MICROCHIP

AN4530

SAMA7G5 Series Temperature Sensor Calibration

Scope

This application note describes how to use the SAMA7G5 Series temperature sensor, and more particularly how to improve the sensor initial reading accuracy by using the calibration data factory-programmed in the One-Time-Programmable (OTP) memory.

Reference Documents

The following reference documents are available on www.microchip.com.

Type	Title	Literature Number
Data sheet(1)	SAMA7G5 Series	DS60001765
Errata sheet	SAMA7G5 Series Silicon Errata and Data Sheet Clarification	DS80001016

Note:

1. This application note refers to the following sections in the SAMA7G5 Series data sheet:
   - Boot Strategies
   - Analog-to-Digital Converter (ADC) Controller
   - OTP Memory Controller (OTPC)
   - Electrical Characteristics

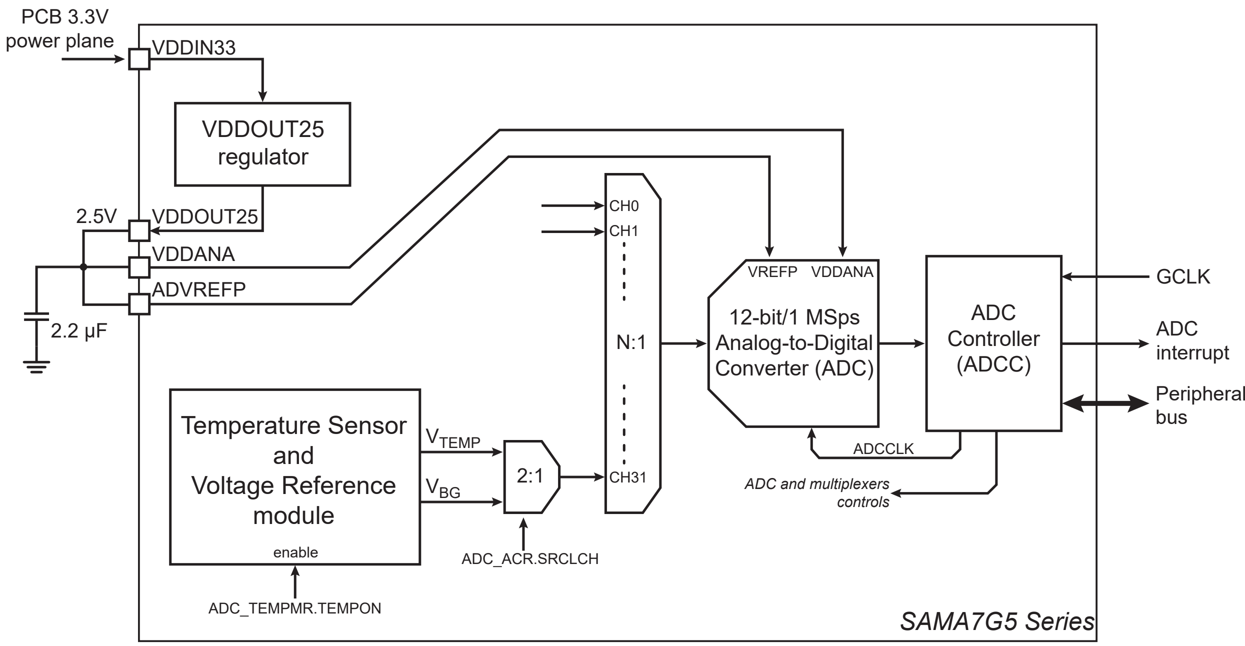
1. Introduction

The SAMA7G5 junction temperature is measured through a temperature sensor module connected to the 12-bit Analog-to-Digital Converter (ADC). The temperature sensor output voltage (V_{TEMP}) varies linearly with the die temperature with a typical slope of 2.08 mV/°C and has a 25°C value ranging from 590 mV to 670 mV. Refer to the SAMA7G5 Series data sheet for more details.

The accuracy of this system is affected by various offset and gain errors, such as ADC offset error, ADC gain error, ADVREFP inaccuracies, V_{TEMP} slope error and V_{TEMP} offset error. The reading accuracy is in the ±20°C range initially, but Microchip narrows down this range by including calibration data in a specific OTP packet during SAMA7G5 manufacturing, reaching a ±5°C accuracy range.

2. Temperature Sensor System Description

Figure 2-1. Temperature Sensor System Block Diagram



The temperature sensor system uses a 12-bit Analog-to-Digital Converter (ADC) managed by an ADC Controller (ADCC) providing an enhanced resolution up to 16 bits. The Temperature Sensor and Voltage Reference module outputs two voltages, V_{TEMP} and V_{BG}, that are internally connected to ADC channel 31.

Both voltages are measured during the temperature measurement process. The selection between those voltages is controlled in the Analog Control register (ADC_ACR). V_{TEMP} is proportional to the absolute temperature voltage (also known as “PTAT voltage”) and V_{BG} is a reference voltage with a very low temperature dependence.

3. Temperature Measurement Principle

To perform a corrected reading of the junction temperature (T_J):

1. Initialize the temperature sensor system (i.e., ADC and Temperature Sensor and Voltage Reference module).
2. Read the V_{TEMP} voltage with the ADC (output code: ADC_{VTEMP}).
3. Read the V_{BG} voltage with the ADC (output code: ADC_{VBG}).
4. Apply a correction formula using the OTP calibration data:
   T_J = f(ADC_{TEMP}, ADC_{VBG}, OTP_CALIBRATION_DATA).

In the case of periodic temperature measurements, step 1 may be done once at the initialization phase of the application. Steps 2, 3 and 4 are repeated each time a temperature reading is required. Considering the temperature variation dynamics, a 1-second interval between two measurements fits most applications.

4. System Initialization for Temperature Measurement

4.1 ADC Clock

Before using the ADC controller, its GCLK must be enabled in the Power Management Controller (PMC). To reach the maximum sampling rate (1 MS/s), the ADCCLK frequency, derived from the GCLK, must be 20 MHz:

$$f_{ADCCLK} = \frac{f_{GCLK}}{ADC\_MR.PRESCAL} = 20MHz$$

f_{ADCCLK} can be set to a value lower than 20 MHz if required by the application (for example, if one of the channels used in the application needs a very long tracking time).

4.2 Temperature Sensor and Voltage Reference Start-Up

Prior to measuring either V_{TEMP} or V_{BG}, the Temperature Sensor and Voltage Reference module must be enabled:

1. Set the ADC_TEMPMR.TEMPON bit.
2. Wait for the specified start-up time.

Considering its low power consumption[1], in most cases there is no benefit to disabling this module between two temperature measurements.

Note:

1. About 200 µA max. Refer to the SAMA7G5 Series data sheet for more details.

4.3 ADC Start-Up, Tracking, and Conversion Times

In the ADC Mode register, set the STARTUP field as specified in the SAMA7G5 Series data sheet to let the ADC internal circuits settle before starting a first conversion:

- Set ADC_MR.STARTUP = SUT512 (about 25 µs with ADCCLK = 20 MHz, i.e., well above the minimum requirement)

The tracking time is the time required by the ADC to charge its input sampling capacitor to the input voltage. This time, specified in the SAMA7G5 Series data sheet, must be set with the fields TRACKTIM and TRACKX in the ADC Mode register.

- Set ADC_MR.TRACKTIM = 6 and ADC_EMR.TRACKX = 1.
  This results in a tracking time t_{TRACK} = 24 x t_{ADCCLK}= 1.2 µs with f_{ADCCLK} = 20 MHz.
- Assuming a constant input mode control of the ADC (single-ended or differential), the conversion time required by one single V_{TEMP} or V_{BG} acquisition is defined as follows:
  t_{CONV}[1] = t_{TRACK} + 14 x t_{ADCCLK} = (24 + 14) x t_{ADCCLK} = 1.9 µs with f_{ADCCLK} = 20 MHz

Note:

1. Refer to 12-bit ADC characteristics in the SAMA7G5 Series data sheet “Electrical Characteristics” section.

4.4 ADC Input Configuration

Both voltages V_{TEMP} and V_{BG} are routed to the ADC channel 31. For these two voltages, the ADC should perform single-ended conversions. The ADC_ACR.SRCLCH bit toggles the input selection between V_{TEMP} and V_{BG}.

- Clear ADC_CCR.DIFF15 to set ADC channel 31 to Single-Ended mode, and either
- Clear ADC_ACR.SRCLCH to sample the V_{TEMP} voltage, or
- Set ADC_ACR.SRCLCH to sample the V_{BG} voltage.

4.5 Conversion Triggering Mode

To fit all application needs, various methods are available to trigger a V_{TEMP} or V_{BG} conversion: a software start, a sequenced start with other channels, or a periodic start dedicated to temperature measurement. Refer to Temperature Sensor in the “Analog-to-Digital Converter (ADC) Controller” section of the SAMA7G5 Series data sheet, and adapt the ADC_TRGR.TRGMOD field to the required behavior.

Note: Considering that the V_{BG}/V_{TEMP} switch cannot be performed by the hardware sequencer, but only by a software write in ADCC_ACR.SRCLCH, selecting a software triggering mode to read the junction temperature is recommended.

4.6 Enhanced Resolution Mode

To improve the stability of the temperature readings, it is recommended to average successive conversions of the V_{BG} and V_{TEMP} voltages. For this purpose, the ADC controller features an Enhanced Resolution mode. Refer to Enhanced Resolution Mode and Digital Averaging Function in the “Analog-to-Digital Converter (ADC) Controller” section of the SAMA7G5 Series data sheet for a detailed description.

- Set ADC_EMR.OSR to the required value. The higher the OSR value, the greater the stability of the temperature reading and the longer the acquisition time. Setting ADC_EMR to a non-zero value changes the raw 12-bit output data to 13-, 14-, 15-, or 16-bit data.
- The following table shows the correspondence between the temperature reading stability and the acquisition time. The temperature reading stability is measured as the standard deviation of a large set of samples.
- Set ADC_EMR.ASTE to perform all required conversions with a single trigger.

Table 4-1. ADC Oversampling Mode Characteristics

ADC_EMR.OSR	ADC Output Data Format	T_J Reading Stability (Standard Deviation)	V_{TEMP} or V_{BG} Acquisition Time
0 (NO_AVERAGE)	12-bit	0.53°C	2 µs
1 (OSR4)	13-bit	0.25°C	8 µs
2 (OSR16)	14-bit	0.14°C	32 µs
3 (OSR64)	15-bit	0.08°C	128 µs
4 (OSR256)	16-bit	0.05°C	0.5 ms

4.7 Initialization Summary

- Enable the ADC GCLK with the appropriate source clock and dividers to reach the required sampling frequency.
- Set ADC_TEMPMR.TEMPON and wait for the specified start-up time.
- Set ADC_MR.STARTUP to SUT512.
- Set ADC_MR.TRACKTIM to 6 and ADC_EMR.TRACKX to 1.
- Clear ADC_CCR.DIFF15.
- Set ADC_TRGR.TRGMOD to the appropriate value.
- Set ADC_EMR.OSR to OSR256.
- Set ADC_EMR.ADCMODE to NORMAL.
- Set ADC_EMR.SIGNMODE to SE_UNSG_DF_SIGN.
- Set the single-ended measurement on VBG channel 31: ADC_ACR.SRCLCH = 1.
- Set the single-ended measurement on V_{TEMP} channel 31: ADC_ACR.SRCLCH = 0.

5. Temperature Sensor Calibration Packet in OTP

5.1 Calibration Packet Address

The temperature sensor calibration data are stored in a regular OTP packet. The physical address of this packet may vary from device to device, therefore identifying this packet must be done by searching for a regular packet located at the second position in the OTP array. To help recognize this packet, the first 32-bit word is programmed with the constant value 'TSCA'.

Important: Out-of-factory, the first packet of the OTP memory is intentionally left blank to enable use of the OTPC Emulation mode. At that stage, the temperature sensor calibration data cannot be read. To read these data, a boot configuration packet must be first programmed in the OTP memory. After this, the OTP Emulation mode is not available anymore. Refer to the “OTP Memory Controller (OTPC)” and “Boot Strategies” sections of the SAMA7G5 Series data sheet for more details.

5.2 Calibration Packet Structure

The following table shows the structure of the Temperature Sensor Calibration packet as programmed in the Microchip factory.

Table 5-1. Calibration Packet Structure

Offset	31:24	23:16	15:8	7:0	Format	Value or Range
0x00	TSCAL_TAG				char[4]	‘TSCA’
0x04	-	-	-	TSCAL_P1	char	-127 to 128
0x08	-	-	-	-	-	-
0x0C	-	-	-	-	-	-
0x10	TSCAL_P4				unsigned int	0 to 2^{32} -1
0x14	-	-	-	-	-	-
0x18	TSCAL_P6				unsigned int	0 to 2^{32} -1

6. Junction Temperature Calculation

6.1 Junction Temperature Equation

The following equation is used with the above-mentioned calibration data to improve the temperature sensor reading.

$$T_J = TSCAL_{P1} + \frac{\left(\frac{ADC_{V_{TEMP}}}{ADC_{V_{BG}}} \times TSCAL_{P6} - TSCAL_{P4}\right)}{(dV_{TEMP}/dT)}$$

Where :

- ADC_{VTEMP} is the averaged ADC measurement of the V_{TEMP} voltage performed at temperature $T_{J.}$
- ADC_{VBG} is the averaged ADC measurement of the V_{BG} voltage performed at temperature $T_{J.}$
- dV_{TEMP} /dT is the V_{TEMP} voltage sensitivity to temperature = 2080.

6.2 Numerical Application

The following OTP content and ADC acquisitions are read from a sample of the SAMA7G54-EK evaluation kit. All are given in decimal format:

- TSCAL_P1 = 27
- TSCAL_P4 = 639436
- TSCAL_P6 = 1198021
- ADC_{VTEMP} = 17974
- ADC_{VBG} = 31416

$$T_J = 27 + \frac{\left(\frac{17974}{31416} \times 1198021 - 639436\right)}{2080} = 49.1°C$$

This result should be understood as 49.1°C ±5°C.

7. Revision History

7.1 Rev. A - 09/2022

First issue.

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