Application Report

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MSP430’s Analog Combo Enables True Single-Chip Pulse Oximeter Designs

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ABSTRACT

This application report provides an overview of a true single-chip solution for pulse oximetry by utilizing the highly integrated analog circuitry within the MSP430FR235x device.

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1 Introduction

A pulse oximeter is a non-invasive device used to monitor the pulse rate and peripheral oxygen saturation (SpO2 %) of blood.

In principle, the oxygenated hemoglobin (HbO2) and de-oxygenated hemoglobin (Hb) respond differently to different wavelengths of light. De-oxygenated hemoglobin absorbs more red light compared to infrared (IR) light whereas oxygenated hemoglobin absorbs more infrared light. As Figure 1 shows, when Red and IR Light Emitting Diodes (LEDs) are driven alternately through a finger, the unabsorbed light received at the other end of the finger (where a photodiode is used as the sensing element) corresponds to the concentration of Hb and HbO2 in the blood.

The photodiode current is converted into a voltage signal by a Transimpedance amplifier (TIA). The amplified and filtered signal is sent to a microcontroller for further noise removal and calculations of SpO2 % and heart rate. For more details on the calculations, see *A Single-Chip Pulsoximeter Design Using the MSP430*.

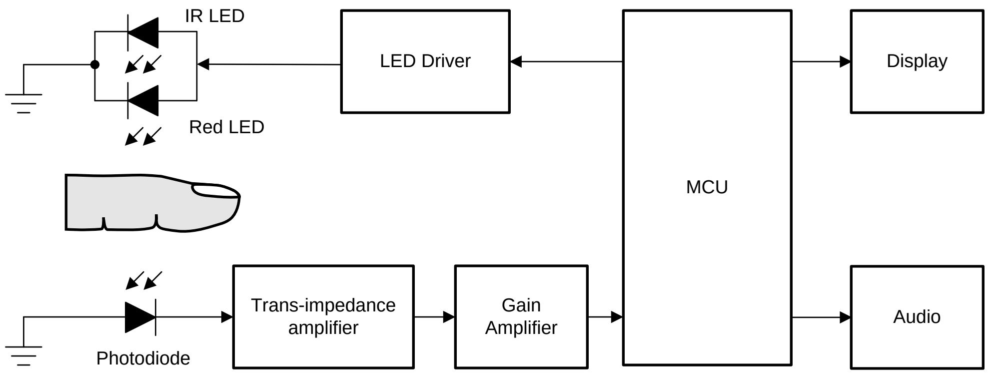

Figure 1. High-Level Block Diagram of a Pulse Oximeter (power supply not shown)

The MSP430FR235x microcontroller enables full transmit and receive signal chain implementation with four integrated Smart Analog Combo (SAC) blocks on-chip. Each SAC includes a high-performance low-power operational amplifier (OA), a programmable gain amplifier (PGA) with gain up to 33V/V, and a 12-bit digital-to-analog converter (DAC). This configurable analog signal chain can be operated in various modes or can be cascaded together or connected with other peripherals as explained in *How to Use the Smart Analog Combo in MSP430™ MCUs*.

Some other important features of MSP430FR235x that can be used in a pulse oximeter application are:

- One 12-Channel 12-Bit Successive Approximation (SAR) ADC with precise internal references (1.5, 2.0, or 2.5 V)
- Ferroelectric RAM (FRAM) gives non-volatile storage comparable to Flash/EEPROM, with low power consumption and fast write access comparable to RAM.
- Multiple serial communication (Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C), Universal Asynchronous Receiver/Transmitter (UART), IrDA) for interfacing with the display, buzzer, and so forth.
- An on-chip temperature sensor which can be used for temperature compensation of LED current strength and photodiode temperature drift.
- Two Enhanced Comparators (eCOMP) with integrated 6-bit DAC that can be used for wake-up detection and power voltage monitoring.

2 Proposed Single-Chip Design

Figure 2 shows the proposed block diagram of a single-chip pulse oximeter design using the MSP430FR235x. All four SACs are utilized optimally: two for the LED drive stage (Red and IR) and other two for the photodiode signal conditioning (TIA and gain stage). Internal clocks and voltage references are selected to minimize the use of external components thus reducing the overall Bill of Material (BoM) cost as well as the footprint of the design.

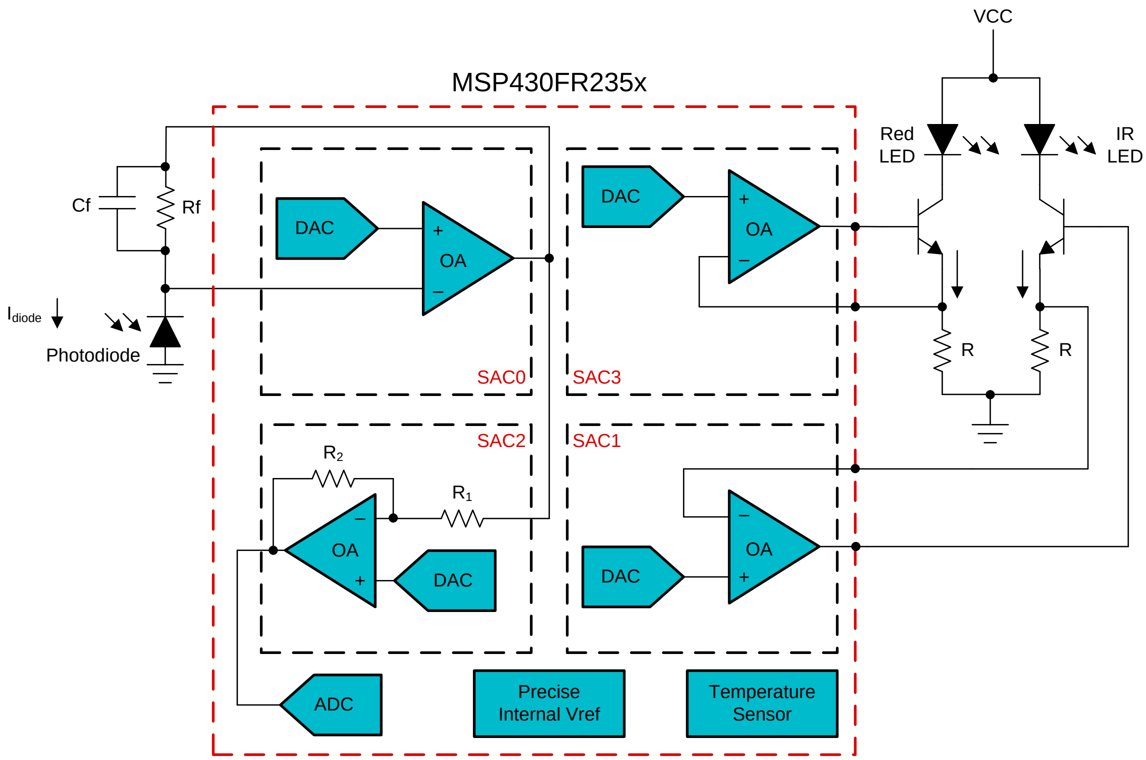

Figure 2. Proposed Block Diagram of a Single-Chip Pulse Oximeter Design Using MSP430FR235x

2.1 Using SAC to Generate the LED Drive

Many pulse oximeter designs use back-to-back connected Red and IR LEDs which need four transistors for driving. The transistors are connected in H-bridge fashion to drive one LED at a time. To eliminate two transistors, the LED can be driven using single transistor as shown in Figure 3. The SAC can be configured as DAC output configuration (the internal register settings should be PSEL=01, NSEL=00, MSEL=xx).

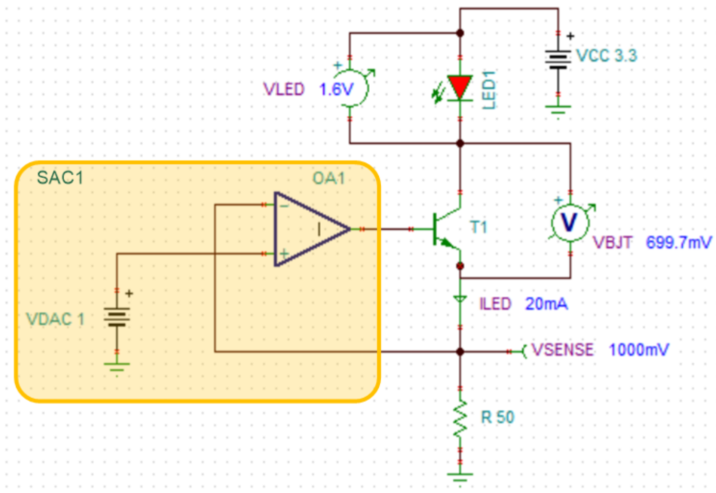

Figure 3. Simulation of the LED Drive Circuitry

In the SAC1, DAC1 voltage can be set to VDAC and is connected to non-inverting terminal of OA1. Due to virtual ground, the inverting terminal will also lock to the same voltage (VDAC) and the output of the OA1 varies in order to keep the inverting and non-inverting OA1 terminals at the same potential (VDAC). This potential gets reflected across the sense resistor R which sets the current flowing through the LED. The current through the LED is calculated as:

$$\text{ILED} = \frac{\text{VSENSE}}{\text{R}} \tag{1}$$

Also, a VCC value should be chosen such that it can sustain the voltage drops across the LED, the transistor and the sense resistor.

$$\text{VCC} = \text{VLED} + \text{VBJT} + \text{VSENSE} \tag{2}$$

Where,

VLED = 2.1 V to 2.8 V for Red LED & 1.3 V to 1.8 V for IR LED

VSENSE= VDAC (programmable) from 0 V to 2.5 V

2.2 Using SAC as TIA and Gain Stage

Figure 4 shows an approximate model of a photodiode and circuit for TIA with gain stage. The photodiode model assumes to have the received signal with both AC and DC components. For more details, see *How to Design an SpO2 and OHRM System Using AFE4403*. The first OA (OA0) forms a TIA stage converting the current signal in voltage terms followed by a gain stage (OA2) for amplification.

To configure SAC as a TIA, put PSEL=01, NSEL=00, MSEL=xx and connect photodiode, external resistor and capacitor (for filtering). For the subsequent gain stage, the SAC can be put in:

- General purpose mode (PSEL=00, NSEL=00, MSEL=xx) and using external resistors to set gain, or
- Inverting PGA mode (PSEL=01, NSEL=01, MSEL=00) and using internal programmable gain values

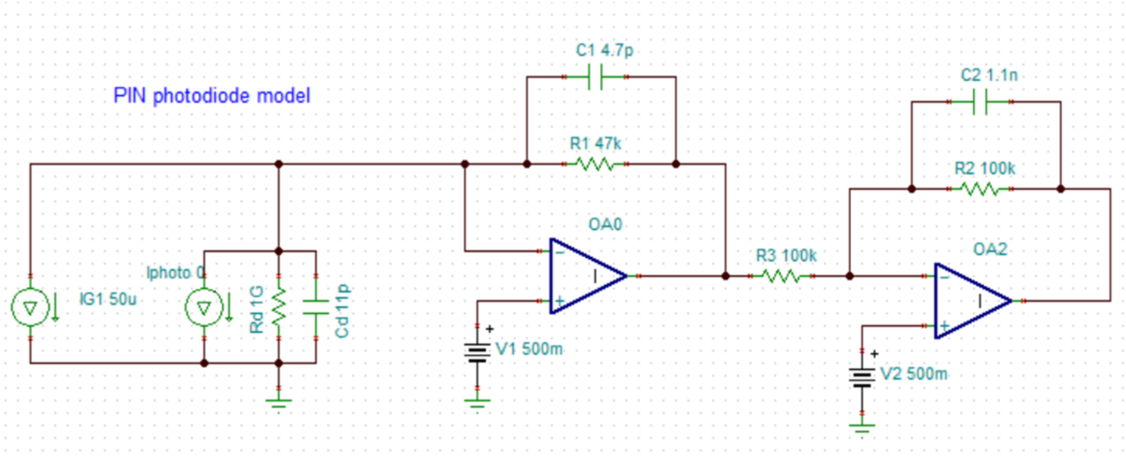

Figure 4. Simulation of TIA and Gain Stage

The outputs of the first stage can be sampled to regulate the LED brightness and, hence, the photodiode current in order to keep the OA from saturating. The sampled values can also be used for tracking the DC component of the photodiode signal and varying the DAC output of the second OA accordingly to extract only the AC component.

2.3 Power Management

Handheld small pulse oximeters are typically powered using two AAA batteries. The discharge in battery voltage (can go till 1.8 V) may lead to improper functioning of the MCU and the transmit chain may shut down. Hence, to ensure proper functionality, designers need to regulate the battery voltage and boost it up to 3.3 V to maintain sufficient margin. (Typical MCU working voltage range is 1.8 V to 3.6 V).

The battery voltage can be increased by either using a dedicated boost converter device (Figure 5) or using discrete boost converter (Figure 6).

- TPS613221A is a synchronous boost converter with only 6.5-µA quiescent current.

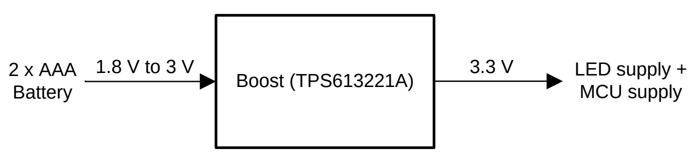

Figure 5. Using TPS613221A to Boost the Battery Voltage

- A discrete boost converter can be implemented by controlling the gate switching through a PWM signal generated from the timer of the MCU and sensing the output voltage by the ADC and varying the duty cycle of the PWM accordingly.

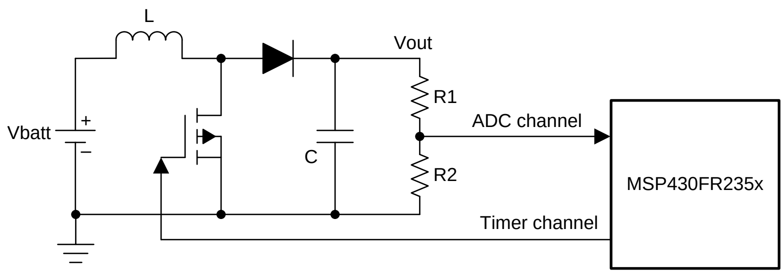

Figure 6. Discrete Boost Converter Implementation

3 Key Benefits

- Reduction in solution size: The MSP430FR235x comes in a small 6 x 6 mm VQFN40 and 4 x 4 mm VQFN32 package. It integrates four SACs (configurable signal chain), temperature sensor, precise voltage reference, and internal clock oscillators. Overall, it eliminates the use of multiple external components.
- Ease of fabrication and assembly of printed circuit board (PCB) due to high integration. With the rich internal connection, the pin usage amount can be saved and external connections will be simpler.
- Improved software infrastructure: Internal Read Only Memory (ROM) library can help save code size and power consumption. It can also help designers with their implementation of algorithms.

4 Summary

The MSP430FR235x device not only enables true single chip pulse oximeter design, but also helps in reducing the form factor of the overall solution due to integrated analog signal chain elements.

5 References

- Texas Instruments: *A Single-Chip Pulsoximeter Design Using the MSP430*
- Texas Instruments: *How to Use the Smart Analog Combo in MSP430™ MCUs*
- Texas Instruments: *How to Design an SpO2 and OHRM System Using AFE4403*