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nanoWatt and nanoWatt XLP™ Technologies: An Introduction to Microchip's Low-Power Devices

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INTRODUCTION

Power consumption has always been an important consideration for the design of any electrical system. This includes the embedded systems at the heart of countless modern devices and the microcontrollers that make most of these systems work. The expansion of embedded systems into markets, such as portable electronics, metering applications and medical devices, has caused power consumption to become one of the foremost concerns for embedded system designers. It is important that a microcontroller not only consume as little power as possible, but also provide features that allow for minimal power consumption in the rest of the design as well. To design the best possible system, the engineer must understand all of the power-saving features that a microcontroller might offer – not only to make the best device selection, but how to exploit these features for the most economical power system.

This application note reviews the power-saving technology in current PIC® microcontrollers, particularly nanoWatt and nanoWatt XLP Technologies. It also discusses how to select the best low-power device for a design and how to use these features to the best advantage.

UNDERSTANDING POWER CONSUMPTION

Before discussing the details of low-power operation, it may be useful to review the factors that make up power consumption. When we consider power consumption in microcontrollers, we are actually considering two components: dynamic power and static power.

Dynamic power is the current consumed by the switching of digital logic. It is mainly influenced by clock speed, although voltage and temperature also have an impact. For this reason, controlling dynamic power is largely a matter of controlling clock speed.

Static power is the current consumed when the main clock is disabled. It is composed mainly of transistor leakage and the current used by voltage supervisors. For many PIC devices, it also includes the clocking of logic necessary to resume operation from the Static mode (e.g., Watchdog Timers).

Static power is affected by the voltage level and temperature, which both have a large impact on the major component of transistor leakage. So, while much of static power consumption is dictated by device design and the manufacturing process, some elements may be influenced by the user.

Since voltage contributes to both static and dynamic power, an application with flexible voltage requirements can benefit from using the lowest supply voltage as the application will allow. For PIC devices with a separate core voltage input (V_{DDCORE}), it is important to note that the core voltage has the most impact on both static and dynamic power.

nanoWatt AND nanoWatt XLP TECHNOLOGIES

For PIC microcontrollers, the original low-power standard was referred to as nanoWatt Technology. Since its introduction in 2003, nanoWatt Technology has become the standard for all new PIC microcontrollers. The primary requirement to be considered a nanoWatt device was an overall power consumption in the nanoWatt range while in Sleep mode. Several new power-saving features were also introduced at the same time:

- Idle mode
- On-chip, high-speed oscillator (INTOSC) with PLL and programmable postscaler
- WDT with extended time-out interval
- Ultra Low-Power Wake-up (ULPWU)
- Low-power option for Timer1 and the secondary (32 kHz) oscillator
- Low-power, software-controllable BOR

The most recent changes to nanoWatt Technology are collectively known as "nanoWatt XLP™ Technology". This version represents a significant reduction of power consumption over the original nanoWatt Technology. To meet the nanoWatt XLP Technology specification, a PIC microcontroller is required to have typical current consumption of less than the following:

- 100 nA for Power-Down Current (I_{PD})
- 800 nA Watchdog Timer Current (I_{WDT})
- 800 nA Real-Time Clock and Calendar (I_{RTCC})

Currently, nanoWatt XLP Technology is available in the most recent members of Microchip's non-DSP microcontrollers, including PIC16, PIC18, PIC24F and PIC32.

All versions of nanoWatt Technology use a combination of proprietary process geometry design techniques, as well as power management features, to reduce power consumption wherever possible. A key part of this strategy is the use of operating modes: a range of software-selectable hardware configurations that allow an application to change its power consumption during run time at will.

Table 1 summarizes the different operating modes available in nanoWatt and nanoWatt XLP Technologies. All of these (with the exception of Run mode, which represents baseline full-power operation) are explained in subsequent sections. A brief comparison of power consumption specifications for several Microchip nanoWatt devices, compared to similar devices from other manufacturers, is provided in Table 2.

TABLE 1: POWER-SAVING OPERATING MODES FOR nanoWatt TECHNOLOGY DEVICES

Operating Mode	Active Clocks	Active Peripherals	Wake-up Sources	Typical Current	Typical Usage
Deep Sleep(1)	• Timer1/SOSC • INTRC/LPRC	• RTCC • DSWDT • DSBOR • INT0	• RTCC • DSWDT • DSBOR • INT0 • $\overline{MCLR}$	< 50 nA	• Long life, battery-based applications • Applications with increased Sleep times(3)
Sleep	• Timer1/SOSC • INTRC/LPRC • A/D RC	• RTCC • WDT • ADC • Comparators • CV_{REF} • INTx • Timer1 • HLVD • BOR	All device wake-up sources (see device data sheet)	50-100 nA	Most low-power applications
Idle	• Timer1/SOSC • INTRC/LPRC • A/D RC	All Peripherals	All device wake-up sources (see device data sheet)	25% of Run Current	Any time the device is waiting for an event to occur (e.g., external or peripheral interrupts)
Doze(2)	All Clocks	All Peripherals	Software or interrupt wake-up	35-75% of Run Current	Applications with high-speed peripherals, but requiring low CPU use
Run	All Clocks	All Peripherals	N/A	See device data sheet	Normal operation

Note 1: Available on PIC18 and PIC24 devices with nanoWatt XLP™ Technology only.
2: Available on PIC24, dsPIC and PIC32 devices only.
3: Refer to **"Deciding Between Sleep and Deep Sleep"** for guidance on when to use Sleep or Deep Sleep modes.

TABLE 2: COMPARISON OF ELECTRICAL SPECIFICATIONS FOR SELECT LOW-POWER DEVICES

Parameter	Device							
	PIC16LF72X	PIC18F46K20	PIC18LF46J11	PIC16LF193X	PIC18LF14K50	PIC24F16KA102	Atmel® ATmega168P/328P	TI MSP430F21X1/ MSP430F21X2/ MSP430F22X2/4
Deep Sleep (nA)	—	—	13	—	—	20	—	—
Sleep (nA)	20	100	54	60	24	25	100(1)	100
WDT (nA)	500	500	830	500	450	420	4200(1)	300-700
32 kHz Oscillator/RTCC (nA)	600	500	820	600	790	520	800	700
I/O Port Leakage (nA)	±5	±5	±200(2)	±50	±5	±50	±1000(1,2)	±50(2)
1 MHz Run (μA)	110	300	272	150	170	195	300	200-270
Minimum V_{DD}	1.8	1.8	2	1.8	1.8	1.8	1.8	1.8

Legend: All numbers are typical values at minimum device V_{DD} as reported in the most recent device data sheet. Values for WDT and/or RTCC include base Sleep mode current. Sleep data is taken with BOR disabled, if possible.

Note 1: Data for 1.8V is not available for these specifications; data for 3V is shown.

2: Typical data is not available, maximum value is shown.

Deep Sleep Mode

Deep Sleep mode is the lowest static power mode, producing the lowest power consumption possible without removing power to the part completely. Deep Sleep reaches this low-power state by internally removing power from most of the components of the part. The core, on-chip voltage regulator (if present), most peripherals, and (in some cases) RAM, are all powered down in Deep Sleep mode.

Deep Sleep offers exceptionally low current, even on devices using an internal regulator, which normally requires a few microamperes of current. Removing the power from most of the part has the additional benefit of lower current consumption at high temperatures, since there are fewer active circuits that leak current.

Reaching power consumption this low has some trade-offs. Deep Sleep has only a few wake-up sources compared to the variety available in Sleep mode:

- POR Event
- $\overline{\text{MCLR}}$ Event
- RTCC Alarm
- External Interrupt
- Deep Sleep WDT

As a result of removing power from the core, a wake-up from Deep Sleep causes a device Reset rather than resuming from the next instruction, like Sleep mode. The Program Counter and SFRs are reset and the device resumes program execution from the Reset vector. Unlike other Resets, all I/O states, as well as the Timer1/SOSC and RTCC, are maintained to allow for uninterrupted operation of the system as a whole. Additionally, Deep Sleep indication bits are set, and some RAM locations are maintained, in order to notify the software that the Reset is a Deep Sleep wake-up and allow the firmware state to be properly restored.

After a Deep Sleep wake-up occurs, the application needs to Acknowledge the wake-up, reconfigure peripherals and I/O registers, and then resume operation as normal. A high-level flow of the process is shown in Figure 1. Refer to the device data sheet for specific Deep Sleep entry and exit sequences.

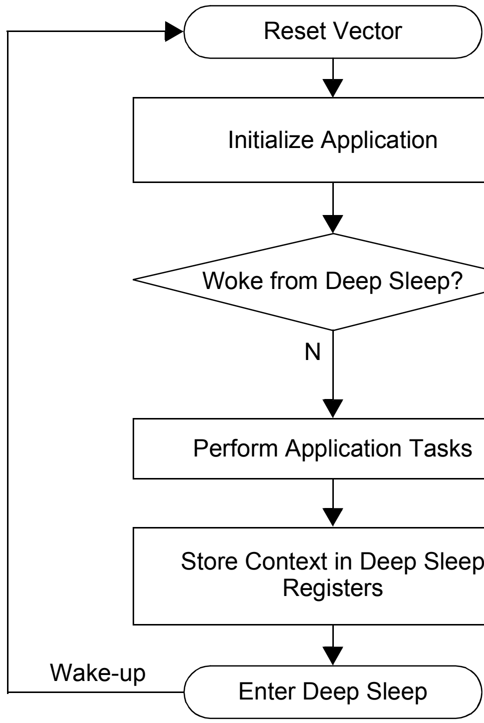
WHEN TO USE DEEP SLEEP MODE

It is important when designing an application to know which low-power mode to use. Deep Sleep mode is intended for use with applications that require very long battery life. The additional requirements for reconfiguring the device after wake-up mean that Sleep mode is better for some applications and Deep Sleep for others.

Ideally, applications that use the Deep Sleep mode have one or more of these characteristics:

- Use long Sleep times (one second or more typical)
- Do not require any peripherals while asleep
- Require accurate timekeeping with minimal current
- Operate in environments with extreme temperatures

FIGURE 1: PROCEDURE FOR WAKE-UP FROM DEEP SLEEP MODE



Sleep Mode

Sleep mode is the standard low-power mode for virtually all PIC microcontrollers; its implementation predates the original nanoWatt Technology. In Sleep mode, the main CPU clock and most peripheral clock sources are shut down, bringing the device to a low-power state. The current device state is maintained, including RAM, SFRs and the Program Counter (PC).

Wake-up sources vary between device families. All PIC devices can use the WDT, the 32 kHz Timer (Timer1 on most devices) and one or more external interrupt sources. PIC18, PIC24 and PIC32 devices also have a number of peripherals that are capable of waking up the device; these include the ADC, comparators and serial communications modules. Total wake-up times also vary between families; most devices implement options to change wake-up time and allow flexibility in design.

WHEN TO USE SLEEP MODE

Sleep mode is the most commonly used and most flexible of the available modes. Typically, there is a very fast wake-up time that requires little to no overhead to handle entry and exit. As a result, it is the best low-power mode for applications that require short Sleep times, and fast wake-up and processing. Sleep is often used in applications with the following characteristics:

- Short loop times with frequent wake-up (generally less than 1 second)
- Require peripheral wake-up sources
- Perform analog sampling with ADC or comparators while asleep

Deciding Between Sleep and Deep Sleep

A helpful way to determine whether Sleep or Deep Sleep is more effective is to calculate the Breakeven Time (T_{BE}) for a particular application. This time indicates how long a device must remain in Deep Sleep mode to have lower total power consumption than Sleep mode, once the higher power requirements for restart from Deep Sleep are accounted for. T_{BE} can be calculated using the three formulas shown in Equation 1.

The first step is to calculate the total charge consumed using Sleep (Q_{SLP}) and Deep Sleep (Q_{DS}). In Sleep, this is simply the Sleep static current (I_{PDSLP}) multiplied by the time the device is in Sleep (T_{PD}) (formula [1]). Charge is used instead of energy because in both cases, the voltage will stay constant, so it can be ignored. Charge also gives an easy comparison to battery capacity specifications when performing power budgeting.

For Deep Sleep, there are three components to the equation: power-up, software initialization and Deep Sleep (formula [2]). The Deep Sleep component, similar to the Sleep energy calculation, is just the Deep Sleep static current (I_{PDDS}) times the Sleep period (T_{PD}).

The POR component includes the POR time (T_{POR}), which starts when the DS wake-up interrupt occurs, until the first instruction is executed. Details on POR time can be found in device data sheets. The POR current (I_{POR}) varies based on a number of device settings and application factors, so it is best taken experimentally. Note that on devices with an internal regulator, the POR time and current will include the time and current required for the regulator to charge the capacitor on the VCAP pin if it has discharged while the device is in Deep Sleep.

The initialization component is the initialization time (T_{INIT}) and current (I_{DD}), starting when the device begins code execution and lasting until the main loop is entered. Both of these vary by application and are best assessed with measurement. However, they can be approximated using published dynamic current specifications to determine current and the Stopwatch feature in MPLAB® IDE to measure the initialization execution time.

Breakeven Time is the point where Q_{DS} and Q_{SLP} are equal. Mathematically, this is the same as setting [1] and [2] to be equal to each other. Solving generically for T_{PD} provides formula [3]; at this point, time in Sleep or Deep Sleep is equivalent to T_{BE}. Deep Sleep should be used if the Sleep duration is longer than T_{BE} and Sleep mode should be used if the Sleep time is shorter than T_{BE}. An application with varying Sleep times can use both Sleep and Deep Sleep to get the most efficient current consumption.

EQUATION 1: CALCULATING BREAKEVEN TIME (DEEP SLEEP vs. SLEEP MODES)

$$Q_{SLP} = T_{PD} \times I_{PDSLP} \qquad [1]$$

$$Q_{DS} = (T_{INIT} \times I_{DD}) + (T_{POR} \times I_{POR}) + (T_{PD} \times I_{PDDS}) \qquad [2]$$

$$T_{BE} = T_{PD} = \frac{(T_{INIT} \times I_{DD}) + (T_{POR} \times I_{POR})}{I_{PDSLP} - I_{PDDS}} \qquad [3]$$

where:

Q_{DS}	=	Total Charge Spent in Deep Sleep
Q_{SLP}	=	Total Charge Spent in Sleep
T_{BE}	=	Breakeven Time (interval at which $Q_{DS} = Q_{SLP}$)
T_{INIT}	=	Initialization Time to Resume Full-Power Operation
T_{PD}	=	Sleep or Deep Sleep Period (defined by context)
T_{POR}	=	Time Required for Power-on Reset
I_{POR}	=	POR Current
I_{PDSLP}	=	Static Current in Sleep mode
I_{PDDS}	=	Static Current in Deep Sleep mode

Idle and Doze Modes

Idle and Doze modes are dynamic power reduction modes that are intended to allow more peripheral functionality than static power modes, such as Sleep, while still reducing current consumption below Run mode. These modes allow for significant power reduction at times when peripheral operation is critical, but CPU activity is not.

Idle mode is a feature introduced with the original version of nanoWatt Technology. In Idle mode, the system clock is removed from the CPU, but is still provided to the peripherals. Depending on the device family, some or all of the peripherals may continue to operate in Idle mode. For PIC24, dsPIC and PIC32 devices, operation in Idle is configurable on a ‘per module’ basis.

In Doze mode (available on PIC24, PIC32 and dsPIC33 devices only), the system clock is split into separate CPU and peripheral clocks. The CPU clock is divided by a specific user-defined factor, while the peripheral clock continues to run at the system clock speed.

WHEN TO USE IDLE AND DOZE MODES

Idle and Doze mode are dynamic modes, so while they consume less power than Run mode, they still consume significantly more power than static modes, like Sleep. As a result, they should be used in cases where it is not possible to enter Sleep, such as:

- Making large DMA transfers (on devices with DMA only)
- Sending or receiving serial data
- Performing high-speed ADC sampling
- Waiting for time-out from synchronous timer
- Waiting for data capture with IC
- Waiting for event using output compare

Any time a loop waiting for a peripheral interrupt to occur would be used, it can be replaced with an entry into Idle or Doze mode. These cases are frequently overlooked, so it is important to review a design for places where the CPU is not being fully utilized to minimize power consumption.

Clock Switching

Also introduced in the original nanoWatt Technology, clock switching is an important low-power feature. This is because it offers enormous flexibility for reducing dynamic current consumption, as clock speed is the most important factor in dynamic power. While Idle and Doze mode both allow the reduction of the speed of the CPU clock, the peripherals are still clocked at full speed and consume full current. Therefore, it is important to be able to reduce the speed of the clocks to the entire device.

The flexible clock switching systems implemented in PIC microcontrollers allow for switching to the most appropriate clock source for a given situation. For example, an application may use a slow clock for code sections that are not time critical, then switch to a full-speed clock source for processing computation intensive or time critical code. Such flexibility is necessary when implementing a low-power system in order to ensure the lowest power consumption possible.

WHEN TO USE CLOCK SWITCHING

As with the other dynamic power-saving modes, clock switching is best used in cases where the use of Sleep or Deep Sleep is not possible. Clock switching should be used instead of Idle or Doze modes in any case where clock speed is not critical for both the CPU and the peripherals, as it can provide significantly lower power than Idle and Doze modes.

CONCLUSIONS

With the introduction of nanoWatt XLP Technology, Microchip continues to focus on power consumption as a key design goal. The result is devices with not only impressive features and performance, but power consumption below long-standing industry minimums.

When creating a low-power application, it is important to approach all aspects of the design from a low-power perspective. This application note has taken an initial look at the low-power modes on PIC microcontrollers with nanoWatt XLP Technology, which are a central source of power savings for many designs.

It is important to be very familiar with how and when these features are used in order to maintain the lowest possible power consumption. Check www.microchip.com/lowpower for future documents covering other important aspects of low-power design.

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