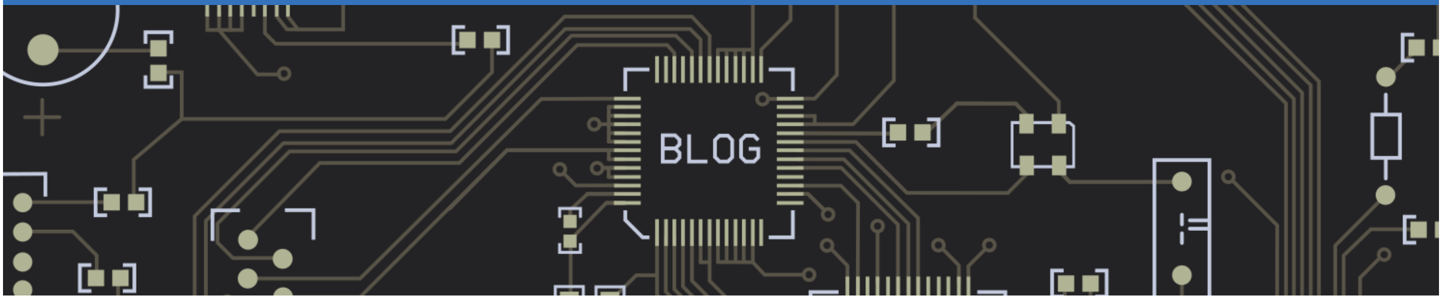

Protecting Your Circuit

BY MARK HARRIS · MON 16 MARCH 2020

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Tagged with: Gas Discharge Tube, EMI, MOSFET, ESD, PCB Design

PCB design is a complex process that depends on many factors. Engineers are usually tasked with looking for cost-effective solutions while maintaining high reliability of their end products. While adding a range of protective measures to your circuit board can add to your per unit cost, it can also greatly reduce failure rates in the wild, which come with their own support and replacement costs. In many scenarios, the additional per unit cost would be insignificant when compared to support and replacement costs, thus turning circuit protection into an indispensable money saving mechanism.

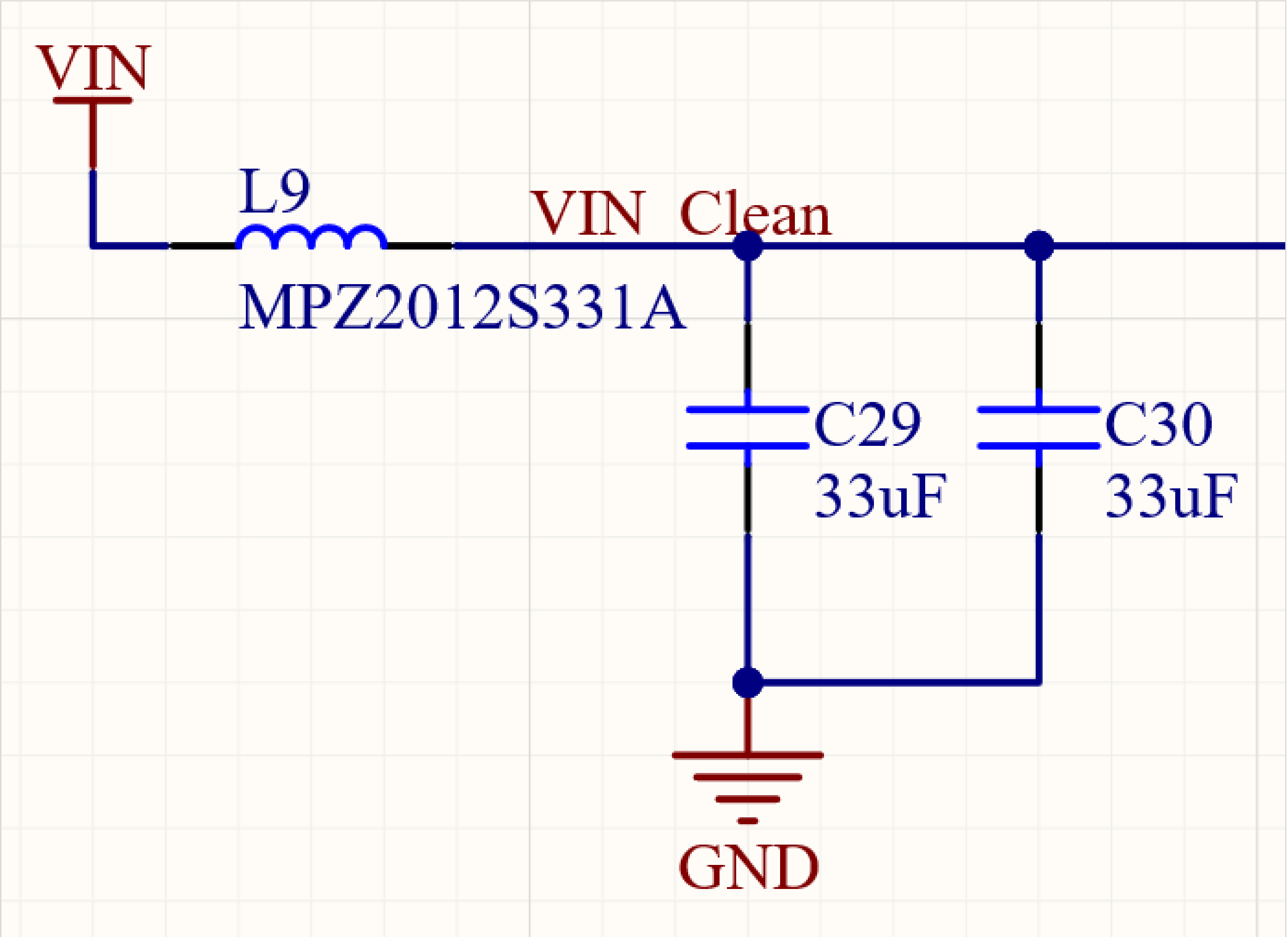
In this article, we're going to take a look at protective devices you can add to your circuit that will not only help make it more forgiving of user error, poor power quality, and unexpected events, but ensure that it's more likely to pass compliance testing. We will go through the commonly encountered safety problems one at a time, starting with electromagnetic interference.

Electromagnetic Interference (EMI)

Reducing radiated electromagnetic energy is critical to meeting electromagnetic compatibility compliance regulations. Furthermore, since electromagnetic interference goes both ways, devices need to be designed with the ability to cope with incoming interference in mind. For most devices, the protection circuits for inputs and outputs are going to be the same, so what gets you through a compliance test is likely to also protect you from picking up energy that will harm signal integrity in your product.

Beyond the usual requirements of electromagnetic compatibility compliance, you might be designing a device which finds itself in an industrial environment full of large currents going to motors or other power hungry devices, or near a powerful radio device. Cables connected to your device could pick up a significant voltage from the induced fields, which would make sensor readings unreliable, or communications difficult. Worse still, your device might be plugged into a power rail that also feeds these electrically-noisy devices, allowing electromagnetic interference to make its way directly into your circuit through the power connection.

Ferrite Chip



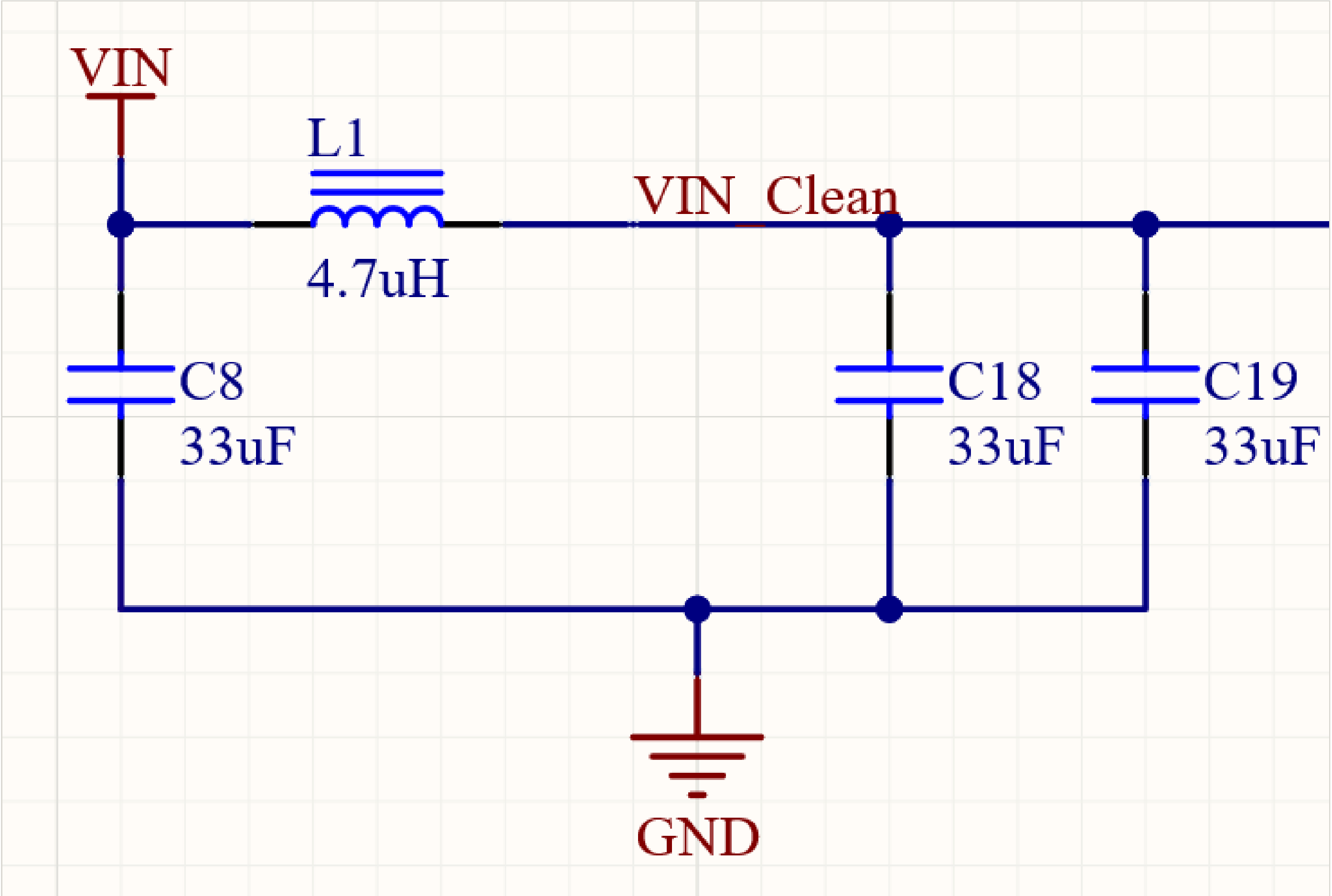
The ferrite bead, or chip (surface mount), is one of the cheapest and simplest methods of protection you can add to your circuit board. The humble ferrite suppresses high frequency noise at the point it is placed, protecting either side from noise generated on the other side. Any conductive cable plugged into your device is an antenna, unless it has effective shielding. This cable can pick up noise from the environment and can also radiate noise from your circuit.

A ferrite chip acts as a low pass filter in your circuit, creating high resistance to high-frequency signals. A critical specification when selecting a ferrite chip or bead is its impedance at given frequencies, which is most commonly measured at either 1MHz, or 100MHz. This specification will be in ohms, as the ferrite chip will appear to signal components of the specified frequency like a resistor of this value.

Another critical specification for your circuit is DC Resistance (DCR(MAX)), which is the series resistance of the ferrite to a DC signal. This series resistance is important, as it will have an impact on your circuit, and if you are trying to pass a large current along the conductor in series with the ferrite, you may find the ferrite gets quite hot—hence the current rating specification, which is important to consider in such cases.

Ferrite beads/chips should be used liberally on low frequency and DC conductors to reduce the impact of both radiated and received noise on cables. You may also consider using one locally in series to the power rail of a sensitive component on your circuit board, such as those present in analog circuits working with very low voltage signals, where noise in the power rail might transfer into the signal.

Pi Filter

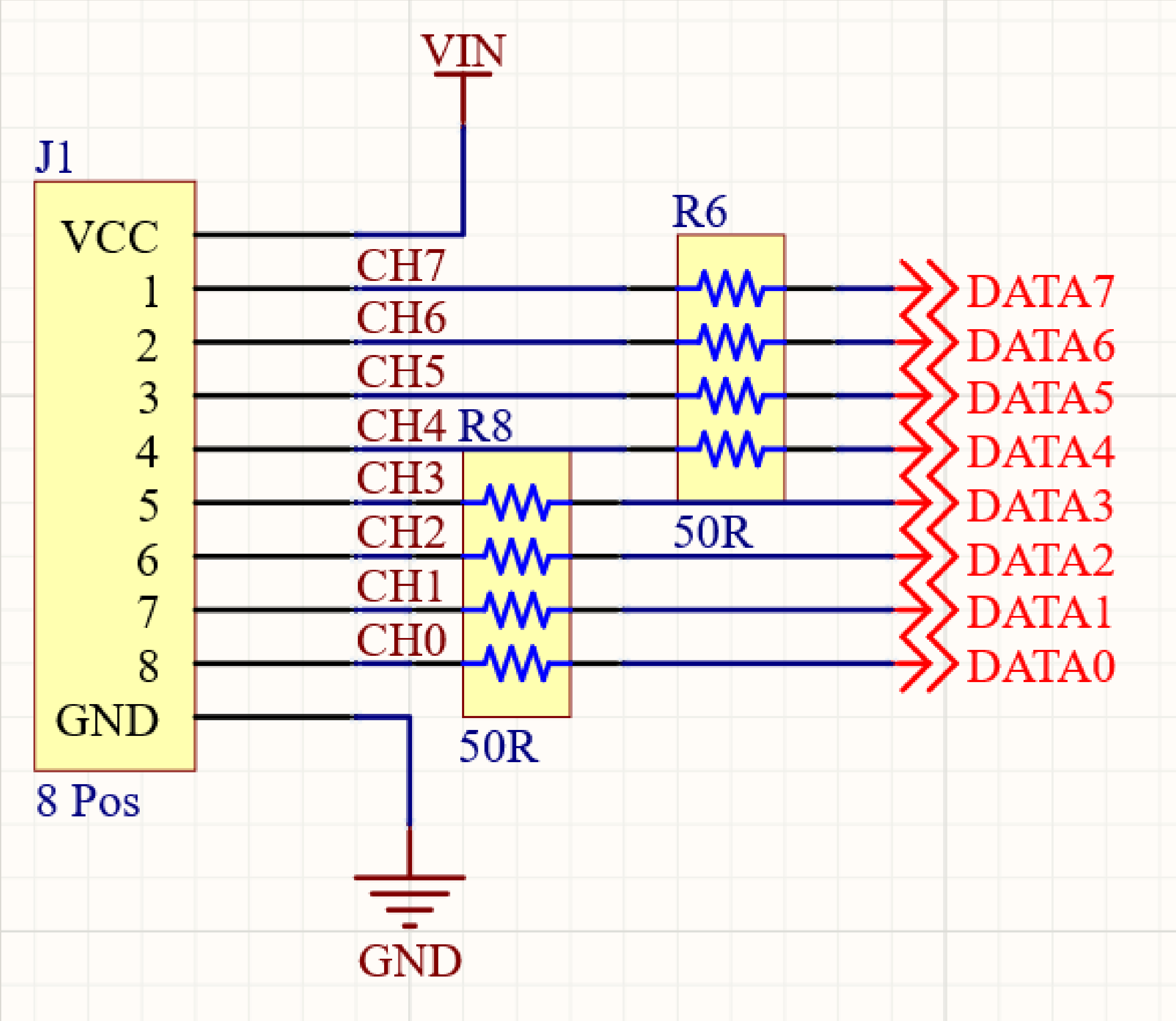


Where ferrite chips act as high resistance to an AC signal, inductors provide high impedance. Inductors are less commonly used for protecting inputs or outputs of devices than ferrite beads are, however, if paired with two capacitors, they can be a powerful tool for reducing conducted noise. The Pi filter is named because it looks like the greek letter π, with an inductor across the top, and the two legs being capacitors. This creates a highly effective low pass filter, with the two capacitors acting as decoupling and the inductor providing high impedance to signals.

If your device is receiving power from potentially noisy source, or has a large switched-mode power supply in it, a Pi filter on your input is likely to provide a significant reduction in EMI problems. Inductors typically have much greater impedance and current handling capabilities than ferrite chips, and lower series resistance as well. If your conductor has several amps flowing along it, or is seeing a significant amount of noise, then a Pi filter will likely provide better protection than a ferrite chip.

Most surface mount, wire wound, ferrite core inductors are available in a shielded version. As you're using the inductor to reduce noise, shielded inductors provide added protection.

Series Termination Resistor



If you have a signal line which has a frequency over a few hundred kilohertz, you may want to consider adding a 50ohm termination resistor to the lines to provide impedance matching and reduce reflections. On digital transmission lines, reflections from an improperly terminated signal can create logic level ambiguity, which results in corrupted data. On analogue lines, reflections can cause power loss and ghosting effects in the signal.

Whilst this isn't so much a protection method as it is good design practice, it's worth mentioning here.

RF Shield

If you are designing an RF product, a circuit dealing with very low voltage sensor signals, or one in a very adverse electromagnetic environment, the ultimate solution to massively reducing electromagnetic interference is to enclose your circuitry in an RF shield. The RF shield is grounded, preventing any electromagnetic interference from making it through into, or out of the exposed conductors and components of your circuit. Furthermore, a well designed solid ground placed in the PCB, which the components are mounted to, will prevent noise from escaping or entering from the bottom side. However, noise can and will enter and exit via conductors to the shielded circuitry. Other measures, such as ferrite chips, can alleviate conducted noise.

RF shields can be purchased in a range of sizes, and are quite cost-effective to have custom-made, even at a low volume of 100 units.

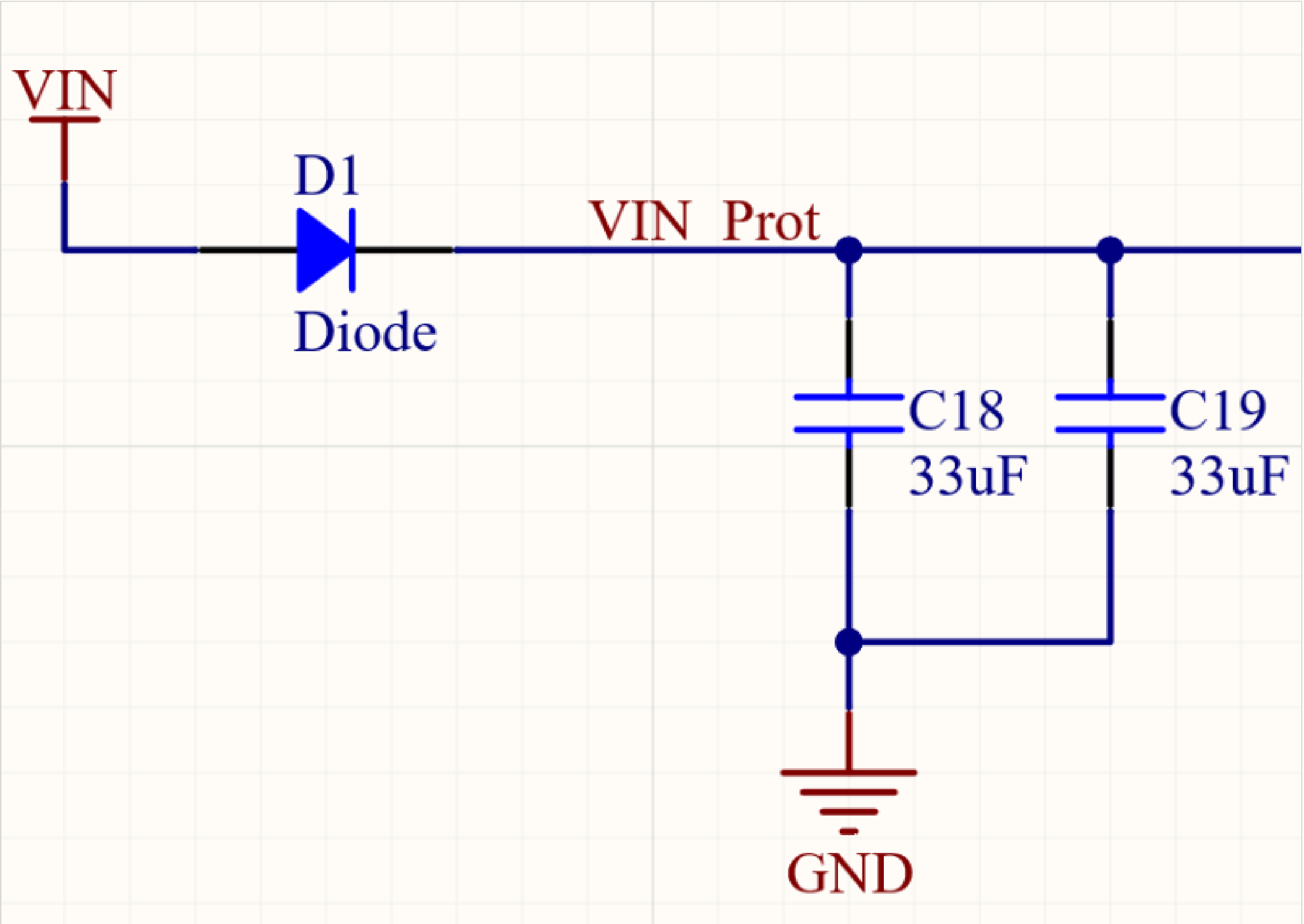
If you are not sure if your board needs an RF shield or not, it's a lot easier to design one onto the PCB and not place it than it is to revise the board and add a land pattern for one. This allows you to choose not to use the RF shield if it proves unnecessary during testing.

Reverse Polarity

Unlike in sci-fi movies, when the captain or engineer yells "reverse the polarity", typically in a battle or other dire circumstance, reversing the polarity of your power supply in the real world is more likely to release the magic smoke than generate a forcefield. If a user uses the wrong type of power cable or the input connector is not polarized, it can be easy to reverse the polarity of power to your device, which might fry every component in your circuit.

Luckily, protecting against reverse polarity events is easy.

Input Diode



The most simple means of adding reverse polarity protection is to simply add a diode in series with your positive conductor. The diode will only conduct forward, so if the inputs are connected incorrectly, no current will flow.

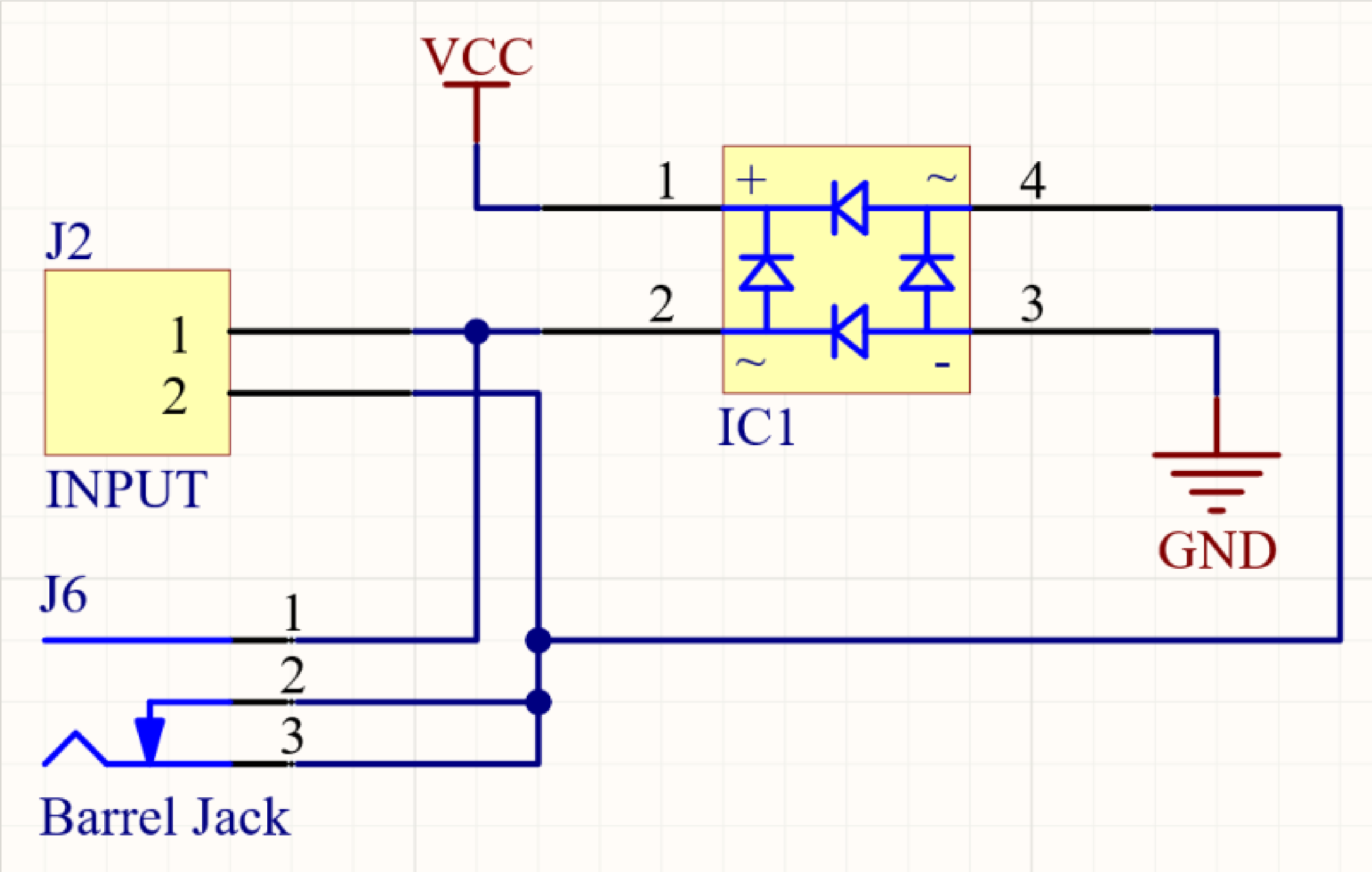
There are some major drawbacks to this approach, and they are related to the forward voltage drop of the diode. If you are supplying your device with the exact voltage it needs to function, the diode may drop the voltage below the point at which your device will operate reliably.

If your device consumes a moderate amount of power, the diode may overheat as it dissipates power proportional to both the magnitude of current and the forward voltage drop. If you choose a diode which has sufficient capacity to deal with this heating, it could provide enough heat to the circuit board to cause other components to act unreliably, or reduce the lifespan of the device due to the increased thermal dissipation within an enclosure.

If your device is battery powered, the input diode will reduce the service life of the battery or charge due to the loss of efficiency from the increased dissipation of the diode. This will result in requiring a larger, heavier, more expensive battery to provide the same run time.

Therefore, an input diode is generally only a good solution for a low current device which has an operating voltage lower than its input voltage. A good example of this would be a basic microcontroller circuit operating at 3.3v or lower powered by a USB cable.

Bridge Rectifier



If the forward voltage drop of a diode and related heat/inefficiency isn't a problem for your application, you can also ignore polarity completely by using a bridge rectifier on the input. A simple bridge rectifier will ensure you always have reliable positive and negative (or ground) voltage rails, no matter how the power is supplied to the device.

I have used this approach in very low power, ultra-miniature devices where a user would supply their own power by soldering wires to the board. The chance of user error was high, and the inefficiency of the bridge rectifier had negligible impact on the device or specific application.

MOSFET

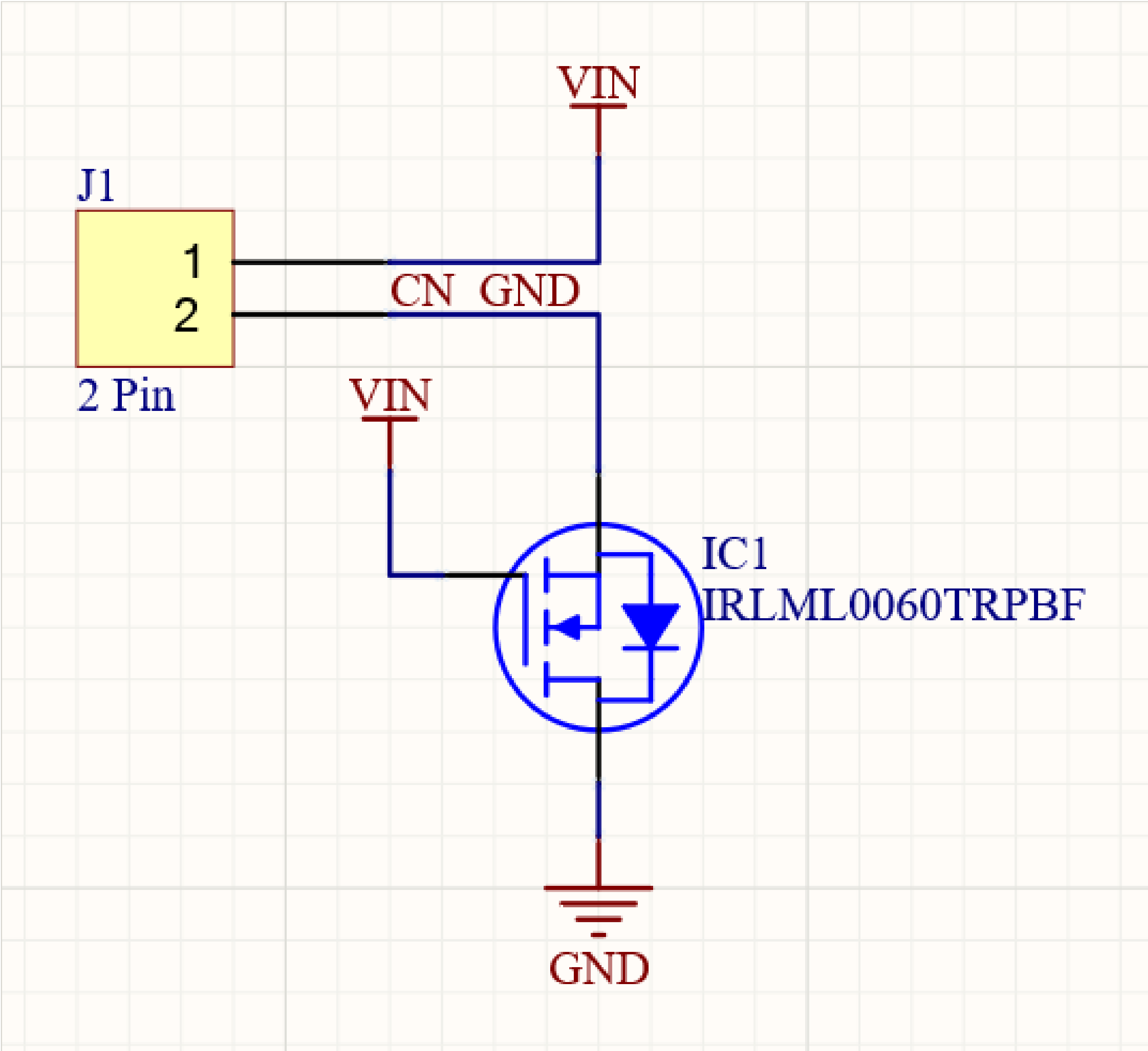
In contrast to the diode above, a MOSFET has very low on-resistance and can provide reverse polarity protection for DC circuits consuming hundreds of amps, or very efficiently reverse polarity protection for battery powered circuits. Because of the low on-resistance, there is virtually no additional thermal burden on the circuit.

You can use a MOSFET for reverse polarity protection as long as the circuit either has a single positive voltage supply terminal (using a P-Channel MOSFET) or a single ground return path (using N-Channel MOSFET). If an arrangement of connected devices or alternate voltage inputs would create an alternate supply or return path, this approach will not be applicable.

An N-Channel MOSFET features lower RDS(ON) than a P-Channel for the same price, which makes it the preferred solution for me where applicable. In devices which need to have the ground return path connected at all times, however, a P-Channel MOSFET is still a very high performance solution compared to a diode.

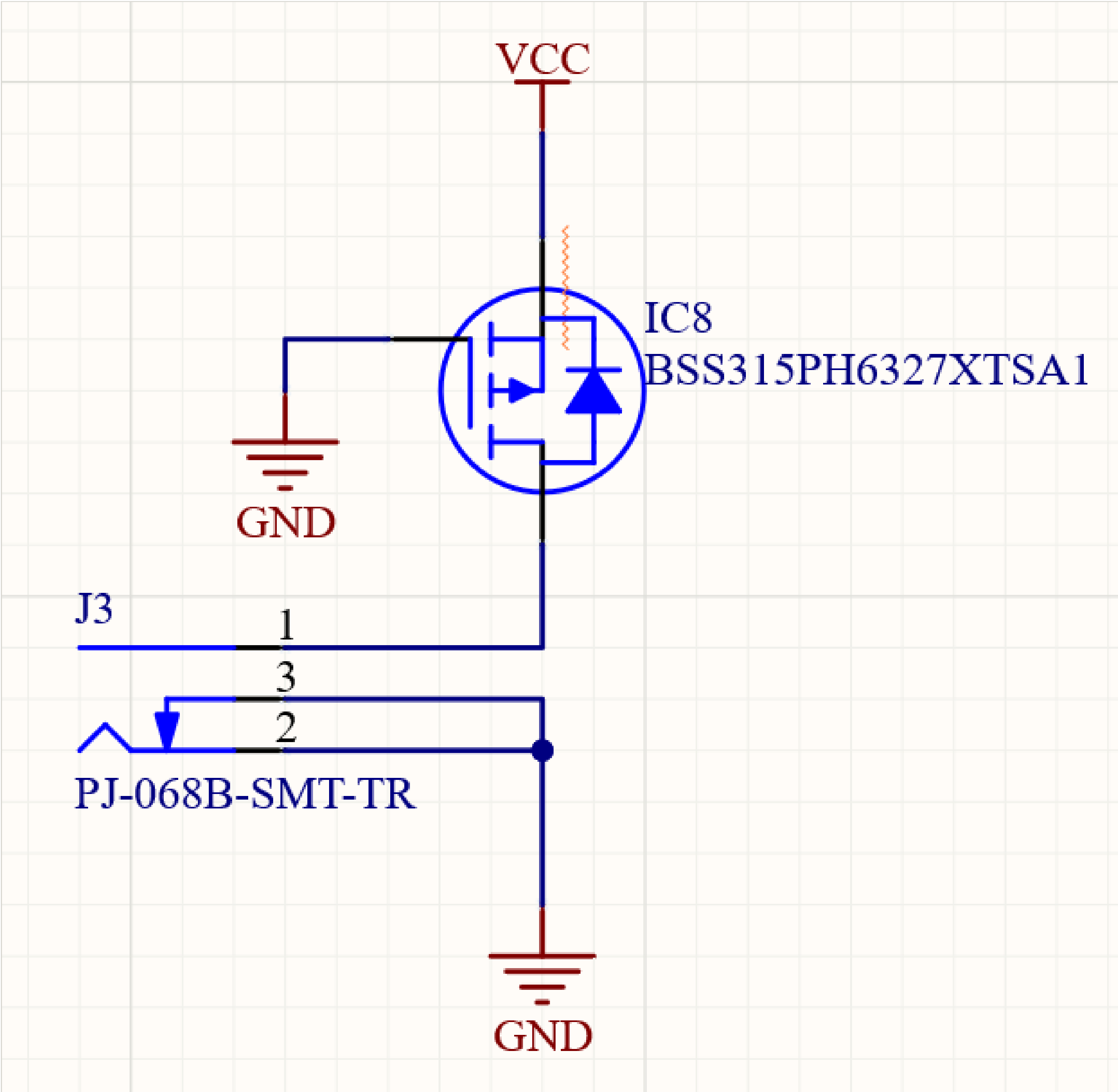
To add reverse voltage protection with MOSFETs, we are able to utilize a couple of their properties. Firstly, the body diode that allows conduction from the source to drain pins, and secondly, the fact that MOSFETs can conduct current in either direction once the gate is charged.

N-Channel MOSFET



An N-Channel MOSFET is installed on the ground return path, at the power connect with the body diode oriented to conduct when the circuit is powered by the correct polarity. The gate is then connected to the positive input voltage rail of the power supply to the device. The body diode completes the circuit when the correct polarity power is connected, allowing the gate to be activated and short the body diode.

P-Channel MOSFET



The setup for the P-Channel MOSFET is basically the reverse of the N-Channel. The body diode is oriented to conduct current from the positive supply to the rest of the circuit, with the gate connected to ground. When the correct polarity of voltage is applied, the gate goes low and charges the MOSFET, which shorts out the body diode, causing the MOSFET to conduct normally, completing the circuit.

Overcurrent

If your product has cables or devices that could consume a lot of current if put into the wrong state (such as a stalled motor), overcurrent protection could save the day. Cables might break internally, or might be damaged by external forces which cause the conductors to short out, inducing a high current load on your board. This can quickly heat up traces that were not intended for that load, causing them to fail, or overtax a power supply or other device attached to those conductors.

Resettable Fuse

A Positive Temperature Coefficient (PTC) fuse is a protective device that ensures your circuit will lose power if the current draw exceeds its rating. After the current draw drops back to normal, the fuse begins conducting again. If your current demands exceed about 10amps, or your voltage exceeds around 60V, then resettable fuses are not for you and you will need to look at alternative options such as glass or ceramic fuses. These fuses offer excellent protection for higher current devices, however, like most protective measures, they do have some drawbacks.

Resettable fuses are created by having conductive particles bound tightly within a plastic filler. When the fuse is at a normal temperature, there is a large amount of conductive material creating a path for current to flow through the device with moderate resistance. As current increases, the fuse heats up causing the plastic to expand. Consequently, this expansion begins to separate the conductive particles, which increases the resistance, causing the fuse to heat up exponentially faster. The fuse reaches a point where only a small amount of current is able to keep the plastic hot enough to maintain a steady state of low conductivity.

This steady state is, in my opinion, the greatest drawback of the fuse. The smallest hold current in a surface mount device I was able to find on the market is 10mA, which corresponds with a 21mA trip at room temperature. This is a fairly narrow range, and a device which would trip it at 21mA could continue operating in a degraded state at 10mA, which may cause damage. In surface mount PTC fuses, the hold current being half the trip current is fairly common, so you would need to ensure that if your device is going to be damaged at the trip current, that it would not also be damaged at half the trip current. If it could be damaged at half the trip current, it should have another method of shutting itself down once it detects this state to prevent damage.

Glass/Ceramic Fuse

If your device is built such that reaching a current threshold definitely means that something has gone horribly wrong, a glass or ceramic fuse could be the way to go. A fast-blow fuse can fail within milliseconds of the rated current being exceeded, whereas a slow-blow fuse can allow you to temporarily exceed the current limit by a small amount if needed, such as for inrush current.

Non-resettable fuses are a pretty final solution, however, they will only protect from current that exceeds the fuse rating. Just a week ago, I saw a lab power supply circuit board from a very high-end brand that had an intact fuse, yet the circuit board was heavily scorched in several places. One MOSFET had failed on the board, for whatever reason, and that failure put too much load on the rest of the H-Bridge MOSFETs which appeared to have failed in a rapid, fiery succession. Yet, the fuse for the device did nothing as each individual MOSFET was failing under less load than the fuse was rated for.

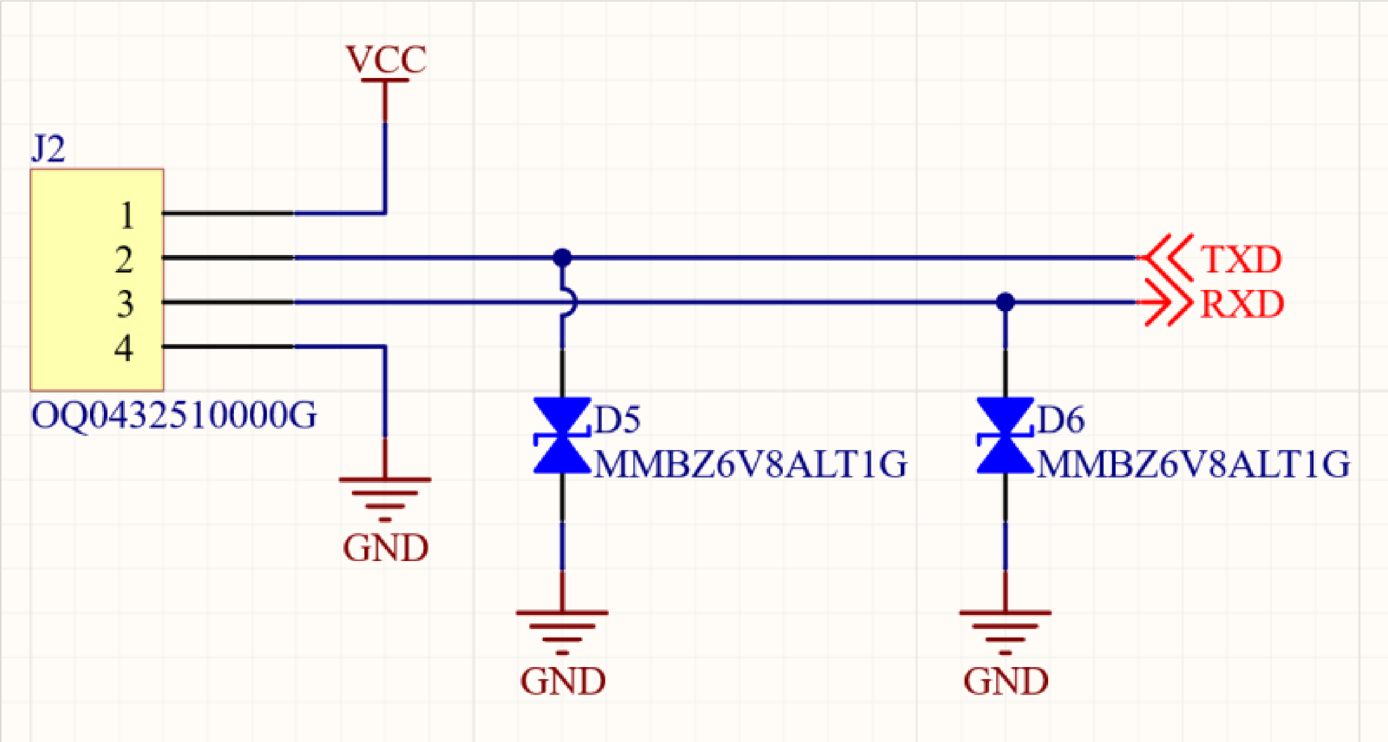
If you are planning to use a fuse, you can buy surface mount fuses which are not user serviceable, or you can buy holders for readily available fuses that can be user serviced. Typically, I prefer to make fuses non-user serviceable, as it forces the client/customer to return the board to you which allows you to investigate why the fuse blew in the first place. It allows you to figure out if the current condition that caused the fuse to blow was caused by a degraded component, or oppositely, the current draw itself caused a degraded component. Simply replacing the fuse and turning the device back on could result in the fuse immediately blowing again, or worse, the degraded component might fail below the fuse threshold and cause much more significant damage to your device. Some people hate fuses that must be serviced by the vendor, but they could prevent the vendor from needing to replace a circuit board worth hundreds of dollars if they are able to investigate the cause of the fuse failure.

Electrostatic Discharge (ESD)

If you live in a low altitude, high humidity region of the world, then ESD might not be something that readily factors into your design process. If you visit a high altitude or low humidity city such as Denver or Calgary, you'll find yourself shocking everyone and everything around you with bolts of lighting from your fingertips. Just because you live in a nice environment where tens of thousands of volts don't build up on your skin to discharge at the first chance possible doesn't mean your product will not end up there. One inadvertent touch from a user who was walking on carpet or taking off a jacket that has given them a big static charge, and your device could be destroyed or seriously damaged.

Providing excellent ESD protection is a fairly large topic, so this article will just cover the options quickly, another article covering ESD protection in depth will be published soon.

TVS Diode



One of the cheapest, most reliable methods of ESD protection for inputs is the TVS diode. TVS diodes also provide excellent protection against unexpected transient voltages.

On most devices I design, I add a TVS diode to every input a user might touch, or get close to touching with a finger. A 22kV discharge should be able to jump about a 20mm gap, so simply having pins on a connector inset is not guaranteed to protect from ESD. TVS diodes are cheap, compact and easy to add to a design, so there is very little reason not to use them. There are plenty of devices available which will not disturb high frequency communications such as USB 3.0, allowing them to be used on all connections.

Whilst I mention that a TVS diode may not survive a very large electrostatic discharge event, having a cheap diode on each line will allow you to survive the vast majority of discharges without the great expense of a gas discharge tube. I have heard some engineers say you shouldn't waste money on ESD protection because it may not protect the circuit from all events, however, the fact that it protects against at least 95% of them is good enough for me.

Gas Discharge Tube Arresters

Gas discharge tubes are not particularly suited for protecting a microcontroller input directly exposed on a connection, but are rather exceptionally good at protecting AC mains inputs or telecommunications equipment from ESD and even lightning. If you need to move a tremendous amount of energy to ground in a hurry, a gas discharge tube is just what you are looking for.

Gas discharge tubes work by the voltage between its input and ground ionising the gas within. Once this threshold is reached, the ionised gas is readily able to conduct far more current than a silicon device of the same size is capable of.

As I said, these are not particularly useful for protecting your microcontroller—stocked quantities of gas discharge tubes by spark over voltage clearly shows why. Approximately 20% have a spark over voltage under 100V, 20% between 150V and 250V, 20% between 250V and 350V, another 20% is between 350V and 1000V with the remainder being over 1000V. This gives you a good idea of application—they're commonly used with 110V devices, 240/250V devices, 380/400V devices and other devices, with only a couple of options available for devices under 90V. This makes your 3.3v microcontroller input likely to be burned out by the voltage and current if a gas discharge tube needs to arrest the incoming energy.

If you have a telecommunications device, or device connected to AC power that should have the capability of handling an ESD event from an installer or lighting, the GDT might do the job for you. Low cost gas discharge tubes can readily handle 5,000amps, and compact options offering up to 25,000amps are available.

To handle this much current, serious thought needs to be put into your ground connection around the gas discharge tube to ensure you don't protect the board by vaporizing the ground return path.

PCB Features

The poor man's ESD protection can be built without any external components. A high voltage wants to make its way to ground as quickly and efficiently as possible and will happily ionize some air to create a conductive path to get there. By creating a couple of triangles pointing at each other on the circuit board, one from the connector pin to be protected, and the other on the ground plane, you can create a simple spark gap. With a sufficiently sized gap which an ESD event would easily spark over but normal device operation would not, you can provide some rudimentary protection for your circuit board.

Despite the ease of use, some engineers question whether spark gaps are worth the time to design as they do have some drawbacks. Like the gas discharge tube, the spark over voltage is relatively high compared to a logic level voltage. This means the spark gap probably will not sufficiently protect your microcontroller or other logic level device input or output from the ESD event. Having a conductor and ground exposed and closely spaced to each other can also allow contamination to potentially span the gap and conduct current, which could distort a signal or degrade the functionality of the connection, if not outright damage something.

Depending on your application, building a spark gap into your connectors may be prudent, however, in other applications it may be a route to premature device failure.

Post Production Protection

Not all of the protection you apply to your circuit boards is just in the circuit. You might also need to apply a substance to the board to ensure it's protected from corrosion and moisture or to improve overall electrical protection.

Conformal Coating

Conformal coating is wonderful for circuit boards that are going to be exposed to a lot of environmental challenges. Conformal coated circuit boards will be moisture resistant or waterproof, and immune to dust or other debris, creating shorts on the board, and also resistant to corrosion from the atmosphere. Conformal coating can help with circuits that are exposed to moderate vibration by providing additional adhesion and stability to parts mounted on the board.

Conformal coating can be sprayed on the board or brushed on it, depending on the geometry you need to cover, both in terms of surface area and complexity. You will not want to get conformal coating on connectors or areas you need to solder wires to, as it will prevent electrical contact. A good percentage of contract manufacturers who specialise in circuit boards for harsh environments or do a lot of mil-spec work will have the facilities to robotically spray conformal coating onto your circuit board for you. If you are working with low volumes, it's relatively quick to apply by hand.

Potting

If you thought conformal coating sounded good, you're going to love the idea of potting your electronics. Potting typically refers to filling the enclosure of your circuit board with a non-conductive resin such as silicone or epoxy that completely isolates your circuit board from meddling hands, and greatly enhances the device's ability to withstand shock and vibration. If you're working with high voltages, replacing air with a much less conductive substance can allow you to get away with smaller creepage gaps between components as well as reducing the chances of failure as air becomes ionized by your high voltage. Potted electronics are typically going to be impervious to the environment they are placed in, with the resin acting as a dust, moisture, and corrosive agent barrier.

You're most likely to consider potting your electronics if you have a requirement for:

- Explosion proof design (i.e., no chance your device will create an explosion in a volatile atmosphere.)
- Very high voltage.
- Handling high vibration or shock.
- Extreme environmental conditions (e.g., corrosion, moisture, pressure, vacuum)

If you pot your device with a resin such as epoxy that is virtually impossible to get off each component, you won't have to worry about someone reverse engineering your product, as it's likely to prove impractical for them to access the board and components.

One downside is that it's pretty much impossible for you to access the board and components too. This means a board can't be repaired or diagnosed once it is potted, so if a board fails once the user receives it, the only option will be a complete replacement.

The other downside is poor thermal conduction. There are thermally conductive resins available, which can offer improved heat dissipation, however, these can be quite expensive. Completely encapsulating your circuit board in a substance that conducts neither heat nor air will cause any devices that need to dissipate considerable amounts of heat to fail due to overheating, while also making the use of heatsinks challenging.

While we've discussed the circuit protection methods relevant to most people, PCB design is integrated in many different industries. Some applications may require more drastic protection methods, while others may be able to get away with very little protection. Let us know what you think in the comments section below.

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