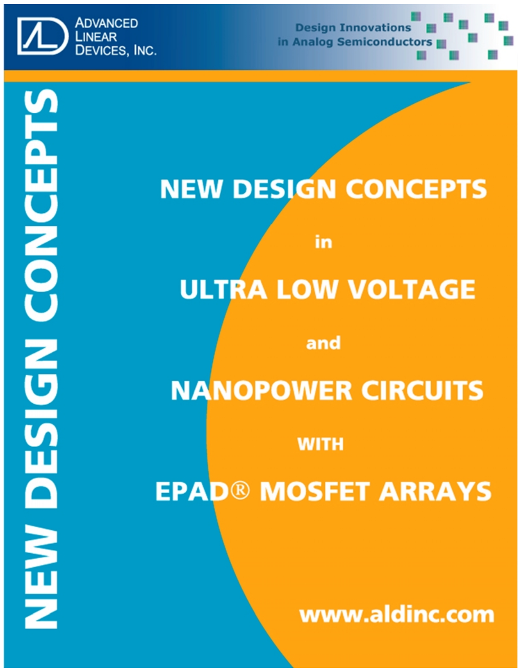

NEW DESIGN CONCEPTS IN ULTRA LOW VOLTAGE AND NANOPOWER™ CIRCUITS WITH EPAD® MOSFET ARRAYS

Advanced Linear Devices, Inc.
URL: www.aldinc.com

Introduction

The quest to achieve ever-lower operating voltage and lower power consumption levels in circuit design is a trend that has placed difficult challenges on electrical engineers as they run up against the very constraints placed upon them by basic semiconductor device characteristics. These characteristics have long been viewed by engineers as fundamental and may have prevented them from maximizing the usable voltage range that would otherwise make a novel circuit successful.

Now analog designers have new options available to them with the introduction of EPAD® MOSFET matched-pair arrays (EPAD MOSFET). One of the key constraints designers deal with is the gate threshold voltage at the basic transistor level. The paradigm that EPAD MOSFET arrays introduce is that gate threshold levels can now be precisely controlled so that analog designers are now unshackled by the constraints that previously limited a broad range of solutions.

This introduction to EPAD MOSFET describes a broad selection of devices with precisely set gate threshold voltage values, including zero threshold mode, enhancement mode and depletion mode. Furthermore, novel circuit designs are presented to illustrate how these devices can be used at a practical level. The brief circuit descriptions presented are intended to stimulate new ways in thinking about circuit design and how these new devices can be implemented to achieve results that were either unattainable or highly improbable.

General Description

ALD EPAD MOSFET matched-pair Arrays are a unique family of monolithic quad/dual N-Channel zero threshold mode, enhancement mode and depletion mode devices. These EPAD MOSFETs are precision matched at the factory using ALD's proven EPAD® CMOS technology. This product family offers tightly controlled threshold voltages ranging from enhancement mode values of +1.40V, to zero threshold value of 0.00V, to depletion values of -3.50V. The tight control of threshold voltages enables predictable transistor operation at very low voltages and currents. Due to their unique characteristics, these MOSFETs can address a wide range of design issues that did not have a practical solution before.

A unique member of this EPAD MOSFET Array family is the Zero-Threshold MOSFET. This device, along with other very low threshold voltage members of the product family, constitute a class of MOSFET devices that enable ultra low supply voltage operation and nanopower small signal circuit designs, applicable in either analog or digital circuits. In some instances, a circuit that depends on a single ultra-low voltage and low-power supply source can be implemented.

This product family is available in the three separate operating mode categories, each providing a distinctly different set of device electrical specifications and characteristics. The ALD110800/ALD110900 products are zero-threshold mode EPAD MOSFETs. The ALD1108xx/ALD1109xx products are enhancement mode EPAD MOSFETs and the ALD1148xx/ALD1149xx products are the depletion mode EPAD MOSFETs.

As basic circuit-design building blocks, each member of this product family can be applied in a wide variety of ways. Each product category enables different applications of circuit designs to be implemented and could result in vastly different end-circuits and their associated performance characteristics. They are particularly versatile as design components for a broad range of analog applications including current sources and current mirrors, differential amplifier input stages, transmission gates, and multiplexers.

ZeroThreshold™ Mode ALD110800 Quad/ ALD110900 Dual

The Zero Threshold MOSFET is a special case in this EPAD MOSFET family where the individual threshold voltage of each MOSFET is fixed at zero. These devices are unique by using ALD EPAD technology to offer very low voltage switching with sharp turn-off and very low leakage characteristics similar to that for a conventional MOSFET.

The zero threshold voltage is defined as Ids =1uA @ Vds=0.1V when the gate voltage Vgs=0.00V. Technically, these zero threshold devices are enhancement mode devices when operated above threshold voltage and current level (>0.0V and >1uA). However, it can also be used as a normally-on MOSFET as the device is conducting a current and behaves like a fixed resistor even when the gate voltage is at 0.0V. A modulating signal voltage at the gate can modulate the drain current, even to negative gate voltage levels, down to a subthreshold voltage level of about –0.4V, at which point the transistor is completely turned off.

A zero threshold MOSFET reduces or eliminates input to output voltage level shift in circuits where the signal is referenced to GND or V+. This feature can significantly reduce output signal level shift from that of the input and enhances operating signal range, especially for very low operating voltage environments. With zero threshold devices an analog circuit with multiple stages can be constructed to operate at extremely low power supply or bias voltage levels.

Enhancement Mode ALD1108xx Quad/ ALD1109xx Dual

The ALD1108xx/ALD1109xx products are enhancement mode EPAD MOSFET devices, which require a positive bias voltage to turn on. Precision threshold values such as +1.50V, +0.80V, +0.20V are offered as standard products. No conductive channel exists between the source and drain at zero applied gate voltage. The threshold voltage level of each product has an impact on circuit bias voltage and current conditions. Selection of different product members affect the required design techniques in determining input or output signal levels, the type of circuits that can be implemented, and in some cases the operating supply voltage of the system. The precision of the threshold voltage facilitates designs that count on repeatable electrical characteristics with tight design tolerance margins. This precise threshold voltage feature enables designs that simplify or reduce circuit complexity in the design and also in the circuit stages that follow. In some situations, supply voltages and supply currents can also be greatly reduced.

Depletion Mode ALD1148xx Quad/ ALD1149xx Dual

ALD1148xx/ALD1149xx products are depletion mode EPAD MOSFETs, which are normally-on devices when the gate bias voltage is at 0.0V. The depletion mode threshold voltage is at a negative voltage at which the MOSFET device turns off. Negative threshold values such as –0.40V, -1.30V and –3.50V are offered. Without supply voltage and with Vgs = 0.0V these EPAD MOSFET devices are already turned on and exhibit a controlled on-resistance between the source and drain terminals.

ALD1148xx/ALD1149xx are unique and different from most other depletion mode MOSFETs and certain types of JFETs in that they have tightly controlled performance characteristics and do not exhibit poorly controlled leakage currents and junction leakage currents. When negative signal voltages are applied to the gate terminal, the designer/user can depend on the fact that the EPAD MOSFET device can be controlled, modulated and turned off at a precise voltage.

For these devices, the conducting channel is controlled similar to that of an enhancement EPAD MOSFET, except that the threshold voltage is linearly shifted by a fixed negative amount. This fixed voltage shift has been enabled by ALD's EPAD® technology in the manufacturing process. The end results are precision threshold-voltage depletion mode EPAD MOSFETs with tightly controlled performance characteristics.

These depletion mode EPAD MOSFET devices can be modulated and turned-off under the control of the gate voltage in the same manner as the enhancement mode EPAD MOSFET. Where the threshold voltage is linearly shifted, the gate control voltages must also shift accordingly relative to the threshold voltage shift in order to turn on, modulate or turn off a specific depletion mode EPAD MOSFET device.

EPAD MOSFET Key Performance Characteristics

EPAD MOSFETs is designed for exceptional matching of device electrical characteristics. These devices are built for minimum offset voltage and differential thermal response. Being integrated on the same monolithic chip, they also exhibit excellent temperature coefficient tracking characteristics.

These EPAD MOSFET devices are designed for switching and amplifying applications in low voltage (1V to 10V or +/-0.5V to +/-5V) or ultra low voltage (less than 1V or +/- 0.5V) systems. These devices also feature low input bias current (<30pA@25C), low input capacitance, fast switching speed and are intended for applications where a combination of these above characteristics are desired. When these EPAD MOSFETs are biased at or below threshold voltage levels, active, always-on circuits can be designed that dissipate power measured only in nanowatts.

Besides matched-pair electrical characteristics, each individual EPAD MOSFET also exhibits tightly controlled parameters, enabling dependable and tight design limits. For example, with a conventional MOSFET with Vgs(th) range of +/-0.3V, a design must allow for an Ids range of +/- 0.4 mA at Vgs = Vds = 2.0V. However, using an ALD110808 with Vgs(th) range of +/- 0.01V, a design must allow for an Ids range of only about +/- 0.01 mA. Even units from different manufacturing lots have correspondingly well matched characteristics. As a result, these devices are ideal for applications where matching between multiple devices either in the same package or across different packages in proximity to each other are desired.

EPAD MOSFET Application Environment

* Low voltage: 1V to 10V or +/- 0.5V to +/- 5V
* Ultra low voltage: less than 1V or +/- 0.5V
* Low power: voltage x current = power measured in microwatt
* Nanopower: voltage x current = power measured in nanowatt
* Precision matching and tracking circuits

EPAD MOSFET I – V Characteristics

The graphs in **Figures 1 – 3** show the electrical characteristics of the EPAD MOSFET Array family. In Figure 1, the graph depicts an EPAD MOSFET turn-on drain current versus drain voltage characteristics as a function of gate voltage at or above threshold voltage. As the threshold voltage is precisely

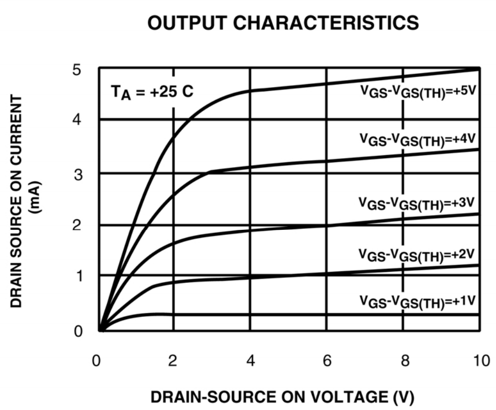

FIGURE 1

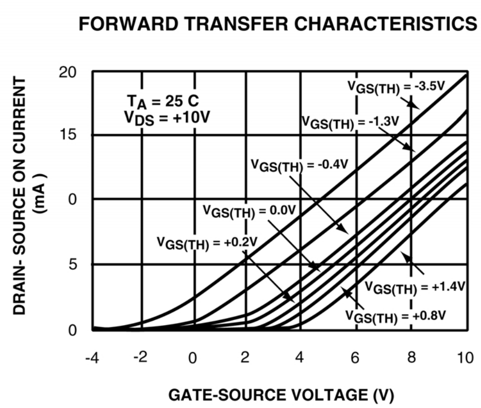

FIGURE 2

controlled, the drain current control at a given gate voltage input is much more uniform when compared to a typical conventional MOSFET.

It should be noted that all the members of the EPAD MOSFET Array family conform to standard MOSFET behaviors and can be used where a conventional n-channel MOSFET is used. The key differentiating factor lies in the fact that when Vgs(th) is now a precisely controlled parameter, many new design topographies and design techniques in circuits and systems are now possible. This is a revelation that may not be apparent upon first impression. However, engineers who took on certain design challenges in the past only to experience fundamental roadblocks may wish to revisit these dead-end results because of the enabling technology now available to them through these EPAD MOSFETs could allow them to advance to the actual circuit implementation stage.

The classic MOSFET device behavior as approximated by the equations below applies to EPAD MOSFET as well. For EPAD MOSFETs, the drain current in the linear region (where Vds < Vgs – Vgs(th)) is given by:

$$Id = (k.W/L).[Vgs - Vgs(th) - Vds/2].Vds$$

k = u. Cox
u is the carrier mobility
Cox is capacitance per unit area of gate electrode
Vgs is the gate to source voltage
Vth is the turn-on threshold voltage
Vds is the drain to source voltage
W and L are the channel width and the channel length respectively

For small values of Vds, the relationship of Vds to Ids is approximated to that of a linear resistor. The Ids value is proportional to Vds value and the device can be used as gate-voltage controlled resistor.

For higher values of Vds where Vds >= Vgs – Vgs(th), the channel of the EPAD MOSFET is in the pinch off region of device characteristics, the saturation current Ids is given by approximately:

$$Ids = (k.W/L). [Vgs - Vgs(th)]^2$$

EPAD MOSFET Subthreshold Voltage Operation

The graphs in **Figure 3A and 3B** show that at or below threshold voltage, the EPAD MOSFET exhibits a turn-off characteristic in an operating region called the subthreshold region. This is a region where the EPAD MOSFET conduction channel rapidly turns off as a function of the applied gate voltage. The channel induced by the gate voltage on the gate electrode decreases exponentially and therefore causes the drain current to decrease exponentially. However, the channel does not shut off abruptly with decreasing gate voltage, but decreases at a fixed rate of approximately 110 mV per decade of current decrease.

Thus, for example, if the threshold voltage of an EPAD MOSFET device is 0.2V, its drain current Ids is 1uA (Vds = 0.1V) at Vgs = 0.2V. At Vgs = 0.09V, Ids decreases to 0.1uA. Extrapolating from this, the drain current is at 0.01 uA (or 10 nA) at Vgs = -0.02V; 1 nA at Vgs = –0.13V; and so on.

Figure 3A shows all members of the EPAD® MOSFET Array family with appropriate parallel subthreshold curves which are linearly adjusted by the different Vgs(th) of the products. **Figure 3B** is a curve of Ids vs Vgs where Vgs is expressed relative to Vgs(th). This subthreshold curve behavior applies to all members of the EPAD MOSFET family.

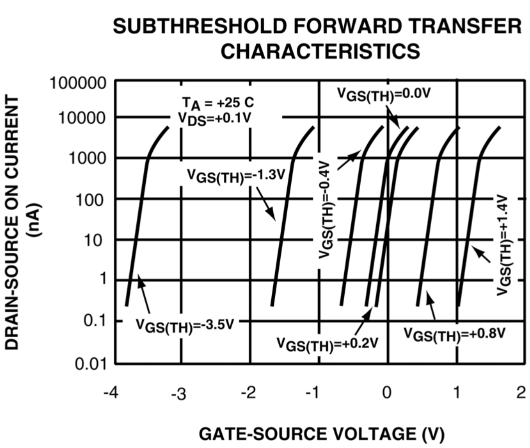

FIGURE 3A

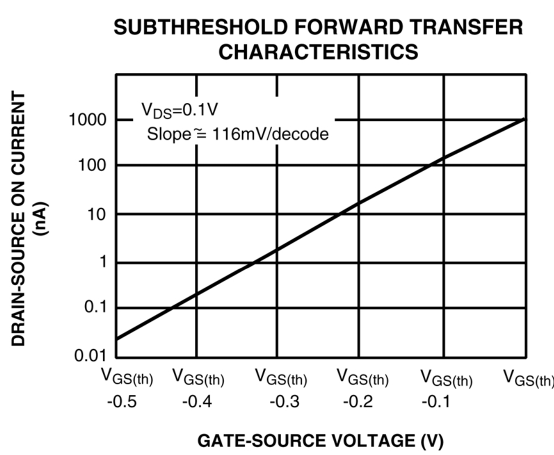

FIGURE 3B

At a drain current to be defined as “zero current” by the circuit designer, the Vgs voltage at zero current can now be calculated and estimated. For example, if the zero current for a specific design is specified to be 10 nA, then the Vgs voltage at that current level is approximately 220 mV below Vgs(th). Note that in this example where the Vgs(th) = 0.2V, its Ids still hovers around 20 nA when the gate is at zero volts (ground).

With precision control of Vgs(th) in the EPAD MOSFET, it is now easier to bias and operate an EPAD MOSFETs in the subthreshold region. When appropriate design margins are taken into account, and using an appropriate circuit design, a device can be biased in this subthreshold region and operate in either the analog mode or the digital mode.

Some of the key features and considerations in operating in the subthreshold region are:

* Very low operating supply voltages
* Very low signal voltage swings
* Very low operating current levels involved
* Ultra low power consumption
* Very high impedances at inputs and outputs without using high-valued resistors
* Exponential I to V characteristics
* Unique transconductance behavior of the device in this region of operation.

Low and Ultra Low Supply Voltage

Low voltage systems operating at 5V, 3.3V or less, typically require active MOSFET devices that have threshold, or turn-on, voltage of 1V or less. For analog designs, this threshold voltage directly affects the operating signal voltage range.

For example, a conventional MOSFET has a threshold voltage equal to 0.7V +/- 0.3V. The circuit designer must allow for maximum variation of the threshold voltage in the design so that the signal voltage is not clipped off when the signal reaches the lower end of the signal voltage limit. Typically a safety margin is added to allow for other system variables.

In the case of a 1V threshold MOSFET device, the minimum supply voltage required is at 1.0V or higher. The useful signal range of the circuit is directly determined and limited by the threshold voltage of the MOSFET used. This so-called “dead-band” overhead voltage situation becomes critical as the threshold voltage becomes an increasing large portion of the supply voltage as supply voltage decreases. Eventually the useful range of the signal swing is entirely used up by this “dead-band” voltage and the circuit ceases to function with any useful signal voltage swing.

Some EPAD MOSFETs are designed to specifically address this low supply voltage situation. The ALD110802, for example, has a turn-on threshold voltage of only 0.2V, which, depending on the circuit biasing conditions, can accept or produce greater than 0.8V signal swing with a 1 V supply. The ALD110800 Zero Threshold MOSFET can produce a full 1V rail-to-rail signal swing in many circuit configurations with only a 1V supply.

Ultra low supply voltage is referred to as supply voltages at less than 1V or less than +/- 0.5V. As an example of an application, a single panel solar cell that put out about 0.45V when loaded can be used to build useful instrument grade circuits using EPAD MOSFETs. The 0.45V can be used in a single supply configuration, or split into +/- 0.225V dual supplies. In its simplest form, an inverter circuit using an ALD110800 device can operate with a mere 50mV supply.

Low Power and NanoPower™ Operation

When supply voltage decreases, the power consumption of a given load resistance decreases as the square of the supply voltage. So one of the key benefits in reducing supply voltage is to reduce power consumption. Although usually decreasing power supply voltages and power consumption go hand-in-hand with decreasing useful AC bandwidth and increasing noise in the circuit, a designer can make the necessary tradeoffs for a given circuit application and bias the circuit accordingly to optimize a number of variables.

From the previous paragraphs a scenario emerges where low supply voltages, in conjunction with the appropriate EPAD MOSFETs and careful circuit design to bias different branches of the circuit optimally, a circuit can be designed so that power consumption can be minimized to previously unattainable levels.

A circuit can be designed using different members of the EPAD MOSFET family so that power consumption is minimized for each intended circuit function. Circuits operating in microwatt or even nanowatt mode can be built and still provide a well-biased and tightly controlled circuit function.

In power critical applications, this power reduction can result in more than a hundred-fold or thousand-fold power consumption reduction, when compared to conventional circuit methods. Potentially nanopower circuits may alter the power source requirements in many applications and enable a breakthrough in power management and portable system design.

EPAD MOSFET Basic Circuits and Examples

An EPAD MOSFET is an active device that can be used as a basic circuit element in a great number of designs. There are many circuits where they can be used to advantage. The number of potential designs and uses using these EPAD MOSFET devices are limited only by the designer’s needs and imagination.

In selection of a particular member of a product family, there are usually one, two or more specifications or features that are of overriding importance for a specific application. As the threshold voltage Vgs(th) is a basic device specification, its selection determines quite a few key parameters that may be fundamental to the way a design is implemented.

Some of these key parameters and considerations include:

1. The voltage level relationship between input and output voltages
2. The desired operating voltage of the power supply (or multiple supplies)
3. The desired frequency response
4. The required signal to noise ratio
5. The desired quiescent current of the design
6. The overall power consumption
7. The output drive and other output characteristics, such as voltage swings, currents, etc.

Once the key factors of a system are determined, one or more suitable members of the EPAD MOSFET family can be selected. Different Vgs(th) devices may be used for different functional blocks.

The following are a few of the basic type of circuits that highlight the capabilities of this product family.

Parallel Connections

EPAD MOSFET arrays lend themselves to easy parallel connections. For example, an ALD110800 can have all the 4 drain terminals shorted together, all the 4 source terminals shorted together and all 4 gates tied together in a parallel connection. The device becomes connected as a single MOSFET device with 4 times the current output. Likewise, a dual EPAD MOSFET can be wired in parallel as a single MOSFET to produce double current output.

EPAD MOSFET Isolation & (Diode) Clamping Circuits

Many circuits require an isolation of their inputs and input impedance from that of the output impedance so that the output loads do not interfere with the input signals. This can be accomplished sometimes by using a transistor buffer or an op amp buffer, each presenting a number of design tradeoffs. Using the ALD110800 Zero Threshold MOSFET, for example, one can provide this isolation and yet provide the output of a circuit biased to a voltage level that is in the same range as the input level. This is a fundamental ability of a Zero Threshold MOSFET. The input and output levels can also be biased around a fixed voltage, such as 0.0V.

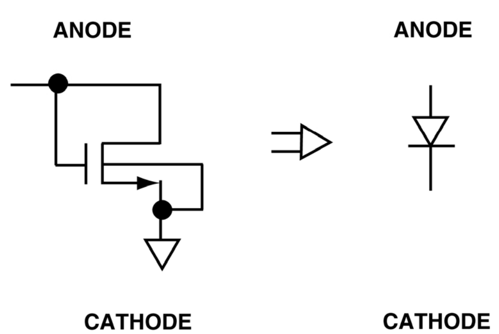

FIGURE 4

Designing an application where input and output levels are at the same levels would be cumbersome without an ALD110800 and would require many components and support circuitry. The use of an operational amplifier in the unity gain mode could do the job, but might also introduce many of the shortcomings associated with using an operational amplifier. When some of these shortcomings become serious limitations, the designer must instead consider using a simpler circuit with a discrete MOSFET such as an EPAD MOSFET.

Another type of a basic circuit is a diode clamping function. For this type of application, one might consider using an ALD110902 or an ALD110900 EPAD MOSFET, which start conducting current right at +0.20V or 0.00V respectively. Since these EPAD MOSFETs exhibit high drain current versus drain voltage characteristics resembling that of a diode turn-on characteristic, a diode clamping circuit with tightly controlled operating characteristics can be easily built by connecting the drain and the gate terminals, as shown in **Figure 4**.

EPAD MOSFET Inverter & Buffer

A basic EPAD MOSFET inverter consists of either a resistor or a MOSFET load and an EPAD MOSFET as the inverting device. By selecting a device with a different Vgs(th), it is possible to create an inverter running at ultra low voltage levels, ultra low power levels, or both. There are infinite numbers of possible combinations of voltage and power levels with various Vgs(th), with the choice determined by the mission of the circuit.

In **Figure 5A** there are a couple of examples to illustrate some of the possibilities. In the first example, the basic inverter is powered with a V+ of only 200 mV, with I+(max) = 0.24 uA, resulting in an average power of about 25 nW(nanoWatt), assuming a 50% duty cycle signal. Another example of this basic inverter changes the Vgs(th) to 0.4V and load resistor to 44MEG Ohm, resulting in the average current of 2.3 nA and power of 0.45 nW, using the same 200 mV supply.

Using the basic inverter as a buffer provides high level of isolation between the input and output. The input bias current to the inverter is specified at 5 pA typical and 30 pA maximum. The input voltage can be biased at a level convenient for the input source. For example, if the input source is a 50 mV peak to peak signal, centered around ground potential, then using ALD110800 Zero Threshold EPAD MOSFET may help eliminate an input level shift stage and the associated noise and distortion that such a intermediate stage can add to the signal. In a second example, where the input is a modulating signal, a depletion mode EPAD MOSFET is used to help bias the output to a desired voltage level and output impedance.

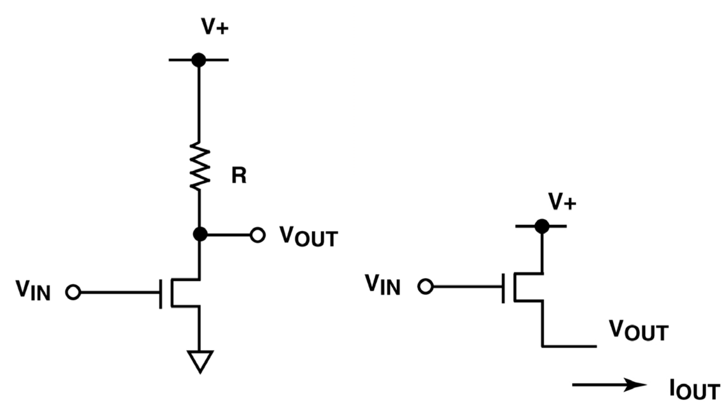

FIGURE 5A FIGURE 5B

The output level in a basic buffer can be designed to produce the proper output voltage range in part by using an appropriate load resistor and by selecting a specific member of the EPAD MOSFET family. The output voltage can be biased and shifted to any voltage output level and output swing range by design.

The basic inverter can also function as a crude inverting amplifier by biasing the EPAD MOSFET transistor in the linear region. This inverting amplifier function is easier to implement using low threshold devices such as the ALD110802 (Vgs(th) = 0.2V) or the ALD110800 (Vgs(th) = 0.0V). As an example of a suggested biasing scheme, the output load resistor can be selected so that the output voltage is nominally at V+/2 when Vin = 0.0V. This type of inverting amplifier can produce 5x to 12x gain.

A simple voltage source using a EPAD MOSFET can be implemented with an EPAD MOSFET connected as a source follower where the output currents are supplied by drain to source currents (**Figure 5B**). This circuit is analogous to the classic emitter follower using a bipolar transistor. In this case the input (source) voltage and its source impedance are completely isolated from the output voltage and output currents due to the extremely high input impedance of the MOSFET. The impedance transformed Vout and Iout are dependent only on the input voltage and the output impedance of the EPAD MOSFET.

EPAD MOSFET Logic Gate

By extension to the basic inverter, a simple logic gate such as a NAND and a NOR gate can be readily implemented using EPAD MOSFETs. While digital logic circuit implementation is not the primary application focus for the EPAD MOSFET family, there may be situations where an unconventional logic function that operates on 0.4V or less power supply is useful.

In **Figure 6 and 7** the EPAD MOSFET family devices are configured to implement logic functions. A single EPAD MOSFET quad array can be used to implement both NOR and NAND gates connected in a compound configuration. **Figure 6** illustrates a two-input NOR gate and **Figure 7** illustrates a two-input NAND gate.

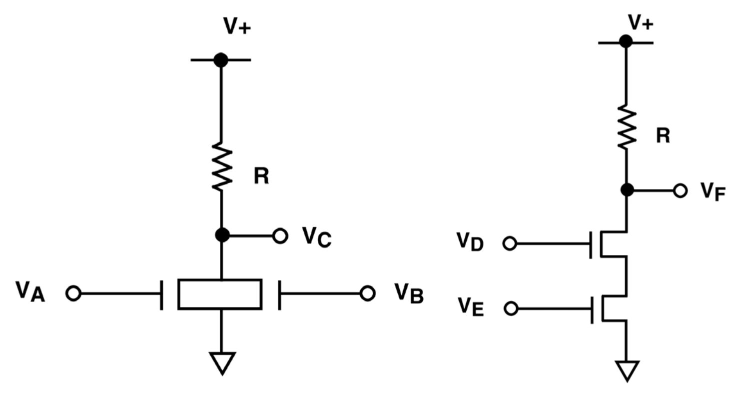

FIGURE 6

FIGURE 7

A key consideration in designing EPAD MOSFET logic is to determine the V+ supply available which will power up the logic circuit. When the V+ supply voltage drops to below 400 mV, EPAD MOSFETs are actually likely to be always in the same “off-state”. They are biased in the subthreshold region, whether in the “1” state or the “0” state of logic.

For example, consider the case of a 200mV supply and an EPAD MOSFET with threshold of 0.20V (ALD110802). In the output “1” state, the output is near 0.2V and the EPAD MOSFET is operating in the low end of the sub-threshold region, with drain current of about 19nA. In the output “0” state, the EPAD MOSFET is operating in the high end of the subthreshold region, with a drain voltage near 0.0V and a drain current of about 230nA. When multiple EPAD

MOSFETs are connected to build logic gates, both the "0" state current and voltage levels and the "1" state current levels must satisfy the desired output voltage and operating temperature range criteria.

The drain current in any circuit configuration depends on the actual circuit topography. The operating frequency of such a logic gate implemented depends on the operating voltage and the amount of current switching between the "1" logic state and the "0" logic state.

As the supply voltage decreases below 0.2V, the available voltage and current margins for the logic switching decreases accordingly, and the environment where such a logic gate can be used become more limited and critical. At 0.1V supply, for example, the voltage noise margin between "1" and "0" state drops down to about 50 mV after the first inverter stage. After several more inverter stages, however, this voltage noise margin gradually drops to about 20 mV.

Factors to consider in designing logic function are:

* Threshold voltage and device output tolerances
* Power supply voltage tolerances
* Output voltage level ranges defined to be acceptable for "1" and "0" levels
* Operating temperature ranges
* Number of logic stages and the noise margins required

EPAD MOSFET Switch

An EPAD MOSFET acts as a switch when it is turned on with an appropriate gate voltage, where a conducting channel forms between the drain and the source terminals (**See Figure 8**). The source terminal acts as the input and the drain terminal as the output. The on-resistance of the switch depends on the channel-on current as controlled by the gate voltage. In this case if an enhancement mode device is used, the switch can be turned-on with a positive bias voltage on the gate terminal, with the signal propagating from the source to the drain terminal. The signal can be either digital or analog in nature, as long as the user takes into account the input and output impedance levels relative to the channel on-resistance of the switch.

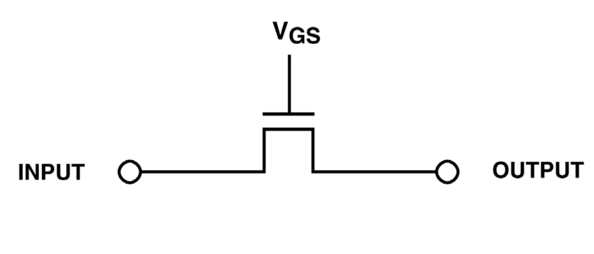

FIGURE 8

The switch can be turned-off by grounding the gate or by setting a gate voltage at 0.4V or less below the threshold voltage. When turned-on, a switch can pass a signal voltage up to the gate voltage minus the Vgs(th). When applied using the EPAD MOSFET Array family, the minimum operating voltage of an EPAD MOSFET switch is limited by the off-state leakage current. In this case, using the subthreshold characteristics mentioned previously, an analog or digital switch could be operated at a minimum supply in the range of 0.4V to 0.2V.

EPAD MOSFET Normally-On Switch

A normally-on switch is a switch that is normally already turned-on when the gate is at ground voltage or when there is no supply voltage present. This function is analogous to a normally closed FORM B (NC) relay with which the contacts are already closed when the relay coil is not energized, and which requires a voltage source to energize the relay coils in order to open the contacts. Depletion mode EPAD MOSFETs are naturally normally-on devices where a conduction channel already exists when there is 0.0V bias on the gate. The resulting conducting channel behaves similarly to a resistor when Vds is at low levels.

However, beware that due to the high input impedance of the gate, the gate voltage can “float” to a value other than zero. In an actual circuit it would be desirable to ground the gate, connect a fixed resistor to the gate or otherwise control the voltage available to the gate.

The key differences between Form B relays and the EPAD MOSFET Array family are that EPAD MOSFETs have higher on-resistances and operate at low voltages (<10V) and low current or power levels. In situations where these EPAD MOSFETs are used as a substitute for the equivalent function of a normally-on switch, they offer significant benefits such as size, density, power consumption, mechanical ruggedness (all solid-state) and cost. Furthermore, the switch channel on-resistance can be modulated and controlled directly by Vgs without using other active circuit elements.

Consider the case of building a normally-on switch using a Zero Threshold MOSFET such as the ALD110900. The device is in the on state and conducting a current at about 1uA when the gate is grounded. This is a reliable and dependable current value, and an external sensing circuit can be designed to detect and utilize this current signal.

In the case of using a Zero Threshold MOSFET as a switch, a signal can pass from V+ rail to 0.0V rail with an appropriate circuit configuration. However, a normally-on switch cannot be turned-off unless a negative voltage relative to the source voltage is available to be applied to the gate in order to turn off the EPAD MOSFET.

Re-arranging the circuit configuration, a Zero Threshold MOSFET can also be used as a high-side switch, which can pass a high level signal that is near or at V+ potential. To turn on such a switch, connect the gate to V+ (Vg = V+). Assuming V+ is at least +0.4V, grounding the gate will turn this switch off.

Likewise, other depletion mode EPAD MOSFETs can also be used either as high-side switches or as normally-on switches, each having a corresponding normally-on on-resistance value and a corresponding turn-off voltage. Tradeoffs can be made between on-resistances desired versus the gate voltages required to modulate and/or to turn on and turn off the switch.

EPAD MOSFET Current Source & Current Mirror

A basic current source is shown in **Figure 9**. Many designs of current sources using conventional MOSFETs can be implemented using the EPAD MOSFET family. The following presents two special notes worthy of discussion.

First, by using a low threshold enhancement mode EPAD MOSFET such as the ALD110902 (dual version with Vgs(th)= 0.20V), the current source starts operating at very low output voltages which extends the useful signal range of the current source.

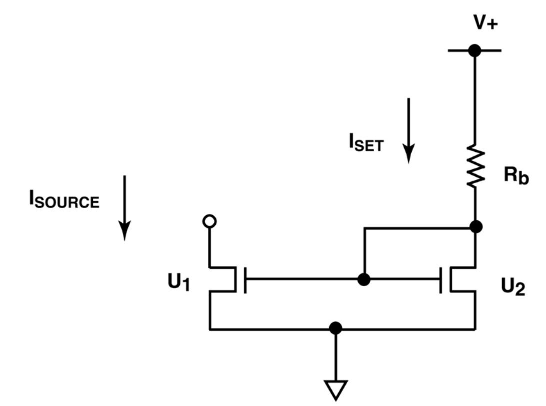

FIGURE 9

Second, in cases where a cascode current source is used, the output voltage overhead lost due to two threshold voltage stages is minimized when low threshold EPAD MOSFETs are used. This enables a cascode current source operating on very low output voltages, especially if it is a low-level current source. For example, by using a Zero Threshold MOSFET, such as the ALD110900 (dual with Vgs(th)=0.00V), as the bottom device in the cascode current source, the current source can start operating at a voltage much closer to zero. With a fixed or a controlling/modulating voltage and resistance combination, this current source can be configured to become a constant current source or one that can be modulated or turned-off with an external applied control signal.

Low Voltage EPAD MOSFET Oscillator

Another circuit function that is widely used is a RC oscillator. **Figure 10** show a low voltage EPAD MOSFET RC oscillator. In this circuit U1A, U1B and U1C form the basic three-stage oscillator with feedback resistor and capacitor network R4, Cosc and R5. The oscillator operates in low frequency ranging from a few hertz to kilohertz. The output is tapped and buffered with U1D as an output buffer stage. Power to the output stage is supplied by Vl. V1 can be either at V+ or at a different value, depending on the desired output high level. If V1 is at a different voltage level, then the output buffer also acts as a level shifter.

Using a low threshold enhancement mode EPAD MOSFET such as the ALD110802 (quad with Vgs(th)= 0.20V), an example of this oscillator operates on less than 0.2V supply voltage and less than 70 nW of power.

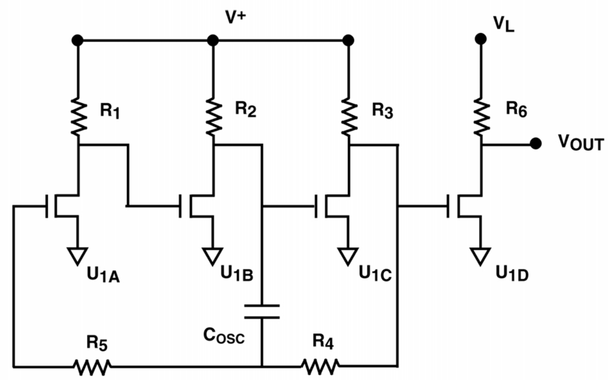

FIGURE 10

Ultra Low Voltage and Nanopower EPAD MOSFET Differential Amplifier

One of the key circuits used in analog design is a differential amplifier circuit. A simple inverting amplifier using an EPAD MOSFET inverter has been mentioned in the previous section. A basic very low operating voltage differential amplifier using EPAD MOSFETs is shown here in **Figure 11**. Different versions of this basic differential amplifier using various low voltage EPAD MOSFETs or Zero Threshold EPAD MOSFETs can be designed to reduce operating voltage or to minimize power dissipation. An example is a differential amplifier designed with EPAD MOSFETs that operate at an ultra supply voltage of 0.2V and consume only 570 nW (nanowatt).

This basic differential amplifier consists of 3 matched pairs. U5 and U6 are a matched-pair and connected to V+ via bias resistor Rb. The purpose of this matched pair is to provide bias to an input differential pair, U3 and U4. U1 and U2 are biased in the sub-threshold region and are used as active loads. This circuit configuration works with many different matched pair Vgs(th) combinations, in conjunction with various combinations of V+, Rb and input/output ranges.

Tradeoffs of key circuit performance of the differential amplifier include parameters such as:

* V+ nominal value (with max. and min. target values)
* Power dissipation goal
* Input voltage range
* Output voltage range
* Output-drive characteristics
* Frequency of operation
* Noise performance
* Offset voltage

This basic differential amplifier, while appearing not very complicated, is unconventional in that it operates the EPAD MOSFET devices in the subthreshold region. Therefore it requires a different perspective in how these EPAD MOSFET transistors are biased and utilized in the circuit. A wide range of possible performances can be associated with each different circuit configuration using different members of the EPAD MOSFET Array family.

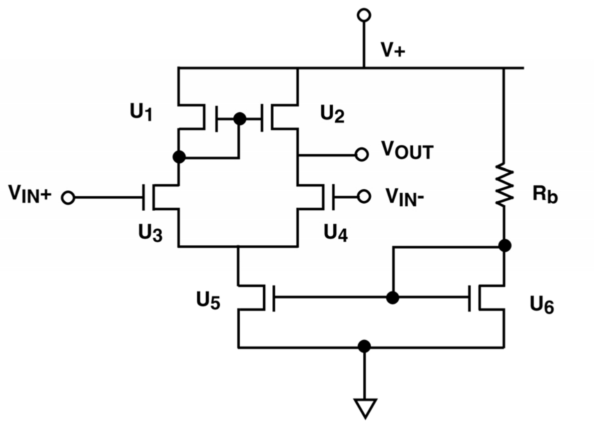

FIGURE 11

For purposes of illustration, the main objectives of this differential amplifier have been focused on ultra low-voltage and ultra low-power versions operating at or near DC. Examples of some key specifications achieved:

Example A.   Products used: ALD110800, ALD110902
Single stage: V+ = 0.5V, Rb = 275KOhm, I+ = 1.9uA, Pd = 960 nW, Gain = 24
Dual stage: V+ = 0.5V, Rb = 275KOhm, I+ = 2.8uA, Pd = 1.4 uW, Gain = 525

Example B. Products used: ALD110800, ALD110900
Single stage: V+ = 0.2V, Rb = 184KOhm, I+ = 2.8uA, Pd = 574 nW, Gain = 20
Dual stage: V+ = 0.2V, Rb = 184KOhm, I+ = 4.8uA Pd = 960 nW, Gain = 238

Conclusion

This paper provides the reader with an understanding and some basic concepts on how useful circuits can be implemented using this EPAD® MOSFET Array family. To a seasoned designer, there is much that is familiar since the EPAD MOSFETs mentioned here are natural extensions to conventional enhancement mode MOSFETs and all the textbook-based theories and equations still apply.

Many circuits that one has used in the past can also be naturally extended and readily applied here. Due to the extension of voltage and current ranges to lower limits and the precision threshold voltages, a new mindset and a fresh look at many old circuits and their related design configuration issues may be appropriate.

The ultra low voltage and NanoPower characteristics of the EPAD MOSFET Array family and how they can be biased and used in a circuit design can enable new products that feature novel power sources. Many circuits that one has designed in the past can now be naturally extended to new ranges and uses with ALD EPAD MOSFETs. These family of products begins to offer possibilities in circuit topographies that are quite novel, and in some cases even revolutionary.