SLEEP MODE AND OTHER LOW POWER STRATEGIES

Application Note

by: Tony Parakka

There is a great demand to reduce operating power for applications in the medical and industrial markets. Advances in battery technology have enabled otherwise AC powered medical equipment to become battery powered, making them cordless, compact and convenient for the patient. Industrial applications have seen a revolution with IoT technology, with strategies for sensing going to a node based, battery powered wireless transmitting module. The move to battery operated equipment - which sets an energy budget before requiring re-charge or replacement of the battery, imposes a requirement on every component in the electronics circuit as well as on data collection strategies to minimize power consumption and thereby maximize operating time on the battery's charge.

Low and ultra-low SMI pressure sensors such as the SM7000/6000/5000 and SM9000 series from TE Connectivity (TE) find extensive use in personal patient care and patient support medical equipment such as continuous positive airway pressure (CPAP) machines, ventilators, oxygen concentrators, etc. which are increasingly battery powered. Similarly, wireless sensor modules are being integrated into conventional building management systems to improve control and operational efficiency. Wireless and battery-operated sensors are desirable since they can be installed in areas which are often remote from AC power and system control wiring. In such applications, it becomes necessary to find means and methods to further reduce the operating power required by the pressure sensor.

In this application note, we explore several methods to reduce power requirements by the pressure sensor. Pros and cons of each method will be discussed to help select an optimal configuration for any given application.

For improved readability, the SM7000/6000/5000 and SM9000 series devices will be referred to as SM-series, and where specific data is needed, the performance figures for the SM7331 from SM7000/6000/5000 datasheet will be used. The methods discussed will apply equally well to other sensors in the SM-series.

Focus on configuration features needed

Application requirements can make it advantageous to use digital pressure data, or an analog voltage for pressure information. While it is helpful in general to have more features in a sensor, in energy limited designs choosing a sensor with just the right feature set can help reduce power consumption. One area for substantial power savings with sensors in the SM-series is by choosing the output configuration best suited for the application. SM-series devices are offered with digital (I^2C) output only (SMxx3x devices), and with both digital (I^2C) + analog voltage outputs (SMxx9x devices).

In many applications pressure data must be fused with data from other sensors in order to make a system level decision and take action. Such systems will benefit from receiving digital pressure data on an I^2C communication bus, such as in the SMxx3x series. The I^2C output on the SMxx3x devices adds the benefits of sharing the data bus with other sensors and also improving immunity to noise. However, the response to a pressure input is delayed by the time required by the system microprocessor to read the data serially, manipulate it and compare it against a threshold. Systems utilizing digital output type sensors should therefore carefully evaluate how such a delay impacts critical response time.

Systems that also need to respond faster to pressure input will benefit from sensors that have an I^2C output as well as an analog voltage output, such as the SMxx9x. In such systems, the microcontroller can use the digital data to execute supervisory control, to monitor and validate sensor operation and may use analytics on the data to take pressure history-based actions. At the same time, the analog voltage output may be used to respond rapidly to abnormal events e.g. closing or opening a relief valve in response to a pressure spike.

The SMxx9x utilize an internal digital to analog converter (DAC) module to convert the digital data (such as from the SMxx3x devices) into an analog output voltage on the AODO pin, and therefore consumes an additional amount of power compared to the SMxx3x devices.

Typical operating current for the SM7331 (digital output only) and SM7391 (digital + analog output) are as shown in Table-1.

Table-1: Operating current for digital output only and digital and analog output

Output Configuration	Device	I(mA) @Vdd=5v
Digital I^2C only	SM7331	3.0
Digital + Analog	SM7391	4.5

Power consumption in the sensor can be reduced by 33% just by choosing a digital-only output configured sensor in case an analog output is not required. In the following sections, we discuss how other low-power strategies such as sleep mode, idle mode and power off method can be used to further reduce in power consumption in the sensor.

Utilizing sleep mode in case of long intervals between reads

Many applications, such as full-day patient monitoring devices, do not need to measure pressure continuously. Pressure monitoring may only be needed hourly, at meal times, or only a few times a day. In such cases, the average power consumption of the sensor can be significantly reduced by putting the sensor into sleep mode.

The SM-series sensors can be put into sleep mode by sending the 16-bit value 0x6C32 to the Command Register, at register address 0x22. The sensor returns to normal operation mode with a rising edge on the I^2C clock input (SCL), such as from initiating a dummy read command. On wakeup, the system must wait 5ms until the output is valid for a read.

In sleep mode, all functional blocks other than the wakeup detect circuitry is turned off, and current consumption is reduced to 6.5µA (typ.). Average current consumption is calculated as the time weighted average of active current during the time the sensor is active and communicating with the microcontroller and sleep current during the time the sensor is in sleep mode.

Example: In this example we estimate average current I_{avg} consumed by a SM7331 sensor (I^2C output only) in a system that puts it in sleep mode between making a pressure measurement at various measurement period T_{tot}.

$$I_{avg} = \frac{I_{act} * T_{act} + I_{slp} * T_{slp}}{T_{act} + T_{slp}}$$

I_{act} = Current during active period (3.0mA)

$T_{act} = T_{wakeup} + T_{pressureRead} + T_{slpCmd}$

T_{wakeup} = Wake up time from sleep (5ms)

Appendix-1 shows how to estimate $T_{pressureRead}$ and T_{slpCmd}

T_{act} = 5ms + 120us + 95us = 5.215ms

I_{slp} = Current during sleep mode (6.5µA)

T_{slp} = Time in sleep mode

$T_{slp} = T_{tot} - T_{act}$

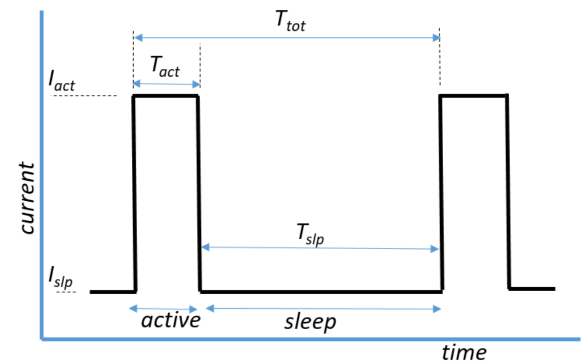

Figure-1: Measurement cycle with active and sleep periods

Table-2 shows average current consumed by the SM7331 using sleep mode between pressure measurements, for a various measurement periods T_{tot}.

Table-2: Average current with sleep mode for various measurement periods

Measurement period T_{tot}	T_{tot} (ms)	T_{act} (ms)	T_{slp} (ms)	I_{avg} (µA)
1 second	1000	5.215	994.8	22.1
1 minute	60000	5.215	59994.8	6.8
10 minutes	600000	5.215	599994.8	6.5

Using idle mode for less sporadic reads

Some applications may require a pressure measurement faster than the power on time typical of waking the sensor from sleep mode. In this case, the sensor can be put into Idle mode by writing 0x7BBA to the Command register at register address 0x22. In Idle mode, the analog front end is shut down while all the digital registers remain readable. For the SM7331, current consumption in idle mode is 0.8mA (typ).

In order to return from idle mode back to measurement mode, the microcontroller must put the sensor into run mode, by writing 0x8B93 to the Command register. After the run command is received, outputs are active within 1ms (typ).

Average current consumption by the sensor when using idle mode can be calculated in the same manner as in the previous example.

Example: This example shows how to estimate average current of a SM7331 sensor in a system which puts it in idle mode between pressure measurements, for various measurement periods T_{tot}.

$$I_{avg} = \frac{I_{act} * T_{act} + I_{idl} * T_{idl}}{T_{act} + T_{idl}}$$

I_{act} = Current during active period (3.0mA)

$T_{act} = T_{runCmd} + T_{startup} + T_{pressureRead} + T_{idleCmd}$

$T_{startup}$ = Startup time from idle (1ms)

Appendix-1 shows how to estimate T_{runCmd}, $T_{pressureRead}$ and $T_{idleCmd}$

T_{act} = 95us + 1ms + 120us + 95us = 1.31ms

I_{idl} = Current in idle mode (0.8mA)

$T_{idl} = T_{tot} - T_{act}$

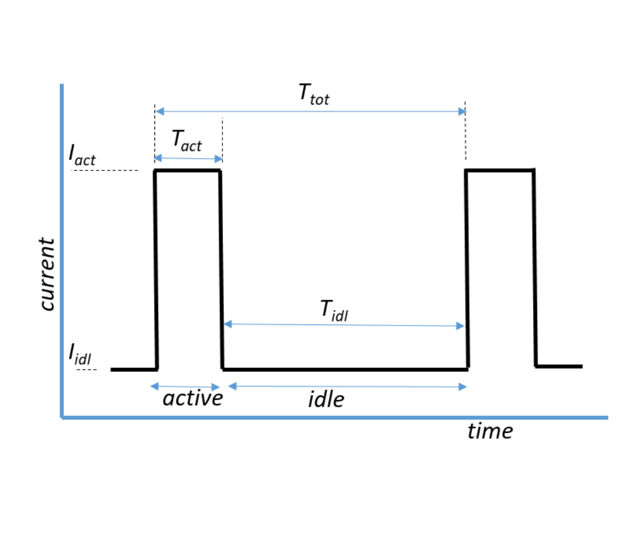

Figure-2: Measurement cycle with active and idle periods

Table-3 shows average current consumed by the SM7331 when idle mode is used between reading pressure, for various measurement periods T_{tot}.

Table-3: Average current with idle mode for various measurement periods

Measurement period T_{tot}	T_{tot} (ms)	T_{act} (ms)	T_{idl} (ms)	I_{avg} (µA)
1 second	1000	1.31	998.7	802.9
1 minute	60000	1.31	59998.7	800.0
10 minutes	600000	1.31	599998.7	800.0

External power control for reducing current consumption between measurements

In applications that require extreme power conservation – such as in applications operating on a coin cell battery, even the 6.5µA sleep mode current can significantly impact battery life. In such situations, average current can be further reduced by using an external switch such as a, Metal Oxide Semiconductor Field Effect Transistor (MOSFET) to turn off power to the pressure sensor. For this discussion, we'll use a simple power on/off circuit using a p-channel enhancement MOSFET (e.g. RV3CA01ZP from Rohm Semiconductor), as shown in Figure-3.

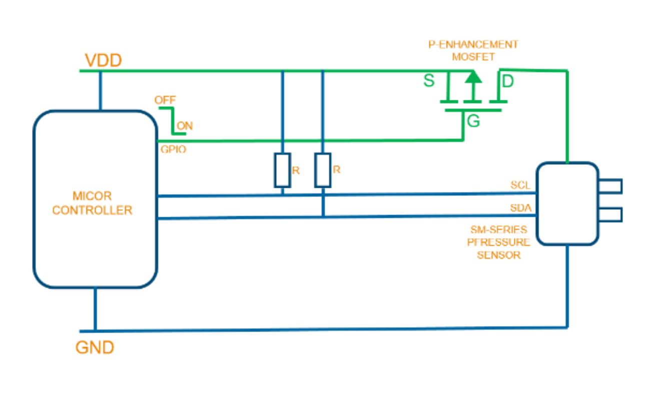

Figure-3: External MOSFET for power control to sensor

The sensor is turned on by pulling the gate terminal of the MOSFET – which is tied to GPIO-pin, to a digital low state. In this state, the gate-to-source voltage (Vgs) of the MOSFET is greater (in magnitude) than its threshold voltage (Vth), which causes the MOSFET to conduct power to the sensor.

The sensor is turned off by raising the GPIO-pin to a digital high state. This makes V_{gs} less than V_{th}, which causes the MOSFET to turn off and cut power to the sensor.

In the power-off state, current through the sensor is the MOSFET's drain to source leakage current, which generally is in the range of 1µA for a small signal MOSFET, like the RV3CA01ZP. Average sensor current in such a system can be calculated in the same manner as in the previous examples.

Example: As a final example, we estimate average sensor current in a system that turns off power to the SM7331, between reading pressure at various measurement times T_{tot}.

$$I_{avg} = \frac{I_{act} * T_{act} + I_{pof} * T_{pof}}{T_{act} + T_{pof}}$$

I_{act} = Current during active period (3.0mA)

$T_{act} = T_{ton} + T_{wakeup} + T_{pressureRead} + T_{tof}$

T_{act} = 1ms + 5ms + 120us + 1ms = 7.12ms

Appendix-2 shows how to estimate T_{ton}, T_{tof} and $T_{pressureRead}$

I_{pof} = Current in power off mode (1μA)

$T_{pof} = T_{tot} - T_{act}$

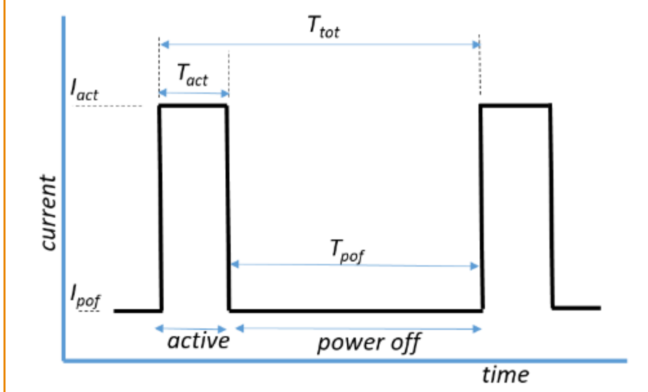

Figure-4: Measurement cycle with active and power-off periods

Table-4 shows average current consumed by the SM7331 when it is powered off between reading pressure, for various measurement periods T_{tot}.

Table-4: Average current with power off for various measurement periods

Measurement period T_{tot}	T_{tot} (ms)	T_{act} (ms)	T_{pof} (ms)	I_{avg} (µA)
1 second	1000	5.124	994.9	16.4
1 minute	60000	5.124	59994.9	1.3
10 minutes	600000	5.124	599994.9	1.0

In each of the power reducing strategies discussed, if additional sensor registers need to be read, then time to read those registers should be added to Tact for average current calculation.

Summary of operating modes for reduced operating current

Table-5 shows a snapshot of operating current for a number of operating modes and for various measurement periods.

Table-5: Average current in various low power modes

Measurement Period	Idle mode (µA)	Sleep mode (µA)	Off mode (µA)
1 second	802.9	22.1	16.4
1 minute	800.0	6.8	1.3
10 minutes	800.0	6.5	1.0

Table-6 summarizes entry/exit methods for the various low power strategies, and some pros and cons associated with each

Table-6: Entry and exit methods for low power modes, with pros and cons

Low power mode	Entry method	Exit method	Pro / Con
Digital-only / Digital + Analog	Choose SMxx3x (digital only) / SMxx9x (digital + analog)		Pro: Substantial power saving, Factory option Con: Fixed feature
Idle mode	write 0x7BBA to CMD (0x22)	write 0x8B93 to CMD (0x22)	Pro: Faster response Con: Higher inactive state current
Sleep mode	write 0x6C32 to CMD (0x22)	Rising edge on SCL	Pro: Lower average current Con: Longer wakeup time
Power off mode	Microcontroller cmd to GPIO	Microcontroller cmd to GPIO	Pro: Very low average current Con: Additional component, longer wakeup time

Summary of Operating modes for reduced operating current

A number of low power operating modes are possible with the SM-series family of pressure sensors for reducing operating current. The best low power mode for an application will depend upon the specific requirements of data sampling and power conservation. Idle and sleep modes are directly programmed from the system microcontroller and can reduce average current to 0.8mA and 6.5µA respectively. With the addition of an external MOSFET driven by the system microcontroller, average current can be reduced to little as 1µA making the sensor suitable for coin cell operated systems. In all cases, average current approaches the inactive state current (sleep current, idle current, power-off current) when the time between measurements becomes very large compared to the active measurement time.

APENDIX-1: I^{2}C Communication times with SM-series sensors

The general I^{2}C communication protocol for the SM7331 is shown in Figure-5.

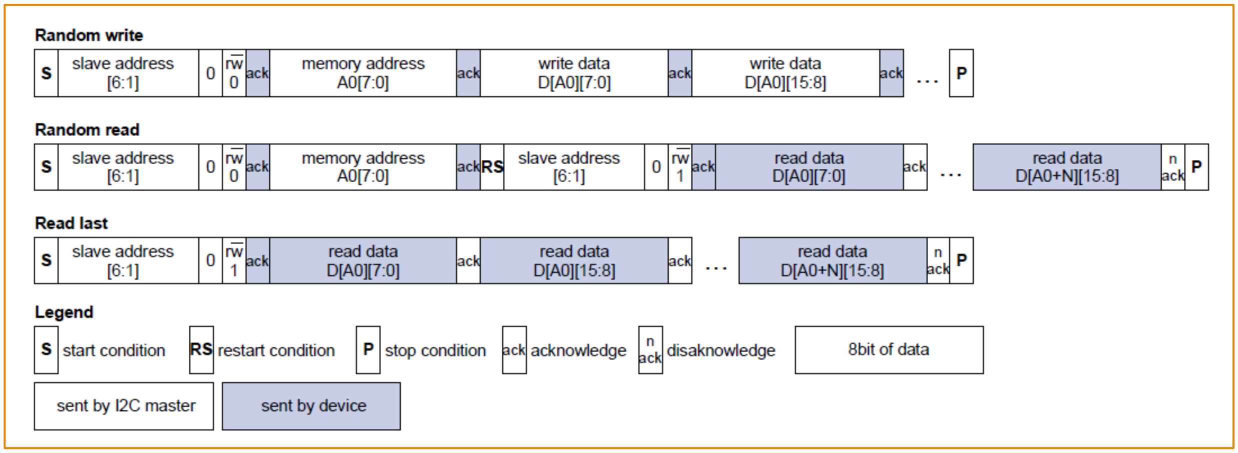

Figure- 5: I^{2}C command format for the SM7331

The protocol shows,

1) Each bit is transferred with a clock period
2) Each communication frame starts with a Start condition and ends with a Stop condition, each being 1 clock period long
3) Each byte transferred requires 8 clock periods and 1 additional period for the Acknowledge condition
4) In case of a random read, after the memory address is acknowledged, a Restart condition is sent, which is one clock period long.

Time for a clock cycle (t_{clock}) for the 400KHz I^{2}C clock rate is

t_{clock}= 1/f_{clock} = 1/400KHz = 2.5us

Counting clock periods, we can estimate the following

Time for a writing Sleep / Idle / Run command = time for 1-byte random-write

($T_{sleepCmd}$, $T_{idleCmd}$, T_{runCmd}) = (S+ (8+1)+ (8+1)+ (8+1)+ (8+1)+ P) * t_{clock} = 38*2.5us = 95us

Time for reading Pressure = time to random-read 2 bytes from the pressure register

$T_{pressureRead}$ = (S+ (8+1) + (8+1) + RS + (8+1) + (8+1) + (8+1) +P)*t_{clock} = 48*2.5us = 120us

APPENDIX-2: Estimating time to power the Sensor on and off with an external MOSFET switch

We will use a conservative approach to estimating time to turn off power to the SM-series pressure sensor in a circuit such as shown in Figure-1, using a hypothetical microcontroller with a 20MHz clock frequency that needs ~10 clock cycles to execute and instruction. We will also use a low signal MOSFET switch (e.g. RV3CA01ZP), with 1µs turn on and turn off time.

The time to turn power to the sensor on and off, is the sum of time the microcontroller takes to set its GPIO-pin on/off (T_{gpio}), and the time the MOSFET switch takes to turn itself on/off (T_{son}, T_{sof}).

$T_{ton} = T_{gpio} + T_{son}$

$T_{toff} = T_{gpio} + T_{soff}$

A microcontroller will need to execute a set of instructions such as the following to set the GPIO-pin high

Read GPIO state and copy to register B (regB),

OR regB with 8bit_GPIO_turnOFF mask // sets the specific bit=high in working regB

Write regB to GPIO // this sets the GPIO-pin=High, which will turn the MOSFET off.

In order to set the GPIO-pin low, the instruction set would look like this

Read GPIO state and copy to regB

AND regB with ! (8bit_GPIO_turnOFF mask) // sets the specific bit=Low in register B

Write regB to GPIO // set the GPIO-pin=low, which turns the MOSFET on, powering the sensor.

So, a total of 6 instructions are required. Considering a microcontroller with a 20MHz clock, which executes each instruction in 10 clock cycles, time to set a GPIO-pin high or low is calculated as:

T_{gpio} = number of instructions * clock periods per instruction * µC clock period

= 6 * 10 * (1/20MHz) = 3µs

The time to turn the MOSFET on - or off, depends on the amount of gate charge. In the case of a small signal mosfet such as the RV3CA01ZP, the gate capacitance is small, and the MOSFET turn on/off time is 1µs max.

$T_{son} = T_{soff} = 1\mu s$

Therefore

$T_{ton} = T_{gpio} + T_{son} = .003ms + .001ms = 0.004ms$

$T_{toff} = T_{gpio} + T_{soff} = .003ms + .001ms = 0.004ms$

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TE CONNECTIVITY
For more information
contact TE Connectivity

Tel. +1 800 522 6752
customercare.mlpt@te.com