Their slope offsets can be matched by the matching if the CiFET ratios and also be fine-tuned with a trim current injected into either iPort input.

Figure 3L is the transistor schematic of the CiFET used to generate these PTAT and CTAT bandgap references. The NiFET Q31L provides the PTAT reference on its iPort 31L and the PiFET Q32L provides the CTAT reference on its iPort 32L. This CiFET device also provides the analog zero bias reference on its output 30L.

The precise linearity of the temperature relationship over an extremely wide temperature range of -150 to +250 degrees Centigrade is plotted in Figure 3m. Note the total linearity. The negative or CTAT output on the PiPort overlays the CTAT when the sign is inverted. This graph suggests the usefulness in measuring temperature over extended temperature limits. The temperature sensitivity is set by the iFET ratio selection shown in Figure 3k. A CiFET device can be tethered on a 3 wire line to sense temperature in hostile environments. This works well because the impedance of the CiFET tethered on the line would be low to minimize noise pickup.

The AC gain and phase performance of the CiFET device is illustrated by a standardized Bode plot in Figure 3n for a 75Ω iPort input resistance CiFET device, and in Figure 3r for a 35KΩ CiFET device, with the Bode plot for a minimum sized CMOS 2-finger inverter of Figure 1i in Figure 3u and the reference CMOS amplifier of Figure 1a Bode plot in Figure 1b for comparison of all device AC properties. All Bode plot scales are the same, frequency from 0.1 Hz to 1.0THz is the horizontal frequency axis using a log scale, gain is in dB on the vertical scale along with phase in degrees. Both gain and phase scales were set to the same set of numbers of 0d to 180d. The gain is the thick black line with dashed cross-hairs at the 3db roll-off point and dotted cross-hairs at the gain cutoff frequency to provide the phase-margin on the phase trace shown as large grey square dots. There are several horizontal lines to identify gain and phase shifts. The upper dot-dash horizontal line is for a 45 degree phase shift form DC which is used to target the 3db gain roll-off point with the dashed cross-hairs. The next grey dashed reference level is at 90 degrees followed by the
dot-dot-dash line at 30 degrees to indicate a minimum acceptable phase-margin. The lower reference line is indicated by small square dots overlaying a thinner solid line to indicate the zero crossover of both gain and phase. This helps compare these three Bode plots to each other.

Following these three Bode plots are three plots Figures 3p, 3s, 3v of the change in voltage gain over power supply voltage so that this property can be compared to the CMOS amplifier of Figure 1a with its comparison plot in Figure 1c. These four plots show the voltage gain as the power supply voltage is decreased in -100 milli-volt steps. The full power supply voltage for the standardized 180nm CMOS process is 1.8 volts and is shown as a solid thick black line which is the widest bandwidth in all example plots. Form this thick black trace, the power supply steps down by a tenth of a volt in the next 7 various dot-dash combination grey traces to the thick dashed plot at a power supply of 1.0 volts. The next solid grey traces are steps from 0.9 to 0.6 volts on the power supply, followed by thin dotted traces going from 0.5 volts to 0.1 volts on the power supply. These plots show that the gain for these circuits actually goes up as power supply is reduced, with the exception of the prior art CMOS amplifier of Figures 1a, 1c which falls off the cliff as power supply voltage is reduced. The thin dotted cross-hair lines are on the gain at full power supply voltage and the dashed cross-hair lines is for the 1.0 volt power supply voltage.

To make this set of plots easier to comprehend, additional graphs follow each plot in Figures 1d, 2q, 3t, 3w. These graphs relate gain and cutoff frequency to the power supply reduction. All plots have the same scales and axis variables. It can be clearly seen that the gain increases as power supply voltage is reduced. The speed or bandwidth penalty can be easily visualized with these plots. Typically bandwidth holds acceptably down to about 0.8 volts of power while gain significantly increases steadily as the power voltage is dropped down to below to about a half a volt. This is because the channels use a higher percentage of weak-inversion like diffusion current as power supply voltage is forced down. It should also be noted that the inverter also increases gain as power is reduced, for the same forced exponential mode operation point of the channels.

Figure 3q shows voltage gain and cutoff frequency as a function of power supply voltage for 75 ohm iPort CiFET device.

It has been observed in Figure 2b that the source channel 23b operates in a “Super-Saturated” mode 28b which possess exponential properties similar to weak-inversion or bipolar Beta. This mode of operation is not limited through the conventional FET threshold voltage, but rather functions with higher gain as the voltages are forced well below the
conventional threshold voltage. This is because the channels are being pushed well down into their diffusion mode of operation. Here a charge injection provides additional carriers in the channel which enables an increase in current flow through the channel. This bodes well with FET transistors because field effect transistors are fundamentally charge controlled devices.

This increase in gain with diminishing power supply voltage boosts weak-inversion like operation, where the charge-transport mechanism produces a higher exponential-class of gain. This is also demonstrated with the conventional CMOS inverter of Figure 1i as shown by the standard AC performance plots of Figures 3u to 3w. Thus there is a methodology of obtaining higher gain with lower power supplies that, when recognized, is an alternative to analog circuits being threshold voltage limited. This completely solves the reduced voltage problem that prior art analog circuits battle in the newer IC processes.

Noise Advantages:

In the end, it comes down to signal-to-noise ratio. Low power supply voltage requirements in ultra-deep-sub-μm IC processes limit the maximum signal swing to a much smaller number than most analog designers are used to. So with a smaller signal, the noise must be equally small in order to maintain the desired signal to noise ratio. It is imperative that noise issues be reduced. This iFET amplifier technology not only reduces noise by an amount as would be necessary, but performs far beyond expectations, delivering ultra-quiet front ends.

1/f noise in the source channel is reduced because the self-bias scheme provides a high field strength on the source channel’s gate, forcing carriers in the channel to operate below the surface where there is a smoother path (fewer obstructions) than along the surface where crystal lattice defects interfere.

1/f noise in the drain channel is also low. Unlike conventional analog designs, the gate is self-biased at the half-way point between the power supply rails as is the drain, while the iPort is within ~100 millivolts of the power rail. With the high electric field along the drain channel, and the gate voltage equal to the drain terminal voltage, the carriers are constrained to flow mostly below the channel surface. This keeps the drain channel out of pinched off conditions, where unwanted 1/f noise would be generated.

Resistance noise is minimized because the self-bias configuration puts the complementary pair at its lowest channel resistance operating point. Resistance noise is
caused by collisions, between carriers and the surrounding atoms in the conductor. The lower the resistance is, the fewer the collisions.

Wide band noise (white-noise) would always be an issue in high gain for high frequency circuits. While conventional designs adjust the gate voltage to establish suitable operating point(s), the designs of the present invention establish the gate voltage at the optimum point (the “sweet-spot”) and then adjust the load to establish the desired operating point. This approach establishes a higher quiescent current where (for reasons explained above) higher current density circuits have lower wide band noise.

High common mode power supply rejection is inherent in the complementary iFET device structure of the present invention. Signals are with respect to the mid-point instead of being with respect to one of the power supply rails, similar to an op-amp with its “virtual” ground. Power supply noise is from one rail to the other, equal and opposite in phase with respect to each other; thus canceling around the mid-point.

Ground-Loop noise is diminished because the circuit ground is “virtual” (just like in many op-amp circuits), rather than ground being one or the other power supply connections where ground or power noise is conducted into the analog signal path. … In the closed-loop case, “Flying Capacitors” are often employed. With “flying capacitors” there is no direct electrical connection between stages, so there is no common ground; virtual or otherwise. The use of “differential decoupling” (flying capacitors) offers transformer like isolation between stages, with the compactness of integrated circuit elements.

Coupled noise from “parasitic induced crosstalk” increases by the square of the signal amplitude. Unintended capacitive coupling into a 1 volt signal causes a lot more trouble than with a 100 mV signal, by a factor of 100:1 (square law effect). The small low impedance charge or voltage signals employed in the analog sections, reduce this capacitive coupled interference substantially. Nearby Digital signals will, by definition, be high amplitude (rail-to-rail). Good layout practices are still the best defense against this digital source of noise.

**Additional Advantages:**

There are a number of additional advantages. For example, bi-directional control on the iPort means that current can flow in-to as well as out of this connection; both directions having a significant and symmetrical control effect on overall channel current. Also, a zero current imposed in the iPort is a valid zero input signal, thus the iPort signals are truly bidirectional about zero. The iPort has about five (5) orders of magnitude more dynamic control range than the gate.
When the low impedance iPort is used to measure an analog Signal, the input impedance may diminish the input voltage, but the energy transfer into the iPort amplifier is high, especially for low impedance sources such as matching an antenna, transmission line, or many biological signal sources.

When a high-impedance analog amplifier is necessary, the gate is sued for the input and the amplifier can contain multiple stages for high voltage gain, while the CiFET can stabilize such an amplifier.

In the CiFET device there are two iPort input signals that precisely sum, thus this structure is an analog adder and can combine the two inputs at RF frequencies to form a RF mixer using a single CiFET device.

The ifET of the present invention yields an analog structure that is significantly faster than logic using the same MOS devices. This speed improvement is due to the fact that the complementary structure expresses its maximum gain (and highest quiescent current) at its natural self-bias point, midway between the power supplies.

Since the iPort voltage does not significantly change, it is immune to the R/C time constant effects of the surrounding parasitics, thus the iPort (current) input responds faster than the gate (voltage) input.

When used as a data bus sense amplifier on a RAM, the iPort’s low impedance rapidly senses minute charge transfer without moving the data bus voltage significantly. Since the iPort input impedance is low, and the iPort is terminated with a fixed low voltage, this sense amplifier approach eliminates the need for pre-charging in the memory readout cycle. Since the ifET operates at better than logic speed, IFET for sensing charge would decrease the readout time impressively.

Since, in most applications of the CiFET compound device structure of the present invention, the output voltage (drain connection point) does not vary greatly, and thus making the output immune to the R/C time constant effects of the surrounding parasitics. A logic signal is slower than analog here because logic signals have to swing from rail to rail.

Drain-induced barrier lowering or (DIBL) threshold reduction is avoided in the CiFET compound device operating in the analog mode. When gain and threshold voltage is important, the drains are operating around half of the power supply voltage, thus eliminating the higher drain voltages where DIBL effects are prevalent.
Definitions of Terms:

**iFET:** A 4 terminal (plus body) device similar to a Field Effect Transistor but with an additional control connection that causes the device to respond to current input stimulus.

**source channel:** A semiconductor region between iPort diffusion and the Source diffusion. Conduction in this region is enabled by an appropriate voltage on the Gate.

**drain channel:** A semiconductor region between Drain diffusion and the iPort diffusion. Conduction in this region is enabled by an appropriate voltage on the Gate.

**Cilnv:** A single stage, complementary iFET compound device shown in Figure 3a.

**super-saturation:** an exponential conduction condition similar to weak-inversion, but with high Gate overdrive and forced low voltage along the conduction channel. Figure 2d #20.

**feed-forward:** A technique to present a signal on an output, early on, in anticipation of the ultimate value.

**self-biased:** Unlike fixed-bias circuits, self-biased circuits adjust to local conditions to establish an optimum operating point.

**dual:** (of a theorem, expression, etc.) related to another by the interchange of pairs of variables, such as current and voltage as in “trans-conductance” to “trans-resistance.”

**trans-resistance:** infrequently referred to as mutual resistance, is the dual of trans-conductance. The term is a contraction of transfer resistance. It refers to the ratio between a change of the voltage at two output points and a related change of current through two input points, and is notated as $r_m$:

$$r_m = \frac{\Delta V_{out}}{\Delta I_{in}}$$

The SI unit for trans-resistance is simply the ohm, as in resistance.

For small signal alternating current, the definition is simpler:

**trans-conductance** is a property of certain electronic components. Conductance is the reciprocal of resistance; trans-conductance is the ratio of the current variation at the output to the voltage variation at the input. It is written as $g_m$. For direct current, trans-conductance is defined as follows:

$$g_m = \frac{\Delta I_{out}}{\Delta V_{in}}$$
For small signal alternating current, the definition is simpler:

$$g_m = \frac{i_{out}}{v_{in}}$$

Trans-conductance is a contraction of transfer conductance. The old unit of conductance, the mho (ohm spelled backwards), was replaced by the SI unit, the siemens, with the symbol S (1 siemens = 1 ampere per volt).

Translinear circuit: translinear circuit is a circuit that carries out its function using the translinear principle. These are current-mode circuits that can be made using transistors that obey an exponential current-voltage characteristic—this includes BJTs and CMOS transistors in weak-inversion.

Sub-threshold conduction or sub-threshold leakage or sub-threshold drain current is the current between the source and drain of a MOSFET when the transistor is in sub-threshold region, or weak-inversion region, that is, for gate-to-source voltages below the threshold voltage. The terminology for various degrees of inversion is described in Tsividis. (Yannis Tsividis (1999). *Operation and Modeling of the MOS Transistor* (Second Edition ed.). New York: McGraw-Hill. p. 99, ISBN 0-07-065523-5.)

Sub-threshold slope: In the sub-threshold region the drain current behavior—though being controlled by the gate terminal—is similar to the exponentially increasing current of a forward biased diode. Therefore a plot of logarithmic drain current versus gate voltage with drain, source, and bulk voltages fixed will exhibit approximately log linear behavior in this MOSFET operating regime. Its slope is the sub-threshold slope.

Diffusion current: Diffusion current is a current in a semiconductor caused by the diffusion of charge carriers (holes and/or electrons). Diffusion current can be in the same or opposite direction of a drift current, that is formed due to the electric field in the semiconductor. At equilibrium in a p–n junction, the forward diffusion current in the depletion region is balanced with a reverse drift current, so that the net current is zero. The diffusion current and drift current together are described by the drift–diffusion equation.

Drain-induced barrier lowering: Drain-induced barrier lowering or DIBL is a short-channel effect in MOSFETs referring originally to a reduction of threshold voltage of the transistor at higher drain voltages.

As channel length decreases, the barrier $\phi_0$ to be surmounted by an electron from the source on its way to the drain reduces.
As channel length is reduced, the effects of DIBL in the sub-threshold region (weak-inversion) show up initially as a simple translation of the sub-threshold current vs. gate bias curve with change in drain-voltage, which can be modeled as a simple change in threshold voltage with drain bias. However, at shorter lengths the slope of the current vs. gate bias curve is reduced, that is, it requires a larger change in gate bias to effect the same change in drain current. At extremely short lengths, the gate entirely fails to turn the device off. These effects cannot be modeled as a threshold adjustment.

DIBL also affects the current vs. drain bias curve in the active mode, causing the current to increase with drain bias, lowering the MOSFET output resistance. This increase is additional to the normal channel length modulation effect on output resistance, and cannot always be modeled as a threshold adjustment (Drain-induced barrier lowering - https://en.wikipedia.org/wiki/Drain-induced_barrier_lowering).

Analogue electronics
http://en.wikipedia.org/wiki/Analogue_electronics
WHAT IS CLAIMED IS:

1. A solid state device comprising:
   a. an input terminal, and an output terminal;
   b. a first field-effect transistor (FET) comprising a first semiconductor
      substrate of a first conductivity type; and
   c. a second FET comprising a second semiconductor substrate of a second
      conductivity type;
      i. wherein said first FET comprising a first source, a first drain, and a
         first gate on said first substrate defining a first channel
         therebetween; and
      ii. wherein said second FET comprising a second source, a second
         drain, and a second gate on said second substrate defining a second
         channel therebetween; and
   d. first and second localized diffusions of corresponding conductivity types
      in said first and second channels respectively, and first and second low
      impedance ports, wherein said first low impedance port is connected to
      said first diffusion in said first channel and said second low impedance
      port is connected to second diffusion in said second channel;
         wherein said output terminal is in connection with said first and second
         drains; and
         wherein said input terminal is connected to said first and second gates,
         and said first and second gates are capacitively coupled to said first and
         second channels contacting said first and second low impedance ports defined
         therein, respectively.

2. A solid state device comprising:
a. first and second field effect transistors,

i. said first transistor comprising

1. a first substrate of a first conductivity type,

2. a first source and a first drain in said first substrate,

3. a first low impedance port in said first substrate between
   said first source and said first drain for defining a first
   source channel between said first source and said first low
   impedance port, and a first drain channel between said first
   drain and said first low impedance port, contacting a first
   localized diffusion of said first conductivity type between
   said first source and said first drain channels;

ii. said second transistor comprising

1. a second substrate of said second conductivity type,

2. a second source and a second drain in said second substrate,

3. a second low impedance port in said first substrate between
   said second source and said second drain for defining
   second source channel between said second source and said
   second low impedance port, and a second drain channel
   between said second drain and said second low impedance
   port, contacting a second localized diffusion of said second
   conductivity type between said second source and second
   drain channels;

iii. an electrical output connecting between said first and second
    drains; and
iv. a common gate electrode capacitively connected to said first and second source and drain channels, said input connection being connected to said common gate.

3. A solid state device comprising:
   a. first and second field effect transistors of first and second conductivity types, each of said first and second transistors comprising a pair of source and drain, defining source and drain diffusion regions of second and first conductivity types, respectively, and said source and said drain of said first transistor defines first channel and said source and said drain of said second transistor defines a second channel,
   b. first and second localized diffusions in said first and second channels respectively,
   c. a first low impedance port contacts a first localized diffusion of said first conductivity type in said first channel,
   d. a second low impedance port contacts a second localized diffusion of said second conductivity in said second channel,
   e. an electrical output in communication with said first and second drains, and
   f. a common gate capacitively coupled to said first and second channels.

4. A solid state device as recited in claim 3, wherein said first and second localized diffusion are located closer to said first and second sources, respectively.

5. A solid state device as recited in claim 3, wherein said first and second localized diffusions are located closer to said first and second drains, respectively.

6. A solid state device as recited in claim 3, wherein the trans-impedance of said solid state device is adjusted by doping and geometric profiles.
7. A solid state device as recited in claim 3, comprising an electrical connection between said electrical output and said common gate.

8. A solid state device as in claim 1 comprising an output connection to said common gate in a manner to provide positive and negative reference voltages and an intermediate analog ground.

9. A solid state device as in claim 8 comprising a solid state analog device having first, second, and third input terminals, said terminals being connected to said first solid state device in a manner to connect at least one of first, second, or third terminals to said positive and negative reference voltages and to said intermediate analog ground respectively.

10. A solid state device as in claim 8 comprising first and second iFETs of first and second conductivity types electrically connected in series, said device comprising first positive and second negative voltage sources for impressing a voltage across said iFETs.

11. A solid stage device as in claim 3 wherein said first FET comprises first source and drain channels and said second FET comprises second source and drain channels wherein each of source and drain channels of said first FET as a width and a length when the width to length ratio is unequal to the width to length ratio of said drain channel.

12. A solid state device as in claim 11 wherein the width to length ratio of said source channel is greater than that of said drain channel.

13. A solid state device as in claim 11 wherein the width to length ratio of said source channel is less than that of said drain channel.

14. A device as in claim 11, 12, 13 wherein said second FET has source and drain width to length ratios to match those in said first FET.
15. A device as in claim 3 wherein first and second FETs are of n-type and p-type conductivity respectively wherein the width of the source to drain channel of said second FET is between 3 to 4 times the width of the source to drain channel of said first FET where the width is taken perpendicular to the source to drain axis for equalizing carrier mobility of first and second FETs.

16. A solid state device comprising:
   a. a first field-effect transistor (FET) comprises a first semiconductor substrate in a first conductivity type; and
   b. a second FET comprising a second semiconductor substrate of a second conductivity type;
      i. wherein said first FET comprises a first source, a first drain, and a first gate in said first substrate defining a first channel therebetween; and
      ii. wherein said second FET comprising a second source, a second drain, and a second gate on said second substrate defining a second channel therebetween; and
   c. first and second localized diffusions of corresponding conductivity types in said first and second channels defining first and second low impedance ports respectively;
      i. wherein said first low impedance port is connected to said first diffusion in said first channel, and
      ii. said second low impedance port is connected to said second diffusion in said second channel.
1. A solid state device comprising:
   a. an input terminal, and an output terminal;
   b. a first field-effect transistor (FET) comprises a first semiconductor
      substrate of a first conductivity type; and
   c. a second FET comprises a second semiconductor substrate of a second
      conductivity type;

wherein:

   said first FET comprises a first source, a first drain, and a first gate on
   said first substrate, defining a first channel between said first source and
   said first drain;

   said second FET comprises a second source, a second drain and a
   second gate on said second substrate, defining a second channel between
   said second source and said second drain;

   a first localized diffusion of the first conductivity type for dividing
   said first channel into a first source channel between said first source
   and said first localized diffusion and a first drain channel between said
   first drain and said first localized diffusion;

   a second localized diffusion of the second conductivity type for
   dividing said second channel into a second source channel between
   second source and said second localized diffusion and a second drain
   channel between said second drain and said second localized diffusion;
f. first and second low impedance ports, wherein said first low impedance port is connected to said first diffusion and said second low impedance port is connected to second diffusion;

said first and second drains are connected together to form said output terminal; and

said first and second gates are connected together to form said input terminal.

2. A solid state device comprising:

a. first and second field effect transistors,

   i. said first field effect transistor comprises

      a first substrate of a first conductivity type,

      a first source and a first drain in said first substrate,

      a first low impedance port in said first substrate

      between said first source and said first drain for defining a first source channel between said first source and said first low impedance port, and a first drain channel between said first drain and said first low impedance port, contacting a first localized diffusion of said first conductivity type between said first source and said first drain channels;

   ii. said second field effect transistor comprising

      (i) a second substrate of said second conductivity type,

       and
a second source and a second drain in said second substrate,
a second low impedance port in said second substrate between said second source and said second drain for defining second source channel between said second source and said second low impedance port, and a second drain channel between said second drain and said second low impedance port, contacting a second localized diffusion of said second conductivity type between said second source and second drain channels;

iii. an electrical output connecting between said first and second drains; and

iv. a common gate electrode capacitively connected to said first and second source channels and said first and second drain channels.

3. A solid state device comprising:

a. first and second field effect transistors of first and second conductivity types, each of said first and second transistors comprising a pair of source and drain, defining source and drain diffusion regions of second and first conductivity types, respectively, said source and said drain of said first transistor defines a first channel, and
said source and said drain of said second transistor defines a second channel,
b. first and second localized diffusions in said first and second channels, respectively,
said first localized diffusion divides the first channel into a first source channel between said source and said first localized diffusion of said first transistor and a first drain channel between said drain and said first localized diffusion of said first transistor,
said second localized diffusion divides the second channel into a second source channel between said source and said second localized diffusion of said second transistor and a second drain channel between said drain and said second localized diffusion of said second transistor
c. a first low impedance port contacts said first localized diffusion of said first conductivity type in said first channel,
d. a second low impedance port contacts said second localized diffusion of said second conductivity in said second channel,
e. an electrical output in communication with said first and second drains, and
f. a common gate capacitively coupled to said first source and drain channels and said second source and drain channels.

4. A solid state device as recited in claim 3, wherein said first and second localized diffusion are located closer to said first and second sources, respectively.
5. A solid state device as recited in claim 3, wherein said first and second localized diffusions are located closer to said first and second drains, respectively.

6. A solid state device as recited in claim 3, wherein the trans-impedance of said solid state device is adjusted by doping and geometric profiles.

7. A solid state device as recited in claim 3, comprising an electrical connection between said electrical output and said common gate.

8. A solid state device as in claim 1 comprising an output connection to said common gate in a manner to provide positive and negative reference voltages and an intermediate analog ground.

9. A solid state device as in claim 8 comprising a solid state analog device having first, second, and third input terminals, said terminals being connected to said first solid state device in a manner to connect at least one of first, second, or third terminals to said positive and negative reference voltages and to said intermediate analog ground respectively.

10. A solid state device as in claim 8 comprising first and second iFETs of first and second conductivity types electrically connected in series, said device comprising first positive and second negative voltage sources for impressing a voltage across said iFETs.

11. A solid state device as in claim 3 wherein said first FET comprises first source and drain channels and said second FET comprises second source and drain channels wherein each of source and drain channels of said first FET as
a width and a length when the width to length ratio is unequal to the width to length ratio of said drain channel.

12. A solid state device as in claim 11 wherein the width to length ratio of said source channel is greater than that of said drain channel.

13. A solid state device as in claim 11 wherein the width to length ratio of said source channel is less than that of said drain channel.

14. A device as in claim 11, 12, 13 wherein said second FET has source and drain width to length ratios to match those in said first FET.

15. A device as in claim 3 wherein first and second FETs are of n-type and p-type conductivity respectively.

16. A device as in claim 15, wherein the width of the source to drain channel of said second FET is wider than the width of the source to drain channel of said first FET where the width is taken perpendicular to the source to drain axis for equalizing carrier mobility of first and second FETs.

17. A device as in claim 15, wherein the width of the source to drain channel of said second FET is between 3 to 4 times the width of the source to drain channel of said first FET where the width is taken perpendicular to the source to drain axis for equalizing carrier mobility of first and second FETs.

18. A solid state device comprising:

   a. a first field-effect transistor (FET) comprises a first semiconductor substrate in a first conductivity type; and

   b. a second FET comprising a second semiconductor substrate of a second conductivity type;
i. wherein said first FET comprises a first source, a first drain, and a first gate on said first substrate, defining a first channel between said first source and said first drain; and

ii. wherein said second FET comprising a second source, a second drain, and a second gate on said second substrate, defining a second channel between said second source and said second drain;

c. first and second localized diffusions of corresponding conductivity types in said first and second channels, respectively,

said first localized diffusion divides said first channel into a first source channel between said first source and said first localized diffusion and a first drain channel between said first drain and said first localized diffusion,

said second localized diffusion divides said second channel into a second source channel between said second source and said second localized diffusion and a second drain channel between said second drain and said second localized diffusion; and

d. first and second low impedance ports, wherein said first and second low impedance ports are connected to said first and second localized diffusion, respectively.

19. A method for improving the functionality of conventional analog signal processing circuit elements using purely digital components, comprising the steps of:
a) providing a complimentary current field effect transistor (CiFET) gain stage which has been formed by modifying a CMOS inverter having source nodes, a common-gate node and a common-drain node, and two channels, each of which is of sufficient length to allow insertion of a diffusion based on the applicable design rules,

by inserting a diffusion into each of said channels to separate said channel into two segments comprising a source channel and a drain channel in series,

wherein each of said diffusions can be used as a current input terminal (iPort);

b) applying a voltage across the source nodes;

c) applying a voltage having a value between the source node voltages to the common-gate node;

d) applying a current input to one or both of the iPorts;

e) utilizing the common-drain node as a low impedance analog output terminal;

whereby the CiFET operates as a trans-resistance gain structure converting current-in to voltage-out.

20. An trans-impedance amplifier using digital components comprising:

a complimentary pair of current field effect transistors comprising:
source nodes, a common-gate node and a common-drain node, and
two channels, each of which is capacitively coupled with said common-gate
node and is of sufficient length to allow insertion of a diffusion as a current
input terminal (iPort) based on applicable design rules, wherein said diffusion
separates a corresponding one of said channels into two segments comprising
a source channel and a drain channel,
wherein:
the source nodes receive first and second voltages;
the common-gate node receives an input voltage having a voltage value between
said first and second voltages;
one or both of the iPorts receives a current input; and
the common-drain node provides a low impedance analog output terminal.

21. The trans-impedance amplifier as recited in claim 20, wherein said
complimentary pair of current field effect transistors comprises first and
second conductivity types.

22. The trans-impedance amplifier as recited in claim 21, wherein said first
conductivity is p-type and n-type conductivities, respectively.
In accordance with Article 19 of the PCT, please replace the claims of International Application No. PCT/US2015/042696 with the claims (claims 1-22) included in the attached Replacement Sheets. Differences between the claims as filed and those as amended are as follows:

i. Claims 1 to 3 replaces claims 1 to 3 as originally filed;

ii. Claims 4 to 14 are unchanged;

iii. Claims 15, 16 and 17 are the result of the division of claim 15 as originally filed.

iv. Claim 18 replaces claim 16 as originally filed; and

v. Claims 19 to 22 are new.

The Basis for Amendments and the Replacement Sheets follow, as required by Rule 46.5 PCT.
Prior Art

2-Finger Inverter

Fig. 1i
Prior Art

Fig. 1j

Prior Art

Fig. 1k
Prior Art

Fig. 1p
Fig. 2m
CIFET

Fig. 3a
Fig. 3h  CiFET Transfer Properties
≡ LINEAR Trans-Resistance
Complementary iFET Device

either iPort input Resistance \( (R_{in}) \)
and TransResistance \( (r_m = \text{gain factor}) \)
(input current forces output voltage)
as a function of iFET Ratio

Fig. 3i
Complementary iFET Device

Input Resistance ($R_{in}$) to TransResistance ($r_m$) Ohmic Step
{equivalent to CiFET Inverter Peak Voltage Gain}
as a function of iFET Ratio

Fig. 3j
Complementary iFET Device

N and P iPort input Termination Voltage
{to their respective power rails}
as a function of iFET Ratio

Fig. 3k
Fig. 3L
PTAT Reference Voltage at iPort
(CIFET Ratioed for Temperature Measurement)
Illustrating Ultra Wide Range and High Linearity

Fig. 3m
35K ohm iPort CiFET Device

Voltage Gain [db] and Cutoff Frequency [MHz] as a Function of Power Supply Voltage [Volts]
Midpoint Biased Gain Methodology

Minimum CMOS Inverter

Voltage Gain [db] and Cutoff Frequency [MHz] as a Function of Power Supply Voltage [Volts]

Fig. 3w
# INTERNATIONAL SEARCH REPORT

**A. CLASSIFICATION OF SUBJECT MATTER**

<table>
<thead>
<tr>
<th>IPC(8)</th>
<th>H03K 19/094 (2015.01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPC</td>
<td>H03K 19/094 (2015.04)</td>
</tr>
</tbody>
</table>

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

<table>
<thead>
<tr>
<th>IPC(8)</th>
<th>H04L 21/822; H03F 3/213, 3/30, 3/345, 3/347; H03K 19/00, 19/0948 (2015.01)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USPC</td>
<td>257/24, 27; 438/186, 188</td>
</tr>
</tbody>
</table>

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

|-----------|------------------------------------------------------------------------------------------------|

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Orbit, Google Patents, Google, ProQuest

Search terms used: complementary mos, pfe, nfe, jfe, source, drain, gate, diffusion, cifet, ifet, low impedance port, well

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>US 4,100,502 A (YAMASHIRO) 11 July 1978 (11.07.1978) entire document</td>
<td>7-10</td>
</tr>
<tr>
<td>A</td>
<td>US 5,528,056 A (SHIMADA et al) 18 June 1996 (18.06.1996) entire document</td>
<td>1-13, 15, 16</td>
</tr>
</tbody>
</table>

* Further documents are listed in the continuation of Box C.  

T: Later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X: Document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y: Document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

&E: Document member of the same patent family

**Date of the actual completion of the international search**

25 September 2015

**Date of mailing of the international search report**

23 October 2015

**Name and mailing address of the ISA/**

Mail Stop PCT, Attn: ISA/AUS, Commissioner for Patents

P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

**Authorized officer**

Blaine Copenhaver

PCT Helpdesk: 571-272-4300

PCT OSP: 571-272-7774
INTERNATIONAL SEARCH REPORT

Box No. II  Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.: because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 14 because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III  Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest ☐ The additional search fees were accompanied by the applicant’s protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant’s protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (January 2015)