Using the SDRAM on Intel's DE1-SoC Board with Verilog Designs

For Quartus Prime 17.0

1 Introduction

This tutorial explains how the SDRAM chip on Intel's DE1-SoC Development and Education board can be used with a Nios II system implemented by using the Intel Qsys tool. The discussion is based on the assumption that the reader has access to a DE1-SoC board and is familiar with the material in the tutorial *Introduction to the Intel Qsys System Integration Tool*.

The screen captures in the tutorial were obtained using the Quartus® Prime version 17.0; if other versions of the software are used, some of the images may be slightly different.

Contents:

- Example Nios II System
- The SDRAM Interface
- Using the Qsys tool to Generate the Nios II System
- Integration of the Nios II System into the Quartus Prime Project
- Using the Clock Signals IP Core

2 Background

The introductory tutorial *Introduction to the Intel Qsys System Integration Tool* explains how the memory in a Cyclone series FPGA chip can be used in the context of a simple Nios II system. For practical applications it is necessary to have a much larger memory. The Intel DE1-SoC board contains an SDRAM chip that can store 64 Mbytes of data. The memory is organized as 8M x 16 bits x 4 banks. The SDRAM chip requires careful timing control. To provide access to the SDRAM chip, the Qsys tool implements an *SDRAM Controller* circuit. This circuit generates the signals needed to deal with the SDRAM chip.

3 Example Nios II System

As an illustrative example, we will add the SDRAM to the Nios II system described in the *Introduction to the Intel Qsys System Integration Tool* tutorial. Figure 1 gives the block diagram of our example system.

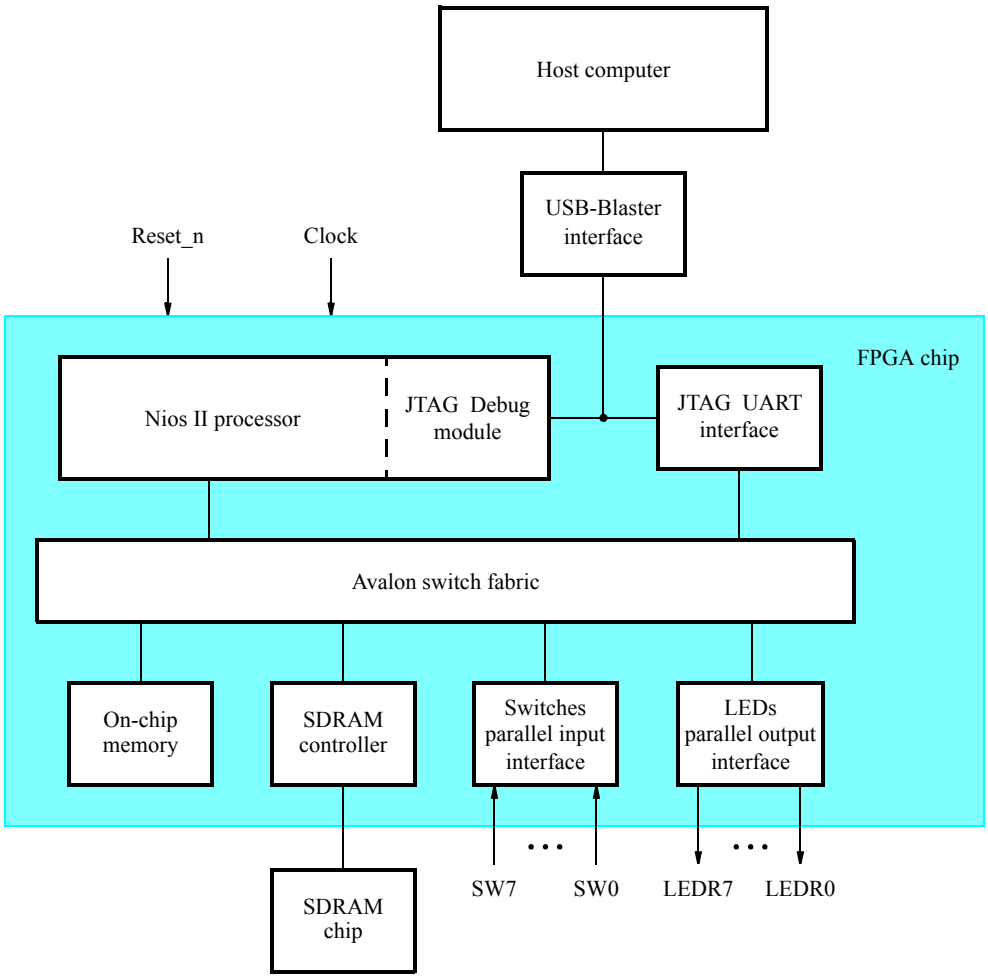

Figure 1. Example Nios II system implemented on the DE1-SoC board.

The system realizes a trivial task. Eight toggle switches on the DE1-SoC board, $SW7-0$, are used to turn on or off the eight red LEDs, $LEDR7-0$. The switches are connected to the Nios II system by means of a parallel I/O interface configured to act as an input port. The LEDs are driven by the signals from another parallel I/O interface configured to act as an output port. To achieve the desired operation, the eight-bit pattern corresponding to the state of the switches has to be sent to the output port to activate the LEDs. This will be done by having the Nios II processor execute an application program. Continuous operation is required, such that as the switches are toggled the lights change accordingly.

The introductory tutorial showed how we can use the Qsys tool to design the hardware needed to implement this task, assuming that the application program which reads the state of the toggle switches and sets the red LEDs accordingly is loaded into a memory block in the FPGA chip. In this tutorial, we will explain how the SDRAM chip on the DE1-SoC board can be included in the system in Figure 1, so that our application program can be run from the SDRAM rather than from the on-chip memory.

Doing this tutorial, the reader will learn about:

- Using the Qsys tool to include an SDRAM interface for a Nios II-based system
- Timing issues with respect to the SDRAM on the DE1-SoC board

Please note that the SDRAM interface described in this tutorial should also work when the user changes to use the Arm-A9 Processor instead of Nios II Processor in the system.

4 The SDRAM Interface

The SDRAM chip on the DE1-SoC board has a capacity of 512 Mbits (64 Mbytes). Each chip is organized as 8M x 16 bits x 4 banks. The signals needed to communicate with a chip are shown in Figure 2. All of the signals, except the clock, can be provided by the SDRAM Controller that can be generated by using the Qsys tool. The clock signal is provided separately. It has to meet the clock-skew requirements as explained in section 7. Note that some signals are active low, which is denoted by the suffix N.

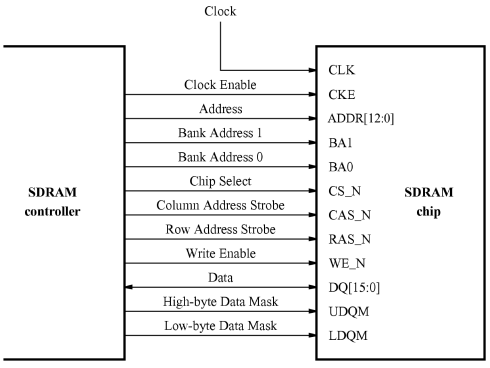

Figure 2. The SDRAM signals.

5 Using the Qsys tool to Generate the Nios II System

Our starting point will be the Nios II system discussed in the *Introduction to the Intel Qsys System Integration Tool* tutorial, which we implemented in a project called *lights*. We specified the system shown in Figure 3.

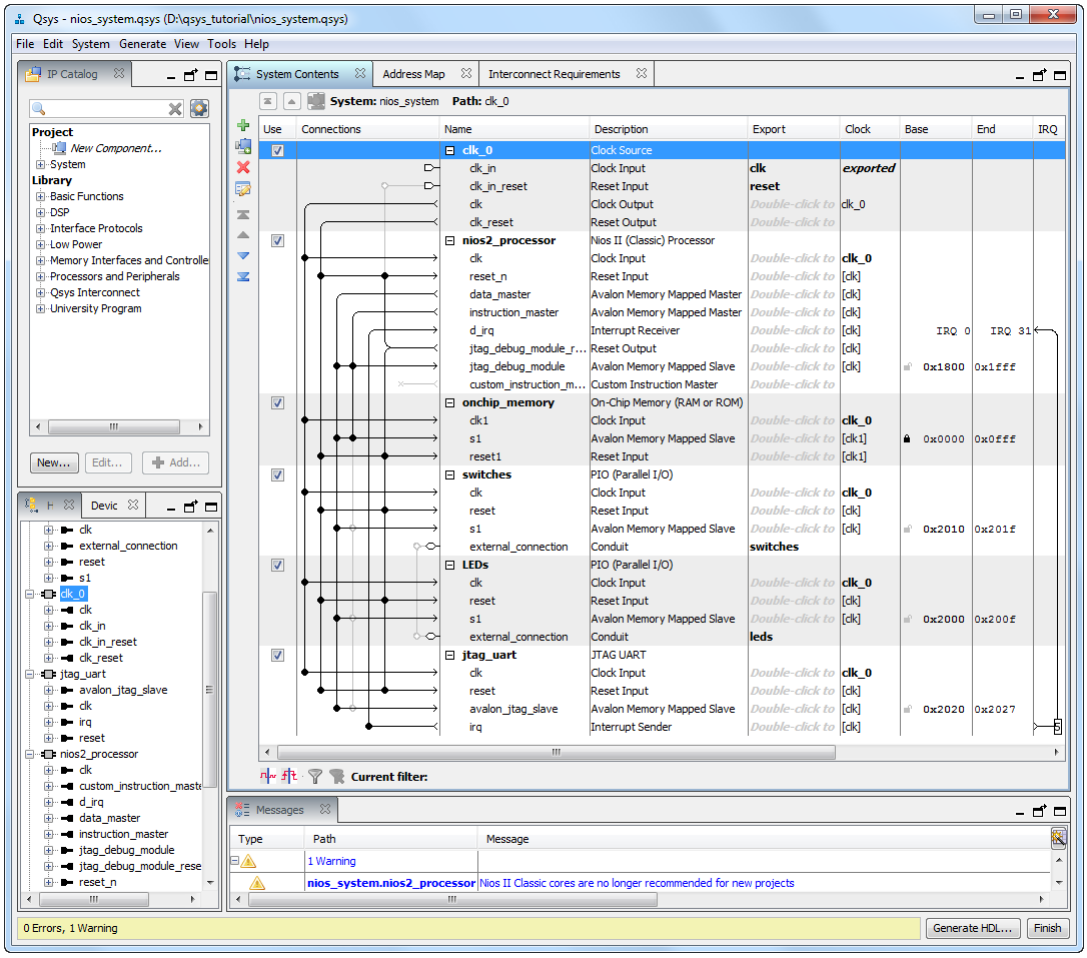

Figure 3. The Nios II system defined in the introductory tutorial.

If you saved the *lights* project, then open this project in the Quartus Prime software and then open the Qsys tool. Otherwise, you need to create and implement the project, as explained in the introductory tutorial, to obtain the system shown in the figure.

To add the SDRAM, in the window of Figure 3 select Memory Interfaces and Controllers > SDRAM > SDRAM Controller and click Add. A window depicted in Figure 4 appears. Set the **Data Width** parameter to **16** bits, the Row Width to **13** bits, the Column Width to **10** bits, and leave the default values for the rest. Since we will not simulate the system in this tutorial, do not select the option Include a functional memory model in the system testbench.

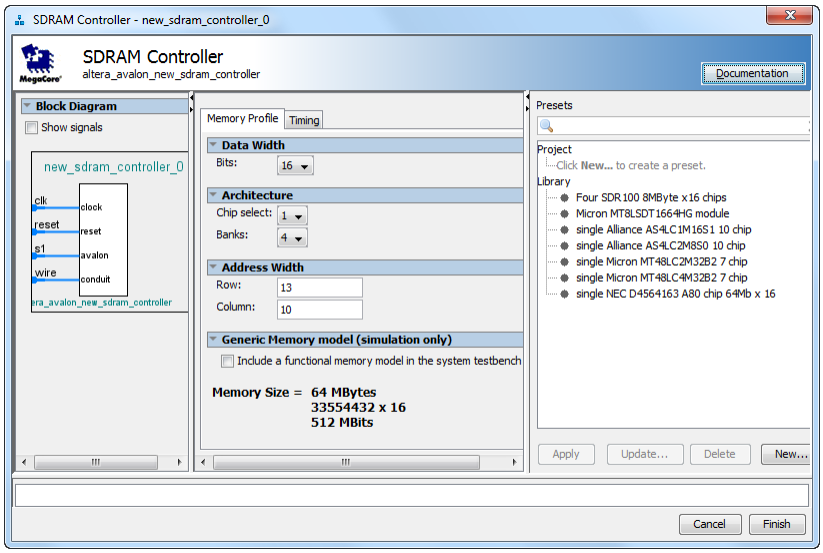

Figure 4. Add the SDRAM Controller.

Select the *Timing* tab to get to the window in Figure 5. Configure the SDRAM timing parameters by setting **Issue one refresh command every** to **7.8125** microseconds, **Duration of precharge command (t_rp)** to **15.0** nanoseconds, **ACTIVE to READ or WRITE delay (t_rcd)** to **15.0** nanoseconds, and **Access time (t_ac)** to **5.4** nanoseconds. Click Finish.

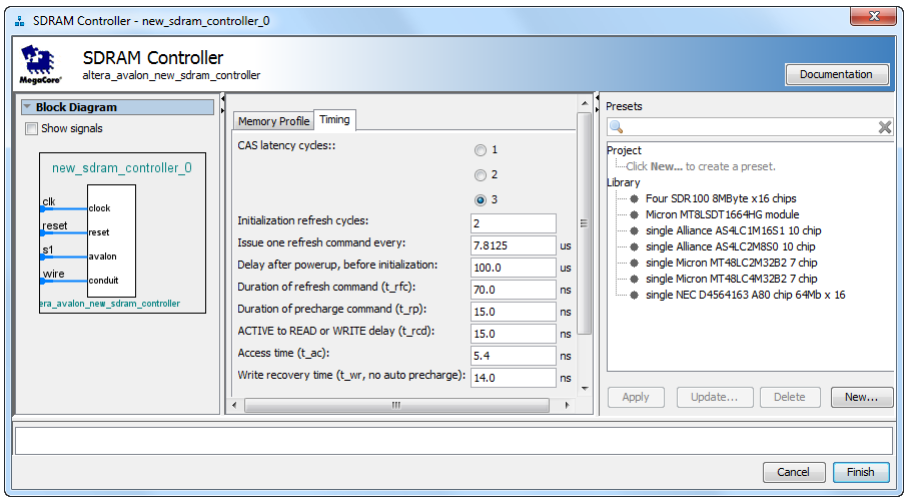

Figure 5. SDRAM Timings

Now, in the window of Figure 3, there will be an **sdram controller** module added to the design. Rename this module to *sdram*. Connect the SDRAM to the rest of the system in the same manner as the on-chip memory, and export the

SDRAM wire port. Double-click on the Base Address of the *sdram* and enter the value 0x08000000 to produce the assignment shown in Figure 6.

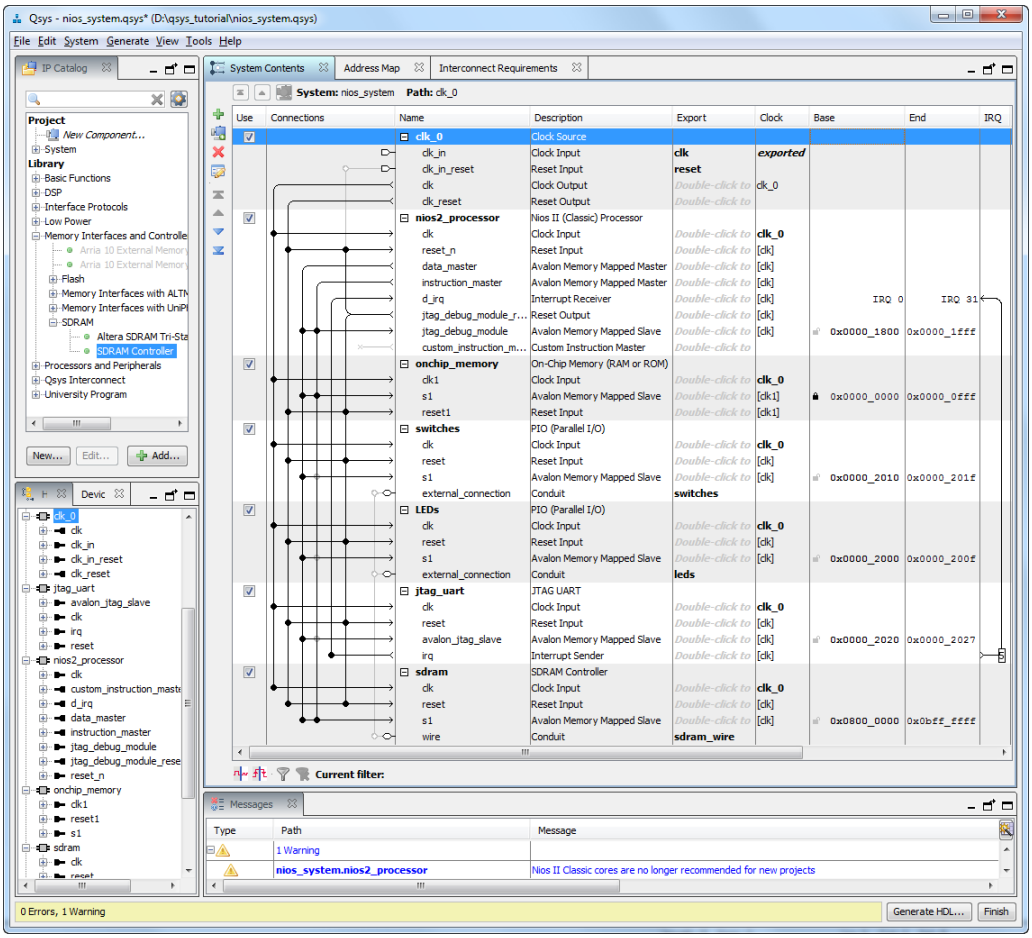

Figure 6. The expanded Nios II system.

To make use of the SDRAM, we need to configure the reset vector and exception vector of the Nios II processor. Right-click on the nios2_processor and then select Edit to reach the window in Figure 7. Select sdram to be the memory device for both reset vector and exception vector, as shown in the figure. Click Finish to return to the System Contents tab and regenerate the system.

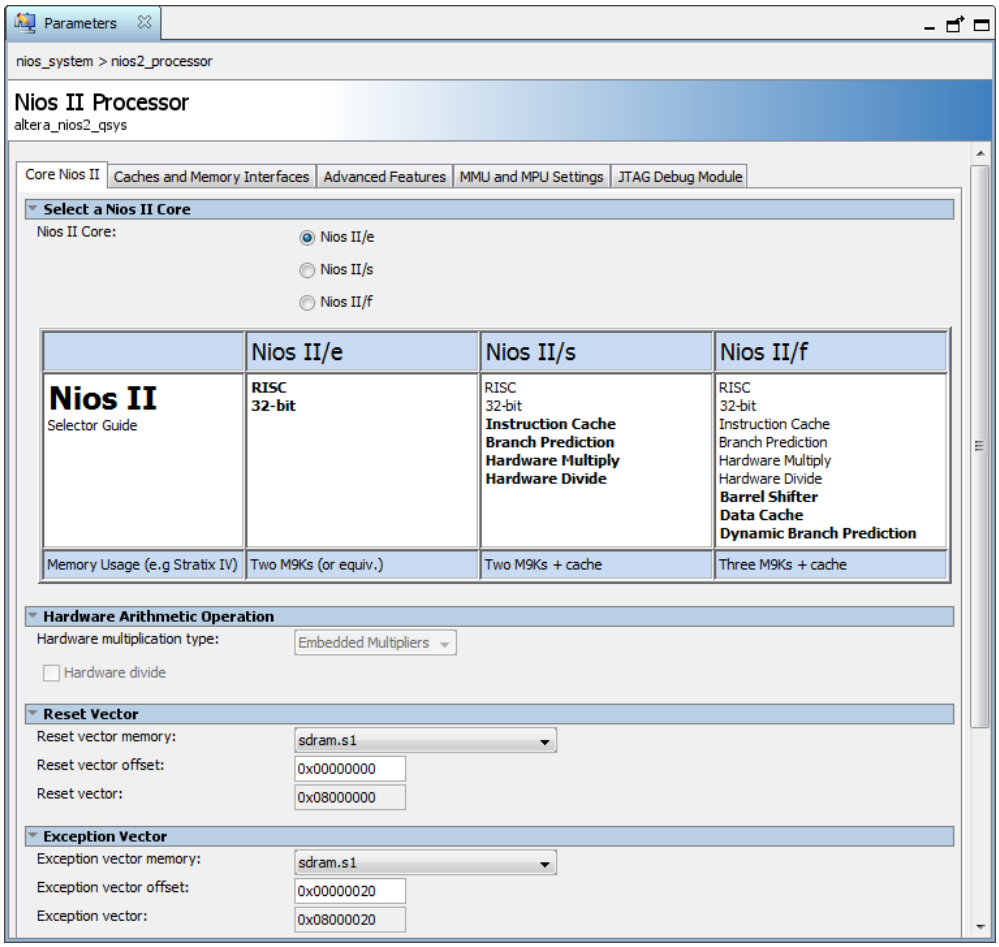

Figure 7. Define the reset vector and the exception vector.

The augmented Verilog module generated by the Qsys tool is in the file *nios_system.v* in the nios_system\synthesis directory of the project. Figure 8 depicts the portion of the code that defines the input and output signals for the module *nios_system*. As in our initial system that we developed in the introductory tutorial, the 8-bit vector that is the input to the parallel port *Switches* is called *switches_export*. The 8-bit output vector is called *leds_export*. The clock and reset signals are called *clk_clk* and *reset_reset_n*, respectively. A new module, called *sdram*, is included. It involves the signals indicated in Figure 2. For example, the address lines are referred to as the **output** vector *sdram_wire_addr[12:0]*. The data lines are referred to as the **inout** vector *sdram_wire_dq[15:0]*. This is a vector of the **inout** type because the data lines are bidirectional.

```
module nios_system (
      input  wire        clk_clk,          //        clk.clk
      input  wire        reset_reset_n,    //      reset.reset_n
      input  wire [7:0]  switches_export,  //   switches.export
      output wire [7:0]  leds_export,      //       leds.export
      output wire [12:0] sdram_wire_addr,  // sdram_wire.addr
      output wire [1:0]  sdram_wire_ba,    //           .ba
      output wire        sdram_wire_cas_n, //           .cas_n
      output wire        sdram_wire_cke,   //           .cke
      output wire        sdram_wire_cs_n,  //           .cs_n
      inout  wire [15:0] sdram_wire_dq,    //           .dq
      output wire [1:0]  sdram_wire_dqm,   //           .dqm
      output wire        sdram_wire_ras_n, //           .ras_n
      output wire        sdram_wire_we_n   //           .we_n
   );
```

Figure 8. A part of the generated Verilog module.

6 Integration of the Nios II System into the Quartus Prime Project

Now, we have to instantiate the expanded Nios II system in the top-level Verilog module, as we have done in the tutorial *Introduction to the Intel Qsys System Integration Tool*. The module is named *lights*, because this is the name of the top-level design entity in our Quartus Prime project.

A first attempt at creating the new module is presented in Figure 9. The input and output ports of the module use the pin names for the 50-MHz clock, *CLOCK_50*, pushbutton switches, *KEY*, toggle switches, *SW*, and red LEDs, *LEDR*, as used in our original design. They also use the pin names *DRAM_CLK*, *DRAM_CKE*, *DRAM_ADDR*, *DRAM_BA*, *DRAM_CS_N*, *DRAM_CAS_N*, *DRAM_RAS_N*, *DRAM_WE_N*, *DRAM_DQ*, *DRAM_UDQM*, and *DRAM_LDQM*, which correspond to the SDRAM signals indicated in Figure 2. All of these names are those specified in the DE1-SoC User Manual and included in the file called *DE1_SoC.qsf*, which can be found on Intel's DE1-SoC web page at https://www.altera.com/support/training/university/boards.html

Finally, note that we tried an obvious approach of using the 50-MHz system clock, *CLOCK_50*, as the clock signal, *DRAM_CLK*, for the SDRAM chip. This is specified by the **assign** statement in the code. This approach leads to a potential timing problem caused by the clock skew on the DE1-SoC board, which can be fixed as explained in section 7.

```
// Implements the augmented Nios II system for the DE1-SoC board.
// Inputs:   SW7−0 are parallel port inputs to the Nios II system.
//           CLOCK_50 is the system clock.
//           KEY0 is the active-low system reset.
// Outputs:  LEDR7−0 are parallel port outputs from the Nios II system.
//           SDRAM ports correspond to the signals in Figure 2; their names are those
//           used in the DE1-SoC User Manual.
module  lights (SW, KEY, CLOCK_50, LEDR, DRAM_CLK, DRAM_CKE,
        DRAM_ADDR, DRAM_BA, DRAM_CS_N, DRAM_CAS_N, DRAM_RAS_N,
        DRAM_WE_N, DRAM_DQ, DRAM_UDQM, DRAM_LDQM);
        input  [7:0]  SW;
        input  [0:0]  KEY;
        input  CLOCK_50;
        output  [7:0]  LEDR;
        output  [12:0]  DRAM_ADDR;
        output  [1:0] DRAM_BA;
        output  DRAM_CAS_N, DRAM_RAS_N, DRAM_CLK;
        output  DRAM_CKE, DRAM_CS_N, DRAM_WE_N;
        output  DRAM_UDQM;
        output  DRAM_LDQM;
        inout  [15:0]  DRAM_DQ;
// Instantiate the Nios II system module generated by the Qsys tool
        nios_system  NiosII  (
                .clk_clk (CLOCK_50),
                .reset_reset_n (KEY[0]),
                .switches_export (SW),
                .leds_export (LEDR),
                .sdram_wire_addr (DRAM_ADDR),
                .sdram_wire_ba (DRAM_BA),
                .sdram_wire_cas_n (DRAM_CAS_N),
                .sdram_wire_cke (DRAM_CKE),
                .sdram_wire_cs_n (DRAM_CS_N),
                .sdram_wire_dq (DRAM_DQ),
                .sdram_wire_dqm ({DRAM_UDQM,DRAM_LDQM}),
                .sdram_wire_ras_n (DRAM_RAS_N),
                .sdram_wire_we_n (DRAM_WE_N)
        );
        assign  DRAM_CLK = CLOCK_50;
endmodule
```

Figure 9. A first attempt at instantiating the expanded Nios II system.

As an experiment, you can enter the code in Figure 9 into a file called *lights.v*. Add this file and all the *nios_system.qip* file produced by the Qsys tool to your Quartus Prime project. Compile the code and download the design into the Cyclone V FPGA on the DE1-SoC board. Use the application program from the tutorial *Introduction to the Intel Qsys System Integration Tool*, which is shown in Figure 10.

```
.equ      Switches, 0x00002010
.equ      LEDs, 0x00002000
.global   _start
_start:
          movia    r2, Switches
          movia    r3, LEDs
loop:     ldbio    r4, 0(r2)
          stbio    r4, 0(r3)
          br       loop
```

Figure 10. Assembly language code to control the lights.

Use the Intel FPGA Monitor Program, which is described in the tutorial *Intel FPGA Monitor Program Tutorial*, to assemble, download, and run this application program. If successful, the lights on the DE1-SoC board will respond to the operation of the toggle switches.

Due to the clock skew problem mentioned above, the Nios II processor may be unable to properly access the SDRAM chip. A possible indication of this may be given by the Intel FPGA Monitor Program, which may display the message depicted in Figure 11. To solve the problem, it is necessary to modify the design as indicated in the next section.

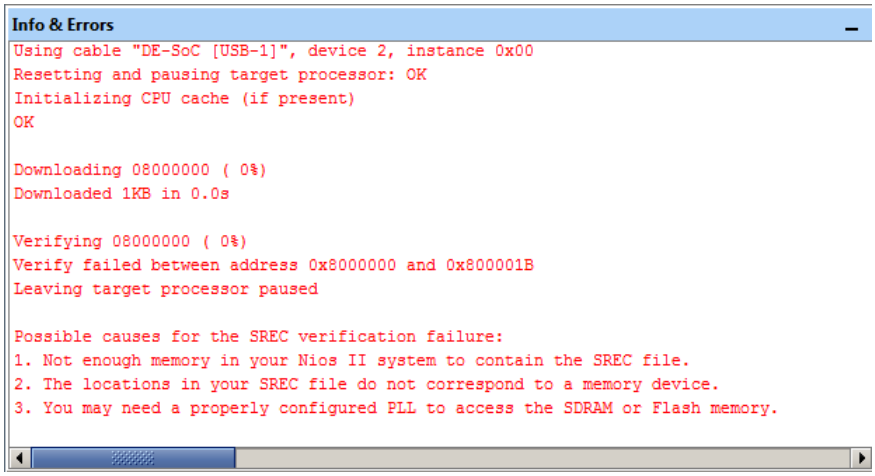

Figure 11. Error message in the Intel FPGA Monitor Program that may be due to the SDRAM clock skew problem.

7 Using the Clock Signals IP Core

The clock skew depends on physical characteristics of the DE1-SoC board. For proper operation of the SDRAM chip, it is necessary that its clock signal, *DRAM_CLK*, leads the Nios II system clock, *CLOCK_50*, by 3 nanoseconds. This can be accomplished by using a *phase-locked loop (PLL)* circuit which can be manually created using the *IP Catalog*. It can also be created automatically using the Clock Signals IP core provided by the Intel FPGA University Program. We will use the latter method in this tutorial.

To add the Clock Signals IP core, in the Qsys tool window of Figure 5 select University Program > Clock > System and SDRAM Clocks for DE-Series Boards and click Add. A window depicted in Figure 12 appears. Select *DE1-SoC* from the DE Board drop-down list. Click Finish to return to the window in Figure 5.

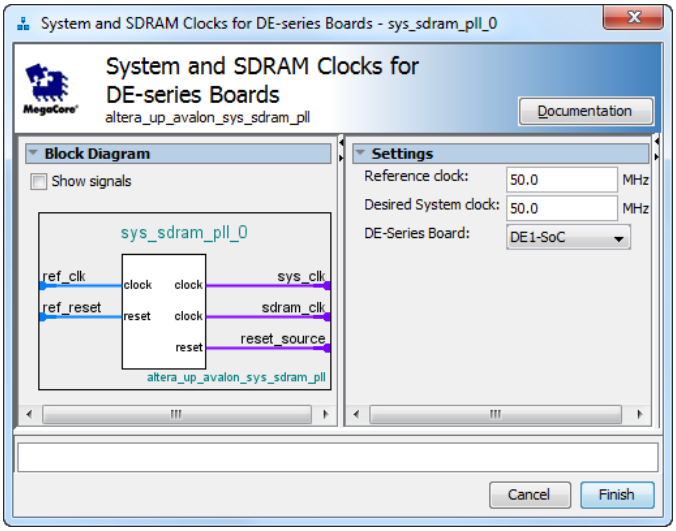

Figure 12. Clock Signals IP Core

Remove the system clock component *clk_0*. All other IP cores (including the SDRAM) should be adjusted to use the *sys_clk* output of the Clock Signal core. Rename the Clock Signal core to *clocks* and export the *sdram_clk* signal under the name *sdram_clk*, the *ref_clk* signal under the name *clk*, and *ref_reset* signal under the name *reset*. The final system is shown in Figure 13. Click on Generate > Generate HDL... and regenerate the system.

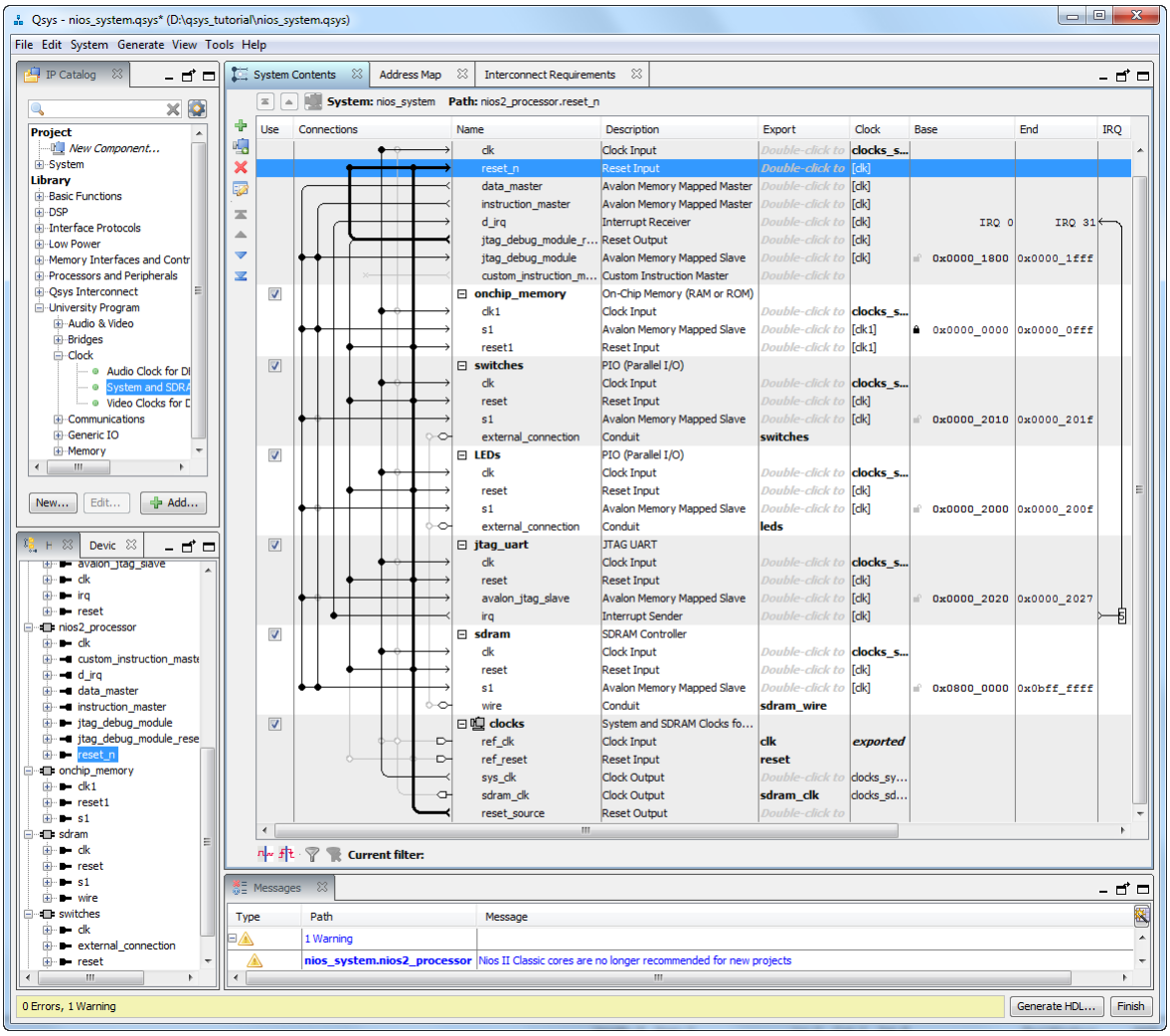

Figure 13. The final Nios II system.

Next, we have to fix the top-level Verilog module, given in Figure 9, to instantiate the Nios II system with the Clock Signals core included. The desired code is shown in Figure 14. The SDRAM clock signal *sdram_clk* generated by the Clock Signals core connects to the pin *DRAM_CLK*. Note that the *sys_clk* signal is not connected since it is for internal use only.

```
// Implements the augmented Nios II system for the DE1-SoC board.
// Inputs:   SW7−0 are parallel port inputs to the Nios II system.
//           CLOCK_50 is the system clock.
//           KEY0 is the active-low system reset.
// Outputs:  LEDR7−0 are parallel port outputs from the Nios II system.
//           SDRAM ports correspond to the signals in Figure 2; their names are those
//           used in the DE1-SoC User Manual.
module  lights (SW, KEY, CLOCK_50, LEDR, DRAM_CLK, DRAM_CKE,
        DRAM_ADDR, DRAM_BA, DRAM_CS_N, DRAM_CAS_N, DRAM_RAS_N,
        DRAM_WE_N, DRAM_DQ, DRAM_UDQM, DRAM_LDQM);
        input  [7:0]  SW;
        input  [0:0]  KEY;
        input  CLOCK_50;
        output  [7:0]  LEDR;
        output  [12:0]  DRAM_ADDR;
        output  [1:0] DRAM_BA;
        output  DRAM_CAS_N, DRAM_RAS_N, DRAM_CLK;
        output  DRAM_CKE, DRAM_CS_N, DRAM_WE_N;
        output  DRAM_UDQM, DRAM_LDQM;
        inout  [15:0]  DRAM_DQ;
// Instantiate the Nios II system module generated by the Qsys tool
        nios_system  NiosII  (
                .clk_clk (CLOCK_50),
                .reset_reset (~KEY[0]),
                .switches_export (SW),
                .leds_export (LEDR),
                .sdram_wire_addr (DRAM_ADDR),
                .sdram_wire_ba (DRAM_BA),
                .sdram_wire_cas_n (DRAM_CAS_N),
                .sdram_wire_cke (DRAM_CKE),
                .sdram_wire_cs_n (DRAM_CS_N),
                .sdram_wire_dq (DRAM_DQ),
                .sdram_wire_dqm ({DRAM_UDQM,DRAM_LDQM}),
                .sdram_wire_ras_n (DRAM_RAS_N),
                .sdram_wire_we_n (DRAM_WE_N),
                .sdram_clk_clk (DRAM_CLK)
        );
endmodule
```

Figure 14. Proper instantiation of the expanded Nios II system.

Compile the code and download the design into the Cyclone V FPGA on the DE1-SoC board. Use the application program in Figure 10 to test the circuit.