Measuring Current in i.MX Applications

Case Study: Measuring i.MX6QuadPlus Current

1. Purpose/Scope

The power consumed by an i.MX applications processor in a system depends on various factors such as the software that is running (apps and OS), and the hardware that is used. The clock frequencies of each subsystem within the device, device temperature, the voltages of the various power supplies, and the power management features that are enabled all impact the power consumption of the device.

The intent of this application note is to detail the factors that impact power consumption and how this current consumption and maximum running current in particular is specified in the respective i.MX data sheets. Various methods of measuring current flow are discussed on operational NXP evaluation boards featuring the i.MX6DQuadPlus along with a table of power measurement points for various i.MX6 and i.MX7 evaluation boards.

In order to keep the scope of this application note manageable, low-power operating modes are not discussed in detail. The NXP Linux BSP available for i.MX processors implements low power modes and power management but it is not fully optimized for ultra-low power battery applications.

Contents

2. What Factors Influence i.MX Current?

The current drawn by the various power supplies of an i.MX application processor is influenced by many factors. Some can be controlled by the user while others are inherent to the constituent materials, the fab process, and the environmental conditions in which the device operates.

2.1. Variation in silicon

Slight variations in the fabrication conditions and materials (such as normal process variation) across a wafer and from wafer-to-wafer result in parametric variation in every silicon device. Some devices are slightly slower and have less leakage while others are faster and have more leakage current. This process and device variation is taken into account by the automated test limits and the specifications in the respective i.MX device's data sheet.

In terms of operating current, this means that customers should expect to see variations in the current consumption from device to device. That is, for a given set of operating conditions and application and OS code, variations in current will be observed due to part-to-part variation. Quantifying the power consumption of an application requires measuring the current draw of a distribution of devices (which requires a number of boards unless a board with a socket is available).

2.2. Temperature

The temperature of a device affects silicon's semiconductor properties, the resistivity of interconnects and other constituent material properties. The overall effect is that increased die temperature results in increased static leakage current in every power supply of the device. Leakage will be present even if the device is not doing anything active.

The packaging of the end application should account for transferring heat generated within the device to the ambient environment. The junction temperature of the device needs to be kept below the specified maximum to guarantee correct operation, to avoid damaging the device, and to a lesser extent, to minimize useless leakage current. The additional leakage current resulting from an increase in temperature is purely a waste of energy. Refer to *i.MX 6 Series Thermal Management Guidelines* (document AN4579).

2.3. Power supply voltage

Increasing power supply voltage results in an increase in IR drop, and in turn the current increases. Increased power supply voltage will also increase heat caused by leakage within the device, increasing the die temperature. In general, to minimize power, an application should use the typical power supply voltages specified in the data sheet rather than the maximum specified for each supply.

2.4. Clock frequencies

Clocks and toggling logic signals contribute to overall current observed in the device in two ways: The dynamic component of the current comes from the power consumed in charging and discharging the cumulative parasitic capacitance of all the switching nodes within the device. There is also an associated

leakage component coupled with the switching currents due to dielectric loss, IR loss in interconnects, and leakage within the constituent devices. The end result is that increasing clock frequencies and the number of switching nodes increases current in the processor. Power can be saved by slowing clocks when possible or shutting them off (clock gating) altogether when they are not used.

2.5. Software

The power consumed by a device is affected by execution of code in the operating system (OS) and application software. Application software requires clocks to run at certain rates, signals to toggle, and a lot of switching. More computationally intensive software draws more current. The power consumed by executing application and OS code can be reduced to a point by optimization and lowering the clock frequencies to the minimum required by the application. The ARM® and GPU platforms are typically the most power intensive complexes on the i.MX SoC's. Software can take advantage of various hardware features on i.MX that allow power optimization.

2.6. Power management

Power management is the use of the OS and application software with the hardware features implemented in the device with the intention of controlling power. In addition to reducing clock frequencies and changing the power supply voltages based on processor speed, the clocks and power to some on-chip modules can be switched off to further reduce power consumption. The OS has to be aware of the demands of the application code and have the power management features implemented to take full advantage of the power-saving features implemented in the specific i.MX device such as:

- Dynamic Voltage and Frequency Scaling - Pre defined set points defined for frequency and Bus Scaling
- On-chip Temperature Monitor - Define thresholds based on temp sensor readings
- Temperature Aware DVFS - Throttle CPU based on temp sensor readings
- Clock & Power Gating - Gate clocks and power domains when not in use
- DDR (MMDC) and I/O Power Optimizations - Optimized ODT settings, Auto power down modes and support for frequency scaling
- GPU Power Management - Reduce Core clock frequency, reducing shader clocks
- LDO Full Bypass – Bypass internal LDO and use external PMIC.

3. Data Sheet Current Specifications

The ARM and SOC power supply domains of the i.MX consume the most current while code is executing. Typically, the absolute maximum power numbers have been published for specific high power consuming domains. More recently, to better assist customers designing systems around the i.MX, the maximum current while executing specific use cases have been added in the i.MX6DQ and i.MX6DQP data sheets: EEMBC's Coremark on the ARM cores and the Samurai and Proxycon game tests from Futuremarks's 3DMarkMobile06 on the GPU.

The "Power Virus" stress test is application code designed specifically to maximize the current in VDDARM. It runs mostly within the core. While it yields a maximum number, it's not necessarily useful to a system design running an OS and application code with natural and unavoidable bottlenecks arising from competition for resources. The Coremark benchmark is a better simulation of a typical real-world application. The "Power Virus" is a stress test for the ARM cores alone. The two game tests of the 3DMarkMobile06 benchmark are used to exercise the GPUs.

It should also be noted that the maximum currents in the data sheet are for the faster devices (higher leakage) of the production distribution of i.MX devices at the maximum junction temperature.

4. Measuring Current

4.1. Current measurement

Current is the rate at which charge flows past a point through a conductor. Four techniques that can be used to measure current in a circuit are:

- Shunt resistor
- Hall effect current sensor transducer
- Current Transformer
- Magneto-resistive current sensor

The focus of this application note is to describe how to measure the current flowing from one (or several) power supply output(s) to the respective power rail input of the i.MX device by using shunt resistors or Hall effect current sensor transducers while in the run condition.

Current transformers are not useful to the present discussion because they can only be used to measure current in AC circuits. Magneto-resistive current sensors will also not be discussed because they typically require external signal conditioning circuitry.

Why can an ammeter not be used to measure the current on a board? While the current is displayed directly with an ammeter, it presents way too much series resistance (the combination of the meter leads and the internal shunt) to the circuit under test. A board will generally not be able to boot if an ammeter is inserted into the VDDARM or VDDSOC current path.

4.2. The venerable shunt

A shunt resistor is a resistor inserted into the circuit under test with the explicit purpose of measuring current. The inserted resistance creates a voltage drop proportional to the current flowing through it (Ohm's law).

Table 1The following table shows the voltage drop and calculated resistance for a shunt resistor formed from a two-inch length of 30-gauge copper wire-wrap wire for various amounts of forced current. The resistance of that length of wire is about 25 mΩ.

Table 1. Demonstration of Ohm's Law with a two-inch length of 30-gauge wire

Current (A)	Voltage drop (mV)	Resistance (mΩ)
0.50000	12.69	25.3749
1.00000	25.75	25.7467
1.50000	38.67	25.7821
2.00000	51.84	25.9223
2.50000	65.36	26.1446

Note that the resistance of the length of wire is not constant. Joule heating in the wire causes its resistance to increase with increased current. Current cannot be calculated easily if the shunt does not have constant resistance. The material selected for the shunt (i.e., the resistor selected) should exhibit relatively constant resistance over the current measurement range. Additionally, the current rating of the shunt must be larger than the maximum current draw or it can be permanently damaged.

It should also be noted that for a current of 2.5 A, this shunt introduces 65 mV of voltage drop within the circuit. Many devices operate with a core supply of about 1.2 V. This shunt would lower the core supply to 1.135 V, possibly outside of the operating limits of the device, if the core were to draw 2.5 A. When selecting the resistance value to use for a shunt, it must not disturb the circuit under test while still providing an accurately measurable voltage drop.

4.2.1. Discrete series resistor and voltmeter

Shunt resistors (or "cut traces" where resistors can be placed) are included in many power supply paths on each of the various i.MX evaluation boards. These are included in the design intentionally to facilitate the measurement of current. On boards that include resistors, the value typically used is 0.02 Ω with a 1% tolerance. "Cut traces" are SMT pads where a resistor may be placed after the short between the pads in the PCB copper is cut (the user must cut the trace with a sharp knife under a microscope). "Cut traces" are denoted in the schematic as a resistor with a shorting line through it. The symbol name is in the form of SHxxx.

The voltage drop for the typical shunt resistor on an evaluation board is shown in the following table. Compared to the shunt in Table 1, this resistor shows relatively constant resistance from 0.5 A to 2.0 A. At 2.5 A, the resistance goes up somewhat but it is still within 1% tolerance while it is dissipating 125 mW of power. This shunt resistor is better suited for current measurement although the 50 mV drop can still be significant to the power supply being tested.

Table 2. **Forced current, voltage drop, calculated resistance and power for a 0.02Ω 1% 1/4W resistor, typical of an i.MX evaluation board**

Current (A)	Voltage drop (mV)	Resistance (mΩ)	Power (mW)
0.50000	10.04622	20.0924	5.02
1.00000	20.09819	20.0982	20.10
1.50000	30.15141	20.1009	45.23
2.00000	40.19972	20.0999	80.40
2.50000	50.07860	20.0314	125.20

The average resistance of this resistor is: 20.08456 mΩ.

NOTE

If this resistor were used to measure a current of 1 mA (say, while the device is in a low power state), the voltage drop across this resistor would be 20 µV, which is much more difficult to measure. The shunt must be sized to the currents to be measured. In the case of low power states, the system must first be powered up and configured, so no shunt or a "run mode" shunt must be used before a larger resistance "sleep shunt" is switched into the circuit in such a way that the system does not lose its configuration.

4.2.2. Shunt and current sense amplifier

Current sense amplifiers can be used with discrete shunt resistors. These amplifiers allow the use of shunts with much lower resistance and avoid issues with interconnection with a digital multimeter (DMM) relatively far away from the resistor. There are a number of such amplifiers available from semiconductor vendors with gains as low as 1 V/V all the way up to 1000 V/V. Bandwidths are typically in the kilohertz range.

4.2.3. Integrated shunt sensor

The INA250A4 is an integrated shunt and current sense amplifier device manufactured by Texas Instruments. The internal shunt has a resistance of 2mΩ and a tolerance of 0.1%. It also contains an internal amplifier, which in this particular variation of the device, has an output voltage scale of 2V/A (the most sensitive version of this device) with a bandwidth of 11 kHz. It is packaged in a 16-lead TSSOP and can handle a continuous current of 15 A.

A small circuit board was built with the INA250A4 (see details of the board in Appendix A) to evaluate its use in measuring the current on an i.MX evaluation board.

4.3. Hall effect current sensor

Hall effect current sensors take advantage of the Hall effect by indirectly measuring the current flowing in a circuit under test via the magnetic field it generates.

4.3.1. Integrated Hall effect sensor

The Allegro device, ACS723LLCTR-10AU-T, is one example of an integrated Hall effect current sensor. It is a unidirectional, open-loop current sensor powered by 5 V with a range of 0-10 A. Internal temperature compensation circuitry enables the device to offer near closed-loop accuracy over temperature. The series resistance of the sensor is 0.65 mΩ, so it minimally disturbs the circuit under test. This 5 V device was selected because the typical output sensitivity of the device is 400 mV/A, which was the largest of Allegro's sensors in the 0-10A range. The output bandwidth is selectable between 20 kHz and 80 kHz.

A small circuit board was built up with the ACS723 (see details of the board in Appendix B) to evaluate its use in measuring current on an i.MX evaluation board.

4.3.1. Clamp-on current sensor

There are a number of clamp-on Hall effect current probes commercially available. One such probe is the Fluke 80i-110s Current Probe. The lower measurement range of 0-10A is suitable for measuring a power supply on an i.MX board. It outputs 100 mV/A with a bandwidth up to 100 kHz. It can be used with an oscilloscope or a DMM.

The biggest disadvantage of current clamp-on probes like this is the size of the clamp. It is physically rather large, because it was made to clamp over relatively large wires carrying up to 100 A. The larger clamp size requires a larger/longer wire loop to be soldered into the circuit under test. A larger wire loop or stiffer wire soldered to the SMT sense resistor pads of the typical i.MX makes it very easy to lift the pads and damage the board.

4.4. Oscilloscope current probes

Oscilloscope current probes offer the highest bandwidth current measurements available by combining a current transformer for the AC components of a current signal with a Hall effect sensor for the DC components. While the majority of oscilloscope current probes can only be used with that vendor's line of oscilloscopes, there are several "universal" current probes available that can be used with virtually any oscilloscope with appropriate input impedance. One such probe is the Tektronix TCP2020, which comes with its own dedicated power supply for the probe's internal circuitry. It outputs 10 mA/mV with a bandwidth of 50 MHz and can withstand 20 A continuous current. Degaussing circuitry is built into the probe because sustained DC currents can partially magnetize the core of the probe.

4.5. Comparison of Various Sensing Techniques

4.5.1. Evaluation circuit

To compare the previously mentioned sensors, the sensors were all connected in series with a Keysight B2902A Source/Measure Unit as shown in Figure 1. The outputs of the two sensor boards and the two probes were connected to a Tektronix TDS3054C 500 MHz oscilloscope. By forcing the same current waveform through all the sensors, each sensor can be compared against the others.

The shunt was a 20 mΩ 1% 1/4Watt 0805 SMT resistor typical of what is installed on i.MX evaluation boards. An Agilent 34401A Digital Multimeter was used to measure the voltage drop across the shunt resistor.
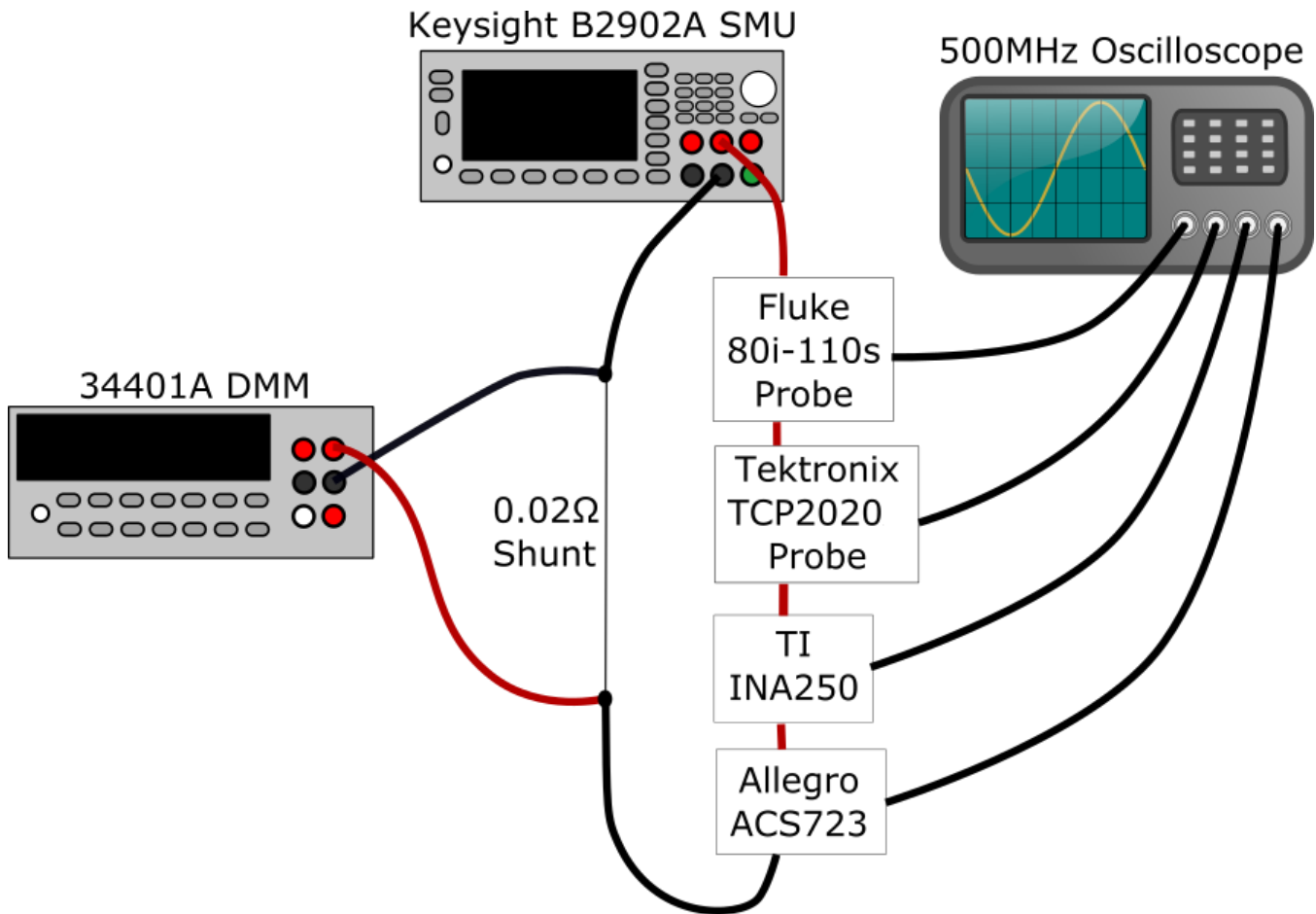

Figure 1. Test setup using all current measurement components

4.5.2. Sensor comparison

Before measuring, the 80i-110S and TCP2020 probes need to be zeroed with no current flowing through the clamp. Additionally, TCP2020 probe should be degaussed prior to making measurements. The ACS723 and INA250A4 are "zeroed" by measuring their output when no current is flowing.

The B2902A SMU was used to accurately force known currents to +/-10 µA through each of the sensors connected in series as in Figure 1.

Table 3 contains each sensor output for various constant currents forced with the B2902A. The ACS723, INA250A4, and shunt resistor need further processing before the sensors may be used to measure arbitrary currents. The number of significant figures in the table has been preserved from the source instrument (the B2902A for forced current, the TDS3054C for of the four sensors and the 34401A DMM for the shunt).

Table 3.   Unprocessed sensor output data for various currents

Current (A)	80i-110S (A)	TCP2020 (A)	ACS723 (V)	INA250A4 (V)	20mΩ Shunt (AVG mV)
0.00000	0	0	0.516	0.170	-
0.50000	0.515	0.504	0.716	1.15	10.04622
1.00000	1.02	1.00	0.911	2.15	20.09819
1.50000	1.52	1.50	1.11	3.14	30.15141
2.00000	2.03	2.00	1.31	4.15	40.19972
2.50000	2.53	2.50	1.50	5.13	50.07860

The 80i-110S has a DC accuracy of <3% of reading + 50mA from 0A to 10A. All the values for the Fluke 80i-110S in Table 3 are within that accuracy. The larges difference is seen at 0.50000A, but it is still within the probe's specification.

The TCP2020 provides DC accuracy of 1% typical and a warranted maximum of 3%. All the values in Table 3 fall within this specification.

Before the ACS723, INA250A4 and the shunt can be used to measure current, calibration factors need to first be obtained.

For the ACS723, two calibration values are necessary: the zero-current baseline output voltage and the sensitivity of the particular device in use. Typical values are given in the data sheet but the values vary slightly from device to device. To make more accurate measurements, these values should be determined for the specific device in use. The zero-current baseline output voltage 0.516V as can be seen in Table 3.

The sensitivity of the ACS723 is calculated by dividing the forced current by the output measured less the zero-current baseline voltage. From the data in Table 3, the average sensitivity for this device is 0.396A/V. With these two values, the current passing through the ACS723 can be determined from its output voltage by using the following equation:

$$current = \frac{(output\ (V) - baseline\ (V))}{sensitivity\ (A/V)}$$

The following equation is derived from the best fit of the data in Table 3 yields the following equation for current based on the INA250 sensor's output voltage:

$$current = 0.5013A/V * output(V) - 0.0791A$$

To make measurements with the shunt resistor, the resistance needs to be calculated. Table 4 contains the same shunt voltage data from Table 3, but with an extra column showing the calculated current based on the shunt resistor's averaged resistance from Section 4.2.1, 20.08456 mΩ.

**Table 4. Calculated resistance for 20mΩ
1% tolerance 1/4Watt 0805 SMD chip resistor**

Current (A)	Voltage drop (mV)	Calc. Current (A)
0.50000	10.04622	0.5002
1.00000	20.09819	1.0007
1.50000	30.15141	1.5012
2.00000	40.19972	2.0015
2.50000	50.0786	2.4934

The math function in the 34401A DMM was used to average the voltage drop across the shunt resistor for about a minute to obtain a more accurate measurement. The minimum, maximum and average values obtained during another set of measurements on the same shunt resistors are shown in the following table.

**Table 5. Values obtained from 34401 DMM from math function for 20mΩ
1% tolerance 1/4Watt 0805 SMD chip resistor**

Current (A)	Minimum (mV)	Maximum (mV)	Average (mV)
0.50000	10.02470	10.06796	10.04720
1.00000	20.07870	20.12266	20.10153
1.50000	30.13899	30.18155	30.16062
2.00000	40.19648	40.24114	40.21993
2.50000	50.25956	50.30700	50.28465

The average difference between the minimum and maximum voltage drop is 0.0444 mV when using the B2902A SMU as a current source. In practice on an i.MX application board, the difference is typically at least two orders of magnitude larger than on the 34401A DMM in this voltage range and fast 5-digit resolution mode. As with the other sensors discussed above, the current measurements using a shunt resistor like this will only be good to 3 significant figures.

5. Instrumenting i.MX Evaluation Boards

An NXP evaluation board for an i.MX typically includes a number of on-board resistors and cut traces that can be opened to enable the user to make current measurements. Table 6 contains a summary of measurement points for most evaluation boards for the i.MX6 and i.MX7 families of devices.

To instrument a board for current measurement by shunts, tap wires should be added to each side of the current sense resistor. If a cut trace or zero Ohm resistor has been placed on the board in place of a sense resistor, a suitable resistor must be selected by the user (see Section 4.2) and added to the board. Note that although sensitive traces are kept away from the vicinity of the cut trace, caution must be observed when cutting the shorting link to avoid damaging anything immediately below.

Shunt resistors should be sized by dividing the desired maximum voltage drop by the expected maximum current in the circuit under test (rearranging Ohm's law: R = E/I). For example, to measure a maximum power supply current of 2.5 A with a maximum voltage drop of 50 mV, R = 0.05V/2.5A = 0.02 Ω, which is the value that's been typically used in several i.MX evaluation boards. To measure a 150 mA maximum supply with maximum drop of 50 mV, R = 0.05V/0.15A = 0.33 Ω.

30-gauge wire-wrap wire is typically used: a twisted pair for sense resistor and a single wire for the voltage measurement point directly underneath the i.MX device. To prevent damage to the board and breaking the tap wires, Kapton tape is used to affix them with a small strain relief loop.

Table 6.   Current probe points for various NXP i.MX6x and i.MX7x Evaluation boards

Board	Target Device	ARM Current	ARMCAP Voltage	SOC Current	SOCCAP Voltage	DRAM Cur &Volt	VDDHIGH Current	VDDHIGH Voltage
i.MX6Q Sabre-SD	i.MX6S i.MX6DL i.MX6D i.MX6Q	R27	C679 C669	R21	C682 C667	R25	SH17	C654
i.MX6QP Sabre-SD	i.MX6DP i.MX6QP	SH5	C679 C669	R27	C682 C667	R25	SH17	C654
i.MX6QP Sabre-AI / CPU3	i.MX6QP	SH502	C620 C653	SH4	C691	SH504 (lumped)	—	C57
i.MX6SL EVK	i.MX6SL	SH2	C75	SH3	C390 C79	SH5	SH4	C405
i.MX6SX Sabre-SD	i.MX6SX	SH10 (lumped)	C243 C242	SH10 (lumped)	C261 C260	R373 (lumped)	R375	C265
i.MX6UL EVK	i.MX6UL	R729 (lumped)	C106	R729 (lumped)	C116	R728	R730	C120
i.MX7D Sabre-SD	i.MX7S i.MX7D	R20	—	R24	—	R23 (lumped)	—	—

To instrument an evaluation board for use with a commercial clamp-on current probe, the sense resistor must be removed altogether and a short wire loop soldered in place. The wire selected for the loop should be chosen with care because movement of the loop can pull traces off the board (not all boards have enlarged pours around the resistor pads). If stranded wire is used, molten solder can wick up the strands making for a stiff lever arm at the resistor pad which can also easily lift a trace with unintentional movement. Finer wire is more flexible but it is also more resistive. The loop resistance should be kept as low as possible (no greater than the resistance of a sense resistor used in that circuit).

Once the clamp-on probe is affixed around the measurement loop, the probe and signal wire should be oriented so that it cannot move and pull the measurement loop off the board.

To use an integrated sensor on a small PCB (as in Appendix A and Appendix B), the sensor board should be affixed to the evaluation board as closely as possible to the sense resistor with a small piece of double stick foam tape. Once the sensor board is attached, short wires can be added between the sensor board and the evaluation board.

CAUTION

Soldering the interconnection wires before affixing the sensor board risks pulling up pads. Also note that the integrated sensors need to be hooked up with the correct polarity so that the output swings in the right direction. To avoid any noise issues, power for the sensor board should be provided from a stable external source and not from the evaluation board's power supply.

For evaluation boards with a cut trace in the power supply path, cutting the trace can sometimes be avoided by lifting one side of that supply's switching inductor to open the path for insertion of a shunt resistor or a wire loop. The downside of doing this modification is that it is dangerously easy to accidentally break the inductor pads or the inductor itself.

6. Case Study 1: i.MX6QuadPlus on Sabre-AI CPU3

A socketed i.MX6QP Sabre-AI CPU3 board[1] was instrumented with 0.02 Ω shunt resistors on the VDDARM and VDDSOC supplies according to Table 6.

6.1. Current vs. frequency

Figure 2 shows the current in the VDDARM and VDDSOC supplies as a function of the core operating frequency. The ambient temperature was 25°C. The device tested was from the "typical" portion of the fab process, meaning that its properties were in the middle of the distribution. That is, this device is representative of most of the population of i.MX6QuadPlus devices.

The operating system used was Linux 4.1.15, built with Yocto built with in the default configuration. Four repeating instances of the Coremark benchmark were launched so that each of the four cores in the i.MX6QuadPlus would be at nearly 100% utilization. At each frequency, the benchmarks were permitted to run sufficiently long to allow the die temperature to equilibrate (usually about 10-20 minutes after the last adjustment of frequency, temperature, or voltage; longer if the software stress was changed). The equalization time is necessary because the current will continue to change until the die temperature stabilizes under those operating conditions. The voltage drop measurement across each shunt was made with a Keysight 34401A DMM, averaging each measurement over three minutes.

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[1] Note: The current revision of the i.MX6QP Sabre-AI CPU3 board has 20-mil signal layer traces in the VDDARM supply path that cause significant voltage drop at high current. These traces should be bypassed when conducting current measurements on this board. For details on of the modification, contact NXP support.
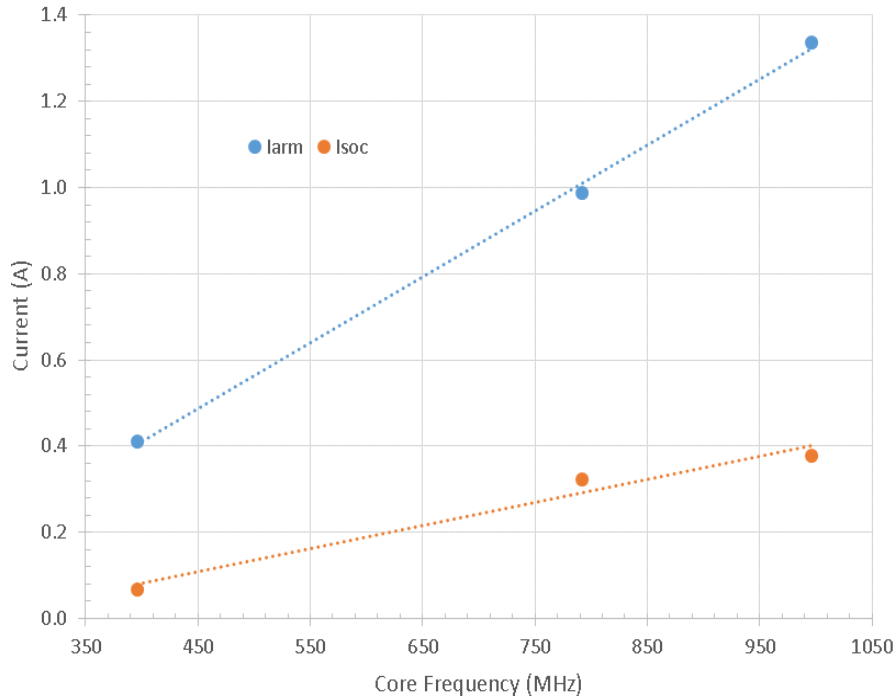
**Figure 2. Current in VDDARM and VDDSOC as a function of core frequency
for a typical device at 25°C ambient while running Coremark on all four cores**

As can be seen in Figure 2, the current for both VDDARM and VDDSOC increases with frequency. The increase in VDDARM current is expected. While the SOC domain is idling (Coremark does not exercise anything in the SOC domain), the VDDSOC current also rises with core frequency increase because the die temperature goes up with frequency as well. The static leakage in all supplies increases as a result of the increased temperature of the die.

6.2. Current vs. ambient temperature

Figure 3 shows a plot of the VDDSOC current for the same device as was used in Section 0 under all the same conditions but instead of running the Coremark benchmark, the 3DMarkMobile06 benchmark was run instead. In this case, though, the ambient temperature was controlled using a thermostream, blowing air of a constant temperature on the socket.

There are two sets of data in Figure 3: one set for a core frequency of 396 MHz (orange) and the other for 996 MHz (yellow). The VDDARM current increases with core frequency as well because the 3DMarkMobile06 benchmark does not run solely in the GPU. There is overhead associated with the operations in the GPU, so increased core frequency allows more benchmark work to get done, with an associated increase in VDDSOC current.
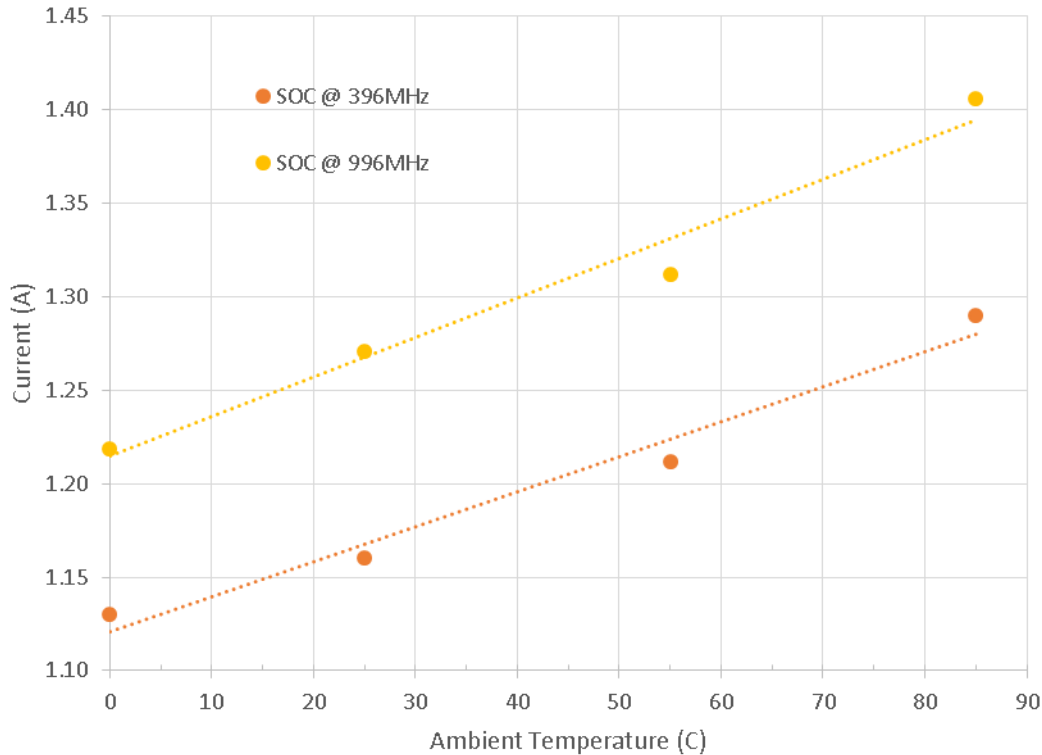
**Figure 3. Current in VDDSOC as a function of ambient
temperature for a typical while running 3DMarkMobile06**

6.3. Current vs. die temperature

To investigate the relationship between current and die temperature, where die temperature is used as indicator for junction temperature[2]. Before any measurements at the maximum operating temperatures of the i.MX6QP, the temperature protection features of u-boot and the Linux kernel first need to be removed. Additionally, the kernel was modified to read out the raw TEMPMON[3] count in addition to the normal calculation of system temperature in milli-Celsius.

Then, the TEMPMON module within each device tested was manually calibrated. This was done using an SD card with u-boot, where the boot script turned on the TEMPMON module and dumped the fuse count.

[2] Junction temperature (T_j) refers to the actual temperature of the transistors' active area. Because there are millions of them in an i.MX and only some portion of them are "working" at any given instant, there is no direct way to measure Tj. Enter the TEMPMON module of the i.MX: we can use the TEMPMON to measure the temperature on the surface of the die in the immediate vicinity of the TEMPMON module. Given enough time to equilibrate (hence the stressing software needs to run continuously), we can assume that the temperature gradient across the die is minimal and that the TEMPMON is pretty close to the T_j of the device.

[3] For more details on the i.MX6 TEMPMON refer to i.MX 6 Temperature Sensor Module (document AN5215)

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For the calibration temperatures of 20°C and 120°C, air flowing at 15 cubic feet per minute (CFM) was blown on the socket. A thermocouple in contact with the socket but out of direct airflow was used to adjust the airflow temperature until the socket equilibrated at the calibration temperature, usually after a soak of at least 30 minutes. Power was applied only long enough for the u-boot script to dump the TEMPMON counts to avoid Joule heating in the device. After several minutes of off time, power was re-applied until six count values at each calibration temperature were obtained. A script running under Linux was used to calculate die temperature from the raw TEMPMON counts using the manually obtained calibration values for each device.

To maintain the desired die temperature, the repeating stress software was launched. Hot air from the thermal stream was blown onto the device at 4CFM, the air temperature slowly adjusted until the die temperature equilibrated. The time for the temperature to settle was usually no less than 15-30 minutes.

Figure 4 shows current consumed in the VDDARM supply for two devices with two and four cores enabled[4] and with each enabled core running a repeating Coremark stress. One of the devices is typical silicon (TYP), representative of the majority of i.MX6QuadPlus devices. The second (FF) was a device from an intentional matrix split that placed it in the highest leakage corner of the wafer fabrication process, representative of the worst leakage of the population of i.MX6QP devices.

While adjusting the temperature of the air from the thermostream, it was noticed that the typical device required hotter air than the FF device to get the same die temperature. This is not at all surprising because the FF device has more wasted leakage that manifests itself as heat generated within the part. It required hotter air to get a typical device with less leakage to the same die temperature than for the FF device.

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[4] Cores 2 and 3 were disabled via Linux command line. Because VDDARM_IN and VDDARM_IN_23 are tied together on the board, the i.MX6QP on this board does not fully simulate the behavior of a properly wired i.MX6DualPlus, which would have the VDDARM_IN_23 and VDDARM_CAP_23 balls grounded. As such, the 2-core currents measured on this board will necessarily be higher than in a proper i.MX6Dual Plus design.
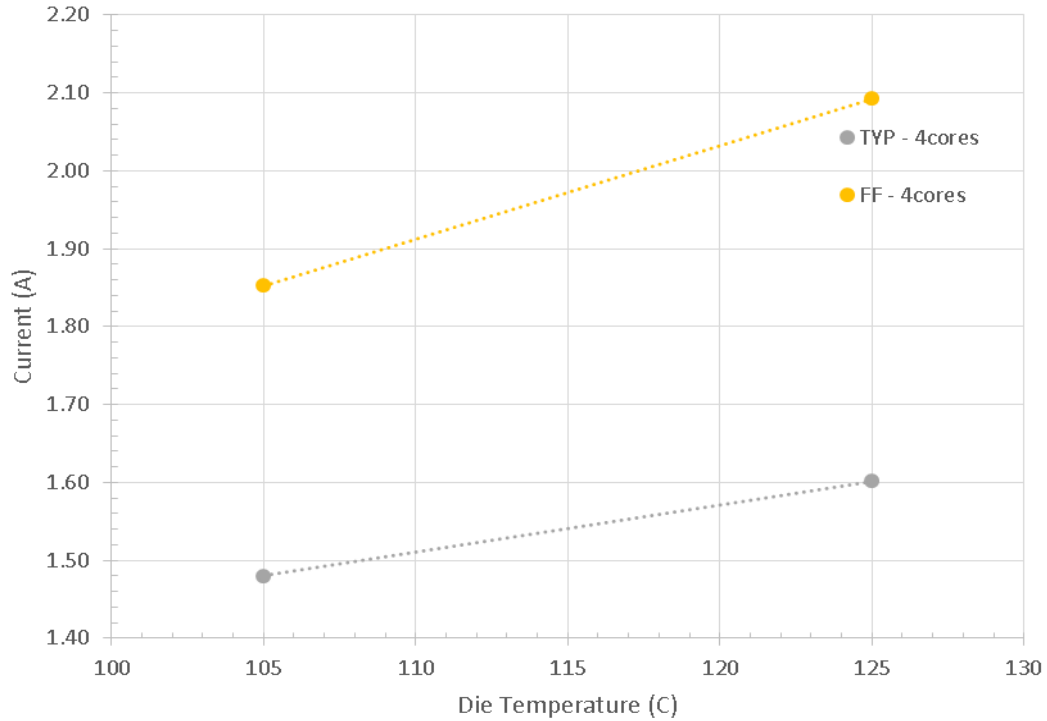
**Figure 4. Current in VDDARM as a function of die temperature
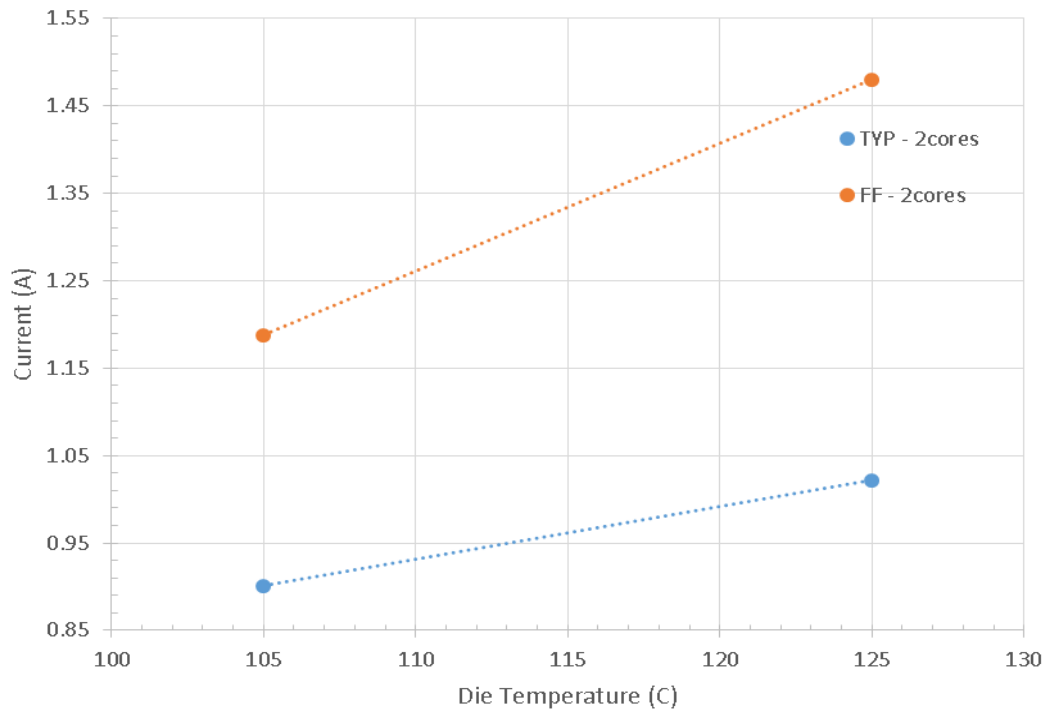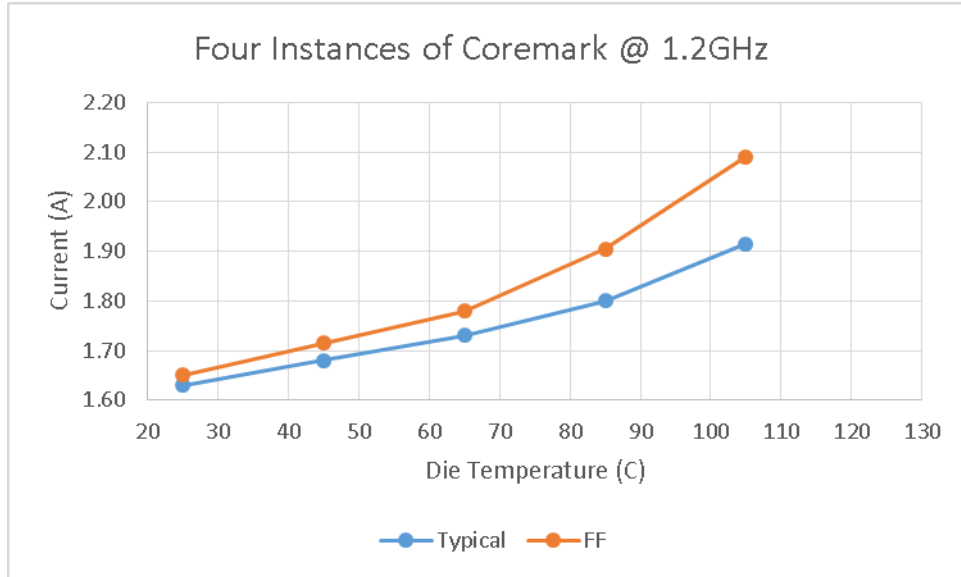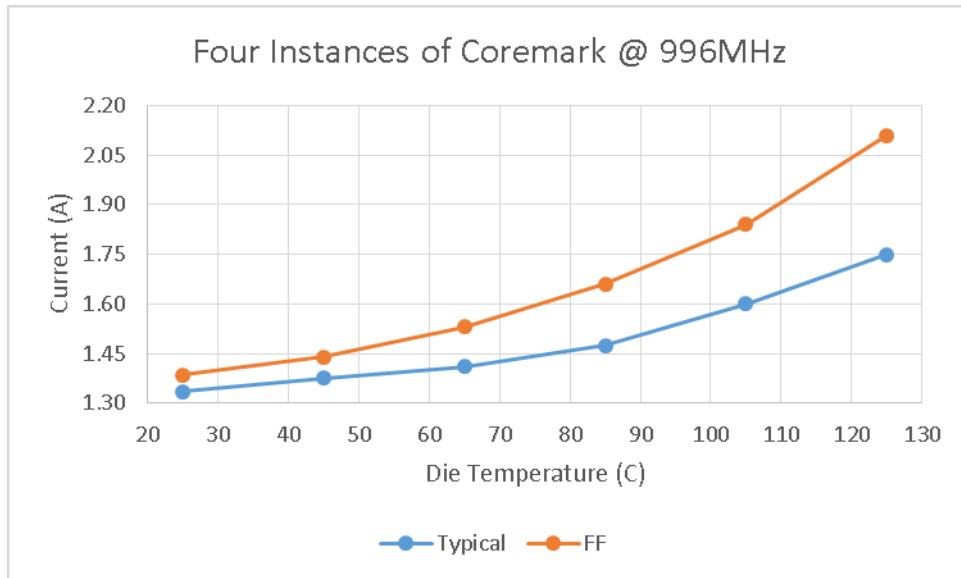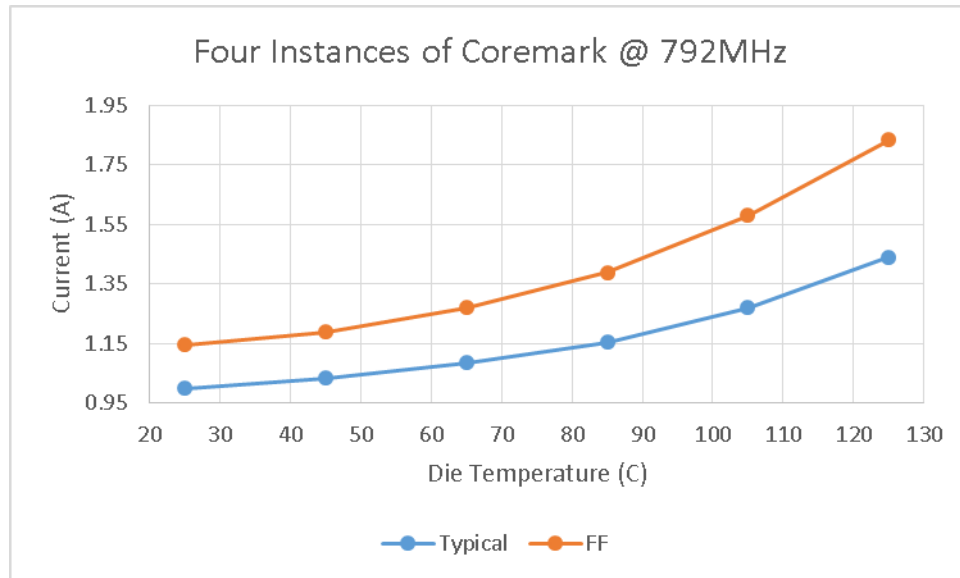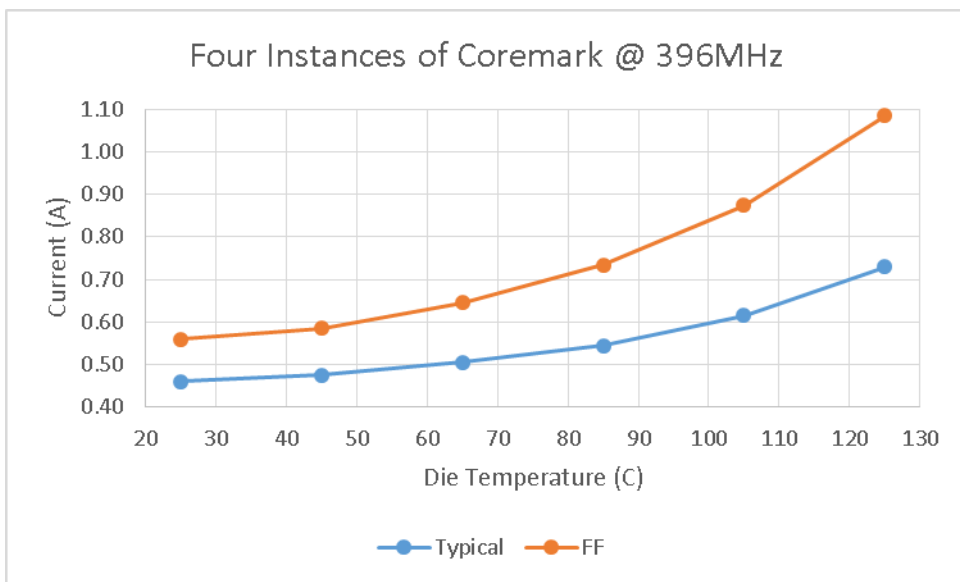for two different devices while running four instances of Coremark**

**Figure 5. Current in VDDARM as a function of die temperature
for two different devices while running two instances of Coremark**

7. Case Study 2: i.MX6QuadPlus on Sabre-SD

Two i.MX6QuadPlus SabreSD boards were instrumented with the INA250A4 current sensor on the VDDARM and VDDSOC supplies according to Table 6. One board was populated with an i.MX6Q device having typical silicon properties, the other was populated with a device (FF) from the leaky side of the silicon process.

The operating system used was Linux 3.14.52. U-boot and the kernel were modified to remove all of the built-in temperature protection features. Die temperature was ascertained via Linux using the built-in thermal management software and calibration data programmed into the devices at the factory.

For core current measurements (VDDARM), four instances of Coremark were launched such that they would continually run, saturating all four cores. For VDDSOC measurements, the core frequency was set to 996 MHz while the 3DMarkMobile ran repeatedly. The default VDDARM and VDDSOC set point voltages in the Linux BSP for each operating frequency were used.

The temperature of air flowing at 4 CFM was adjusted with a long soak time until the desired die temperature was reported by Linux. The cpufrequtils package was used to lock the core frequency to the desired value.

7.1. VDDARM current

Figure 6 and Figure 7 show the core current as a function of die temperature and core frequency for typical and FF leaky silicon, respectively. As would be expected, current increases with increasing temperature and increasing core frequency.
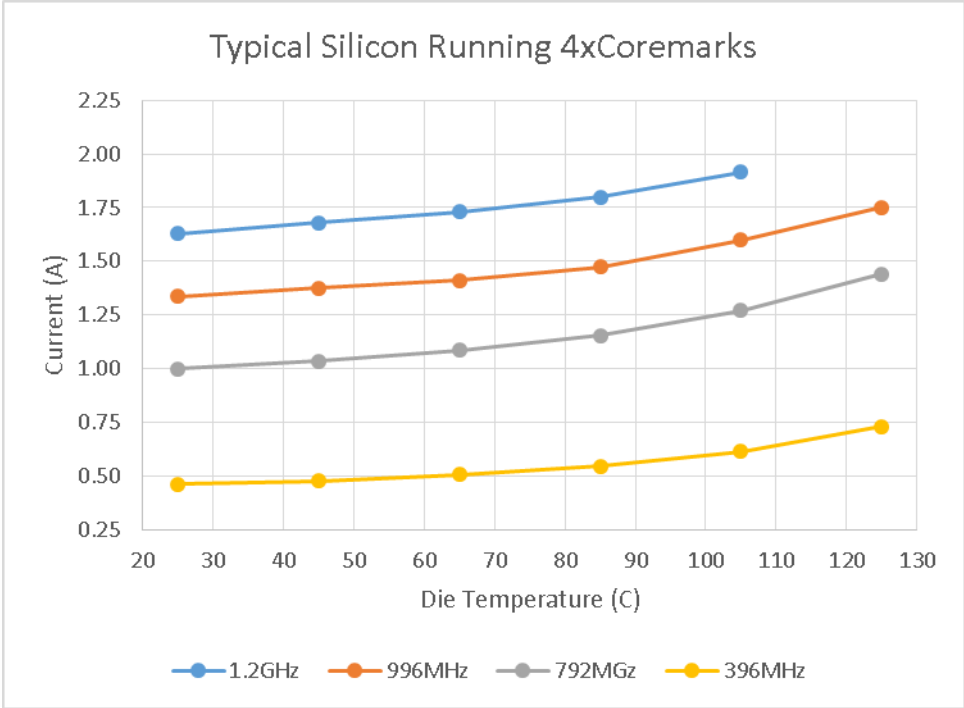
**Figure 6. Current in VDDARM of a typical device as a function of die temperature and
core frequency for a typical device while running four instances of Coremark**
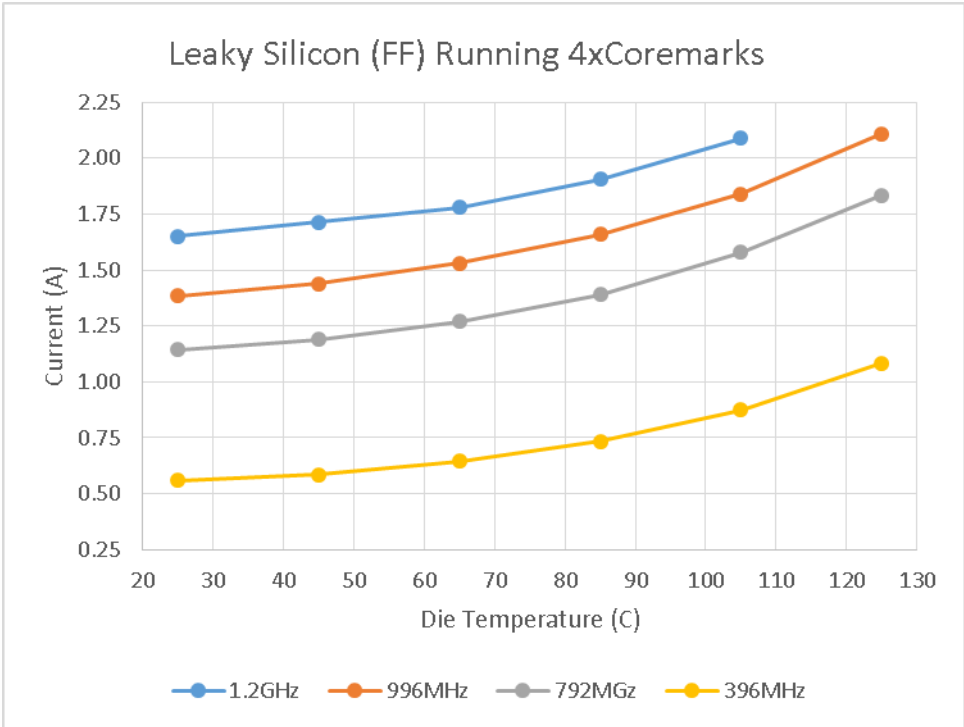
**Figure 7. Current in VDDARM of a leaky device as a function of die temperature and
core frequency for a typical device while running four instances of Coremark**

To better compare the current in the typical device with the leaky device, the data above was replotted as single frequency charts containing the data for each device (Figure 8 to Figure 11).

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Figure 8. Current in VDDARM as a function of die temperature for two devices while running four instances of Coremark at 1.2 GHz

Figure 9. Current in VDDARM as a function of die temperature for two devices while running four instances of Coremark at 996 MHz

**Figure 10.   Current in VDDARM as a function of die temperature
for two devices while running four instances of Coremark at 792 MHz**

**Figure 11.   Current in VDDARM as a function of die temperature
for two devices while running four instances of Coremark at 396 MHz**

7.2. VDDSOC current

The following figure is a chart of the VDDSOC current as a function of temperature while running a repeating instance of 3DMarkMobile06. As expected, current increases with increasing die temperature.
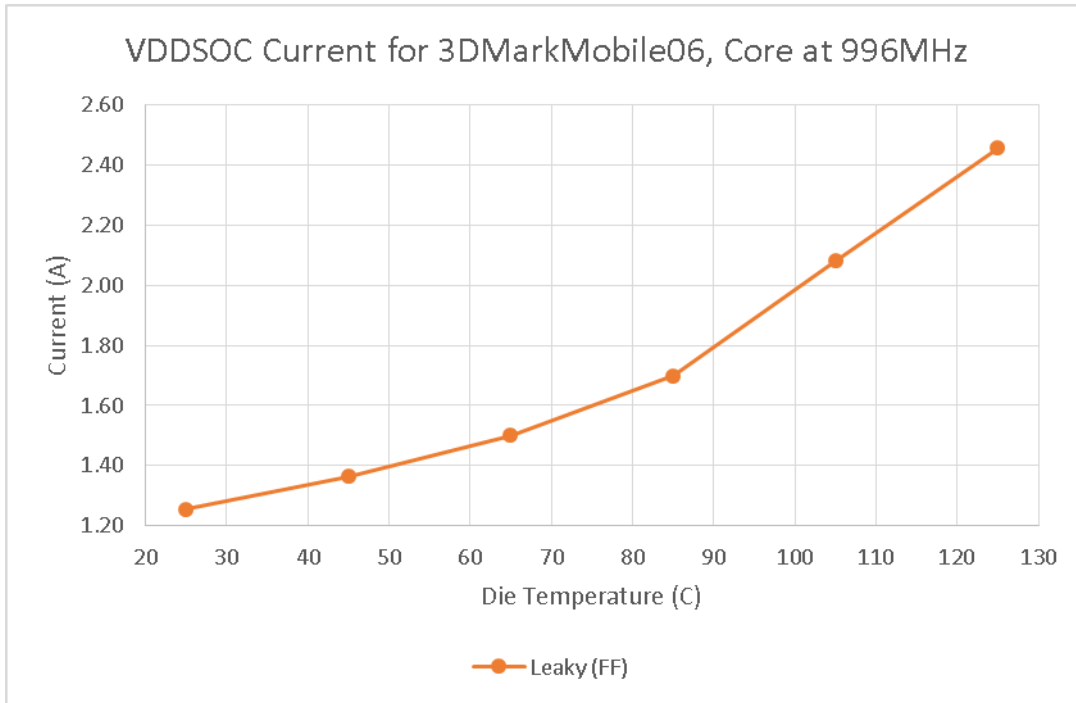
**Figure 12. Current in VDDSOC as a function of die temperature
for FF device while running 3DMarkMobile06 at core frequency 996 MHz**

In comparison to the relatively steady supply current in the core side while all four cores are nearly consistently 100% loaded, the current in VDDSOC while running the 3DMarkMobile06 benchmark had a much different profile, as can be seen in the following figure.
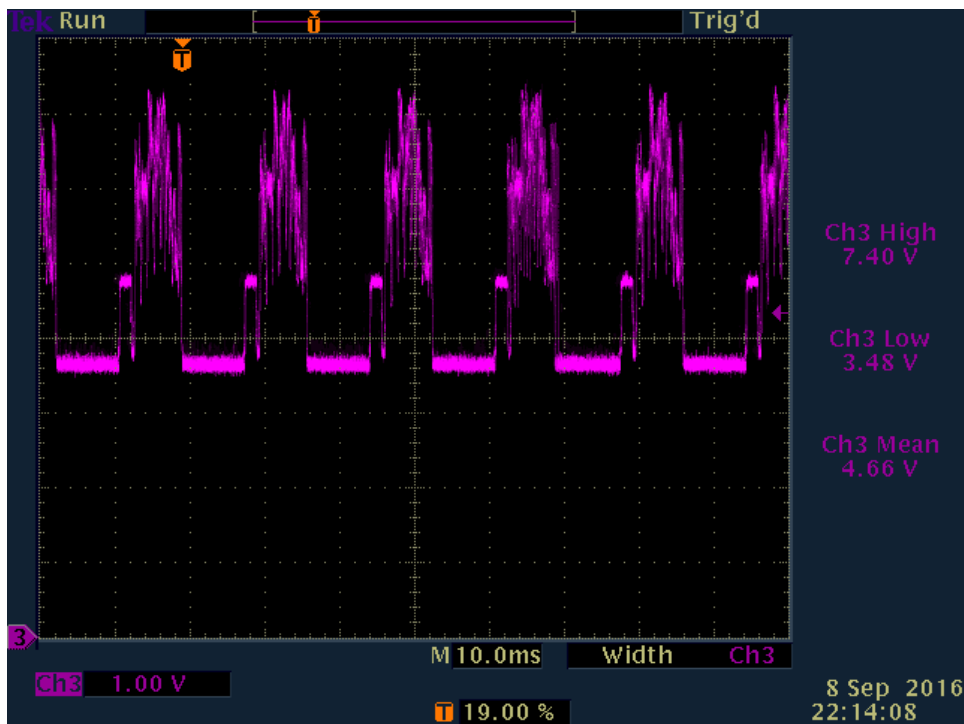
**Figure 13. Raw output of INA250A4 (measuring VDDSOC) at 125°C
for FF device while running 3DMarkMobile06 at core frequency 996 MHz**

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The peaks in current in this figure reach 3.7 A (7.4 V * 0.5 A/V) while the average current is 2.33 A.

8. Conclusions and Recommendations

This application note presented several methods by which to measure supply current on an application board along with the factors that can influence it.

Being able to measure operating current on an i.MX evaluation board is useful during the design phase for sizing the power supply for the end application. It's also useful for tuning application code to consume less current and thereby generate less heat.

After working with the various methods for measuring current, using an oscilloscope probe such as the Tektronix TCP2020, an integrated current sensor like the INA250A4 or a shunt and current sense amplifier is recommended. The ACS723 Hall effect sensor is not recommended because its open loop nature makes it difficult to keep calibrated, especially when measuring over temperature. The Fluke 80i-110s probe is also not recommended because its physical size requires a sizable wire loop to accommodate it and it's easier to damage the board under test. The currents to be measured are very close to the resolution limit of the probe, which reduces its ability to measure accurately.

The shunt resistor and DMM is by far the easiest way to go but the DMM is relatively slow. The voltages across the shunt tend to be close to the resolution of the DMM, so noise has a larger influence. There is also no way to visualize what the current waveform looks like or to see what the duration of current peaks and troughs are.

Hall effect current sensor probes for oscilloscopes do well in this application but they are fairly expensive. They have the fastest response, upwards of 50 MHz, some going as high as 125 MHz. The biggest issue found with this type of probe was that the ferrite core of the probe would magnetize if left clamped onto the wire loop while the board was equilibrating at temperature. To degauss the core and re-zero the probe, it had to be unclamped. With every clamp and unclamp cycle, there is the very real risk of damaging the board. A further disadvantage of oscilloscope probes is that one can only simultaneously measure as many power supplies as there are probes available.

The INA250A4 built onto a small board can be used to instrument any number of power supplies on a target board. Depending on the gain of the device used, the current can be measured with relatively large swings on an oscilloscope. Once affixed to a board, no further intervention is necessary. The INA250A4 introduces minimal additional series resistance – much less than the 20 mΩ typically installed on evaluation boards if the interconnection wires can be kept short.

To further reduce space and keep interconnects short, a very small board with a current sense amplifier (some of which are available in packages smaller than 2 mm square) can be connected to the on-board shunt, essentially the INA250A4 but without the integrated shunt.

In addition to run currents, low currents, such as during low-power sleep modes, can be measured using a larger valued shunt resistor shorted with an FET. This allows the board to boot up and operate normally. Once the device has been put into the desired low power mode, the FET can be turned off so the current sense amplifier measures the voltage across the "sleep" shunt resistor.

In short, there is no one-size-fits-all answer to the question, "How much power does the i.MX consume when it performs my application?" But there is much that can be done on NXP i.MX evaluation hardware to quantify the power consumption of your particular application during initial software development.

9. Revision History

Table 7.   Revision history

Revision number	Date	Substantive changes
0	12/2016	Initial release

Appendix A. INA250A4 Sensor Board

A.1. Circuit description

The INA250A4 was connected as shown in the schematic shown in the following figure. The figure also includes an enlarged layout of the two-layer board. The board measures about 1" x 0.75".
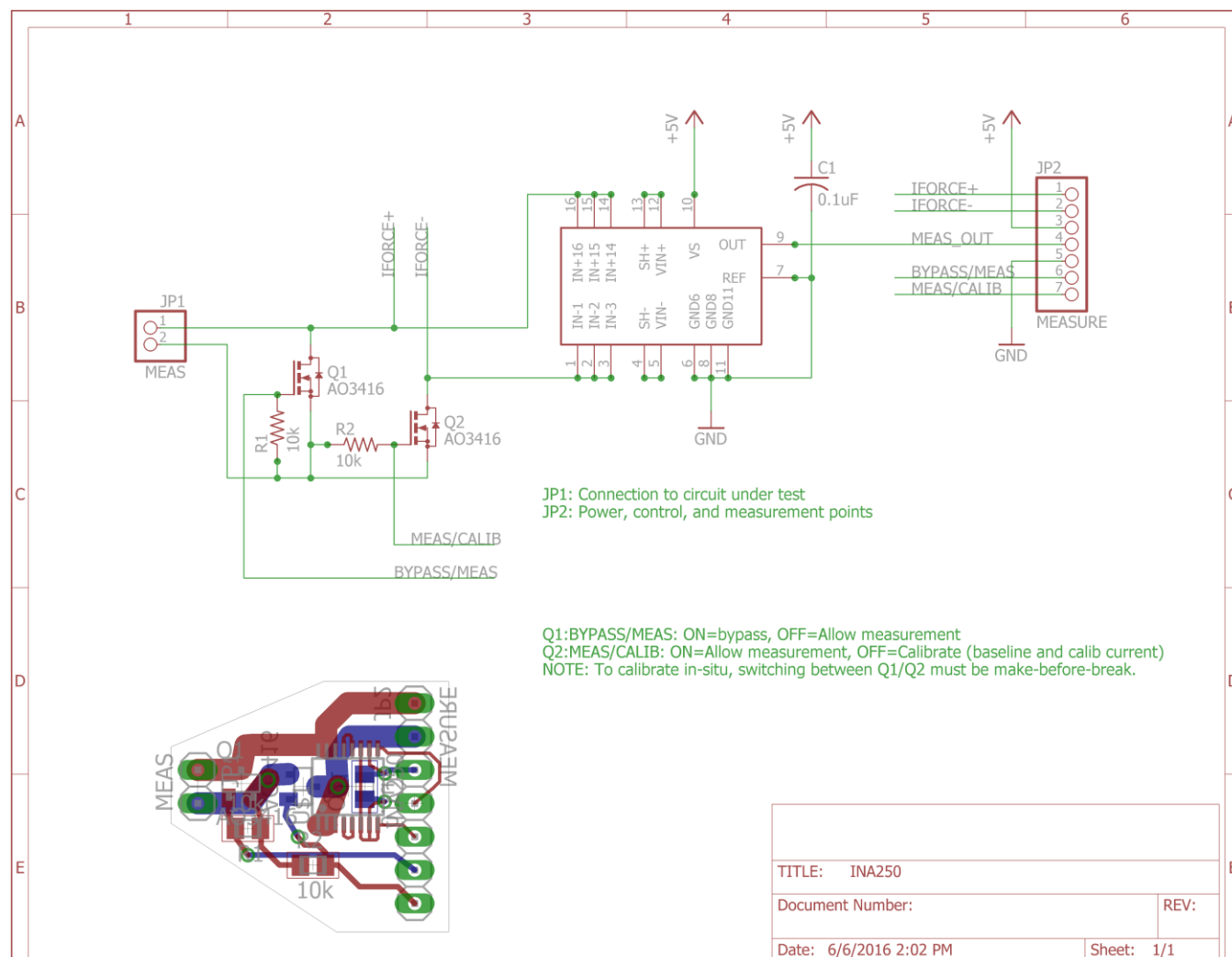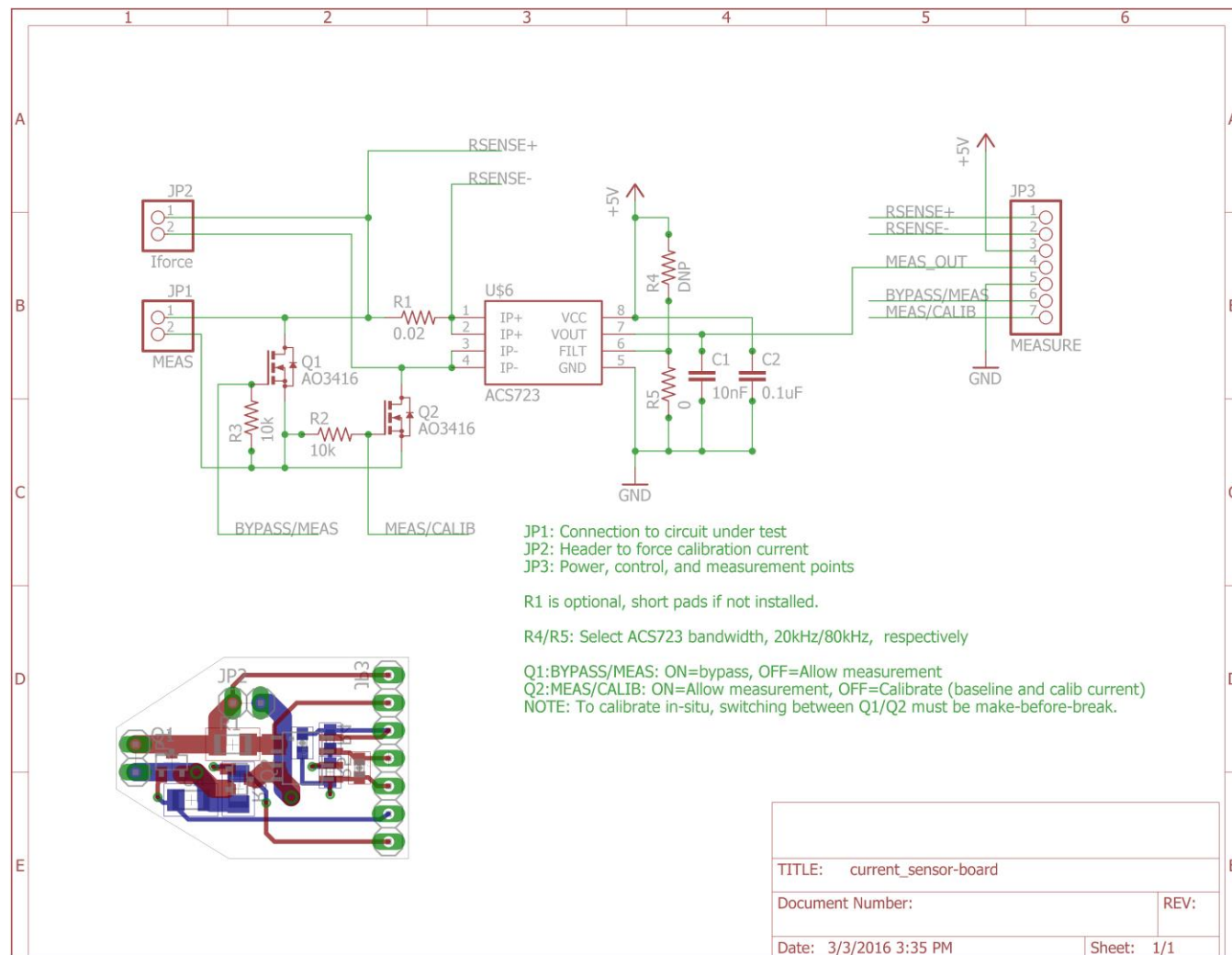

Figure 14.   Schematic and board layout for INA250A4

A.2. Usage

The sensor board connects to the target board via JP1. Polarity is important in order for the INA250A4 output to measure the current properly. FET Q1 is used to short the pins of JP1, allowing the INA250A4 to be taken out of the measurement loop. FET Q2 is used to take one leg of the INA250A4 out of the measurement loop so that calibration of the sensor may be performed immediately before making a

measurement to minimize temperature effects on the sensor. Once disconnected, a known current may be applied to the INA250A4 via pins 1 and 2 of JP2.

Switching of the FETs Q1 and Q2 is done manually. Once the target board is booted, switching the states of these transistors requires make-before-break to avoid depriving the target of power in the supply being measured. To minimize the series ON-resistance introduced by the FETs, three devices were stacked vertically on top of each FET footprint on the board. The DMN1019USN, with a lower R_{DSON} of 10mΩ, can be substituted for the three AO3416, which have a minimum R_{DSON} of 22 mΩ each.

Copies of this PCB may be ordered from OHS Park at the project link: https://oshpark.com/projects/WOYWS8vI. Be sure to select the 2 oz copper option to reduce the resistance of the high current traces.

In order to simplify the board, Q1, R1, and R2 should be left unpopulated and the source and drain of Q2 shorted. These were copied over from the ACS723 board but were found to not be necessary.

Appendix B. ACS723LLCTR-10AU-T Sensor Board

B.1. Circuit description

The Allegro ACS723 was connected as shown in the schematic shown in the following figure. The figure also includes an enlarged layout of the two-layer board. The board measures about 1" x 0.75".

Figure 15.   Schematic and board layout for ACS723

B.2. Usage

The sensor board connects to the target board via JP1. Polarity is important because the part number ACS723LLCTR-10AU-T specifies a unidirectional 0-10A DC current sensor. FET Q1 is used to short the pins of JP1, allowing the ACS723 to be taken out of the measurement loop. FET Q2 is used to take one leg of the ACS723 out of the measurement loop so that calibration of the sensor may be performed immediately before making a measurement to minimize temperature effects on the sensor. Once disconnected, a known current may be applied to the ACS723 via JP2.

Switching of the FETs Q1 and Q2 is done manually. Once the target board is booted, switching the states of these transistors requires make-before-break to avoid depriving the target of power in the supply being measured. To minimize the series ON-resistance introduced by the FETs, three devices were stacked vertically on top of each FET footprint on the board. The DMN1019USN, with a lower R_{DSON} of 10mΩ, can be substituted for the three AO3416, which have a minimum R_{DSON} of 22 mΩ each.

Copies of this PCB may be ordered from OHS Park at the project link: https://oshpark.com/projects/20gifdoz. Be sure to select the 2oz copper option to reduce the resistance of the high current traces.

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