In-Package Magnetic Current Sensing

TI Precision Labs – Magnetic Sensors

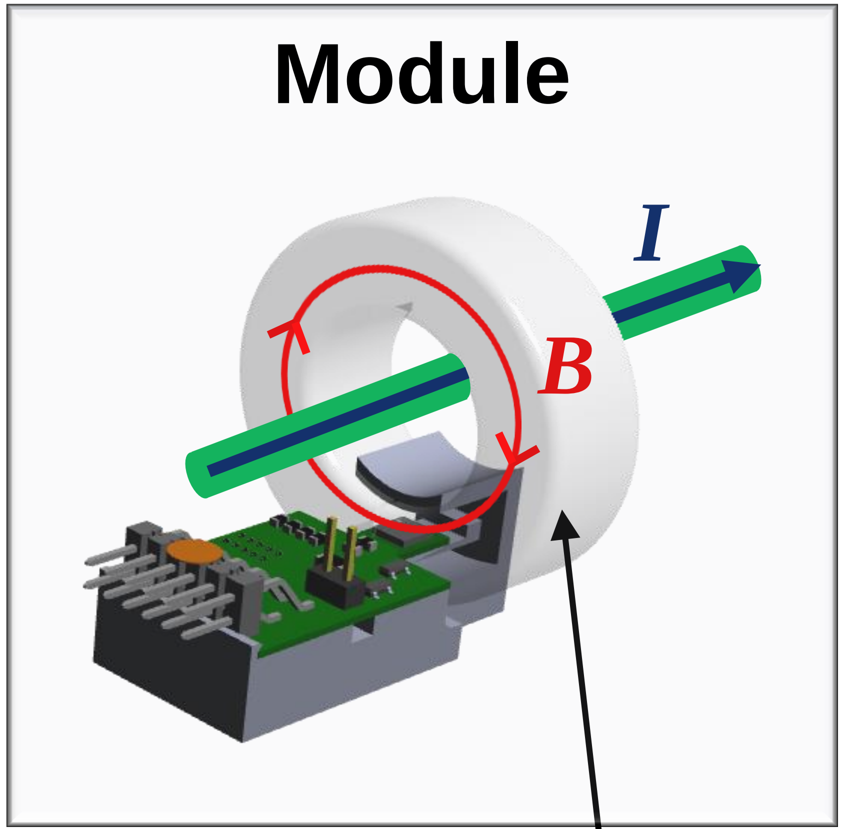
Presented by Ian Williams

Prepared by Steven Loveless and Ian Williams

Hello, and welcome to the TI precision labs series on magnetic sensors. My name is Ian Williams, and I’m the applications manager for current sensing products.

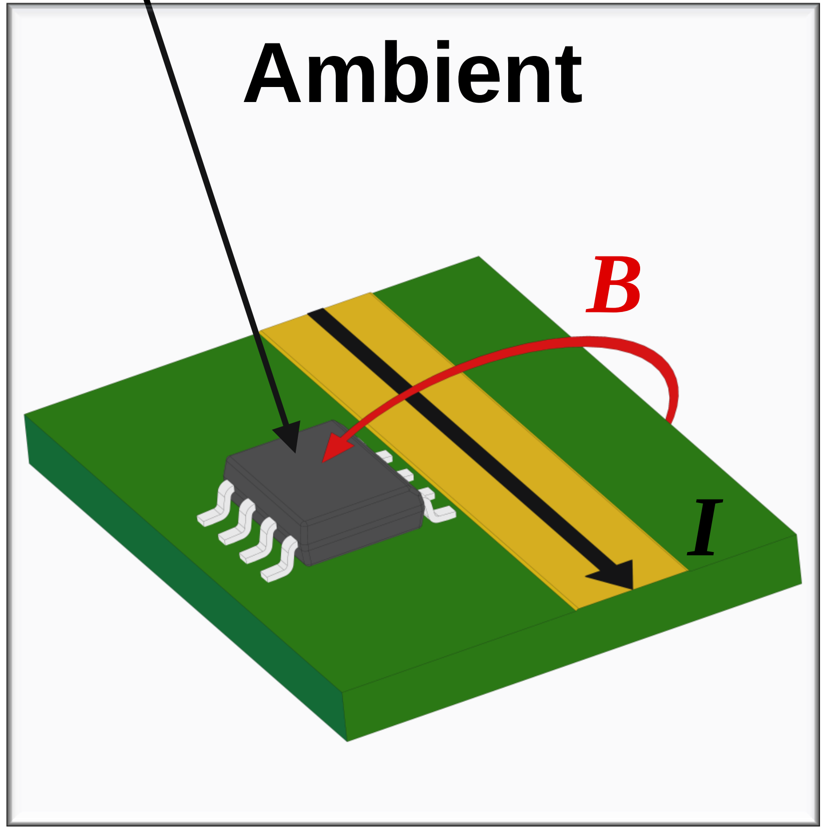
In this video, we will discuss in-package magnetic current sensors, including how they work, the benefits they bring to current sensing applications, and key application challenges such as isolation, magnetic interference, and thermally-limited current capability.

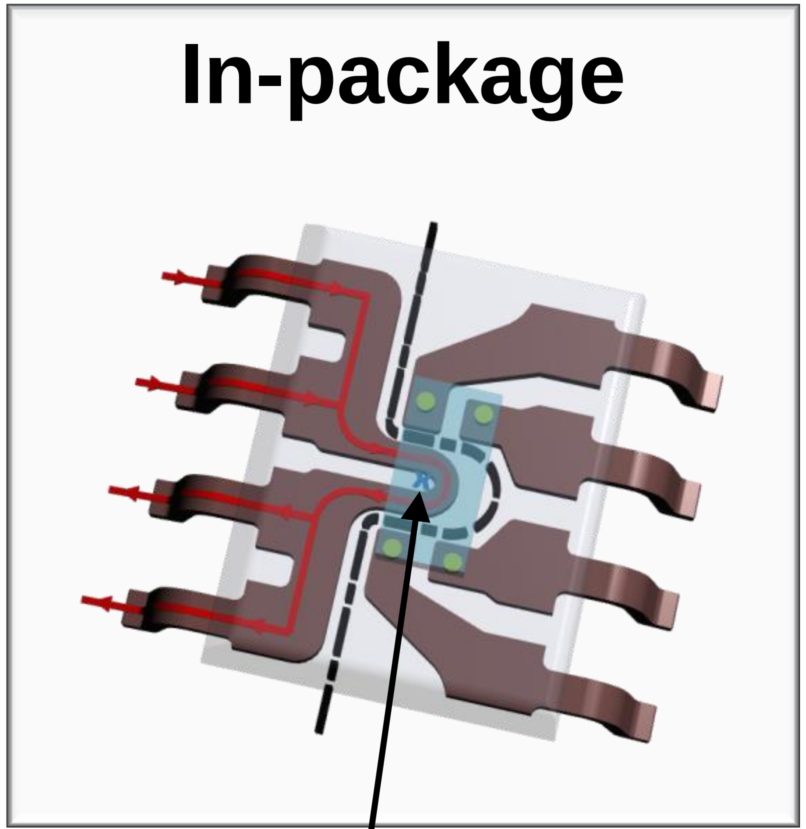
Types of magnetic current sensing (MCS)



Uses toroid to concentrate magnetic field around a current-carrying conductor

Measures magnetic field in air around a PCB trace, bus bar, or other conductor





Measures magnetic field generated by current flow through lead frame

Let’s briefly review the different types of magnetic current sensing, or MCS.

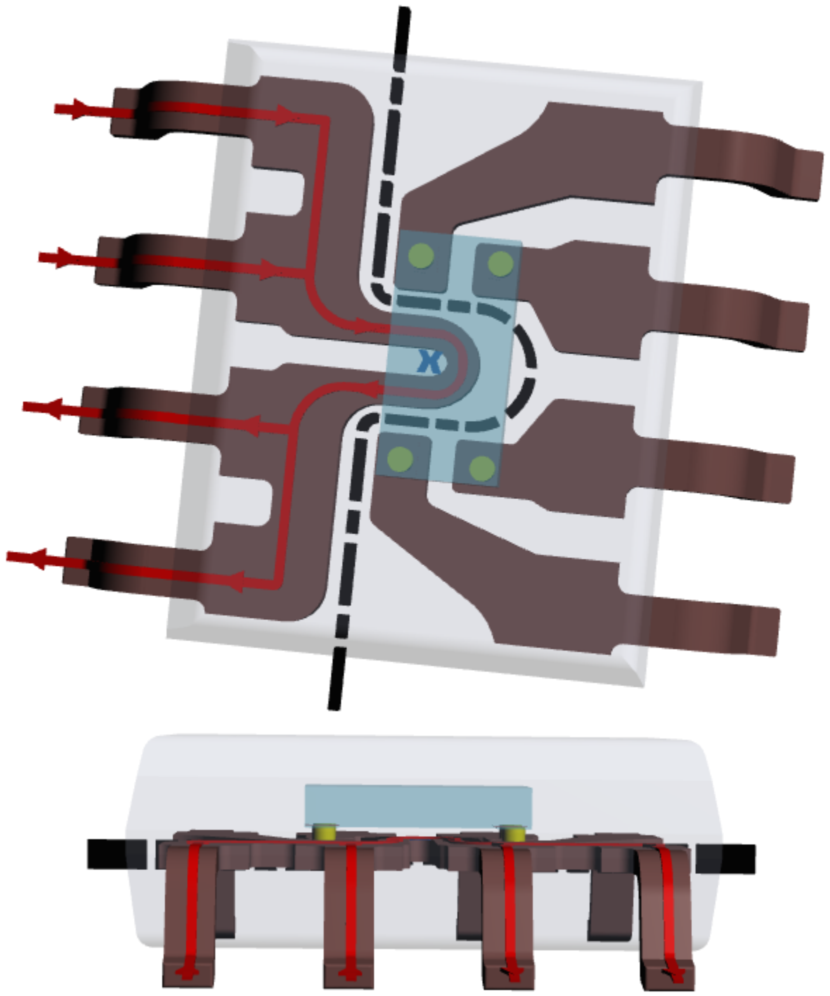
First, module based sensing typically utilizes a magnetic toroid or other geometry to concentrate the magnetic field generated by the current carrying conductor. These systems are typically sold by a third party manufacturer, as there is a high degree of magnetic design required.

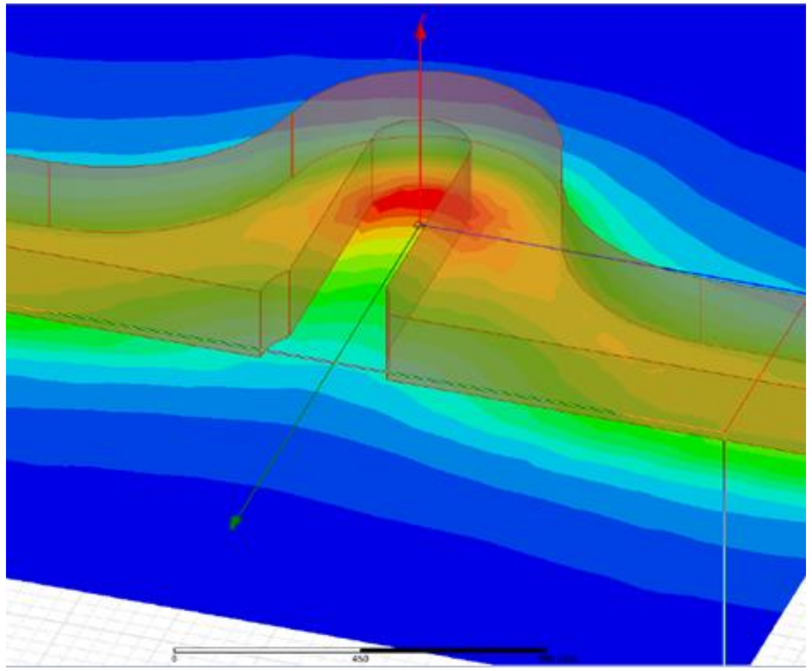
Next, ambient magnetic current sensing utilizes the ambient in-air field generated by a PCB trace, bus bar, or other conductor to sense current. This is accomplished using a linear Hall or other magnetic sensor at some fixed mechanical distance from the conductor. This type of solution can also utilize a magnetic concentrator or shield to improve signal levels or reduce the impact of stray fields.

Finally, the third type is in-package magnetic current sensing, which we will focus on today. In this technology, the current to be measured actually passes through the device package, and the magnetic field generated by the current flow through the leadframe is measured internally with an isolated sensor IC.

In-package MCS basic explanation

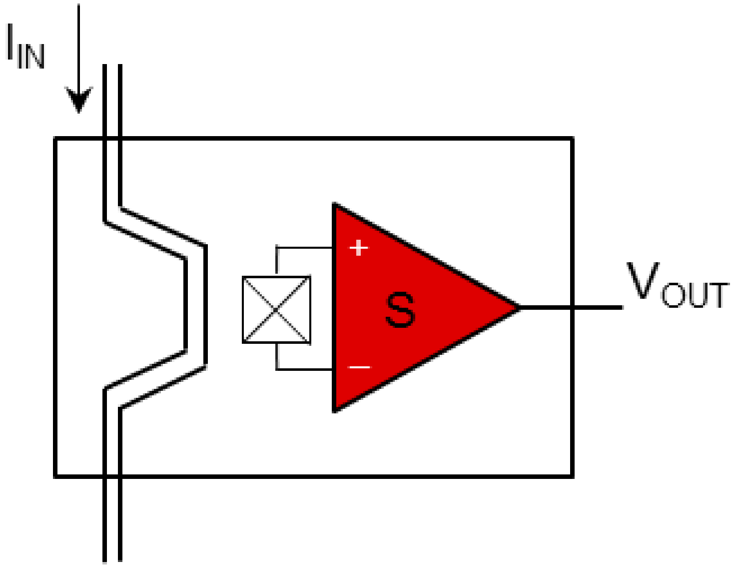
Current flows through lead frame, electrically isolated from die





Lead frame loop generates magnetic field proportional to current

Precision Hall effect sensor converts magnetic field to voltage signal



$$V_{OUT} = S * I_{IN} + V_{OUT\_0A}$$

Let’s talk a little bit about in package MCS and how it fundamentally works.

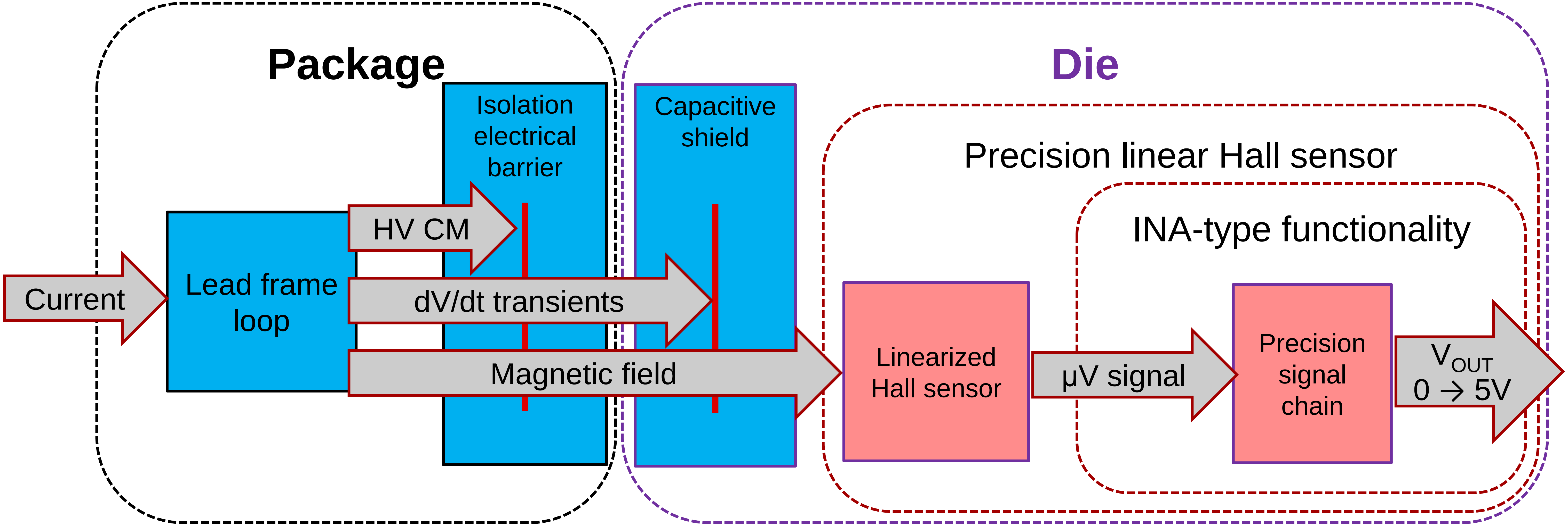
In this type of solution, the current to be measured passes through the device package via a low-impedance lead frame, shown here on the left side of the package. The lead frame is the metal structure inside the package that carries signals between the die and the outside world. The flow of current through a specific lead frame geometry, shown here as a loop or “U” in the left side of the lead frame, generates a concentrated magnetic field, shown here. Following Ampere’s law, this magnetic field is proportional to current, and thus can act as our signal representation of the current flowing through the package.

The lead frame is split into a high voltage isolated side, and a low voltage side for the sensor. The sensor is assembled above the high voltage side of the lead frame which carries the current, so there is no electrical connection between the lead frame and the sensor. This vertical spacing between the die and the current carrying conductor provides an electrical barrier which provides isolation capability for the device.

The sensor itself is a precision linear Hall sensor, with its sensing element placed directly above the most concentrated portion of the magnetic field generated by the lead frame. This precision Hall sensor converts the magnetic field signal back into a voltage, where the output voltage is proportional to the current input by some sensitivity, shown here by “S”, and which also can be offset by some offset voltage as required by the end application.

This conversion from an electrical current to a magnetic signal, and then back into a voltage output signal provides two signal domain transformations, which is what creates some of the inherent challenges and features of the technology.

Signal flow and domain transformation



- High CMRR & transient immunity
- Directly measure AC or DC signals
- Completely integrated passive front-end

- Full-scale analog output
- Current sense amplifier feel & flexibility
- Signal chain tuned to sensor & package

Let’s dig a little deeper into the signal flow and domain transformation of in-package MCS. Remember that the input signal to be measured is a current that is passed through the package lead frame, and in many cases through a loop in the lead frame. The lead frame itself has several signals that are either on the loop itself or generated from it.

It has the common mode high voltage of the input current signal. This could be a DC voltage, or a relatively low-frequency AC voltage like that coming from an AC grid. The vertical gap between the lead frame and the sensor die is an electrical barrier, blocking the common mode high voltage from the isolated side, and is based upon the packaging construction.

There can also be significant voltage transients if the input voltage waveform has some switching in it, like a PWM signal. A capacitive shield is integrated into the sensor die assembled above the lead frame loop. This capacitive shield stops the high “dV/dt” transients from passing into the signal chain and output signal.

The result is a magnetic field signal, void of electrical coupling between the lead frame and the sensor IC. This results in excellent immunity to both common mode changes as well as voltage transients, enabling direct measurement of DC or AC signals. The completely integrated passive front end removes the need for any isolated supply, electronics, or external components on the high voltage side.

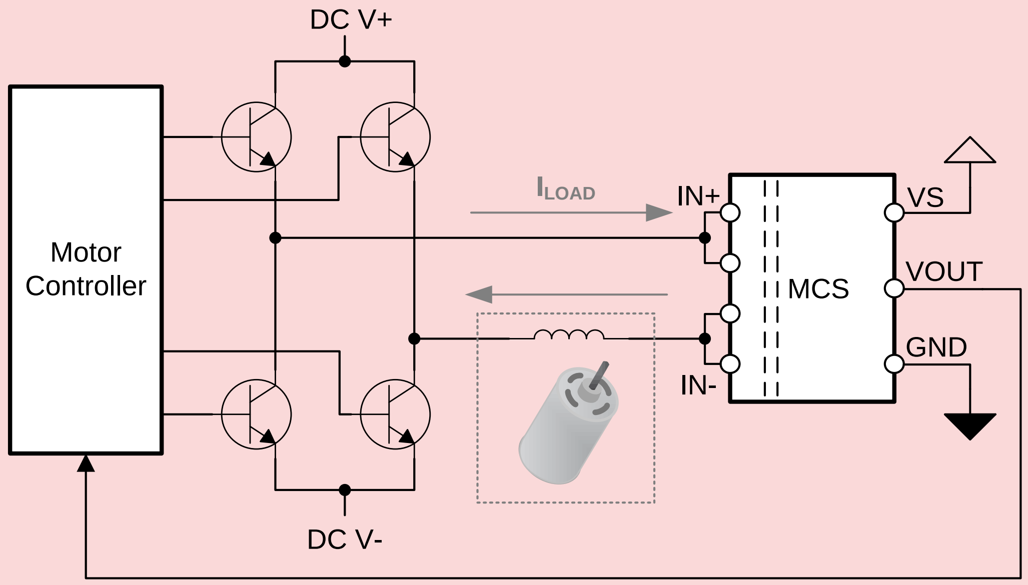
The resulting magnetic field is a relatively small signal, requiring a high precision linear Hall sensor IC in order to accurately be measured. A linearized Hall sensor converts the magnetic field back into the electrical domain in the form of a small voltage signal, on the order of microvolts. Here a precision signal chain very similar to the functionality of an INA-type current shunt amplifier is needed to recover this small signal and amplify it to a full scale analog output voltage which can easily be interfaced to the rest of the electronic system.

Because the entire signal flow is integrated into a single monolithic unit, the signal chain can be tuned and calibrated to match the sensor and package mechanics. This enables an out of the box system level performance based heavily on the performance and flexibility of the signal chain itself.

MCS benefits and key applications

In-line PWM

- High common-mode rejection
- High CMTI

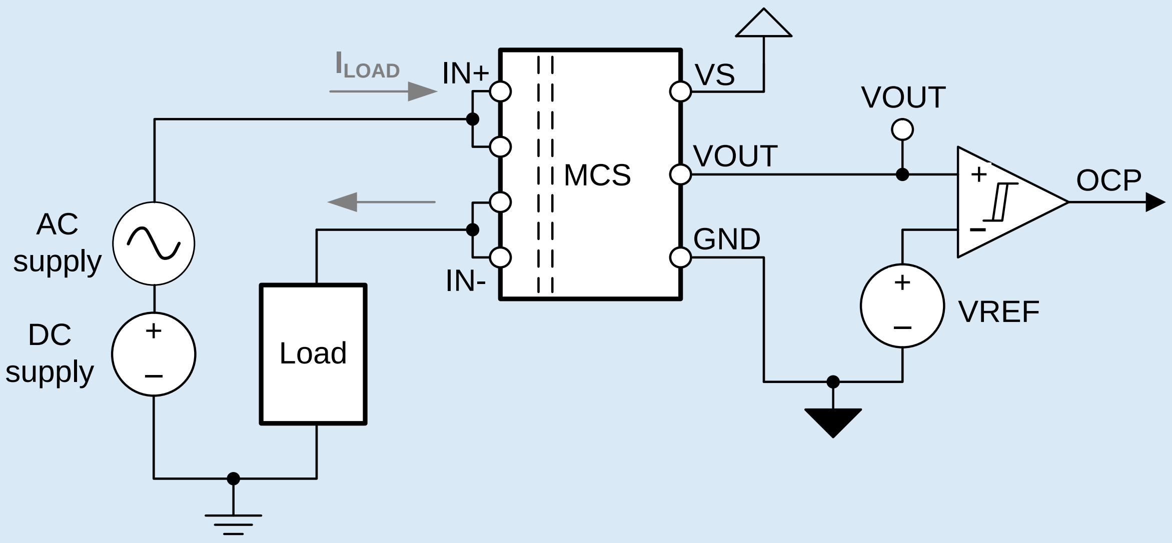


Common

- Inherent isolation
- High voltage
- Ease of use
- Small size
- Low power loss
- High performance over temp.

Isolated AC/DC w/ OCP

- No hot-side components
- Direct AC/DC sensing



The integration of an in-package MCS provides inherent system level benefits, especially in certain key applications.

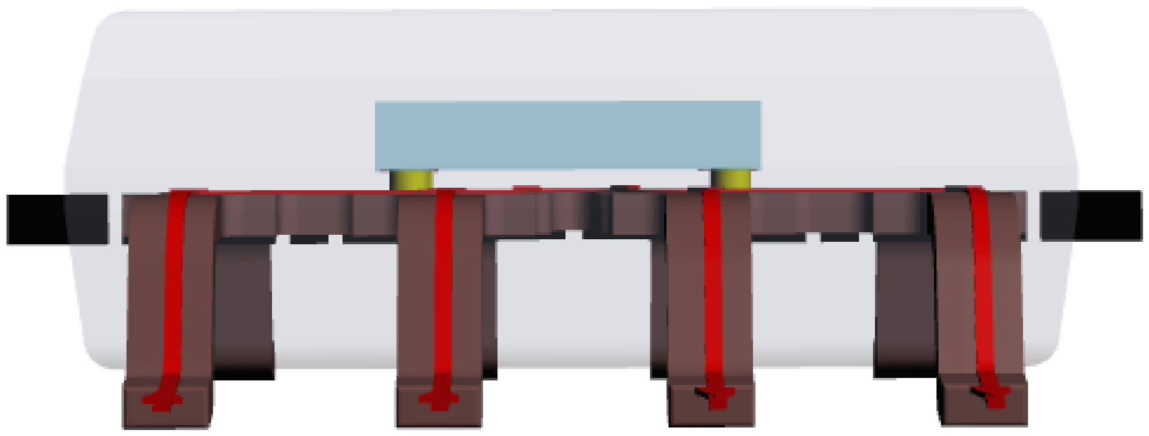
For example, as shown on the left, MCS devices are well suited to in-line pulse-width modulated (PWM) current sensing, such as in brushless DC motor control circuits. Since the system quickly switches between high voltages, the high common-mode rejection ratio and high common-mode transient immunity (CMTI) of MCS devices ensure accurate operation.

Another application example, shown on the right, is isolated high-voltage AC and DC power monitoring with over-current protection (OCP). Here, the fact that an MCS device does not need any hot-side components and can sense the AC/DC signals directly is very appealing to system designs.

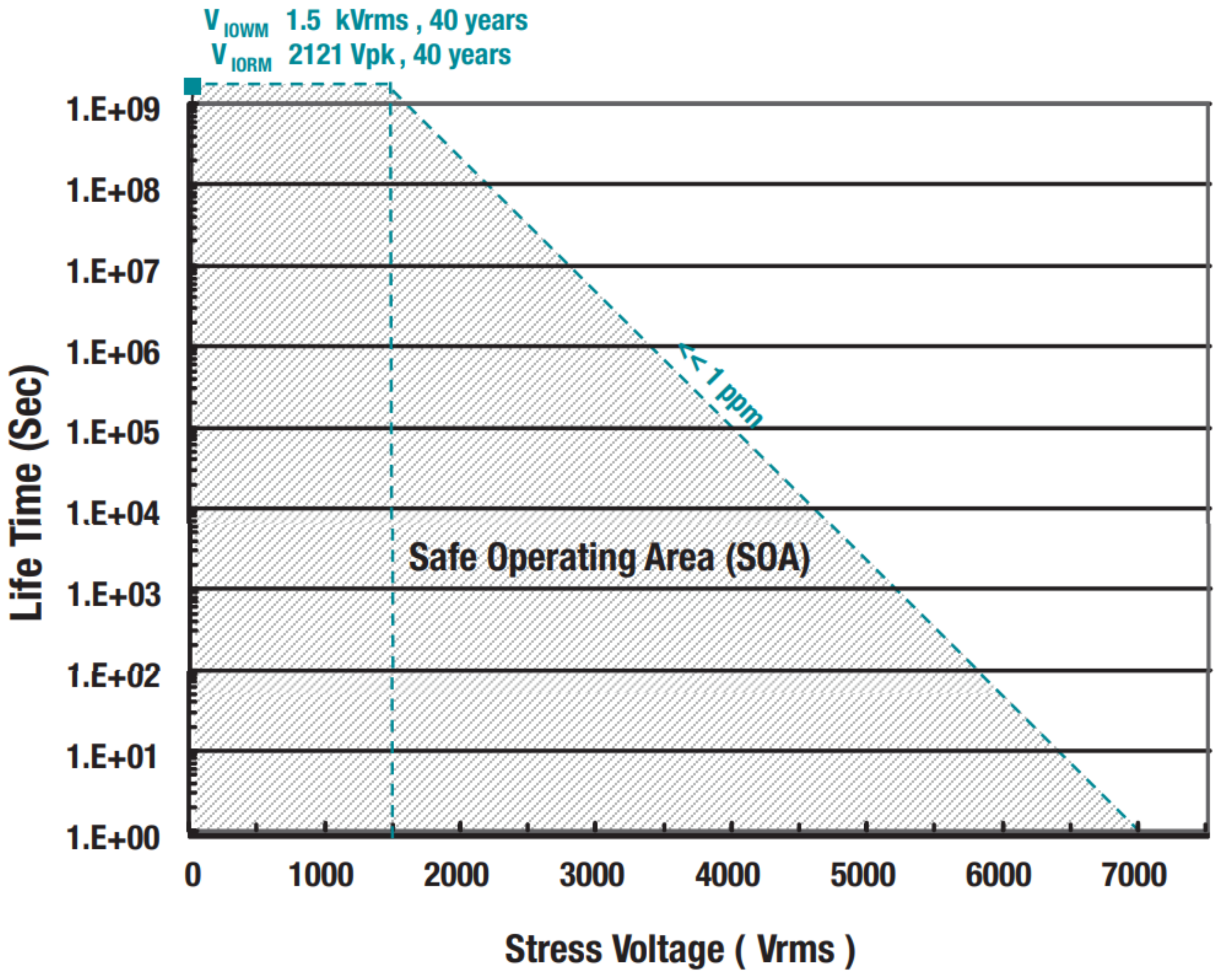
Finally, many benefits of MCS devices are common to a wide variety of current sensing applications. These include their inherent isolation and handling of high voltages, ease of use, small solution size, low power loss due to the low impedance of the lead frame, and high performance over temperature.

Isolation barrier capability

- Isolation barrier is vertical separation between high-voltage lead frame and die
- Specified by survivability to voltage stress:
  - V_{IORM} – maximum repetitive voltage
  - V_{IOWM} – working voltage
  - V_{IOTM} – maximum transient isolation voltage
  - V_{ISO} – isolation withstand voltage
  - V_{IOSM} – maximum surge isolation voltage



Device side view



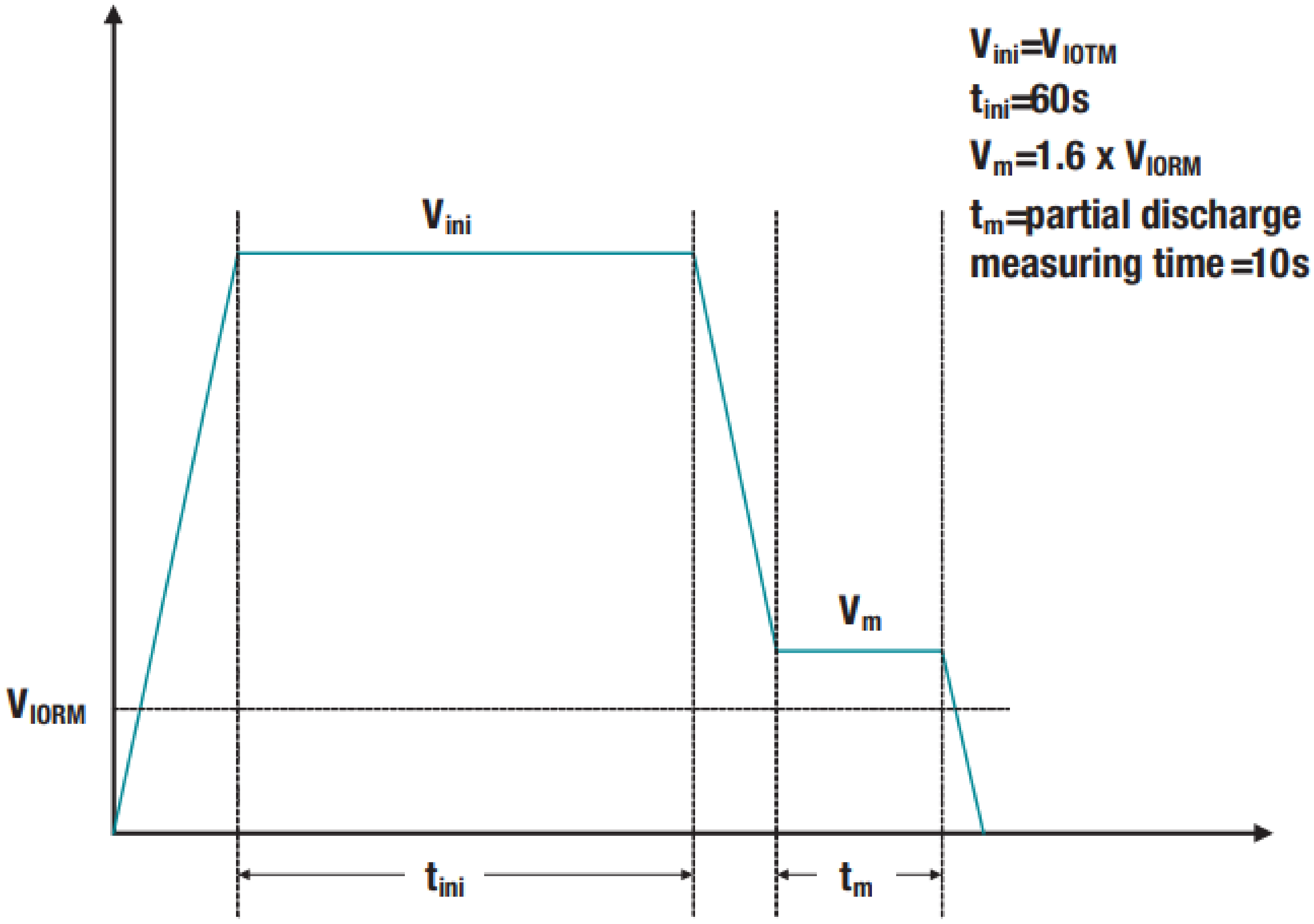
Example TDDB plot

For in-package magnetic current sensors, the isolation barrier is typically a very narrow gap between the lead frame the sensor IC, that is often determined by the quality of the assembly manufacturing process.

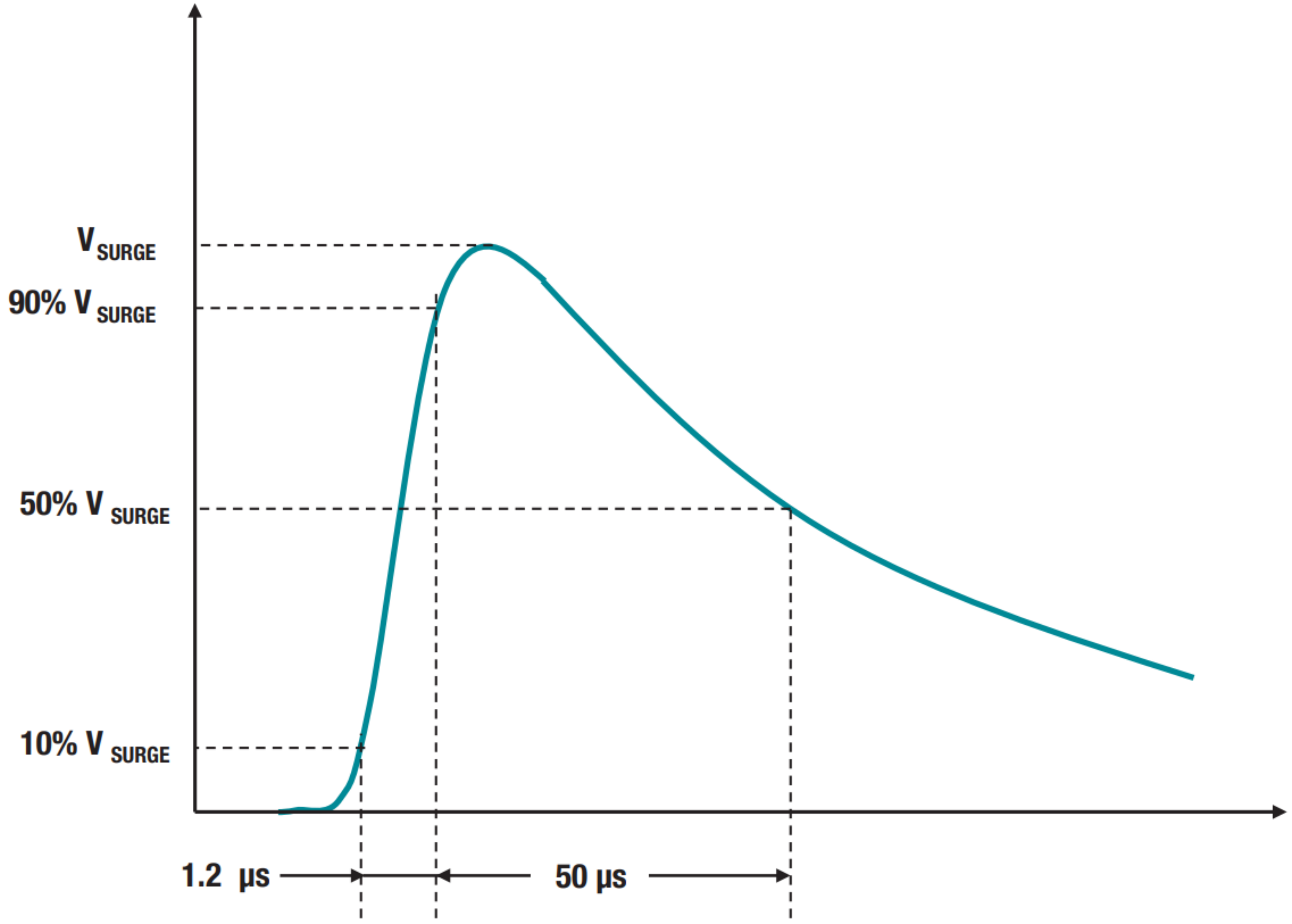
High-voltage isolation performance of an isolator is given at the component level by parameters including maximum repetitive peak voltage (VIORM), working voltage (VIOWM), maximum transient isolation voltage (VIOTM), isolation withstand voltage (VISO), and maximum surge isolation voltage (VIOSM). These parameters represent the isolation barrier's ability to handle high-voltage stresses of different magnitude and transient profiles, and have a direct mapping to realistic operating situations.

The first two specs, maximum repetitive (VIORM) and working voltage (VIOWM) are both intended to quantify the ability of an isolator to handle high voltage across its barrier on a continuous, day-to-day basis, throughout its lifetime. The plot on the right shows an example of time-dependent dielectric breakdown, or TDDB. The safe operating area, or SOA, shown as the region under the dashed blue line, defines the combination of voltage and life time which will result in failure rates of less than 1 part per million (ppm). The device in this example achieves a working voltage of 1.5kVrms and maximum repetitive voltage of 2.1kVpk for 40 years.

Isolation test methodologies



Simplified Method A test profile



Surge impulse test profile

More info: High-voltage reinforced isolation: definitions and test methodologies

Maximum transient isolation voltage (VIOTM) and the isolation withstand voltage (VISO) are both intended to quantify the ability of an isolator to handle high voltage across the isolation barrier for very short periods of time. This is tested during certification by stressing the isolator at VIOTM for 60 seconds, followed by a partial discharge test at 1.6 times VIORM for 10 seconds. This is called Method A testing.

Maximum surge isolation voltage (VIOSM) quantifies the ability of the isolator to withstand very high voltage impulses of a specific transient profile, including a charge to 90% of the surge voltage over 1.2 microseconds, followed by a discharge to 50% of the surge voltage in 50 microseconds. Surge voltages can be caused in an installation due to direct or indirect lightning strikes, faults and short circuit events.

For more information on high-voltage isolation and the tests used to qualify isolated devices, please read the white paper linked here.

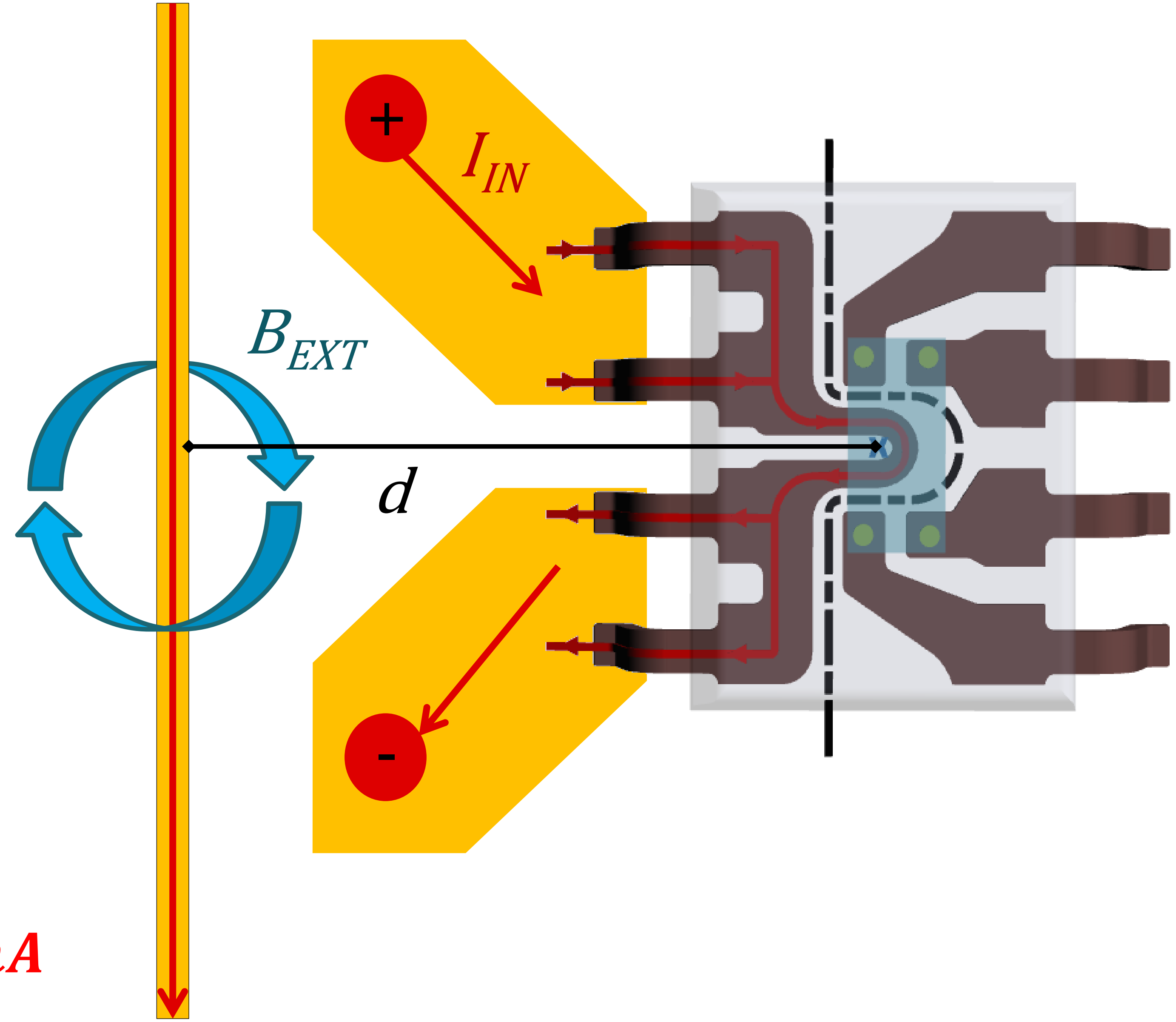
Magnetic interference

- Field from external currents B_{EXT} adds to magnetic field on lead frame
  - **Ex:** 10A wire @ d = 10mm ≈ 200μT
- B_{EXT} creates input current error, divided by Magnetic Rejection Ratio BRR and lead frame magnetic coupling factor G

$$V_{OUT} = \left(I_{IN} + \frac{B_{EXT}}{BRR * G}\right) * S + V_{OUT\_0A}$$

  - **Ex:** If G = 1.2 mT/A, and BRR = 1, then 200 μT ≈ 167 mA of input current error

$$I_{IN\_ERR} = \left(\frac{B_{EXT}}{BRR * G}\right) = \left(\frac{200\mu T}{1 * 1.2\, mT/A}\right) = \mathbf{167mA}$$



Because magnetic current sensors measure current via the total magnetic flux at the sensor location, they are susceptible to interference from external magnetic fields from multiple sources. If, for example, a current trace runs perpendicular to the device y axis, it will generate a magnetic field at the sensor depending upon the trace geometry, current level, and distance from the current sensor. As an approximation, an infinite length wire 10 mm away from the sensor and carrying 10 amps will generate a field of roughly 200 microTesla at the sensor location.

To the sensor, the external field looks like it is generated by input current through the lead frame, and can be referred to the input of the device as an additional error current. In order to do so, the external field should be divided by the magnetic coupling factor G, how much field an Amp of lead frame current generates, as well as the magnetic rejection ratio BRR if the sensor utilizes differential sensing to reject external fields.

This additional error current is then summed with the true input current and reflected in the output. Continuing our example with a 200 microTesla external field, if G is equal to 1.2 milliTesla per amp, and the sensor does not reject external fields for a BRR equal to 1, the sensor will effectively see an error input current of 167 milliAmps.

This additional error can be calculated the same way as an offset error, by dividing by the actual input current.

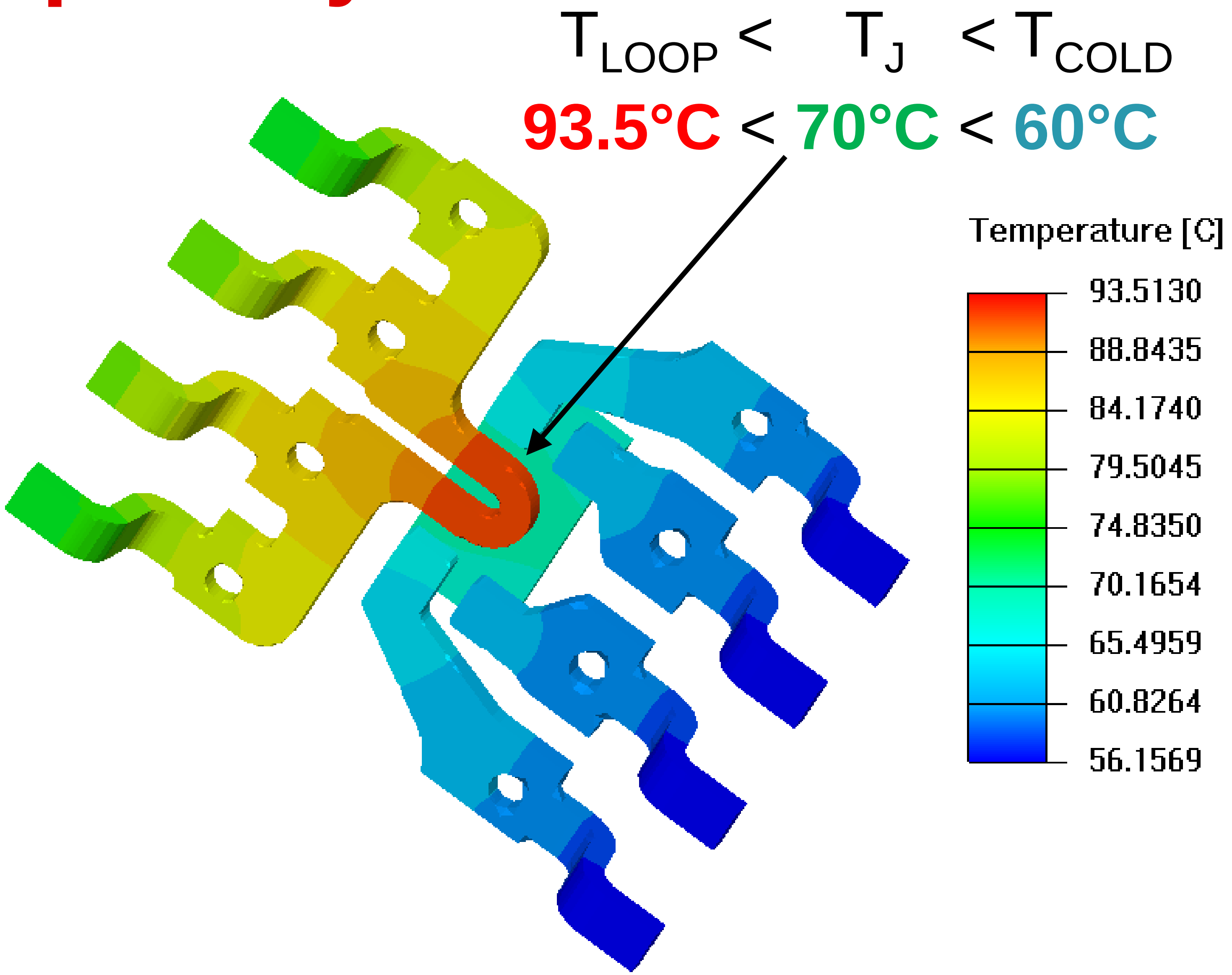
External fields can be dealt with in several ways in the application, whether by calibration, careful layout and orientation, or magnetic shielding of the device.

Thermally limited current capability

- Continuous input current range is set by the max junction temperature
  - Most power dissipated in the **loop**
  - Input power P_{IN} is a function of input current I_{IN} and lead frame temperature T_{LF}

$$T_{J\_max} = T_A + R_{\theta JA} \times P_{IN}(I_{IN}, T_{LF})$$

- Higher current pulses are **OK** when faster than thermal time constants (seconds)



20 A input current thermal model,
T_A = 25°C

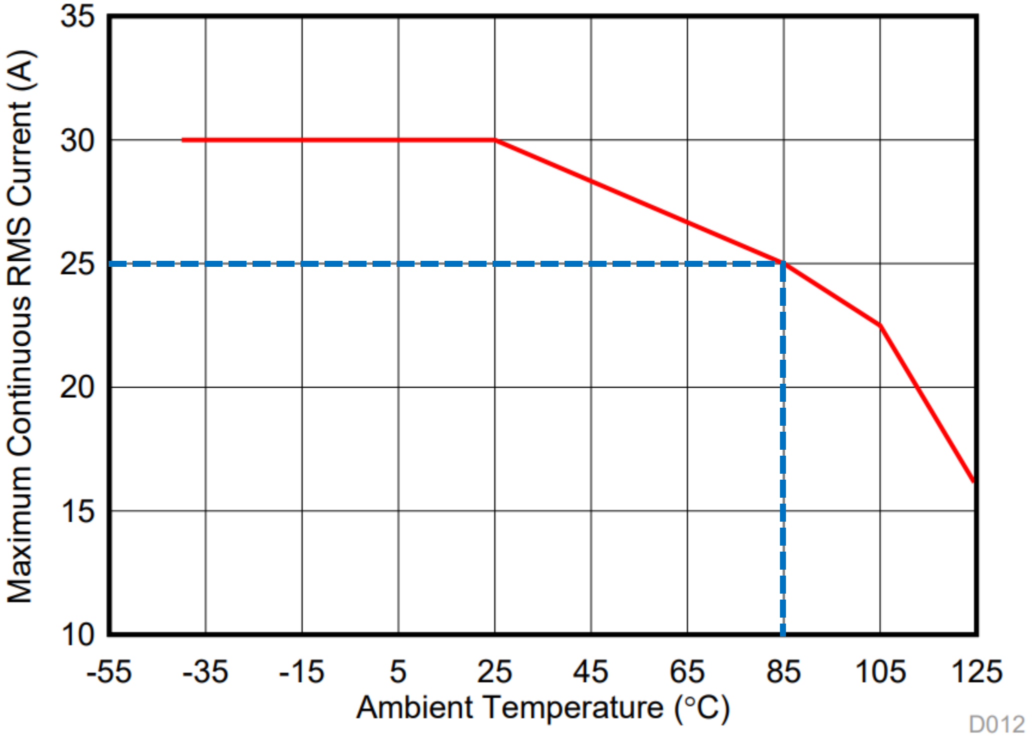
The input current capability of any in-package current sensor is fundamentally limited by thermal considerations of the device and the larger system. Shown here is a thermal model of a typical device under 20 amps of continuous input current on a specific PCB.

Resistive heating in the loop, due to both higher local resistance and current crowding due to the tight loop geometry, causes a large portion of the applied power to be dissipated right at the loop. This makes high temperatures develop on the loop, which results in elevated temperatures on the entire lead frame as well as the silicon die. In the simulation shown on the right, we see that the die temperature (~70C) is roughly between the temperatures of the loop (93C) and the low-voltage lead frame (60C).

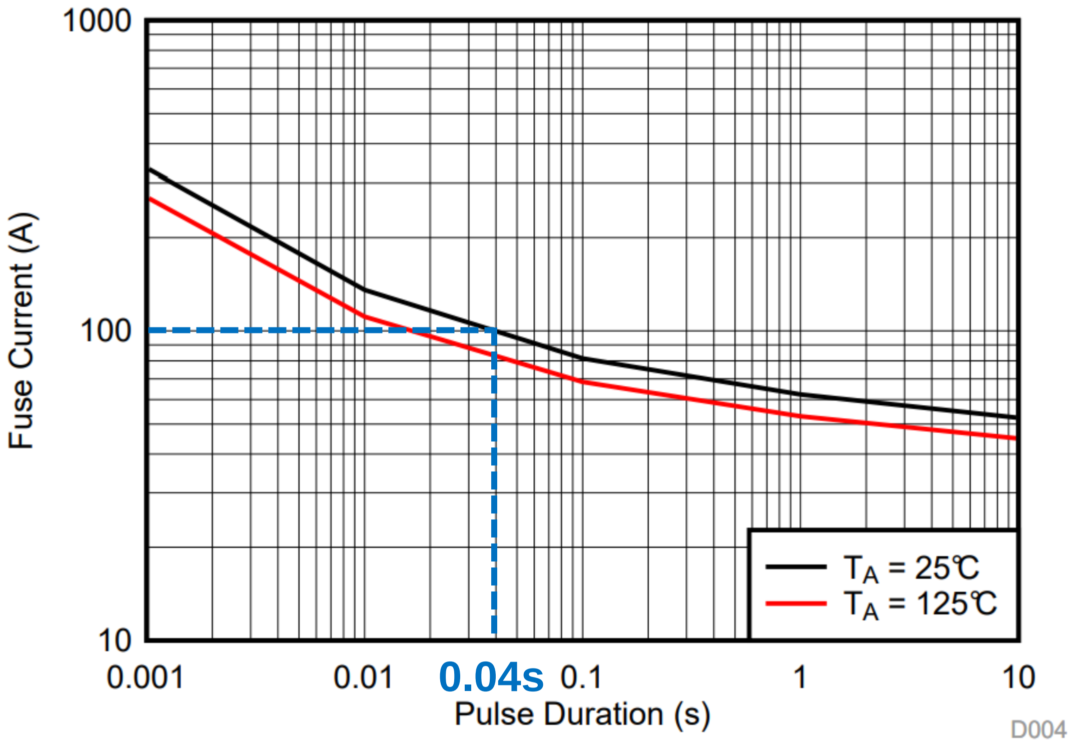
Maximum junction and package temperatures limit the allowable power dissipated in the current path. Because the lead frame has a resistive temperature coefficient, total power input is a function of both current and lead frame temperature. This power must be dissipated by the thermal resistance of the device to the ambient environment, known as R theta J-A, and is effectively added to the ambient temperature. This means that the continuous current capability of the device declines at higher ambient temperatures, and is a strong function of the thermal environment such as the PCB layout, airflow, and heatsinks.

It is also worth noting that the thermal time constants of the device when on a PCB is on the order of seconds, so shorter duration, but higher amplitude pulses, are tolerable, so long as they are short enough in duration to prevent excessive heating of the lead frame.

Thermally limited current capability



Example continuous current capability



Example pulse current capability

PCB thermal design tips:

- Thicker copper layers
- Large radiation planes
- Thermal via "farms"
- Airflow and heatsinks

Note: thermal behavior can be modeled and simulated using software like FEMM or ANSYS

Because the thermal capability of an in-package magnetic sensor is so dependent on its PCB layout and system environment, many characteristics of a sensor are characterized and specified to a particular board layout, usually that device's evaluation module or EVM. Please read the device datasheet to see how specs like maximum continuous current and pulsed current capability are defined. Note that if you use a different PCB design in your application, you will observe different results.

The plots shown here are some typical examples of how an in-package magnetic current sensor's current capability is defined. The plot on the left shows continuous RMS current capability versus ambient temperature. For example, if the application has an ambient temperature of 85 degrees C, the maximum allowed RMS current is 25 amps. Again, this only applies when using the specified PCB layout.

The plot on the right gives fuse current vs. current pulse duration. Fuse current is the current at which the lead frame of the device begins to fuse open, leading to damage and functionality loss. This information is useful both when designing for pulsed current measurements greater than the device's continuous current capability, or when trying to understand the conditions the device can survive if exposed to high current transients. For example, if ambient temperature is equal to 25 degrees C, given by the black curve, and a 100 amp pulse is applied, the device can survive for 0.04 seconds, or 40 milliseconds, until it becomes damaged.

To improve the thermal capability of your PCB, follow these tips:
Use thicker copper board layers, such as 2 ounce or 3 ounce
Place large radiation traces on both the high voltage and low voltage side
Add "farms" of large amounts of thermal vias near the device pins, to improve energy transfer out of the IC and package.
Add airflow and heatsinks to the system to help dissipate and remove more heat from the environment

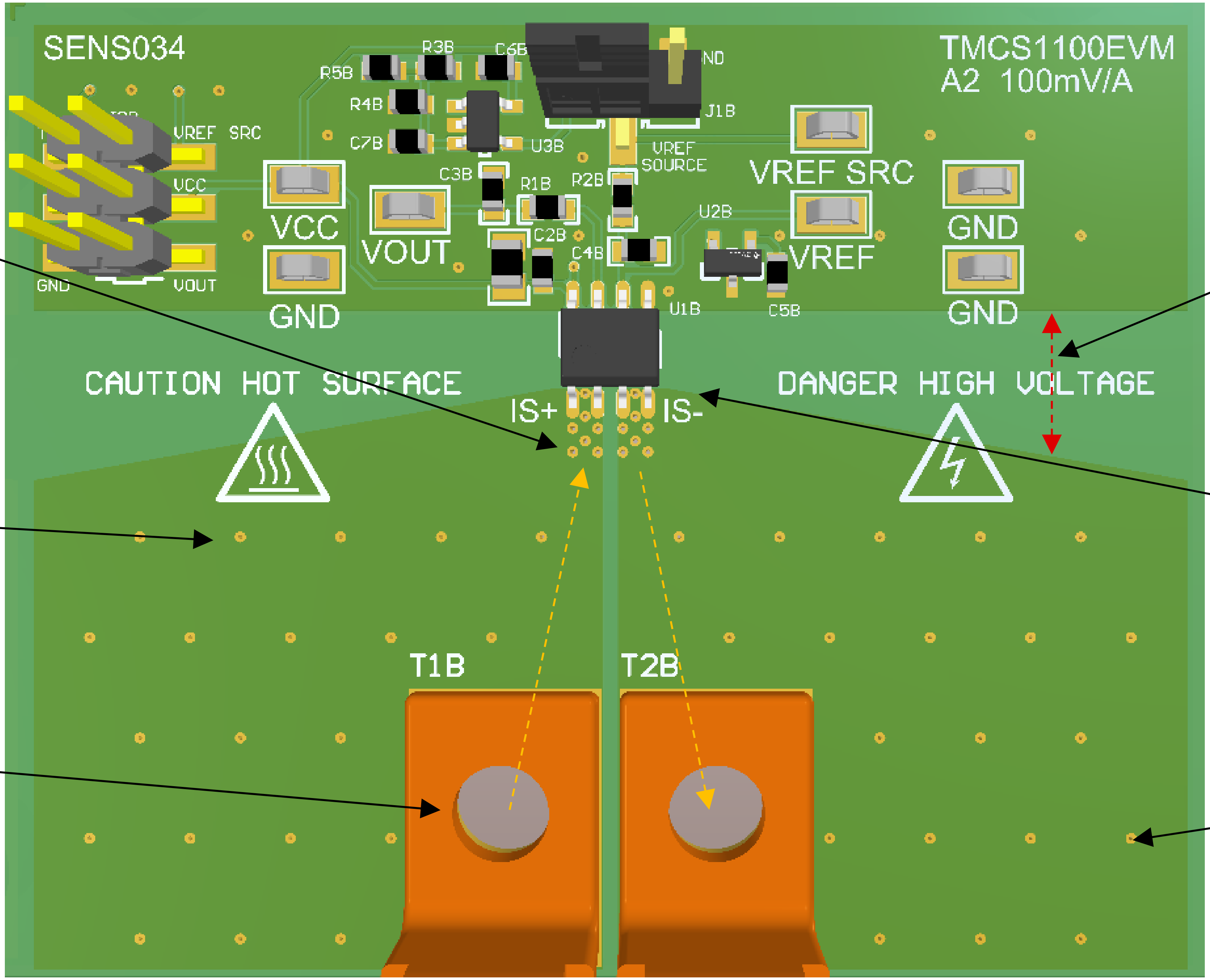
Finally, note that thermal behavior can be modeled and simulated using software like FEMM or ANSYS. While these tools can take time to learn, they can be invaluable in predicting and optimizing your thermal designs.

PCB layout example

Via farm at IC pins
for thermal connection to bottom copper

Input current path
with large side-by-side polygons of 3 oz. Cu, top and bottom of PCB

Input current lugs
on a straight line to the IC input pins



Plenty of clearance
from high-voltage to low-voltage sides of PCB

Polygon entry angle
≤ 80° prevents current imbalance at IC pins

Via array on input current path for good thermal connection between top and bottom copper

Achieving good performance with in-package magnetic current sensors, while also ensuring good thermal capability and safety, requires careful attention be paid to the printed circuit board (PCB) layout. The example here with the TMCS1100EVM shows several of the most beneficial PCB layout techniques for these devices.

TI recommends these best practices for optimal thermal capability:
1. Use large copper areas for the input current path, placing 3 ounce copper on both top and bottom layers of the PCB
2. Place an array of vias right at the IC pins to help sink heat out of the lead frame
3. Also, place an array of vias throughout the input current path to ensure a good thermal connection between top and bottom copper

TI recommends these best practices for optimal magnetic current sensing performance:
1. Place the input current lugs or connectors on a direct path straight to the IC input pins, and
2. Design the input current copper areas to enter the IC at an angle of 80 degrees or less. Both of these techniques ensure balanced current distribution through the lead frame for best sensitivity error.
Also, design the input current copper areas symmetrically and side-by-side, which helps cancel stray fields from the input current flowing on the PCB.

Finally, ensure that plenty of clearance is provided between the high-voltage and low-voltage sides of the PCB to meet any applicable isolation safety standards.

To find more magnetic current sensing technical resources and search products, visit ti.com/halleffect

That concludes this video – thank you for watching! Please try the quiz to check your understanding of the content.

For more information and videos on magnetic current sensors please visit ti.com/halleffect.

In-Package Magnetic Current Sensing

TI Precision Labs – Magnetic Sensors

Quiz

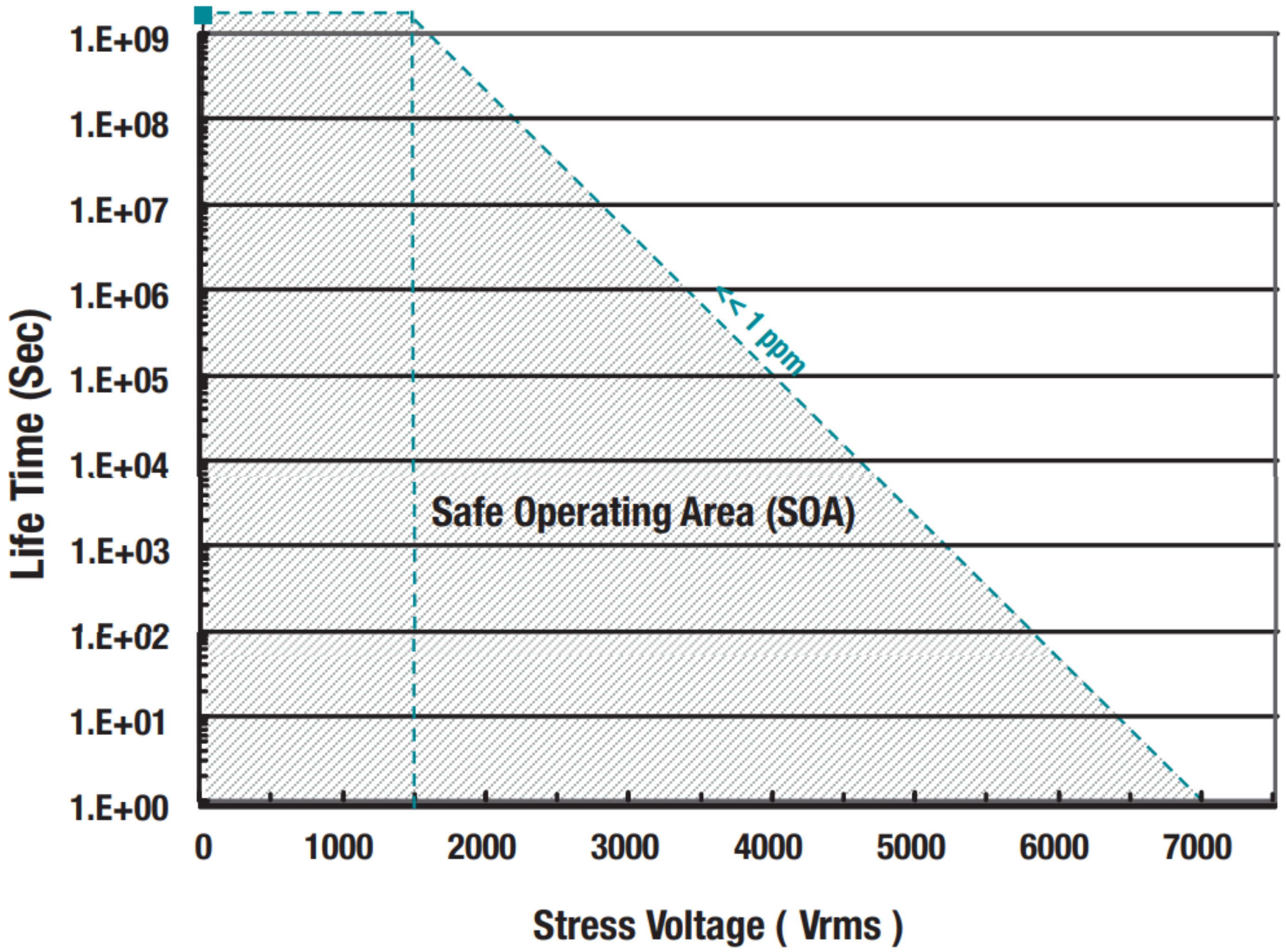
In-package magnetic current sensing – quiz

1. With in-package magnetic current sensors, the magnetic field to be measured is generated by ____________________.
   a) Load current flowing through the sensor lead frame
   b) Magnetic fields generated by nearby PCB traces
   c) The Earth's ambient magnetic field
   d) Electromagnetic interference generated by other circuit components

2. The purpose of the capacitive shield on the MCS is to ________________.
   a) Block high voltage present on the input current
   b) Sense the generated magnetic field
   c) Suppress high dV/dt transients from entering the signal chain
   d) Amplify the small Hall sensor output to a usable level

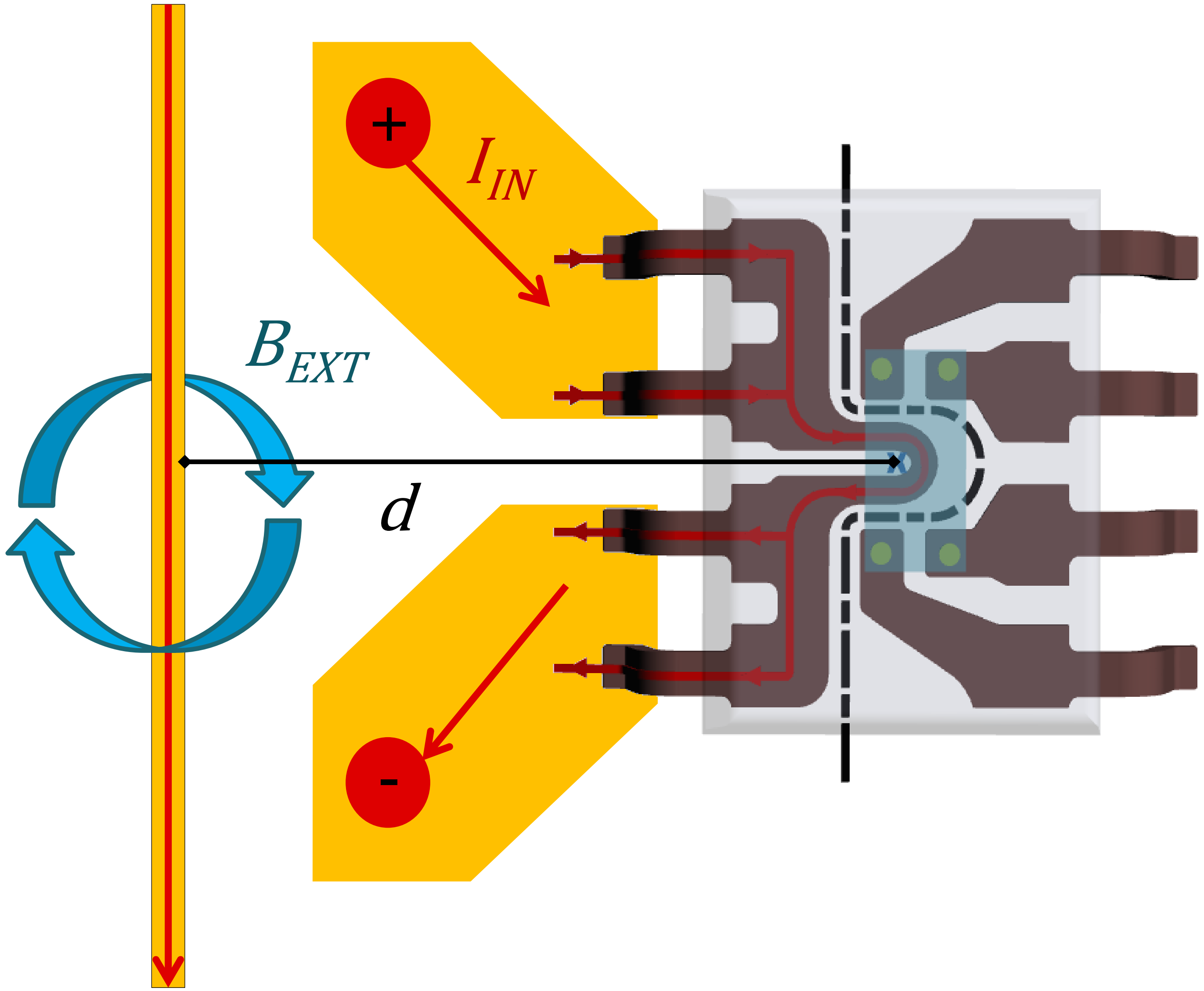
In-package magnetic current sensing – quiz

3. In the example TDDB plot shown, what is the approximate safe operating life time for a stress voltage = 4500 Vrms?
   a) 8,000 minutes
   b) 100 seconds
   c) 3.8 years
   d) 2.8 hours



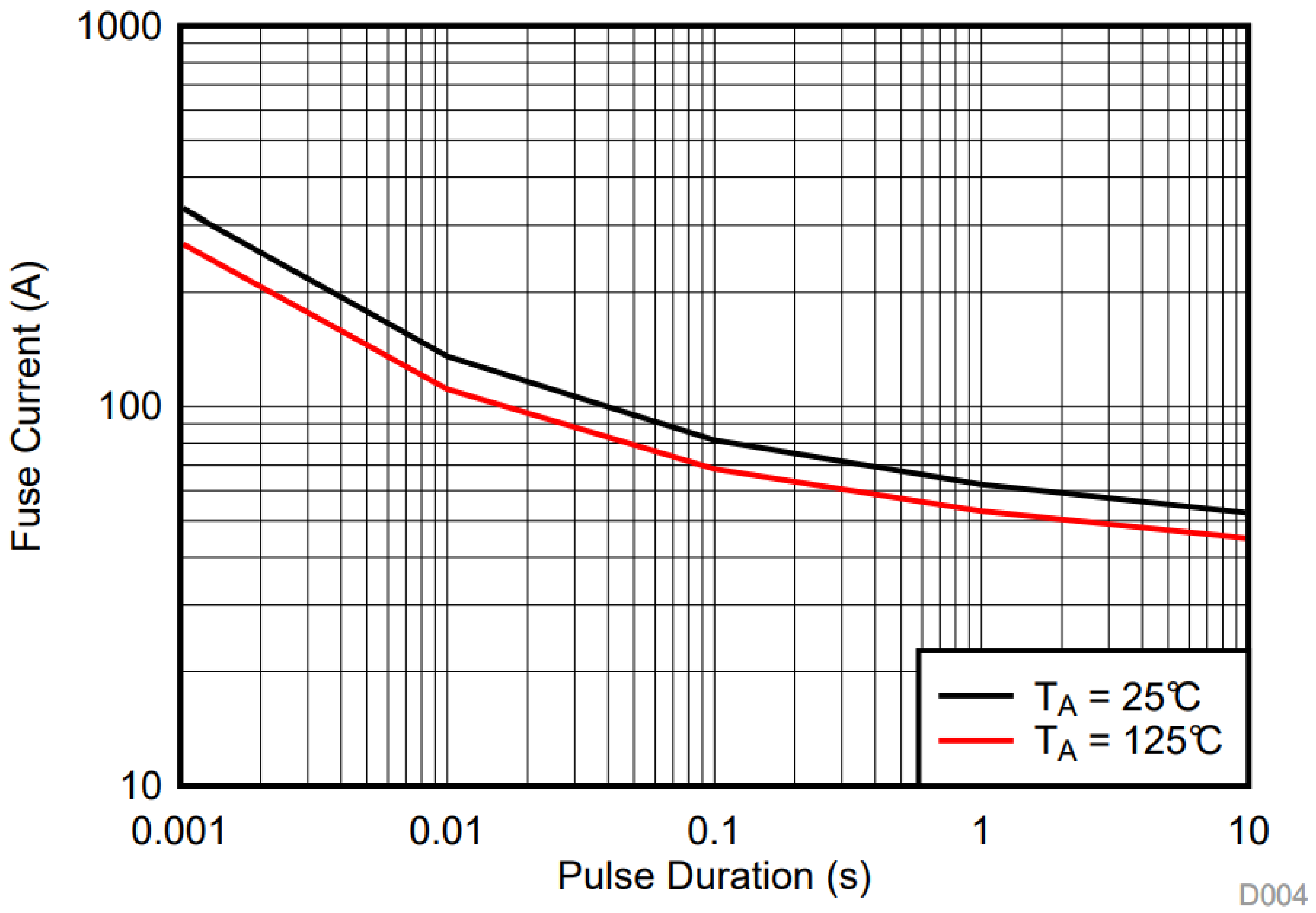
In-package magnetic current sensing – quiz

4. Assuming the parameters below, calculate the total input current error in mA.
   - Stray field B_{EXT} = 75 µT
   - Mag. coupling G = 1.2 mT / A
   - BRR = 60 dB



In-package magnetic current sensing – quiz

5. In the plot shown, what is the maximum survivable pulse duration when T_A = 125°C and fuse current = 60 A?
   a) 0.002 seconds
   b) 0.05 seconds
   c) 0.3 seconds
   d) 6 seconds



Answers

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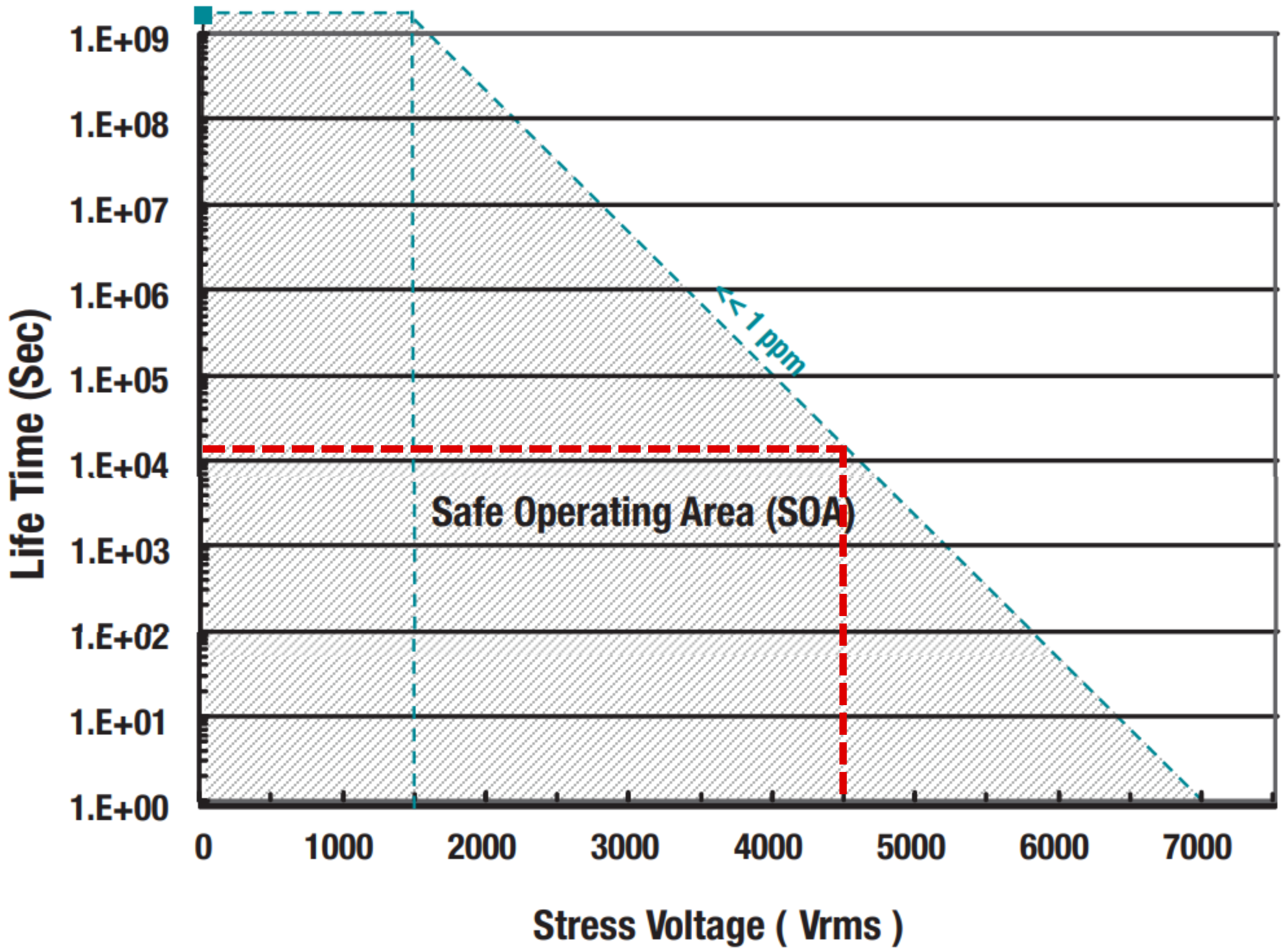
$$Life\ Time \approx 1e4\ (seconds)$$

$$1e4\ sec = 1e4 * \frac{1\ min}{60\ sec} * \frac{1\ hr}{60\ min} = \mathbf{2.8\ hrs}$$



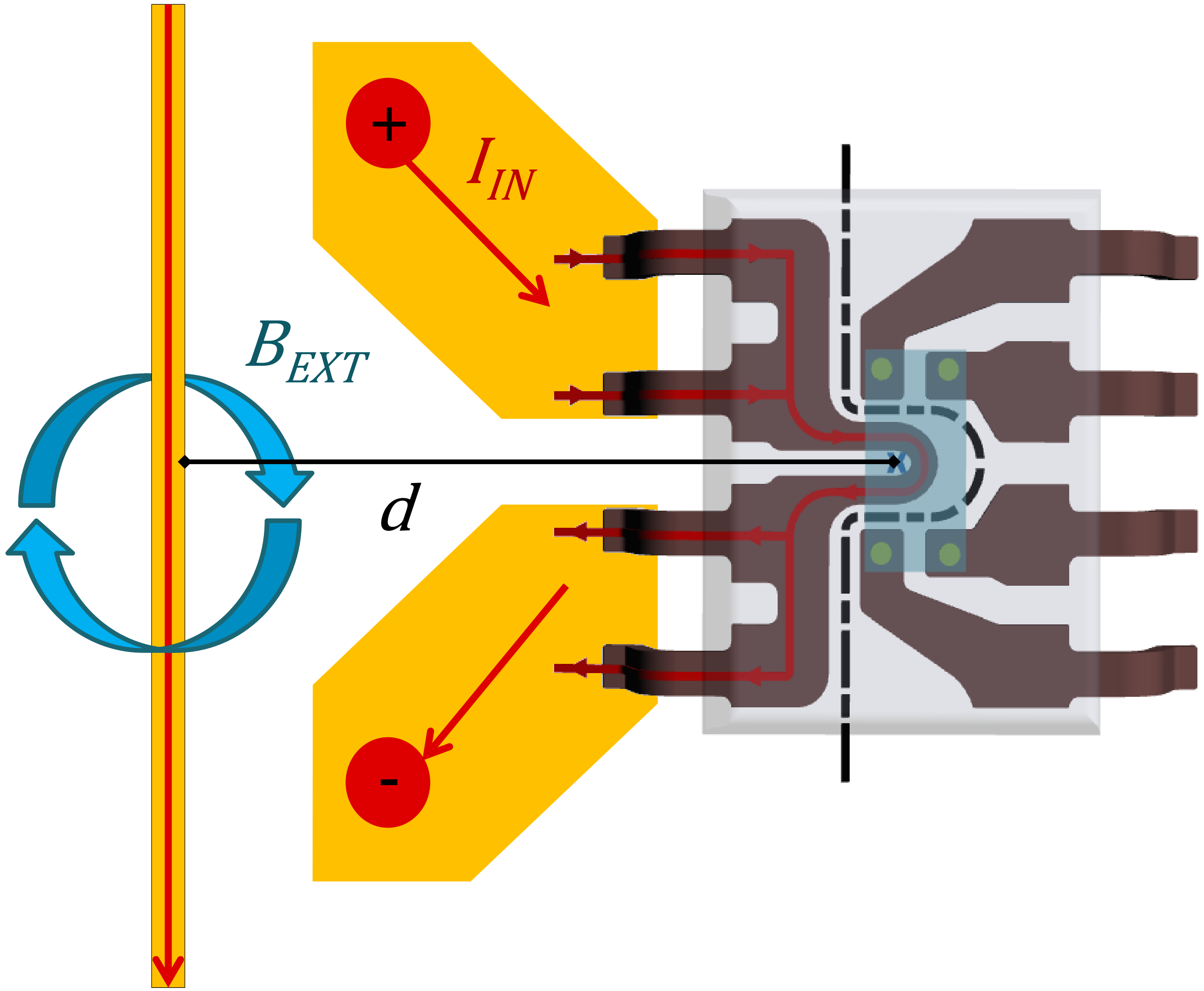
In-package magnetic current sensing – quiz

4. Assuming the parameters below, calculate the total input current error in mA.
   - Stray field B_{EXT} = 75 µT
   - Mag. coupling G = 1.2 mT / A
   - BRR = 60 dB

$$BRR(linear) = 10^{\left(\frac{-BRR(dB)}{20}\right)} = 10^{\left(\frac{-60}{20}\right)} = 0.001$$

$$I_{IN\_ERR} = \left(\frac{B_{EXT}}{BRR * G}\right)$$

$$I_{IN\_ERR} = \left(\frac{75\mu T}{0.001 * 1.2\, mT/A}\right) = \mathbf{62.5mA}$$



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