Using ESD Diodes as Voltage Clamps

By Paul Blanchard and Brian Pelletier

Abstract

When external overvoltage conditions are applied to an amplifier, ESD diodes are the last line of defense between your amplifier and electrical over stress. With proper understanding of how an ESD cell is implemented in a device, a designer can greatly extend the survival range of an amplifier with the appropriate circuit design. This article aims to introduce readers to the various types of ESD implementations, discuss the characteristics of each implementation, and provide guidance on how to utilize these cells to improve the robustness of a design.

Introduction

In many applications where the input is not under system control but rather connects to the outside world, such as test equipment, instrumentation, and some sensing equipment, it is possible for input voltages to exceed the maximum rated voltage of a front-end amplifier. In these applications, protection schemes must be implemented to preserve the survival range and robustness of the design. The front-end amplifier's internal ESD diodes are sometimes used for clamping overvoltage conditions, but many factors need to be considered to ensure these clamps will provide sufficient and robust protection. Understanding the various ESD diode architectures that are inside of front-end amplifiers, along with understanding the thermal and electromigration implications of a given protection circuit, can help a designer avoid problems with their protection circuits and improve the longevity of their applications in the field.

ESD Diode Configurations

It is important to understand that not all ESD diodes are simple diode clamps to the power supplies and ground. There are many possible implementations that can be used, such as multiple diodes in series, diodes and resistors, and back to back diodes. Some of the more common implementations are detailed below.

Diode Connected to the Power Supply

Figure 1 shows an example of an amplifier with diodes connected between the input pins and the supplies. The diodes are reverse-biased under normal operating conditions, but become forward-biased as the inputs rise above the positive supply voltage or below the negative power supply voltage. As the diode becomes forward biased, current flows through the amplifier's inputs to the respective supply.

In the case of the circuit in Figure 1, the input current is not inherently limited by the amplifier itself when the overvoltage goes above $+V_s$, and will require external current limiting in the form of a series resistor. When the voltage goes below $-V_s$ the 400 Ω resistor provides some current limiting, which should be factored into any design considerations.

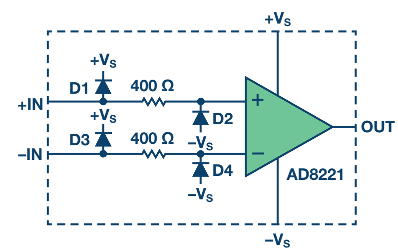


Figure 1. Input ESD topology of AD8221.

Figure 2 shows an amplifier with a similar diode configuration, but in this case the current is limited by the internal 2.2 kΩ series resistor. This differs from the circuit shown in Figure 1 by not only the value of the limiting R but also the 2.2 kΩ protects from voltages above $+V_s$. This is an example of the intricacies that must be fully understood to optimize protection when using ESD diodes.

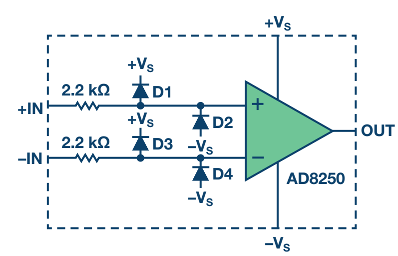


Figure 2. Input ESD topology of AD8250.

Current-Limiting JFETs

In contrast to the implementation in Figure 1 and Figure 2, current-limiting JFETs may be used in IC designs as an alternative to diode clamps. Figure 3 shows an example where JFETs are used to protect a device when the input voltages exceed the specified operating range of the device. This device is inherently protected up to 40 V from the opposite rail by the JFET inputs. Because the JFET will limit the current into the input pins, the ESD cells cannot be used as additional overvoltage protection.

Where voltage protection up to 40 V is required, this device's JFET protection offers a well controlled, reliable, fully specified option for protection. This is often in contrast to using ESD diodes for protection, where information on diode current limits are often specified as typical, or possibly not specified at all.

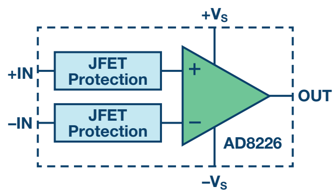


Figure 3. Input protection scheme of AD8226.

Diode Stacks

In applications where the input voltage is allowed to exceed the power supply voltage or ground, a stack of diodes may be used to protect the input from ESD events. Figure 4 shows an amplifier that implements a stacked diode protection scheme. In this configuration, the diode string is used to protect from negative transients. The string of diodes are used to limit the leakage current in a usable input range, but provide protection when the negative common mode range is exceeded. Keep in mind the only current limiting will be the equivalent series resistance of the diode string. An external series resistance can be used to decrease the input current for a given voltage level.

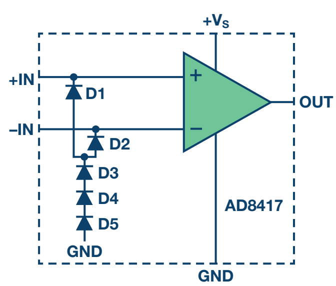
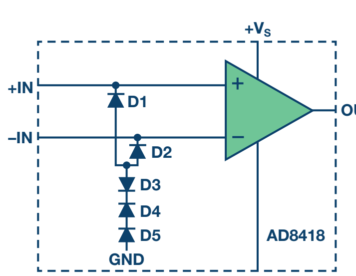


Figure 4. Low-side input protection scheme of AD8417.

Back to Back Diodes

Back to back diodes are also used when the input voltage range is allowed to exceed the power supply. Figure 4 shows an amplifier that implements back to back diodes to provide ESD protection on a device that allows voltages up to 70 V using a 3.3 V supply. D4 and D5 are high voltage diodes used to standoff the high voltages that could be present on the input pins and D1 and D2 are used to prevent leakage currents while the input voltages are within the normal operating range. In this configuration, using these ESD cells for overvoltage protection would not be recommended because exceeding the maximum reverse bias of the high voltage diode can easily lead to situations that cause permanent damage.



Note: D4 and D5 Are High Voltage Devices

Figure 5. High-side input protection scheme of AD8418.

No ESD Clamps

Some devices do not include ESD devices on the front end. While it is obvious that a designer cannot use ESD diodes for clamping if they are not there, this architecture is mentioned as a situation to look out for when investigating overvoltage protection (OVP) options. Figure 6 shows a device that uses only large value resistors to protect the amplifier.

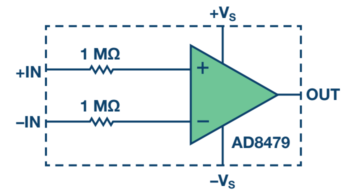


Figure 6. Input protection scheme of AD8479.

ESD Cells as Clamps

In addition to understanding how the ESD cells are implemented, it is important to understand how to utilize the structures for protection. In a typical application, a series resistor is used to limit the current over a specified voltage range.

When amplifiers are configured as shown in Figure 7 or where the inputs are protected by a diode to the supply, input current is limited using the equation in the following formula.

$$I_{DIODE} = \frac{V_{STRESS} - (V_{SUPPLY} + 0.7\text{ V})}{R_{PROTECTION}} \tag{1}$$

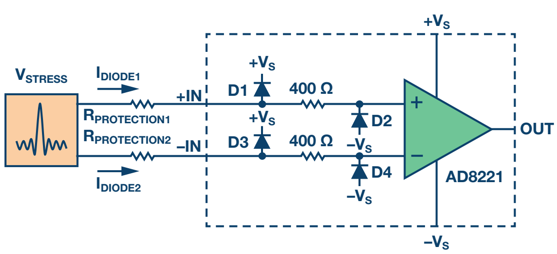


Figure 7. Using ESD cells as clamps.

An assumption used for Equation 1 is that $V_{STRESS} > V_{SUPPLY}$. If this is not the case, a more precise diode voltage should be measured and used for the calculation instead of the 0.7 V approximation.

An example calculation follows for protecting an amplifier using ±15 V supplies, from input stresses up to ±120 V, while limiting the input current to 1 mA. Using Equation 1, we can use these inputs to calculate the following.

$$I_{DIODE} = \frac{V_{STRESS} - (V_{SUPPLY} + 0.7\text{ V})}{R_{PROTECTION}} \tag{1}$$

$$1\text{ mA} = \frac{120\text{ V} - (15\text{ V} + 0.7\text{ V})}{R_{PROTECTION}} \tag{2}$$

$$R_{PROTECTION} = 104{,}300\ \Omega \tag{3}$$

Given these requirements, an $R_{PROTECTION} > 105$ kΩ would limit the diode current to <1 mA.

Understanding the Current Limitations

Maximum values for I_{DIODE} will vary from part to part, and also be dependent on the particular application scenarios in which the stress is applied. The maximum current will be different for a one-time event lasting milliseconds vs. if the current was constantly applied over the entire 20 or more year mission profile life of the application. Guidance on the particular values may be found in amplifier data sheets in the absolute max section or application notes and are usually in the range of 1 mA to 10 mA.

Failure Modes

The maximum current rating for a given protection scheme will ultimately be limited by two factors: the thermal implication of the power dissipated in the diode and the maximum current rating for the current path. The power dissipation should be kept below a threshold that maintains the operating temperature in a valid range and the current should be chosen to be within the specified maximum to avoid reliability issues due to electromigration.

Thermal Implications

When current flows into the ESD diodes, there will be a temperature increase due to the power dissipated in the diodes. Most amplifier data sheets specify a thermal resistance (usually specified as Θ_{JA}) that will indicate how junction temperatures will increase as a function of power dissipation. Considering the worst-case application temperature, along with the worst-case temperature increase due to power dissipation, will give an indication of the viability of a protection circuit.

Electromigration

Even when the current does not cause thermal problems, the diode current could still create a reliability problem. There is a maximum lifetime current rating for any electrical signal path due to electromigration. The electromigration current limit for the diode current path is typically limited by thickness of the internal traces in series with the diodes. This information is not always published for amplifiers, but needs to be considered if the diodes are active for long portions of time, as opposed to transient events.

An example where electromigration can be a problem is when an amplifier is monitoring, and therefore connected to, a voltage rail that is independent of its own supply rail. When there are multiple power domains, there can be instances where power supply sequencing can cause voltages to temporarily exceed absolute maximum conditions. By considering the worst-case current path, the duration over life that this current could be active, and understanding the maximum allowable current for electromigration, reliability issues due to electromigration can be avoided.

Conclusion

Understanding how an amplifier's internal ESD diodes are activated during electrical overstress events can enable simple improvements to the robustness of a design. Examining both the thermal and electromigration implications of a protection circuit can highlight potential problems and indicate where additional protection may be warranted. Considering the conditions outlined here enables designers to make smart choices and avoid potential robustness issues in the field.

Paul Blanchard [paul.blanchard@analog.com] is an applications engineer at Analog Devices in the Instrumentation, Aerospace, and Defense business unit, located in Wilmington, MA. Paul started with ADI in 2002 in the Advanced Linear Products (ALP) group covering instrumentation amplifiers and variable gain amplifiers. In 2009, as part of the Linear Products Group (LPG), he was primarily responsible for automotive radar, current sensing, and AMR related applications. Currently, as part of the Linear and Precision Technology (LPT) Group, he is working on precision input signal conditioning (PISC) signal chain technologies. Paul earned his bachelor's and master's degree in electrical engineering from Worcester Polytechnic Institute.

Paul Blanchard

Brian Pelletier [brian.pelletier@analog.com] is a product development engineer in the Linear Product Technologies division of Analog Devices. He joined ADI in 2003 after obtaining a bachelor's degree in electrical engineering from the University of Massachusetts. Brian specializes in precision amplifiers, including instrumentation amplifiers and current sense amplifiers.

Brian Pelletier