



ELECTRICALLY PROGRAMMABLE ANALOG DEVICE (EPAD™) APPLICATIONS

INTRODUCTION

The ALD1108E/ALD1110E are the first members in a growing family of Electrically Programmable Analog Device (EPAD) integrated circuits from Advanced Linear Devices. An EPAD is a new class of analog IC, like the operational amplifier and the A/D converter.

The ALD 1108E/ALD110E are based on CMOS MOSFET devices with precision electrically programmable threshold voltage, which sets their on-resistance characteristics. This programmed on-resistance is in turn used to set a voltage or a current level with the use of external, inexpensive fixed precision resistors.

When used in combination with an inexpensive ALD E100 EPAD Programmer and Adapter Module, the EPAD allows analog circuit trimming in up to 20,000 discrete steps with 0.1mV increments. In engineering environments, the EPAD is quickly and easily programmed to fit the needs of a specific application. In test environments, it can be programmed in-system, that is, as an integral part of a circuit board assembly — thereby providing precise control over the entire system. The EPAD technology is designed for use in low voltage, low power circuits where a precision voltage or current trimming function is necessary. In addition, it provides a simple, inexpensive method for achieving remote trimming of circuits within user-controlled environments.

The ALD1108E is a quad (4-channel) EPAD device; the ALD1110E is dual (2-channel) EPAD device. Both EPADs can be configured to operate in single or dual channel mode, enabling unlimited variations in functionality. Both EPADs are supplied as stand-alone, individually programmable devices encased in standard IC packaging. They can be pre-programmed before being placed into a circuit (application-specific programming), providing control of standard linear functions such as operational amplifiers and voltage comparators. Alternatively, they can be integrated directly into a circuit, enabling in-system programming of the entire assembly after it has been built (in-system programming).

The ALD1108E/ALD1110E EPADs do not need other active circuitry to enable functionality. As such, these devices are extremely versatile as both circuit element and design component. EPAD technology presents the user with a wealth of possible applications, limited only by the imagination of the user and the many ways an adjustable bias voltage/current device can be used as a circuit design element.

The applications listed below outlines in a general way some of the applications for which EPAD can be used in telecommunications, instrumentation, medical devices and industrial process control systems. Note that although automation can be an important end goal, a primary benefit of EPAD technology is that it simplifies the manufacturing and control process, by enabling electrical programming of an analog circuit transfer function without resorting to difficult and expensive trim pots or an even more expensive system of microcontrollers, RAMs, ROMs, EPROMs, data converters and an entire overhead of system functions. The EPAD is also an ideal solution for trimming of packaged modules where trim pot access is no longer readily available.

GENERAL DESCRIPTION

The ALD1108E/ALD1110E devices are based on monolithic CMOS FETs (Field Effect Transistors) with electrically programmed threshold voltages that can be precisely controlled via stored, non-volatile charges. Control of these threshold voltages is enabled through a DOS-based user interface, an EPAD Programmer and control software supplied by Advanced Linear Devices.

Each channel in the EPAD can be individually programmed to a different threshold, or bias, voltage. The range of threshold voltage adjustment is 2000mV; programming voltage resolution is 0.1mV respectively. For a given input voltage, precisely changing the threshold voltage of a channel (MOSFET) also changes its drain on-current, resulting in an on-resistance characteristic that can be precisely controlled and set.

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EPAD programming is monotonic: that is, the channel can only be programmed to an increase in threshold voltage and a decrease in drain-on current as a function of a given input bias voltage. However, each channel can be programmed many times before the threshold limit is reached. In addition, the baseline current level can also be adjusted lower, creating the same effect as lowering the bias voltage.

A pair of EPAD channels can also be connected differentially such that one channel is used to adjust a parameter in one direction and the other channel is used to adjust the same parameter in the other direction, thereby providing bi-directional control capability. EPADs can be programmed in stand-alone programming mode, application-specific programming mode, or in-system programming mode, after the entire assembly has been built. In all these cases, a combination of the ALD E100 EPAD Programmer and an Adapter Module is required.

In stand-alone programming, the exact adapter module may vary depending on the intended application. For example, the EA101 Adapter Module programs EPAD threshold voltages with a fixed resistor. The EA102 Adapter Module is specially designed to program the EPAD with current sources set at a Zero Temperature Coefficient (ZTC or Zero tempco) current level of 68 μ A.

Both of these Adapter Modules can be readily modified for other types of application-specific programming. For instance, to enable direct control of an operational amplifier, the user changes the resistor component values on the adapter module, which creates a corresponding change in bias drain current level. Entire lots of EPADs can be programmed in this way with a single adapter module. These programmed EPADs are then inserted into a user circuit board.

With In-System Programming, the ALD1108E or ALD1110E device is designed into an application circuit where it becomes an integral part of the circuit function. The device is inserted into a finished circuit and accessed or programmed through the use of a special programming cable or a number of preassigned edge connector pins. For more information please refer to In-System Programming section described later.

The E100 EPAD Programming System contains voltage measurement and voltage programming capabilities to measure the baseline voltage and program it to the desired value. To set different current levels, the bias resistor values within

the Adapter Module circuit board must be changed. Alternatively, the user can switch in current setting resistors which can be placed under software control and implemented with analog or relay switches.

DEFINITION OF TERMS

Terms that are used in this article are defined as follows:

Baseline voltage level.

The initial threshold voltage V_t , defined as drain and gate diode-connected voltage at a drain current of 1 μ A, when source voltage is at 0.0 Volt. The initial threshold voltage is also a default factory setting. However, the user can change this default baseline voltage and set the drain current value of the threshold voltage to a desired value, thereby allowing the device to be "zeroed out", or "set" to a new bias level.

Bias voltage, V_{bias}

Same as threshold voltage, except at a drain-source bias current different from that specified at threshold voltage. For example, the threshold voltage of the ALD1108E/ALD1110E is specified at drain source bias current of 1 μ A. The useful bias current range of the ALD1108E/ALD1110E is from 4nA to 3mA.

Drain Current, I_{ds}

Drain Current is the current that flows from drain to source.

Drain Voltage, V_{ds} .

Drain voltage is the voltage across drain and source pins.

Gate Voltage, V_{gs} .

Gate voltage is the voltage across gate and source pins.

Threshold voltage, V_t .

Threshold voltage of an EPAD is the voltage across Gate and Source when 1 μ A is forced into the Drain terminal as the Drain and Gate are connected together. The term threshold voltage is used interchangeably with "bias voltage."

Threshold voltage programming.

Encompasses all combinations of programmed gate bias voltages, drain bias voltages and drain current levels.

Zero Temperature Coefficient, ZTC.

Operating point of an EPAD where voltage and current changes as a function of temperature is zero.

FUNCTIONAL DESCRIPTION

Each EPAD's input and output functional characteristics can be modeled as a MOSFET with adjustable threshold voltage. Each EPAD has five terminals, namely, the Gate, Drain, Source, Programming and Substrate terminals. The programming terminal is used only during electrical programming to inject charge into the device. The injected charge is permanently stored and raises the threshold voltage of the device. For a given current level and a gate voltage, the drain voltage varies according to the threshold voltage. After programming, the programming terminal can be left open or connected to the source voltage.

A basic connection configuration is to connect gate and drain terminals together. At a selected drain current, this gate-drain connected voltage can be precisely set by using the EPAD Programmer. After electrical programming, the EPAD Programmer can be disconnected, and the device retains the set voltage indefinitely under normal operating conditions, even when power is turned off. This connection configuration is referred to as a diode-connected configuration.

The ALD E100 EPAD programmer injects a small, measured amount of charge by pulsing the programming terminal. An EPAD is in programming mode when both the gate terminal and the programming terminal are pulsed together, through the EPAD programmer, at approximately 12V. The number of pulses required to bring the threshold voltage to a given voltage value is determined by the EPAD programmer control software. All that the user needs to do is to input the desired threshold voltage value. If a drain current other than $1\mu\text{A}$ is desired, that current level can be set by the user by changing the value of the set-current resistor on the EPAD Adapter Module. This drain current can also be any bias current supplied by the user from an application circuit, such as that from an external current source.

Please refer to the individual EPAD specifications for more details on operating voltage and current ranges. With the control software supplied with the EPAD Programmer Adapter Module, the desired target threshold voltage value can be fed in either as a keyboard entry, or as a variable by a user-written program.

The gate voltage V_{gs} of an EPAD can be set as an input voltage and the drain voltage V_{ds} can be used as an output voltage. When the Gate and the Drain terminals of the EPAD are shorted together, in the diode-connected configuration, V_{ds} , equal to V_{gs} , is the output voltage. For many applications, it may be desirable to force V_{ds} of an EPAD to a dif-

ferent drain bias voltage at a given circuit bias current, before programming. The user then determines the final threshold voltage necessary to adjust the transfer function of the application circuit to a desired final value. The final bias voltage is then the V_{ds} voltage where the EPAD needs to be set for that particular circuit.

SPECIAL DESIGN FEATURES

Each channel in the ALD1108E/ALD1110E EPAD devices can be programmed separately or in matched pairs. For certain applications, effects such as temperature coefficients can be canceled out by using the matched pair capability. Matched pairs are also ideal for applications where variables must be adjusted in both directions. In this case, a circuit parameter or variable can be adjusted in both directions allowing "trimming" or "calibration" of the parameter variable by the user to minimize temperature effects.

ZERO TEMPERATURE COEFFICIENT

Each channel within an ALD1108E/ALD1110E has a positive temperature coefficient current range and a negative temperature coefficient current range. The crossover current level is the zero tempco current level.

For the ALD1108E/ALD1110E EPADs, this current level is approximately $68\mu\text{A}$. When biased at this current level, the drain voltage and the drain current have significantly reduced temperature coefficients, minimizing variation of the drain voltage and related parameters throughout a given temperature range.

In applications where the system must have minimal variations due to changes in temperature, matched pair circuits biased at $68\mu\text{A}$ is recommended. Many of the applications mentioned in this application note can be biased at zero tempco current. When biased at zero tempco current, the typical single channel voltage tempco is 50ppm and the matched pair relative voltage tempco is less than 10ppm.

COARSE OR FINE TRIMMING

EPADs can be used for both coarse and fine trimming applications. In coarse trimming, a single EPAD can be used in conjunction with a single resistor to form a resistor network. In this configuration, and depending on the resistor value and the bias current level of the EPAD, the tempco of the circuit may not be well controlled, translating to a relatively low resolution trimming and circuit stability. However, this is also a quick, low-cost and easy voltage adjustment applica-

tion that can be readily automated. In fine trimming applications, in general, two EPADs are used in a matched circuit with temperature effect cancellation. As two EPADs within an IC package are matched by design and in close proximity to each other, their respective relative temperatures are closely matched. As ambient temperature changes, both EPAD channels have equal temperature effects. The two matched EPAD channels can be used in a circuit with temperature effect subtraction, resulting in a circuit that is temperature-stable. As a general rule, the temperature coefficient effects of a circuit with matched EPAD temperature cancellation are an order of magnitude less than single EPAD circuits.

Furthermore, in the zero tempco current mode, the corresponding temperature coefficient effects of a dual EPAD-based circuit can be reduced by one and a half orders of magnitude, resulting in a circuit that is temperature-stable and suitable for fine trimming applications. Note that zero tempco bias mode can be used in both single and matched pair EPAD applications, resulting in either coarse or fine trimming of circuits that have improved temperature characteristics.

RELAXATION VOLTAGE & RELAXATION TIME CONSTANT

After an EPAD has been programmed, the bulk of the electrons are stored on a polysilicon gate capacitor with high barrier energy and remains stored indefinitely. However, a small number of residual electrons at a few oxide sites near the oxide-to-silicon interface can gain sufficient energy to become detrapped, causing a small loss of electrons. This loss of electrons decreases exponentially with a time constant.

This loss of electrons is shown as the difference between the initial measured threshold voltage of an EPAD and its subsequently measured threshold voltage. After a short time period, the threshold voltage stabilizes and reaches a final threshold voltage that remains fixed indefinitely thereafter. The amount of this residual charge loss causes a small voltage drop, referred to as the relaxation of the threshold voltage. The Relaxation Voltage is defined as the voltage drop after three Relaxation Time Constants.

The EPAD Programmer control software supplied with the Adapter Module compensates for the Relaxation Voltage by programming the threshold (bias) voltage to a higher initial threshold voltage. The control software contains a default

Relaxation Voltage compensation setting which can be altered by the user. For the ALD1108E/ALD1110E, typical Relaxation Time Constant is 2 hours and the Relaxation Voltage is -0.3% of the threshold voltage.

DESIGN PRECAUTIONS

The ALD1108E/ALD1110E EPAD devices are designed for use in low voltage, micropower circuits. The maximum operating voltage during normal operation should remain below 10 Volts at all times. Care should be taken to insure that the application in which the devices are used does not experience any positive or negative transient voltages that cause any of the terminal voltages to exceed this limit.

All inputs or unused pins except the programming pins should be connected to V- so that they do not become floating pins, since input impedance at these pins is very high. If any of these pins are left undefined, they may cause unwanted oscillation or intermittent excessive current drain. As these devices are built with CMOS technology, normal ESD and latchup handling precautions, operating and storage temperature limits as stated in the data sheet must be observed.

APPLICATIONS

The application circuits as described in this application note have been functionally tested by Advanced Linear Devices' application staff. However, these circuits are for illustrative purposes only, and should not be used for production or for a specific application unless independently verified by the user and found to be in conformance with all other user requirements.

BASIC CIRCUITS

The basic circuit connection is shown in Figure 1. In this connection, the gate terminal of the device is connected to the drain terminal of the device. This connection forces the gate and drain voltage to be equal at all times. As the gate input has extremely high input resistance — at a few pA input leakage current at room temperature — most or nearly all of the bias current through the device flows from the drain to the source terminal. This bias current can be set externally by a combination of V_t programming, selection of a bias reference voltage and a bias resistor R . For some applications, it may be appropriate to replace R with a current source so that the current I_{ds} is relatively constant before and after EPAD programming. The simplest bias method is just to use a single resistor with value R ohms.

To calculate the value of the resistor R , first refer to the data sheet to insure that a desired current level is within the device specification. The resistor value R is simply given by the following Ohm's Law equation:

$$R = (V_+ - V_{tm}) / I_{ds}$$

where

V_{tm} is the nominal midpoint value of the desired V_t adjustment range,
 V_+ is the power supply voltage, and
 I_{ds} is the desired drain source current (equal to the current through resistor R)

For example, with the ALD1108E, if a current level of $68\mu A$ is chosen for I_{ds} for minimum tempco, and if the supply voltage is 8.3V, and the V_t adjustment range is expected to be between 1.000V and 2.000V, then V_{tm} is 1.5V.

With these values in the equation, we get:

$$R = (8.3 - 1.5) V / 68\mu A = 100 \text{ Kohms}$$

Note that for the above circuit the current I_{ds} does not remain constant for different V_t values, as the current varies with the value of the programmed V_t . In addition, the magnitude of the I_{ds} current value and the tempco of the resistor R can also cause variation of I_{ds} . These effects can be reduced with a circuit such as the one shown in Figure 2. When a current source is connected to an EPAD instead of a biasing resistor R , the I_{ds} of the EPAD is set by the current source and its variation depends primarily on the current source variations.

For different V_t values, if the current from the current source is constant, then the I_{ds} value also remains constant. The V_t values could change due to programming, but if the I_{ds} is constant, the tempco of the V_{ds} voltage also remains constant. In this case, V_t programmed to any desired target V_t value setting, is capable of remaining relatively temperature stable. In many applications, this advantage may be worth the extra circuitry required to produce a current source.

Figure 1
Basic Circuit Connection

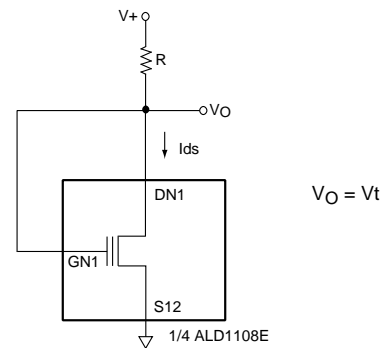


Figure 2
Basic Circuit Connection with Current Source

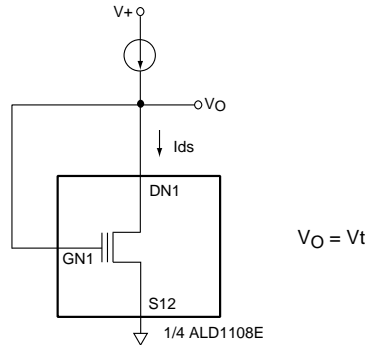
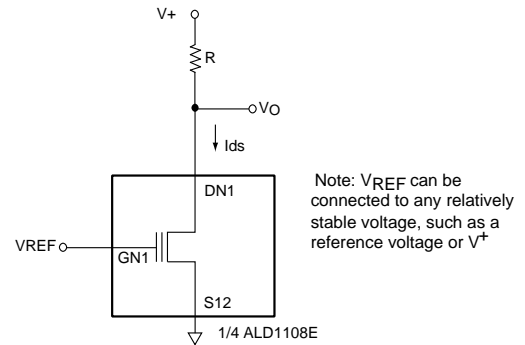


Figure 3
Voltage Controlled Resistor



VOLTAGE CONTROLLED RESISTOR

One of the basic characteristics of the EPAD is that its MOSFET output on-resistance can be controlled with a reference bias voltage. When the EPAD is biased off, as when the reference bias voltage (the input gate voltage) is set to more than 0.5V below V_t , the output resistance is greater than 10 Gigaohm. When the bias reference voltage is increased to V_t , the EPAD is biased on, and its on-resistance is 1 Mohm. As the reference bias voltage is set to above V_t , the output resistance decreases.

For the ALD1108E/ALD1110E devices, the output on-resistance decreases from 1 Mohm to approximately 1.5 Kohm at a reference voltage of 5 Volts. This represents many orders of magnitude of change in on-resistance. For a given reference bias voltage, the on-resistance of an EPAD is adjustable within a certain range. This may be useful in applications where a fixed reference voltage is available, and where many different on-resistance values are desired. In Figure 3, with the addition of a fixed resistor, the circuit becomes a voltage divider. The output voltage varies according to the resistance ratios between the fixed resistor and the EPAD on-resistance. As the on-resistance of the EPAD is adjusted, the output voltage is changed, producing the desired V_O permanently.

MATCHED EPAD PAIRS

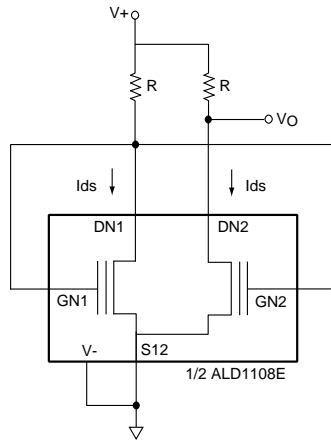
Matched EPAD pairs used in application circuits have many significant circuit advantages over single EPAD circuits. Within a pair of EPADs, many parameters can be matched and the parasitic and temperature effects of these devices can be manipulated to cancel each other. The net result is a much more balanced and temperature-stable circuit.

For ALD1108E, the first and second channels form one EPAD pair and the third and fourth channels form another. Note that the matched EPAD pairs share common source connections. When connected in a differential configuration, two EPAD channels also provide for bidirectional parameter adjustment capabilities, as illustrated in Figure 4 and Figure 5.

The output in these circuits, V_O , can be adjusted up or down by programming the respective EPAD channel. If the circuit is designed into an application where an adjustment is necessary, EPAD1 and EPAD2 V_t can be progressively programmed, allowing multiple up and down adjustments to the V_O .

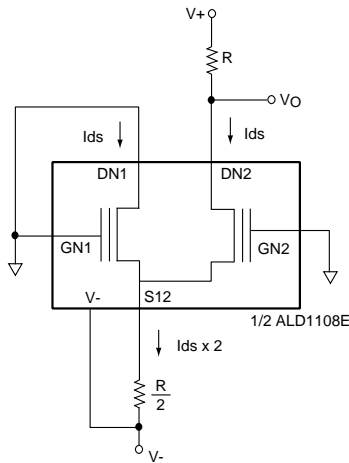
One noteworthy aspect of this capability is that the overall gain of the circuit depends on the value of R . For larger values of R , the gain of the circuit is greater, and the mismatched offset voltage is amplified by the gain. For best results, the drain current of the EPADs should be set to 68 μA , which effectively minimizes the temperature dependence of the output voltage V_O . If the resistors are also matched, as may be the situation when using resistor packs, then the respective resistors also experience tempco cancellation, further enhancing the overall circuit stability.

Figure 4
Mached EPAD Pair With A Single Supply



For low tempco set $I_{ds} \approx 68\mu A$
For $V+ = +5V$, $R \approx 47K\Omega$

Figure 5
Matched EPAD Pair With Dual Supplies

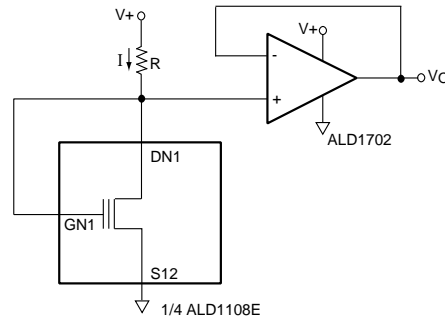


For low tempco set $I_{ds} \approx 68\mu A$
For $V+ = +5V$ & $V- = -5V$, $R \approx 47K\Omega$

EPAD VOLTAGE OUTPUT WITH BUFFER

A simple voltage follower is shown in Figure 6. The voltage follower isolates the output and prevents it from loading the EPAD bias resistor and causing loading effects. Again, for low tempco, set R such that the current I is $68\mu A$.

Figure 6
EPAD Output With Buffer Amplifier



For low tempco set $I_{ds} \approx 68\mu A$
For $V+ = +5V$, $R \approx 47K\Omega$

BASIC CURRENT SOURCE

A basic current source with output I_O is shown in Figure 7. Value of resistor R is selected such that current through R is approximately $68\mu A$ for low temperature effects. Resistor Rset is biased with the same voltage registered across the EPAD. This voltage is set by bias resistor value R and the EPAD programmed threshold voltage. The tempco of output current I_O is directly proportional to the tempco of Rset. This tempco can be minimized by selection of an appropriate resistor type. In this circuit, the output current can be set by programming the EPAD threshold voltage.

In order to set the output current I_O , a current meter can be set up to monitor I_O through ALD1106 N-Channel MOSFET while a voltage source forces a voltage on Vbias. Once a desired current level is attained, then that voltage which produces this desired current, Vbias, can be noted. The EPAD V_t can now be programmed to Vbias, using the same supply voltage and resistor R. This entire process can be fully automated with the appropriate equipment, setup and customized control software.

Figure 7
Current Source With EPAD Trimming

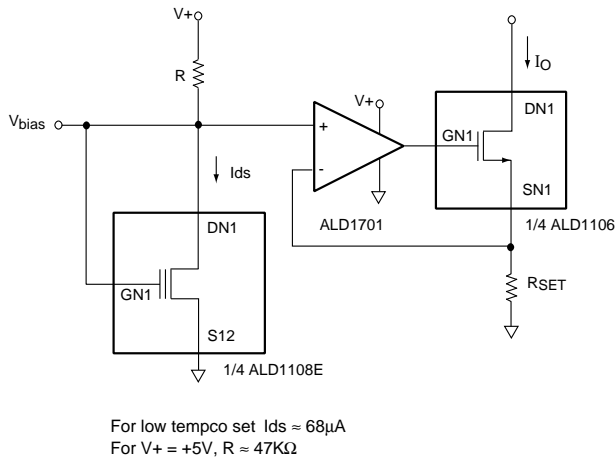
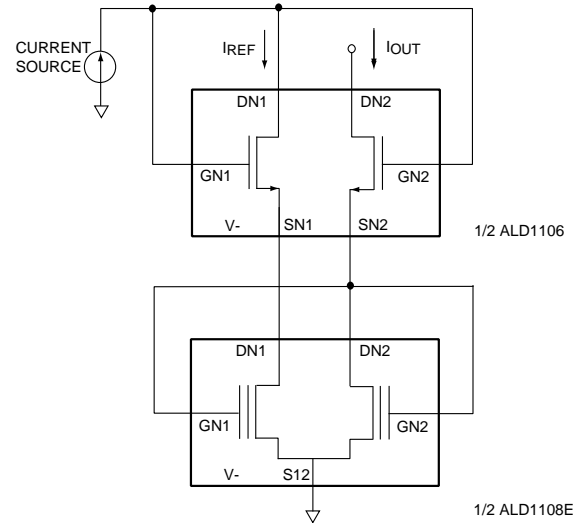


Figure 8A
High Output Impedance Current Mirror

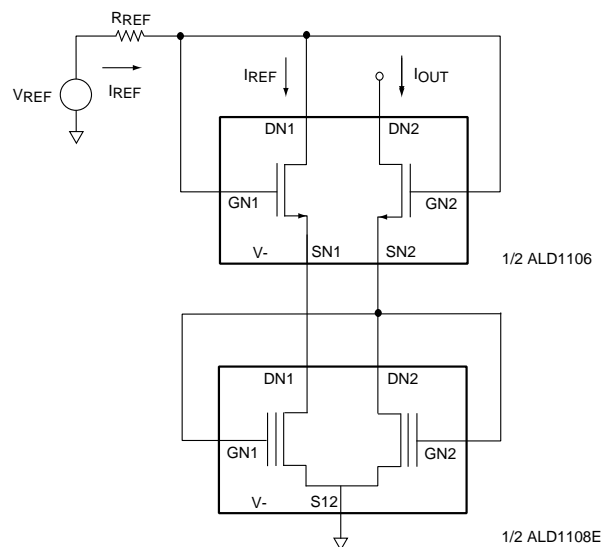


HIGH OUTPUT IMPEDANCE CURRENT MIRROR

A calibrated cascode current mirror is shown in Figure 8A. The input reference current can be set by means of a reference bias voltage and a fixed resistor by programming the EPAD connected to the input reference current. The output current I_{OUT} of the current mirror can be set to within 1% of the desired current mirror value. Although the mirrored current can be matched to the input reference current, it can also be set to a ratioed current value, where I_{OUT} is proportional to the current source. The output impedance of this programmable current mirror is approximately 20 Mohms.

The current mirror in Figure 8A can be easily modified to become an electronically calibrated current source that can be programmed and set at $68\mu A$, as shown in Figure 8B. Note that a reference voltage V_{REF} or a relatively stable voltage source is required. The tempco of R_{REF} is the key factor that determines the tempco of the current source.

Figure 8B
High Output Impedance Current Source



EPADs WITH ACTIVE CIRCUITS

The EPAD threshold voltage V_t can be scaled, ratioed and shifted with operational amplifier circuits. Many of these circuits are common operational amplifier circuits. A few of these circuits are illustrated below in Figure 9, Scaling Adjustable V_t ; Figure 10, Select V_O Adjustment Range by using Resistor Ratios and Figure 11, Amplify and Shift EPAD Adjustment range with an operational amplifier. Obviously many more types of operational amplifier circuits can also be used with an EPAD as an adjustment vehicle.

Figure 9
Scaling Adjustable V_t

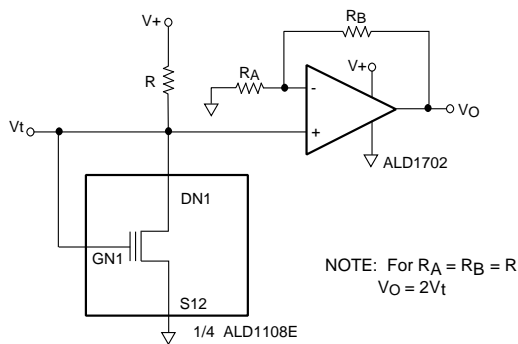


Figure 10
Select V_O Adjustment Range by Using Resistor Ratios

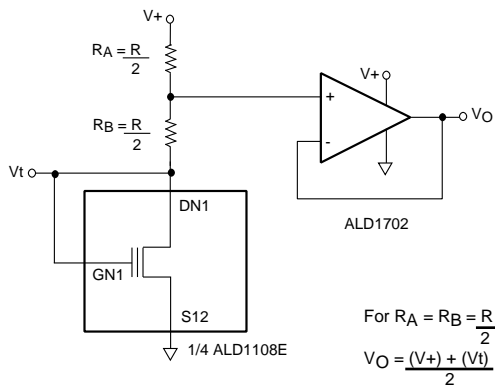
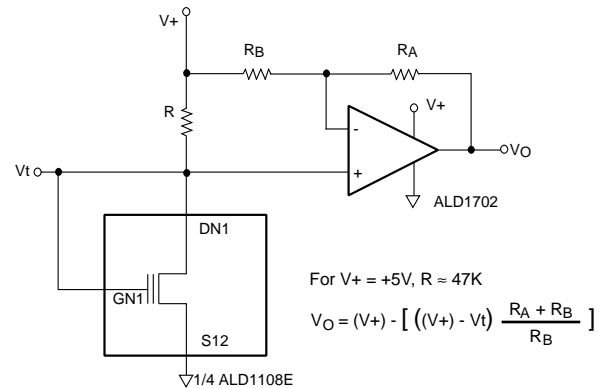


Figure 11
Amplify and Shift EPAD Adjustment Range with an Operational Amplifier



USEFUL HINTS

A couple of useful hints in designing with EPADs would be appropriate here. First, in general, a relatively large EPAD V_t adjustment range should be used. A recommended adjustment range would be from a 1V range such as $V_t = 1.000V$ to 2.000V range. This minimizes error budget due to programming voltage errors and temperature effects causing a shift to V_t .

For example, assume a V_t adjustment range of 1.000V to 2.600V range, giving a voltage programming range of 1600mV. Assume further that the maximum system error is estimated to be 32mV. The error voltage in this case would be 32mV/1600mV, or 2 percent. Matched EPAD circuit techniques and zero tempco biasing can further reduce the error. For more limited temperature ranges, such as may be the case for some laboratory equipment operating environments, the errors can be brought down to about 10mV with careful design and error budgeting. For example, using a 2V adjustment range of $V_t = 1.000V$ to 3.000V would yield an error of 10 mV/2000mV, or 0.5 percent.

If a lower adjusted absolute error voltage is desired, voltage scaling can be used. Using the above example, an adjustment range of 2000mV with an error range of 10mV can be, with the help of some active circuitry, scaled down to an adjustment range of 200mV with an error range of 1mV. Note that additional errors may be introduced by active scaling of the circuit. However, keep in mind that if scaling-induced adjustment error is fixed and temperature and time invariant, it can be adjusted through EPAD programming.

EPAD CIRCUIT WITH BI-DIRECTIONAL V_t ADJUSTMENT

For applications where multiple adjustment of a voltage parameter is necessary, two EPADs can be employed in a circuit such as Figure 12. In this circuit, V_O can be adjusted up or down multiple times, by programming the respective EPAD. Care should be used in the design such that the amount of V_t adjustment step be kept small enough so that the two EPADs can be programmed upwards many times alternately. On the other hand, the V_t adjustment step should be large enough to minimize error due to other various error terms. The resistor value of R_f should be high relative to the value of R to avoid excessive loading down resistor R and affecting the bias current supplied to the EPAD.

To isolate the outputs of the EPAD stages from the output amplifier in Figure 12, the same circuit can be buffered with unity gain buffer amplifiers, as shown in Figure 13. In this circuit, the resistor value R can be set to produce a zero tempco bias current of $68\mu A$, or any other desired current level. Due to differential EPAD pairs feeding the same output amplifier stage at the output, temperature effect due to one of the EPAD circuits cancels out that of the other. The resulting circuit is temperature-stable. The resistors R_A and R_B can also be set to other values as needed, as this circuit eliminates the EPAD bias current level sensitivity to the resistor values of R_A and R_B .

Figure 12
EPAD Circuit With Bi-directional V_t Adjustment

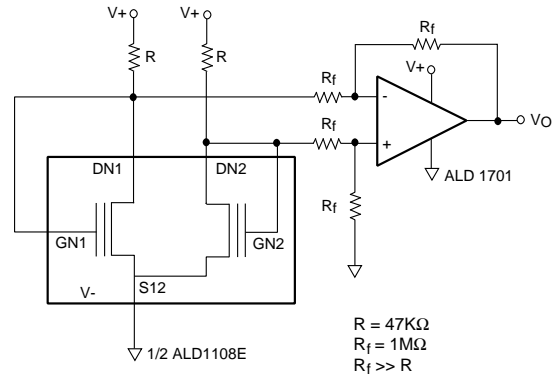
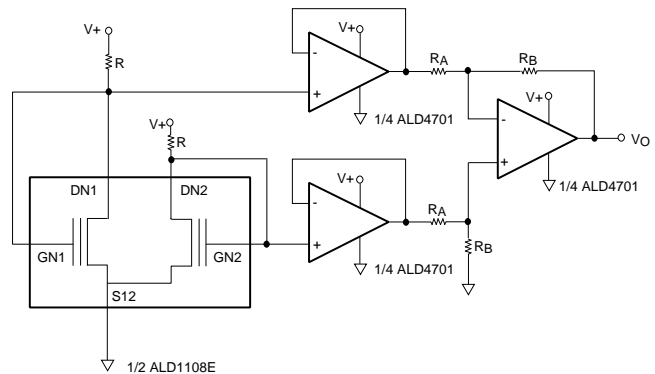


Figure 13
EPAD With Buffered Outputs Providing Bi-directional V_t Adjustment



NEURAL NETWORK CIRCUIT

For applications where neural network circuit function is desired, or where multiple inputs and their respective weights are summed at the output, an EPAD-based neural circuit can be constructed as shown in Figure 14.

The precision and resolution of the circuit depends on the reference voltage, the output resistor and the accuracy and resolution available from the EPAD. The weights of the neural network, in this case, are the corresponding resultant drain currents at the output as a result of programming of the V_t values. The output node is at the same time also a summing node, where all the currents are summed through the output resistor, R_L .

This circuit may be most suitably used where the "learning" is already accomplished, and the "learned" function requires hardware implementation. The key consideration here is simplicity of the circuitry involved. This circuit is especially appropriate for low cost, stand-alone hardware implementation of neural networks.

The circuit shown in Figure 14 implements the following equation:

$$V_{out} = \sum \{ V_{in}(x) * w(x) \}$$

$$= R_L * I_{sum}$$

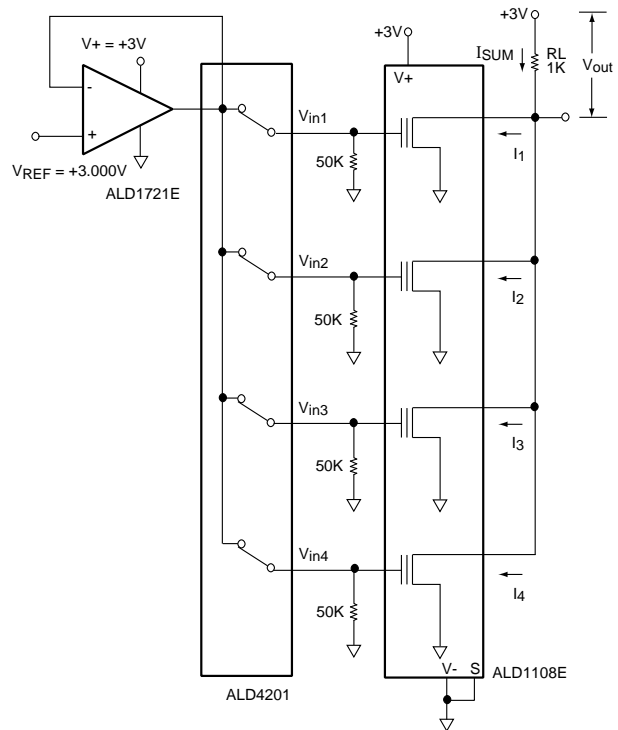
$$= R_L * \sum \{ I(x) \}$$

where

- $V_{in}(x)$ = input to each neural channel
- $w(x)$ = weight of each neural channel
- R_L = summing resistor at the output node
- I_{sum} = sum of the currents through the EPADs
- V_{REF} = reference voltage

Once the weights of a given neural network circuit have been derived through a learning process, these values can be programmed into each EPAD in each respective neural network channel.

Figure 14
Neural Network Circuit



$$V_{out} = \sum V_{in}(X) * w(X) = R_L * I_{sum} = R_L * \sum I(X)$$

Figure 15. Standard Stand alone EPAD Programming System

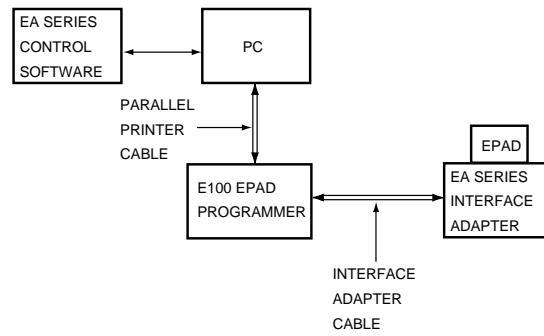
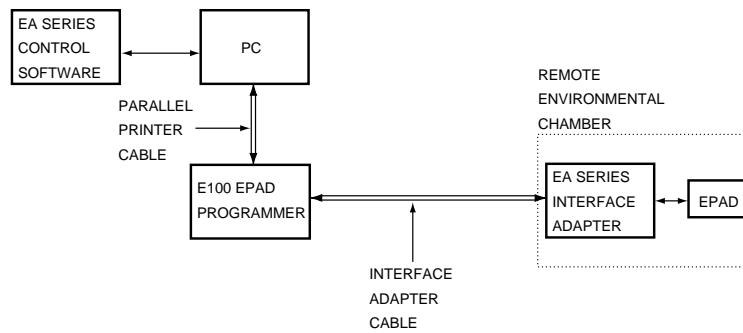
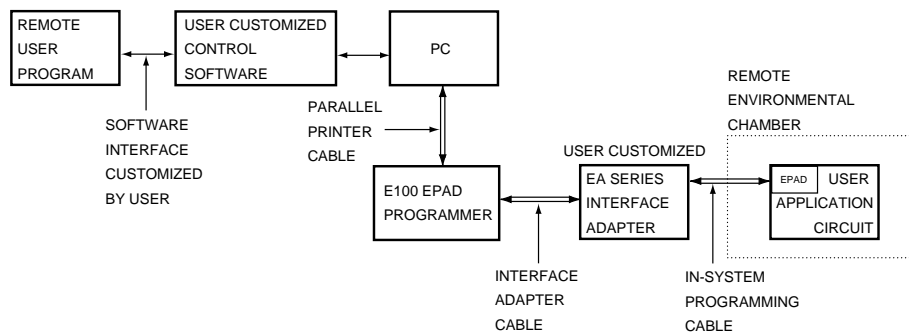


Figure 15B. EA Series Interface Adapter Module Custom Tailored to Application-Specific Conditions and Environment



* EA Series Control Software, Interface Adapter Cable And Interface Adapter can All be customized by User for specific application, if necessary.

Figure 15C. In-System Programming With EPAD Incorporated into User Application Circuit



EPAD PROGRAMMING

Figure 15A shows a standard EPAD programming system. The setup and programming by the user is simple and straight forward. The user provides a personal computer, a parallel printer cable and an external DC power supply. The entire system can be set up in a laboratory environment and be ready to start programming in a matter of minutes.

APPLICATION-SPECIFIC PROGRAMMING

For applications where custom setup and special conditions are desired, such as operating at different power supply voltages, different bias current or reference voltage conditions, and/or different temperature environments, the supplied interface Adapter Module can be readily modified by the user to reflect these conditions. In addition, the Adapter Module, application circuit and EPAD can be set up inside an environmental chamber for EPAD adjustment under precise environmental conditions. The diagram of this setup is illustrated in Figure 15B.

A simple example of Application-Specific Programming is to change the operating voltage of an EPAD circuit. As an Adapter Module has a factory preset operating voltage, if a user application system voltage is at a different voltage level, a small supply voltage induced error may be introduced into the system. This small error can be eliminated by disconnecting the V+ of the Adapter Module from the EPAD Programmer, and bringing in external supply into V+ terminal instead. EPAD can now be programmed to user system supply conditions. Often this kind of hardware change is simple and effective in eliminating system errors without any control software programming change.

When using environmental chambers, care must be taken to insure that the Adapter Module's voltage and temperature ratings are not exceeded. For continued high temperature applications, the user is advised to set up a custom adapter circuit board with a connection to a separate high temperature socket for EPAD programming.

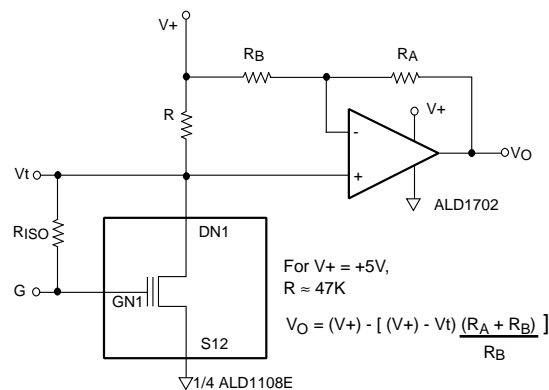
IN-SYSTEM PROGRAMMING (ISP)

For some applications, the user may desire to have the EPAD soldered onto the production circuit board before EPAD programming. This is accomplished by designing the application circuit to accommodate two modes of operation — a normal operating mode and a programming mode. Once such a circuit is designed, a special cable enables in-system programming. Refer to Figure 15C. Many of the preceding circuits from Figure 1 through Figure 14 may also be viewed as examples of EPAD programmable in-system circuits.

In order to program an EPAD as an in-system element, the gate terminal of the EPAD must be able to be pulsed by the EPAD Programmer. The application circuit in which the EPAD is embedded can be powered by any user-selected voltage. However, it must allow the gate voltages of the EPAD to be pulsed without a low impedance path to other circuit nodes, so that the EPAD programmer pulsing circuit can function properly.

For many of the circuits, such as those in Figures 1 through 13, the bias resistor R should be set at greater than 20 Kohms. In Figure 12, in particular, the resistor value of Rf should be much greater than resistor value of R. If setting R value greater than 20 Kohms is not possible, a 50 Kohm resistor or greater isolation resistor Riso can be used to connect drain and gate terminals.

Figure 16
In-System Programming: Amplify and Shift EPAD Adjustment Range with an Operational Amplifier



For example, the circuit in Figure 16, In-System Programming, is a modified circuit based on Figure 11 to provide conditions suitable for programming mode. In this case, this is accomplished by the addition of a single resistor R (iso). When the gate terminal is now pulsed during programming, the drain terminal is effectively isolated from the gate terminal. During normal operation, the gate terminal voltage is not appreciably affected as a result of R(iso) because the gate input impedance is very high.

This in-system approach to programming the EPAD is potentially the most powerful in adjusting system level errors involving other components, such as variations in unit to unit sensor parameters and passive component parameters. If integration of the EPAD programming is desired, while system testing and/or calibration is taking place, then more circuit design and software programming may be necessary.

A special In-System Programming extension cable allows temporary connection of the EPAD programmer to the in-system EPAD element directly within the application circuit. The cable is disconnected for future use after programming.

CONTROL SOFTWARE

Control software supplied with the EPAD Programmer Adapter is used to control the programming routines and to send commands to the EPAD Programmer to control, measure and compute programming conditions for the specific adapter module. In most cases, the recommended custom adaptation of this control software is to input a desired voltage value that can be measured at the drain terminal of the EPAD. The control software algorithm then takes over. When in programming mode, the gate and programming terminals are pulsed in a controlled, optimal sequence of voltage biasing conditions. These conditions must be preserved by the user in order for the programming system to function properly.

For more assistance in application-specific or in-system EPAD programming, please contact an Advanced Linear Devices' applications engineer. If you have a circuit question or problem, Fax or e-mail us at:

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