Time-to-Digital-Converter

Application Note

Ultrasonic Heat metering with the TDC-GP21 Time-to-Digital Converter

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Overview

In December 2010 acam launched the TDC-GP21 Time-to-Digital Converter. It comes with extended functionality and provides great benefit to designers that demand for ps resolution in time of flight applications, e. g. like ultrasonic flow- and heat meters. Especially, the integration of analog elements like a chopper stabilized comparator and analog switches simplifies the hardware design and reduces the number of external components to a minimum.

This application note is intended as an add on to the TDC-GP21 datasheet that describes the implementation of an ultrasonic heat meter front-end with the TDC-GP21. It provides additional information that helps to decrease design time and avoid circuit problems due to wrong component values or incorrect configuration of the device. Additionally it includes layout guidelines and the full schematics of a demo board to help avoid circuit malfunction and to avoid noise problems. Finally, the application note contains a generic software example that shows atypical measurement flow.

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1 Introduction

This application note describes the implementation of an ultrasonic heat meter front-end that is based on acam's TDC-GP21 Time-to-Digital Converter. The GP21 operates as a front-end device that provides fully automated control of the flow- and temperature measurement sequence. The amount of heat dissipated is calculated from the flow rate and the temperature difference of the incoming and outgoing fluid by an external micro-controller.

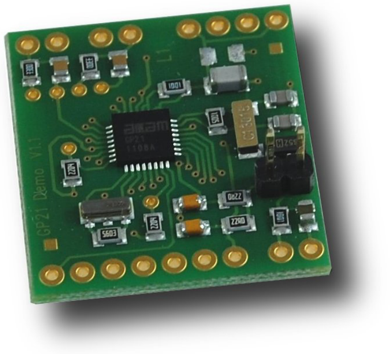


Figure 1.1: GP21 Front-end electronics for heat meters

Design Goals:

- Compact and cost saving hardware design that keeps external components to a minimum
- Low current consumption (down to 2 µA for a complete measurement cycle including the analog part, transducers and Pt sensors)
- High resolution time-of-flight measurement that allows compact and small spool pieces with small diameters
- High resolution but low current temperature measurement
- Open system architecture offers a high degree of flexibility with an external microcontroller and a modular system design

1.1 Flow Measurement

The ultrasonic flow measurement is based on the transit-time principle. Two transducers are connected to the TDC-GP21. They can both operate as an ultrasonic transmitter or receiver.

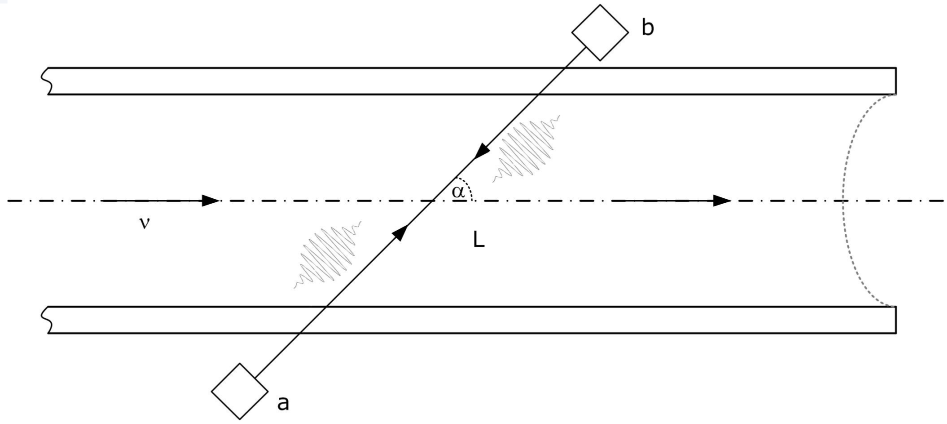


Figure 1.2 Basic principle of ultrasonic flow metering by means of transit time difference measurement

The GP21 alternately transmits a 1 MHz signal burst (20 pulses) between the two transducers and measures the transit time that a pulse burst takes for traveling from transducer a to b and the opposite direction from b to a. The transit time of the ultrasonic signal propagating in flow direction is shorter than the transit time of the signal propagating against flow direction.

For a given average fluid velocity v, a measurement path L and a sound velocity C_0 in the fluid, an acoustic signal needs the time t_{up} for the upstream path and t_{down} in downstream direction. They can be calculated as follows:

$$T_{up} = \frac{L}{C_0 + v * cosa} \qquad [1]$$

$$T_{down} = \frac{L}{C_0 - v * cosa} \qquad [2]$$

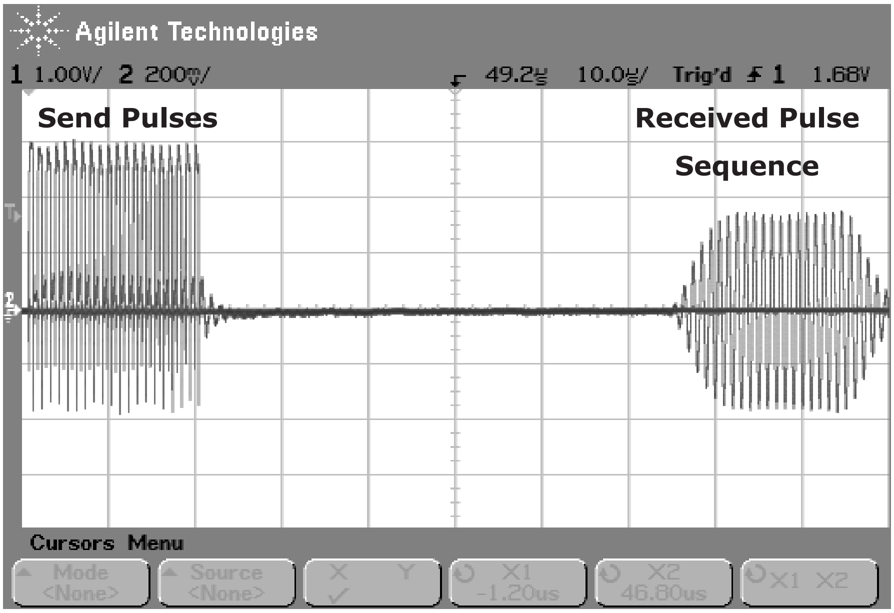


Figure 1.3: Send- / received pulse sequence

The computation of the result is then performed by an external microcontroller. In a first step it calculates the time difference of the delay times in up- and down direction.

$$\Delta t = T_{up} - T_{updown} = \frac{2 * L + v + \cos a}{C_0^2 - v^2 * cos^2 a} \approx \frac{2 * L * cosa}{C_0^2} * v \qquad [3]$$

Then it calculates the flow velocity V and subsequently the flow rate Q. A is the inner diameter of the pipe and K represents an instrument specific coefficient that is usually determined by calibration.

$$V = \frac{\Delta T * c_0^2}{2 * L * cosa} \qquad [4]$$

$$Q = K * A * v \qquad [5]$$

1.2 Temperature Difference Measurement

To measure the temperature difference of the incoming and outgoing water the TDC-GP21 uses the PICOSTRAIN method. It transfers the temperature dependent resistance variation of an RTD in an accurate time interval measurement. A capacitor is discharged alternately through the RTD sensor and a temperature stable reference resistor and the discharge times are measured with picosecond resolution. The Figure below shows a typical signal curve for a temperature measurement sequence with two additional Fake[1] measurements.

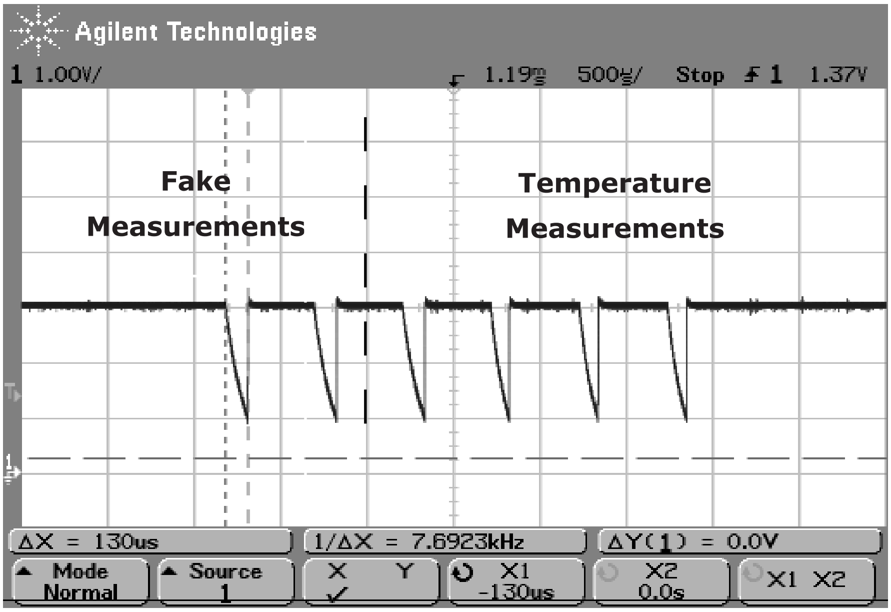


Figure 1.4: Oscillogram of the fake- and temperature measurement charging-/discharging cycles, measured at R9

The result is then provided in the corresponding GP21 result register 0 to 3. The ratio of the discharge time shows the deviation of the sensor resistance relative to the reference resistor. From the given results T_{RTD} and T_{Ref} the external microcontroller calculates the temperature difference as follows:

$$R_{RTD} = \left(\frac{T_{RTD}}{T_{Ref}} - 1\right) * R_0 \qquad [6]$$

Now the temperature can be calculated by solving the RTD transfer function for the temperature:

$$\vartheta = \frac{-R_0 * A + \sqrt{(R_0 * A)^2 - 4 * R_0 * B * (R_0 - R)}}{2 * R_0 * B} \qquad [7]$$

---

[1] Fake measurements improve stability of the temperature measurement by adding additional charging /discharging cycles before the actual temperature measurement starts

Finally, the temperature difference is calculated as follows:

$$\Delta\vartheta = \vartheta_{RTD} - \vartheta_{Ref} \qquad [8]$$

2 Circuit Description

The complete schematics and the layout can be found in section 3 of this document. To get best results and to avoid circuit problems we recommend to use it as a reference for your design. The main considerable design items are now described in the following chapters.

2.1 Power Supply Considerations

The TDC-GP21 needs two supply voltages for chip internal power supply. The core supply voltage Vcc and the I/O supply voltages Vio. Both can be generated from one and the same source. Usually, a linear regulator. Here, the XC6206 from Torex Semiconductor is used. Because of its very low quiescent current of only 1µA in operation it is ideal for power critical applications, like battery driven heat or flow meters. Additionally, a good decoupling and bypassing is recommended for noise reduction. The below schematics gives a reference for your design:

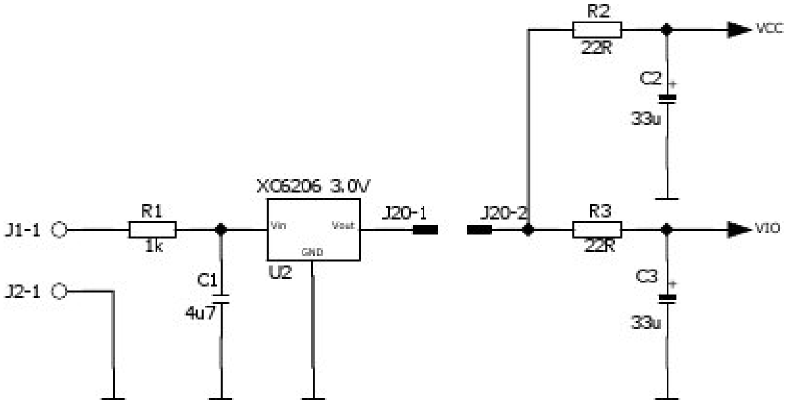


Figure 2.1 Power supply bypassing and decoupling

Important Note:

Do not use switched regulators in your power supply design. They would introduce a lot of noise that significantly reduces the measurement quality.

2.2 External Clock Sources

Battery driven applications like heat meters demand for very low current consumption. According to that the GP21 operates with two LVCMOS or LVTTL compatible clock sources. A 32.768 kHz quartz and a 4 MHz ceramic oscillator. For power efficiency the 4 MHz clock is controlled by the 32 kHz quartz and only switched on during time measurement.

2.2.1 The 32,768 Hz Quartz

The 32.768 kHz quartz is responsible for start-up control of the 4 MHz clock and is used as reference for calibrating the 4 MHz ceramic oscillator, as explained in chapter 2.2.2. The 10 pF capacitors together with the paralleled 10M resistor guarantuees stable oscillation.

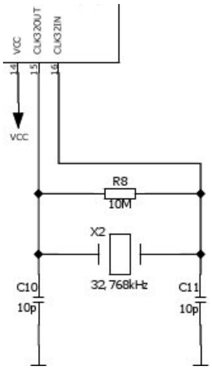


Figure 2.2: Connecting the 32.768 kHz quartz oscillator

2.2.2 The 4 MHz High Speed Clock Oscillator

As 4 MHz clock source a standard ceramic oscillator in combination with a 560 k parallel resistor can be used. The high speed clock circuit is shown below.

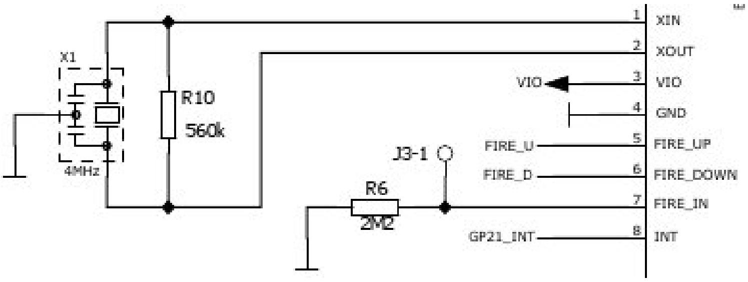


Figure 2.3 Circuit diagram for the 4 MHz ceramic resonator

Compared to a crystal oscillator it is more cost efficient and thanks to the short settling time it can be operated in a power saving switched mode. Then the active states are controlled by the GP21 internally.

The GP21 integrated clock calibration helps to overcome the poor accuracy and temperature drift behavior that is typical for a ceramic oscillator. This offers quartz accurate time measurement, even when a ceramic oscillator is used as high speed clock. For more details about how to use the clock calibration please have a look to section 5.2 of the TDC-GP21 datasheet.

2.2.3 Clock Option for external Microcontroller

To save external components the GP21 can provide a 4 kHz or a 32 kHz signal, e. g. as a system clock for the external microcontroller. The 32 kHz can be provided through EN_START pin and has to be configured by SEL_TSTO2 parameter in configuration register 1. A 4 kHz signal is available on FIRE_IN by appropriate configuration of the SEL_TSTO1 parameter in configuration register 1.

2.3 Transmitter / Receiver Circuit

Basically, the transmission circuit consists of two first order high pass filters. They are connected to Fire_Up and Fire_Down pins of the TDC-GP21 and their resistor outputs drive the piezo transducers. On the receiver side the capacitor outputs are connected to GP21 analog inputs. Here, COG capacitors should be used to achieve highest temperature stability. An integrated analog multiplexer operates the transducers alternatingly as transmitter / receiver. All elements are controlled by the TDC-GP21 and only powered up during measurement.

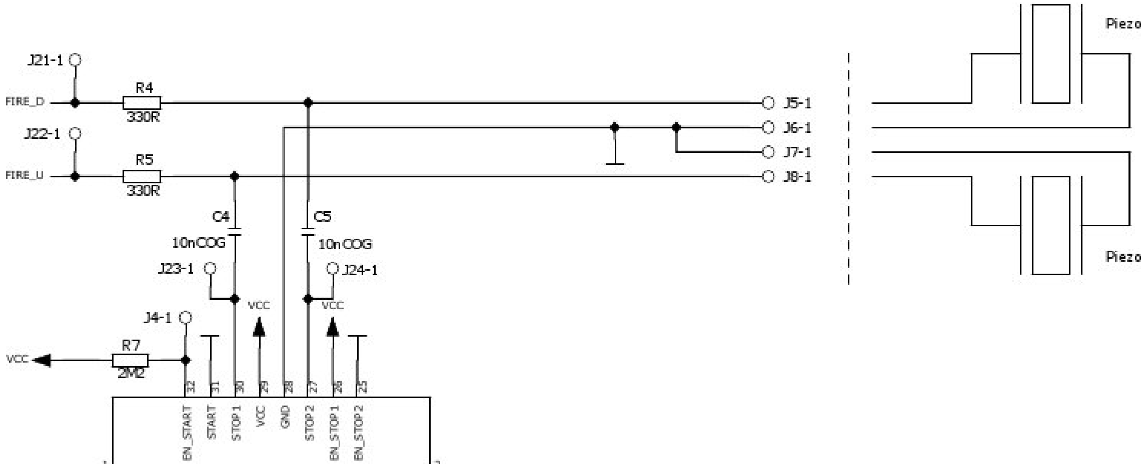


Figure 2.4 Circuit diagram of the transmitter / receiver signal path

As the integrated comparator cannot handle GND as threshold the LoadC capacitors (C4, C5) in the receiving path switch the signal to the comparator threshold of 1/3 Vcc. Then it is coupled to the TDC-GP2 analog inputs. Figure 2.5 shows the corresponding oscilloscope trace.

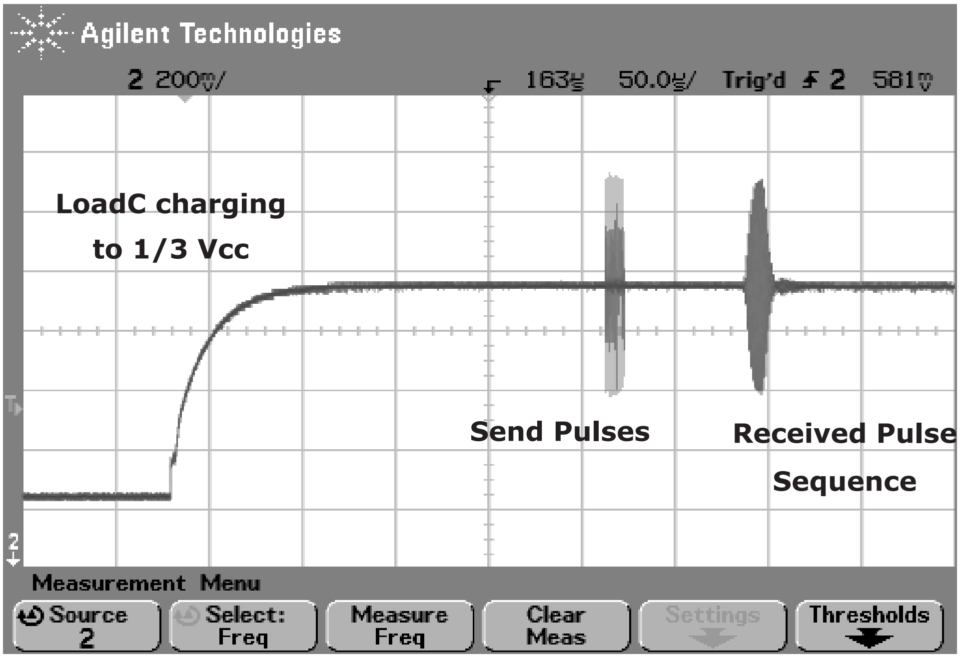
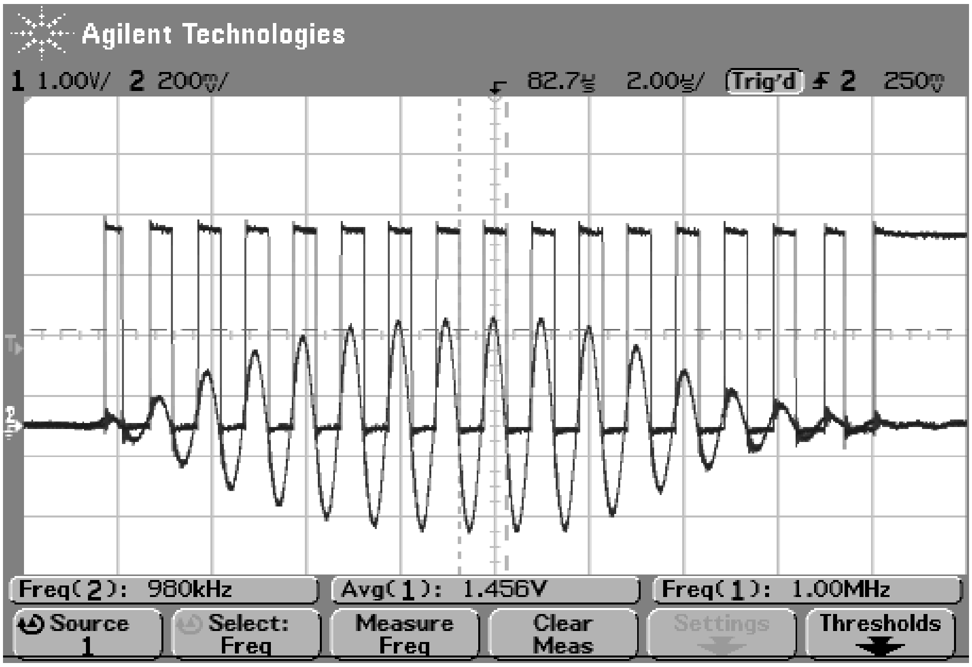


Figure 2.5: Signal curve on on non-inverted comparator input

Finally, the integrated low noise comparator generates a square wave signal from the received pulse sequence that provides the stop pulses for the GP21 internal time measurement unit.



Freq(2): 980kHz
Avg(1): 1.456V
Freq(1): 1.00MHz

Figure 2.6: Received pulse sequence and corresponding coparator output signal

More details about the GP21 analog unit and how it operates can be found in section 4.3 of the TDC-GP21 datasheet.

2.3.1 Time Windowing by Stop Masking

Additionally, the GP21 supports a time based windowing option that can be individually applied to three incoming stop pulses (Hit1 to Hit3). This enables the suppression of unwanted echoes as the GP21 stop input is only switched active during reception of the wanted echo pulses. The configuration is done by simple register configuration of the delay values DELVAL1 to DELVAL3. Each delay value is assigned to one of the up to three possible stops in ascending order. The Figure below shows a typical configuration with DelV al1 = 10500, DELVAL2 = DELVAL3 = 0. This applies a time window with a delay of 82031,25 ns delay (@ 4 MHz high speed clock) before the stop 1 channel is activated to detect the incoming stops. DELVAL2 and DELVAL 3 are not required and set to 0. More details are described in section 4.2.3 of the TDC-GP21 datasheet.

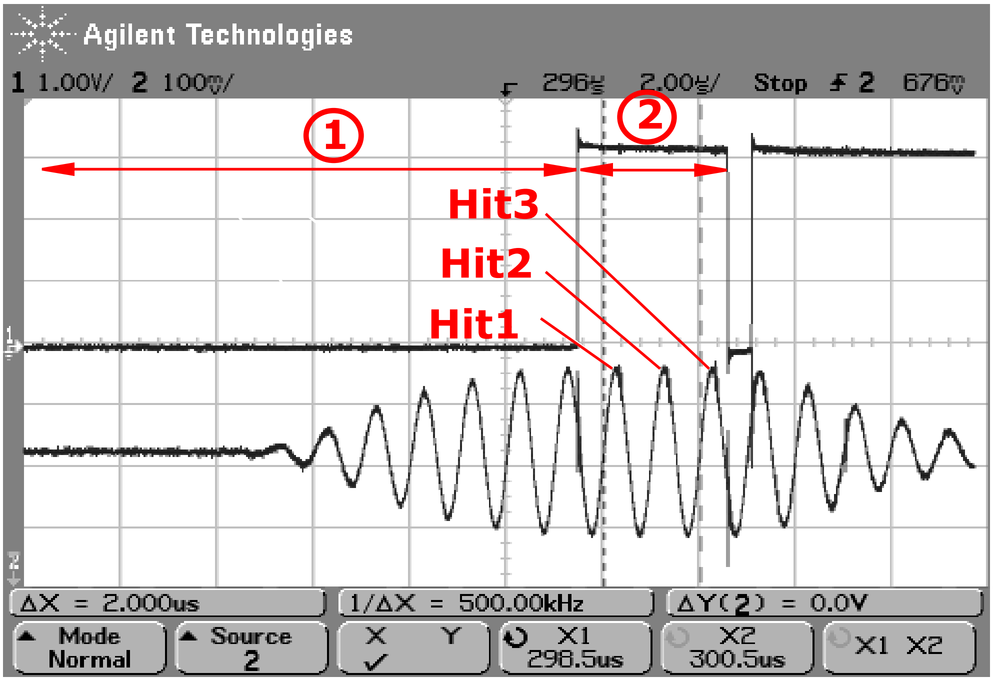


Figure 2.7: Received pulse sequence and stop masking signal curve, measured on Fire-in output with SEL_TSTO1 = 5 (sets Fire_In as EN_STP by DELVAL output).

① GP21 Stop input is disabled by DELVAL setting

② GP21 Stop input is enabled by DELVAL setting

2.4 Temperature measurement

A pair of Pt 1000 sensors in combination with a temperature stable 1k reference resistor (R9, 50 ppm), is used for hot / cold temperature difference measurement.

A 100 nF COG type capacitor operates as load capacitor (C8). To minimize the number of external components the GP21 internal Schmitt-Trigger is used.

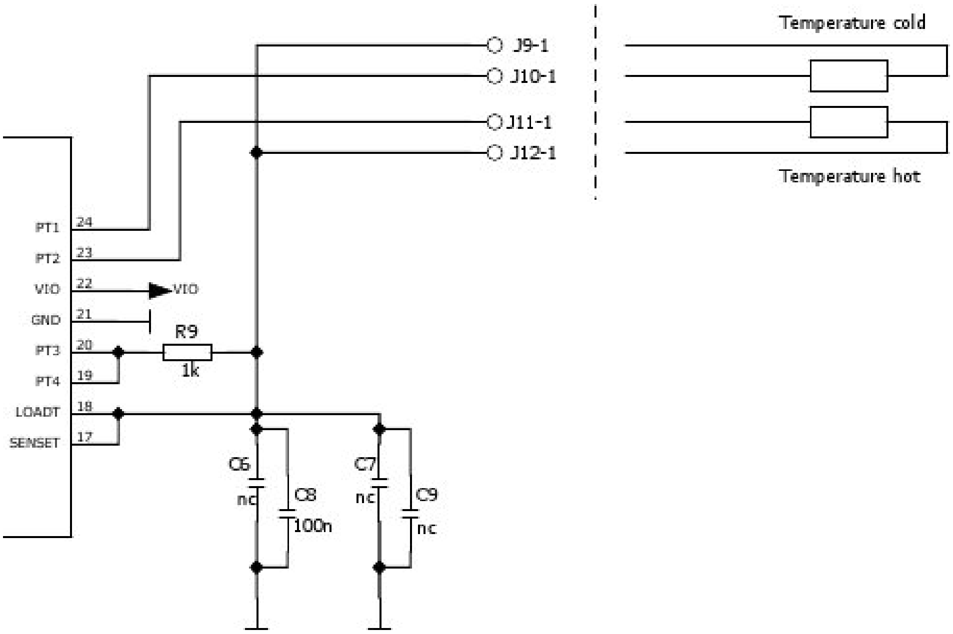
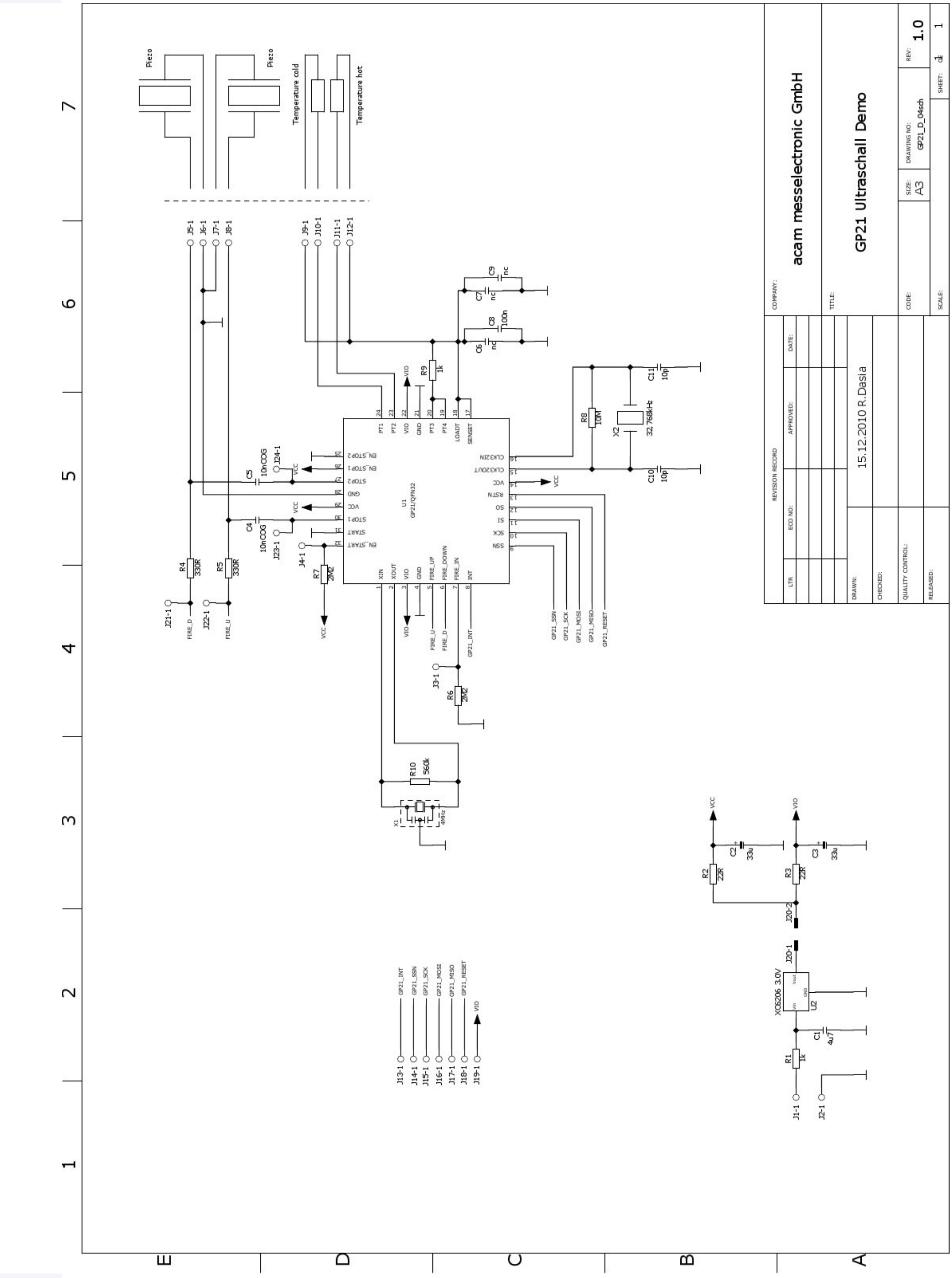


Figure 2.8 Temperature measurement circuit

3 Layout & Schematics of a demo board

3.1 Full Schematics



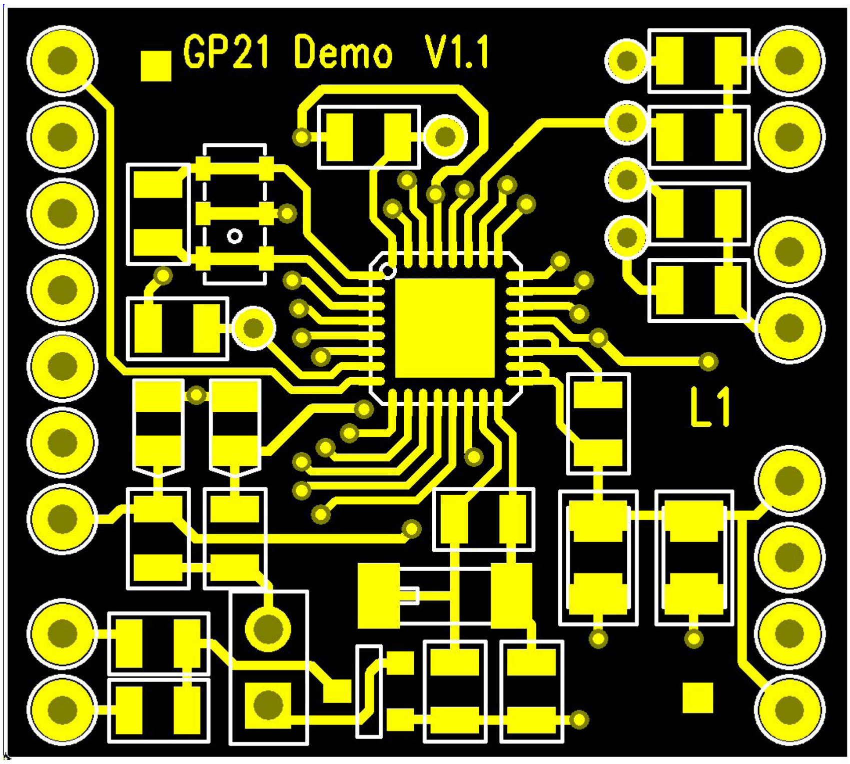
3.2 Layout

The PCB has significant influence on the measurement quality so stick as close as possible to the design and the recommendations given in this chapter. Then a 2 layer should be sufficient.

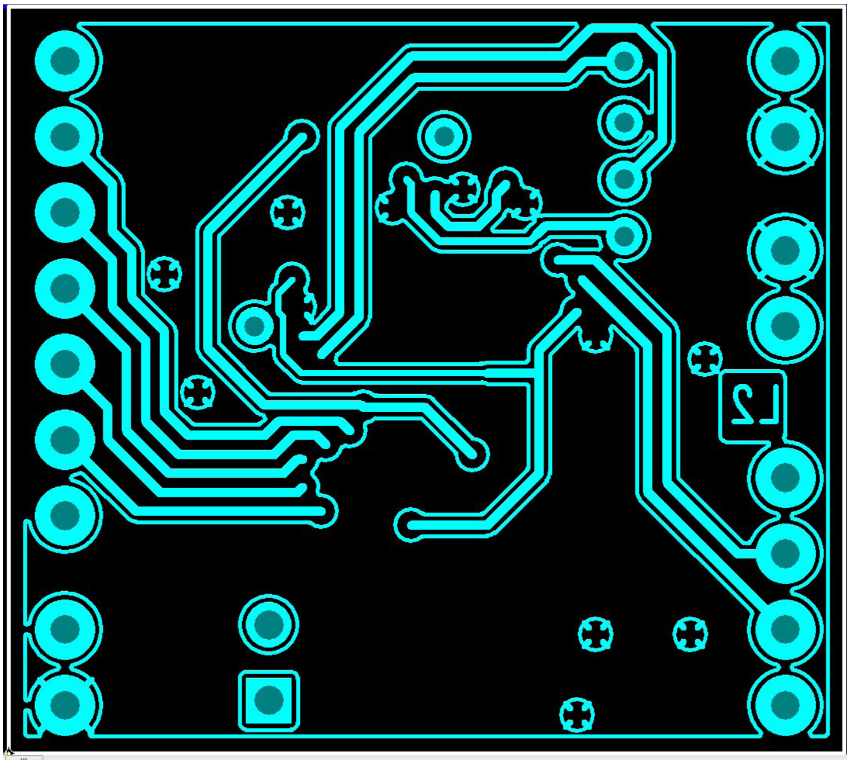
Summary of the most important layout considerations:

- Place the oscillators very close to the device
- Do NOT cross the SPI lines with the load or I/O lines
- Do NOT cross the load line with the oscillator lines
- Place the bypassing capacitors C2 and C3 close to the supply voltage pins of the GP21
- Keep the temperature port lines as short and symmetric as possible
- If possible, use flooded planes around the oscillators

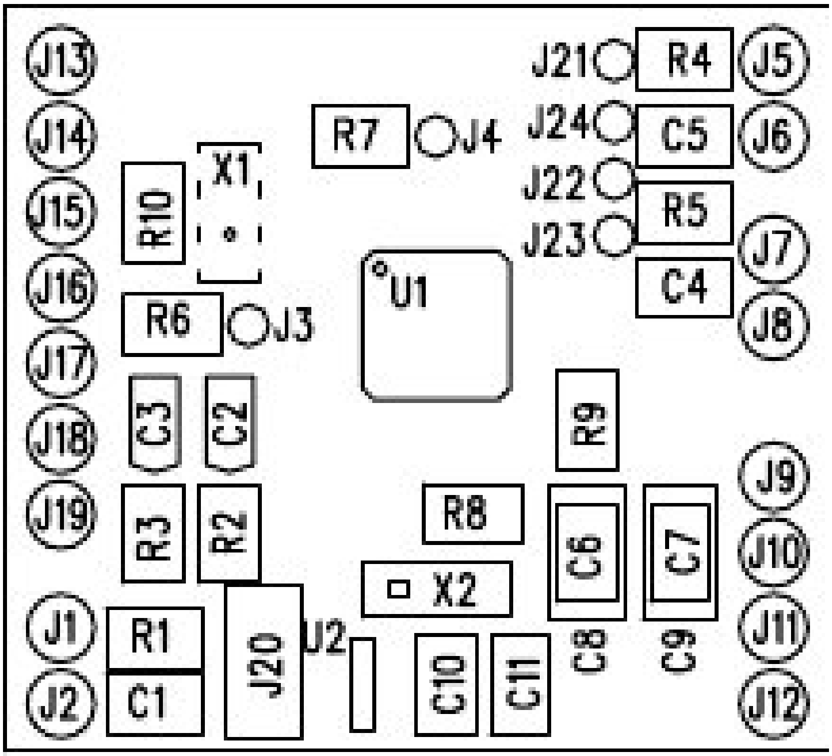
3.2.1 Top Layer



3.2.2 Bottom Layer



3.2.3 Component Placement



4 Example configuration

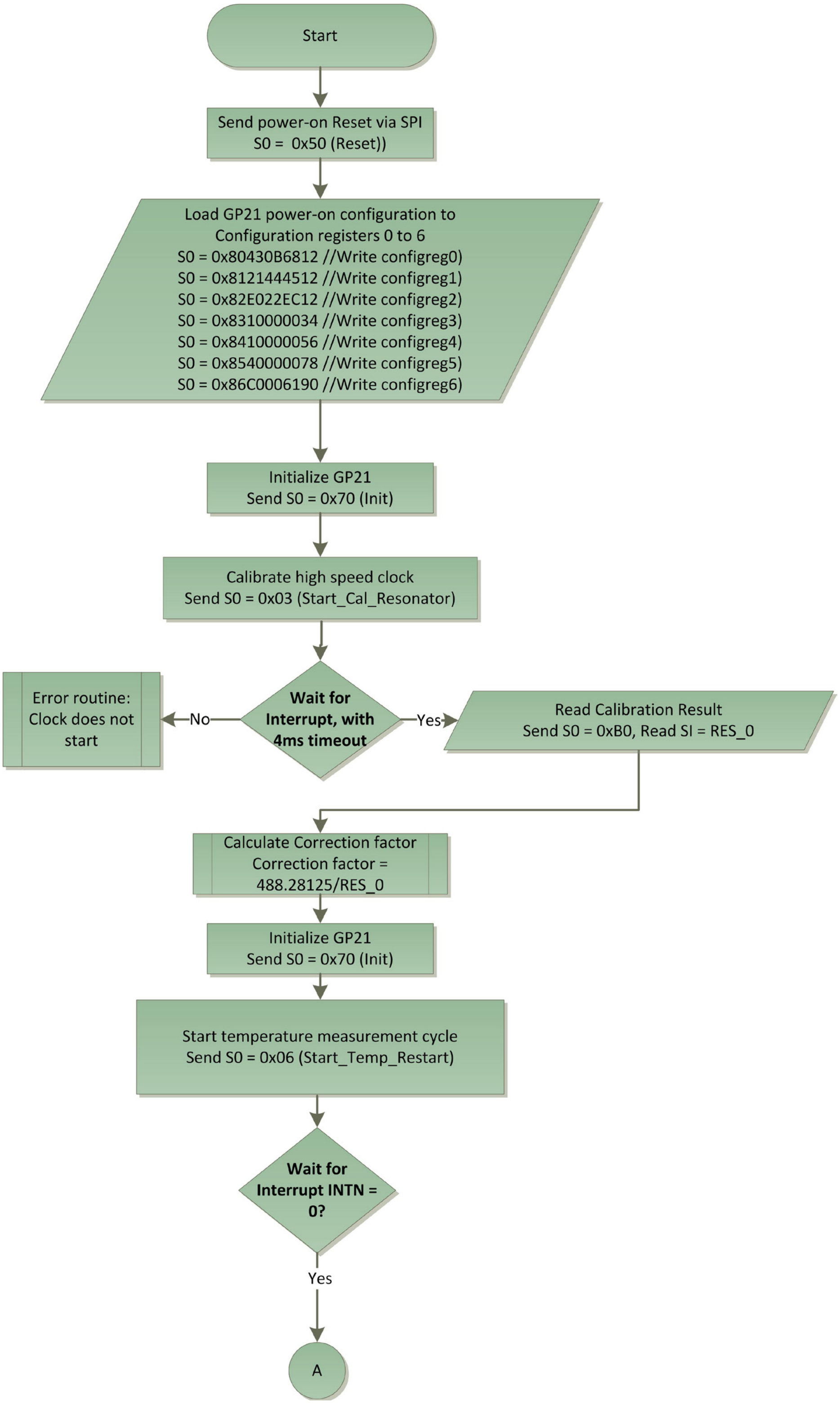
The following chapter gives an example configuration for a heat meter application and describes the settings of all relevant parameters. A detailed description of the configuration bits is further provided in section 3 of the TDC-GP21 datasheet.

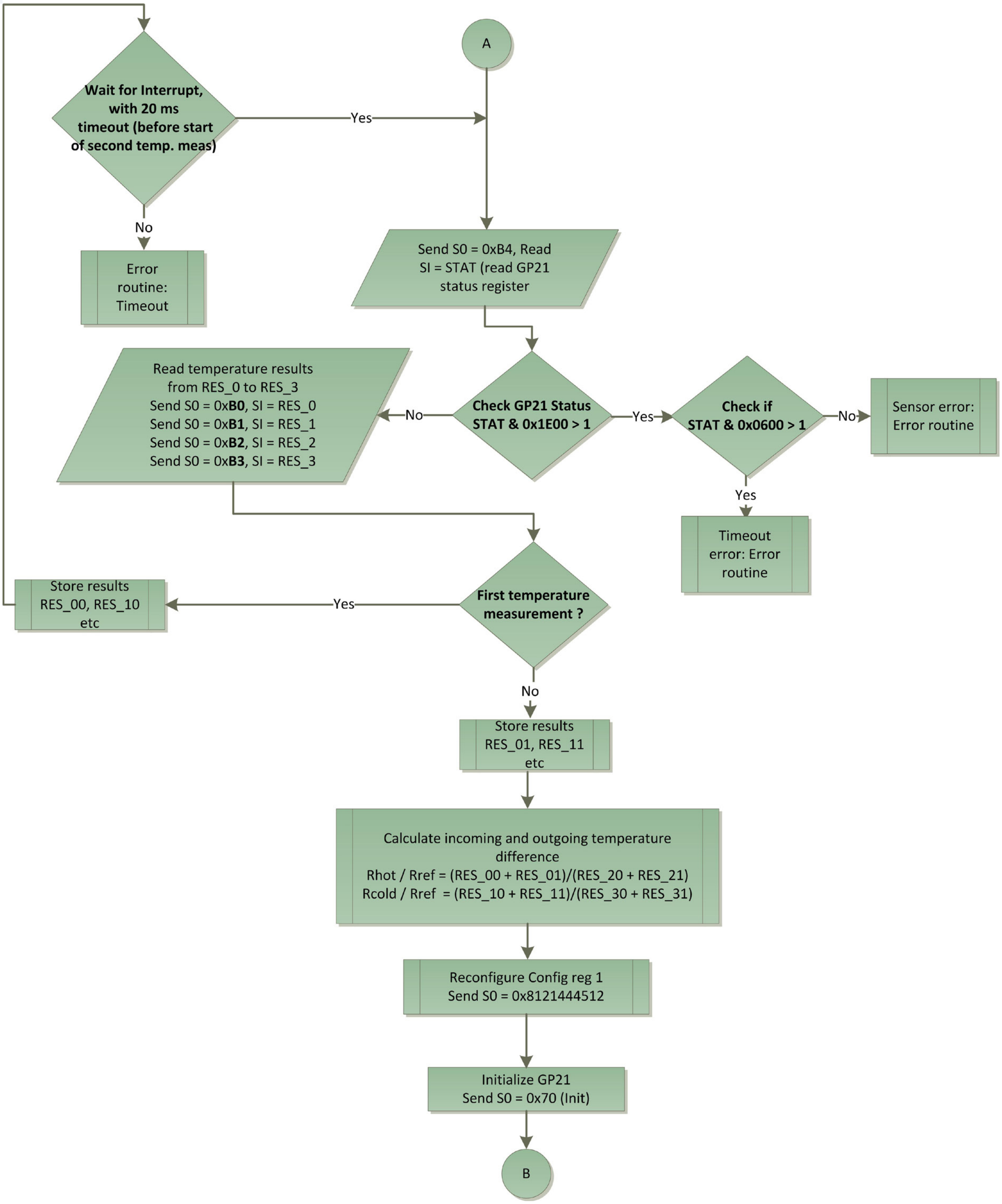
Register	Value (hex)	Description of the relevant Parameters
Register 0	h430B6800	ANZ_FIRE = 20 Number of pulses within a burst = 20 (see register 6, too) DIV_FIRE = 3, fire pulse frequency = 4 MHz/4 = 1.0 MHz ANZ_PER_CALRES = 3, the 4 MHz is calibrated by a 488.81µs measurement (3 periods of the 32.768 kHz quartz) DIV_CLKHS = 0, the 4 MHz ceramic oscillator is internally used as it is, without clock division START_CLKHS = 2, the ceramic oscillator operates in switched mode and has 480 µs time for settling ANZ_PORT = 1, use all 4 ports (PT1 to PT4) for the temperature measurement TCYCLE = 1, 512 µs cycle time for the temperature measurement (@4MHz) ANZ_FAKE = 0, 2 fake measurements SEL_ECLK_TMP = 1, use the 4 MHz clock for the temperature measurement cycle definition (32 µs period, refers to 128 high speed clock cycles @ 4 MHz) CALIBRATE = 1, TDC calibration on, mandatory in measure mode 2 NO_CAL_AUTO = 0, mandatory in measure mode 2 to have auto-calibration of the TDC MESSB2 = 1, switch on measure mode 2 for measuring delays > 2,5 µs. NEG_STOP/NEGSTART = 0, edge sensitivity of the start / stop channels is set to rising edges ID0 = h10, together with ID1 this could be interpreted as configuration version 1.0.1.2
Register 1	h21444712	HIT2 = 2, HIT1 = 1: calculate 1. Stop - Start in measure mode 2 EN_FAST_Init = 0, off HITIN2 = 0, no hits stop channel 2 (only stop1 is supported in measure mode 2) HITIN1 = 4, measure 3 stops (in measure mode 2 this includes the start hit, too, giving 4 hits) CURR32K = 0, use default SEL_START_FIRE = 1, use the internal direct wiring from the fire pulse buffer to the TDC start SEL_TSTO2 = 0, pin EN_START not used SEL_TSTO1 = 5, The FIRE_IN pin is used as output and provides the 32.768 kHz to the microcontroller ID1 = h12

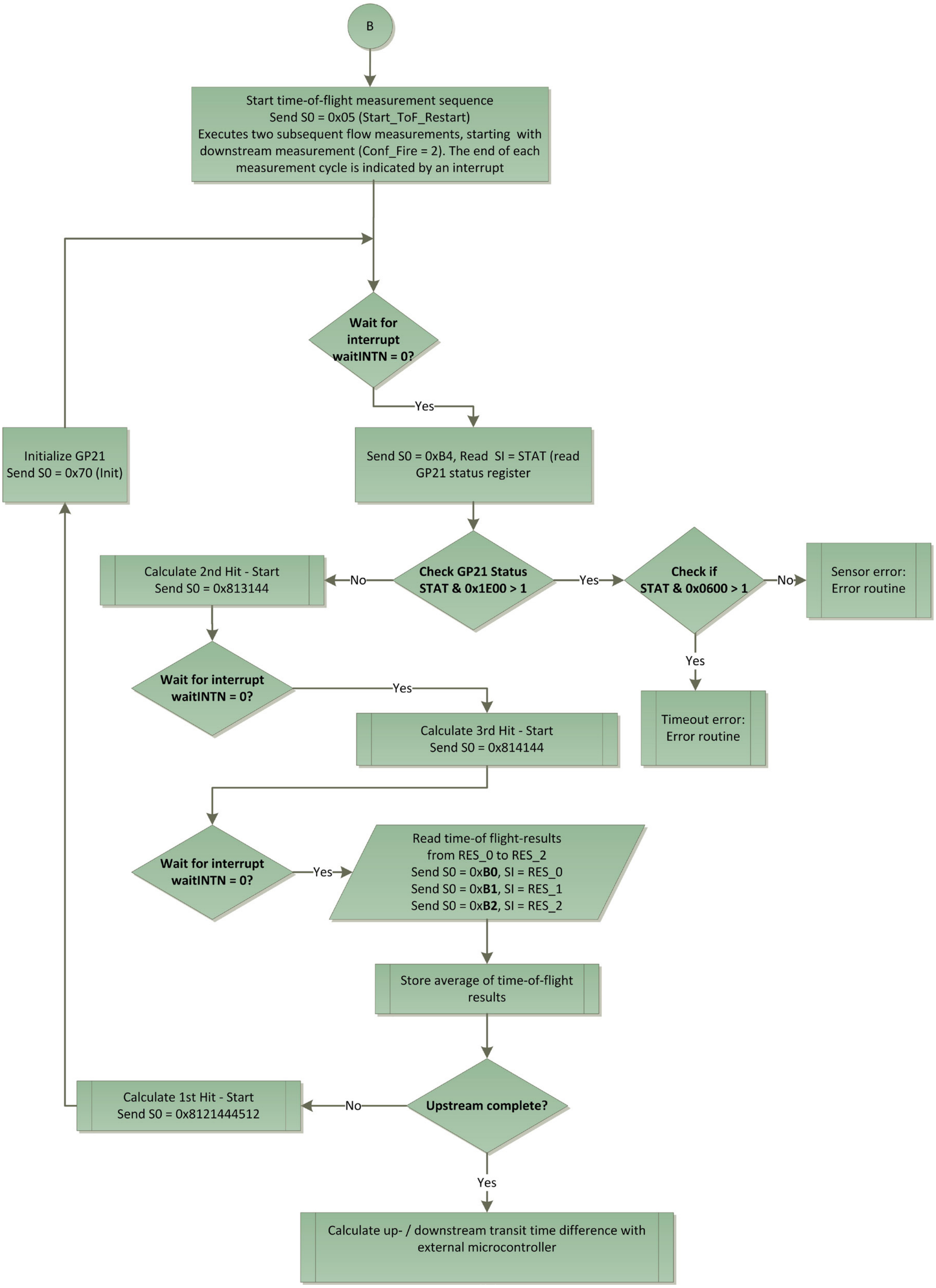
Register 2	hE0290412	EN_INT = all interrupts enabled (interrupt given by timeout, ALU ready end hits or end of EEPROM action (see also register 6) RFEDGE1 = RFEDGE2 = 0, use only rising edges DELVAL1 = 328,125, the first stop is accepted after 82.0375 µs ID2 = h12, could be part of a serial number h1234567890
Register 3	h08000034	EN_ERR_VAL = 0, there is enough time to read the status register SEL_TIMO_MB2 = 1, time out is generated after 256 µs DELVAL2 = 0, the second stop is detected immediately after the first one (no masking for the second stop)) ID3 = h34, could be part of a serial number h1234567890
Register 4	H10000056	DELVAL3 = 0, the third stop is accepted immediately after the second one (no masking for the third stop) ID4 = h56, could be part of a serial number h1234567890
Register 5	H40000078	CON_FIRE = 2, disable FIRE_UP; Fire1 and Fire2 are used alternately. The flow measurement sequence starts in downstream direction EN_STARTNOISE = 0, switch off DIS_PHASESHIFT = 0, phase noise unit is active to improve the statistical behavior REPEAT_FIRE = 0, no sing-around PHASE_FIRE = 0, no phase change in the fire pulse sequence ID5 = h78, could be part of a serial number h1234567890
Register 6	hC0006190	EN_ANALOG = 1, use the internal analog circuit NEG_STOP_TEMP = 1, use the internal Schmitt trigger for the temperature measurement TW2 = 1, 120 µs delay to charge up the capacitors of the high pass filters EN_INT = b1101, interrupt given by time out, ALU ready or end of EEPROM action (see also register 2) START_CLKHS = 2, the ceramic oscillator has 480 µs to settle (see also register 0) CYCLE_TEMP = 1, use factor 1.5 for the delay between two measurements CYCLE_TOF = 0, use factor 1.0 for the delay between two TOF measurements HZ60 = 0, 50 Hz base FIREO_DEF = 1, High Z state of the unused fire output, mandatory when using the internal analog circuit QUAD_RES = 1, use 22 ps resolution of the TDC DOUBLE_RES = 0, mandatory as quad resolution mode is selected TEMP_PORTDIR = 0, standard order for T measurement ANZ_FIRE = 20 (see register 0, too) ID6 = h90, could be part of a serial number h1234567890

5 Software Implementation

This chapter describes a typical measurement flow. Error routines or plausibility checks of the measured results are not within the scope of this example.




A
Wait for Interrupt, with 20 ms timeout (before start of second temp. meas)
Yes
No
Error routine: Timeout
Send S0 = 0xB4, Read SI = STAT (read GP21 status register
Read temperature results from RES_0 to RES_3
Send S0 = 0xB0, SI = RES_0
Send S0 = 0xB1, SI = RES_1
Send S0 = 0xB2, SI = RES_2
Send S0 = 0xB3, SI = RES_3
No
Check GP21 Status STAT & 0x1E00 > 1
Yes
Check if STAT & 0x0600 > 1
No
Sensor error: Error routine
Yes
Timeout error: Error routine
Store results RES_00, RES_10 etc
Yes
First temperature measurement ?
No
Store results RES_01, RES_11 etc
Calculate incoming and outgoing temperature difference
Rhot / Rref = (RES_00 + RES_01)/(RES_20 + RES_21)
Rcold / Rref = (RES_10 + RES_11)/(RES_30 + RES_31)
Reconfigure Config reg 1
Send S0 = 0x8121444512
Initialize GP21
Send S0 = 0x70 (Init)
B


B
Start time-of-flight measurement sequence
Send S0 = 0x05 (Start_ToF_Restart)
Executes two subsequent flow measurements, starting with downstream measurement (Conf_Fire = 2). The end of each measurement cycle is indicated by an interrupt
Wait for interrupt waitINTN = 0?
Yes
Send S0 = 0xB4, Read SI = STAT (read GP21 status register
Initialize GP21
Send S0 = 0x70 (Init)
Check GP21 Status
STAT & 0x1E00 > 1
No
Yes
Calculate 2nd Hit - Start
Send S0 = 0x813144
Check if
STAT & 0x0600 > 1
No
Sensor error:
Error routine
Yes
Timeout error:
Error routine
Wait for interrupt
waitINTN = 0?
Yes
Calculate 3rd Hit - Start
Send S0 = 0x814144
Wait for interrupt
waitINTN = 0?
Yes
Read time-of flight-results
from RES_0 to RES_2
Send S0 = 0xB0, SI = RES_0
Send S0 = 0xB1, SI = RES_1
Send S0 = 0xB2, SI = RES_2
Store average of time-of-flight results
Upstream complete?
No
Calculate 1st Hit - Start
Send S0 = 0x8121444512
Yes
Calculate up- / downstream transit time difference with external microcontroller

Description:

After an initial power-on reset the basic register configuration is transferred to the TDC-GP21 and the device is initialized through calling the init-instruction.
Then the Start_CAL_Resonator instruction forces the GP21 to execute a calibration of the GP21 high speed clock.
From now on the complete program flow is interrupt driven.
The external microcontroller reads the result and calculates the ratio from the measured result RES_0 and the reference value that is given by the number of 32.768 Hz clock cycles that are used for calibration. Here, we use three periods of the 32.768 kHz clock according to the ANZ_PER_CALRES parameter in the example configuration. This equals to a reference value of 488,28125 µs.

After that the init instruction resets the pointer result register and the interrupt line, reinitializes the TDC-GP21 and prepares it for the next measurement.
The temperature measurement sequence is started by sending the Start_Temp_Restart opcode. By doing that the GP21 executes the temperature measurement sequence twice. Once for the hot- and once for the cold temperature measurement. The end is indicated by an interrupt. The microcontroller then error checks the GP21 status register and reads the results from result register RES_0 to RES_3 to calculates the temperature difference. The relating formulas are described in section 1.2 of this paper.
Again, the init instruction prepares the GP21, but now for the time-of-flight measurement sequence.

With the Start_ToF_Restart instruction the TDC-GP21 automatically executes the complete measurement sequence for a transit time measurement in upstream and downstream direction. Here, we start with the downstream measurement (CONF_FIRE = 2) and send a pulse packet of 20 pulses (ANZ-FIRE 0 20). After reception of the echo signal the TDC-GP21 starts calculating the transit times from its internally stored raw values. It first calculates the time between the first incoming stop and start (Stop1 – Start) according to the settings of HIT1 and HIT2 operator in register 1 (HIT1=1, HIT2 = 1). An interrupt indicates the end of the calculation.
After checking the status register a rewrite of register 1 by setting HIT2 to 2 and HIT1 to 1 forces the GP21 to calculate the second time interval. Here, the GP21 calculates the transit time between the second incoming stop pulse and start (Stop2 –Start). Again,

an interrupt indicates the end of the calculation before an error check of the status register is executed.
Finally, register 1 is rewritten again to calculate the third time interval between the third stop and start. (Stop3 - Start.). The subsequent interrupt indicates that now the transit times between start and three incoming stops are available in result register RES_0 to RES3. They are read from the external microcontroller and stored for further calculation. After these steps the init instruction prepares the device for the upstream measurement sequence. It starts automatically (according the repetition rate that is specified by the HZ60 parameter in register 6) and executes the same steps as described for the downstream measurement.

Finally the external microprocessor reads the upstream results and calculates the amount of heat by using the formulas described in section 1 of this paper.

6 Example Code

This is a generic example code for a complete heat meter measurement flow including clock calibration of the high speed ceramic resonator, written for a ST32 microprocessor.

```
/*************************************************************************************
* File Name          : GP21_Sample_code.c
* Description        : Sample Program code for communication and measurement
*                      using the GP21 chip. The subroutines can be found at the
*                      end of the main program.
********************************************************************************

/* Includes ------------------------------------------------------------------*/
/* Private variables ---------------------------------------------------------*/
#define   LOOP_DLY_100US              2000
#define   FOUR_MILLISECONDS_TIMEOUT   4300
#define   TWENTY_MILLISECONDS_TIMEOUT 20300

uint32_t  Calib_result;
float     Correction_factor;
u32        timeout_counter;
uint16_t  Temp_status_bytes;
float     Temp1_Result0;
float     Temp1_Result1;
float     Temp1_Result2;
```

```
float    Temp1_Result3;
float    Temp2_Result0;
float    Temp2_Result1;
float    Temp2_Result2;
float    Temp2_Result3;
u32       No_of_temp_meas = 1;
float    Rhot_by_Rref;
float    Rcold_by_Rref;

uint16_t TOF_status_bytes;
float    Result0;
float    Result1;
float    Result2;
float    average_Result_up;
float    average_Result_down;
float    Time_of_flight;
u32      hit_count = 1;
u32      stream_count = 1;
bool     upstream = FALSE;
bool     configured_true=FALSE;
uint32_t Dummy_var   = 0;

// For mathematical calculations
int         i;
int         j;

/* Function declarations --------------------------------------------------*/
void Dly100us(void *arg);
void Simple_delay_750ns(void *arg);
void gp21_send_1byte (uint8_t gp21_opcode_byte);
void gp21_wr_config_reg (uint8_t opcode_address, uint32_t config_reg_data);
uint16_t gp21_read_2byte_status(void);
uint32_t gp21_read_4bytes(uint8_t read_opcode_addr);

/*******************************************************************************
* Function Name  : main
* Description    : Main program.
* Input          : None
* Output         : None
* Return         : None
*******************************************************************************/
```

```
void main(void)
{
      gp21_send_1byte(0x50);            // Power on Reset to GP21
      Dly100us((void*)5);               // 500 us wait for GP21

//----------- read-write communication test --------------
//      gp21_wr_config_reg(0x81, 0xABCDEF34); // Config reg 1
//      gp21_read_4bytes(0xB5);
//------------------------------------------------------------

// Writing to the configuration registers
      gp21_wr_config_reg(0x80, 0x430B6812); // Config reg 0
      gp21_wr_config_reg(0x81, 0x21444512); // Config reg 1
      gp21_wr_config_reg(0x82, 0xE022EC12); // Config reg 2
      gp21_wr_config_reg(0x83, 0x10000034); // Config reg 3
      gp21_wr_config_reg(0x84, 0x10000056); // Config reg 4
      gp21_wr_config_reg(0x85, 0x40000078); // Config reg 5
      gp21_wr_config_reg(0x86, 0xC0006190); // Config reg 6

//------------------------ Sending Init-----------------------
     gp21_send_1byte(0x70); // Opcode INIT to GP21

// .............................................................................
// ....................TEMPERATURE MEASUREMENT................................
// .............................................................................

//-------------------- Sending START_CAL_RESONATOR-------------
     gp21_send_1byte(0x03);   // Opcode START_CAL_RESONATOR to GP21
     timeout_counter = FOUR_MILLISECONDS_TIMEOUT; // Gives approximately 4 ms

    // Waiting for interrupt or timeout after 4 ms when Oscillator doesn‘t start
     while ( (GPIO_ReadInputDataBit(GPIOB, GPIO_Pin_9)==1) &&
           (timeout_counter!=0)
         )
          { timeout_counter--;
          }

//--- Reading 4-word RES0------
    Calib_result = gp21_read_4bytes(0xB0);

// Calculation of Correction factor
    Correction_factor = 488.28125/Calib_result;
```

```
    gp21_send_1byte(0x70);      // Opcode INIT to GP21
    gp21_send_1byte(0x06);      // Opcode START_TEMP_RESTART to GP21

while(No_of_temp_meas<3)
{
   timeout_counter = TWENTY_MILLISECONDS_TIMEOUT; // Gives approximately 20 ms

// Waiting for interrupt or in case of second temp meas. for interrupt or 20 ms timeout
   while ( (GPIO_ReadInputDataBit(GPIOB, GPIO_Pin_9)==1) &&
           (timeout_counter!=0)
         )
          {if(No_of_temp_meas==2) timeout_counter--;
          }

//----------------------------Reading Status----------------------------------
             Temp_status_bytes = gp21_read_2byte_status();

             if((Temp_status_bytes & 0x1E00)!=0)
               {
                 if((Temp_status_bytes & 0x0600)!=0) { // Timeout Error routine
                                            }
                 else
                 { // Sensor error routine
                 }
               }
             else
               {
                //......RES_0 : Temp1_Result0, Temp2_Result0 word = 4 Byte......

                 if(No_of_temp_meas==1)  Temp1_Result0 = gp21_read_4bytes(0xB0);
                 if(No_of_temp_meas==2)  Temp2_Result0 = gp21_read_4bytes(0xB0);

                //......RES_1 : Temp1_Result1, Temp2_Result1 word = 4 Byte......

                 if(No_of_temp_meas==1)  Temp1_Result1 = gp21_read_4bytes(0xB1);
                 if(No_of_temp_meas==2)  Temp2_Result1 = gp21_read_4bytes(0xB1);

               //......RES_2 : Temp1_Result2, Temp2_Result2 word = 4 Byte.......

                 if(No_of_temp_meas==1)  Temp1_Result2 = gp21_read_4bytes(0xB2);
                 if(No_of_temp_meas==2)  Temp2_Result2 = gp21_read_4bytes(0xB2);
```

```
               //......RES_3 : Temp1_Result2, Temp2_Result2 word = 4 Byte.......
                 if(No_of_temp_meas==1)  Temp1_Result3 = gp21_read_4bytes(0xB3);
                 if(No_of_temp_meas==2)  Temp2_Result3 = gp21_read_4bytes(0xB3);
               //...............................................................
               }

No_of_temp_meas++;
} //corresponds to while loop with No_of_temp_meas

  Rhot_by_Rref  = (Temp1_Result0+Temp2_Result0)/(Temp1_Result2+Temp2_Result2);
  Rcold_by_Rref = (Temp1_Result1+Temp2_Result1)/(Temp1_Result3+Temp2_Result3);

//-------------------------End of Temperature Measurement-----------------------

// .............................................................................
// .....................TIME OF FLIGHT MEASUREMENT..............................
// .............................................................................

//---------------- Rewriting Config reg 1  --------------------
  gp21_wr_config_reg(0x81, 0x21444512); // Config reg 1

//------------------------ Sending Init------------------------
  gp21_send_1byte(0x70);      // Opcode INIT to GP21
  gp21_send_1byte(0x05);      // Opcode RESTART_TOF to GP21

while (stream_count <= 2)
{
  while(hit_count<4)
  {
    // Timeout_ctr is set 25 ms ONLY for the time between downstream and upstream meas.
    // Else it is set 4 ms to wait for the possible timeout for first interrupt (first
hit)
    timeout_counter = ( (upstream==1) && (hit_count==1) ) ? TWENTY_MILLISECONDS_TIMEOUT
: FOUR_MILLISECONDS_TIMEOUT;

   // Waiting for timeout of 4ms only on first hit, else wait for interrupt
    while ( (GPIO_ReadInputDataBit(GPIOB, GPIO_Pin_9)==1) &&
           (timeout_counter!=0)
         )
          {if (hit_count==1) timeout_counter--;
          }
```

```
switch (hit_count)
{
 case 1:
   {
          TOF_status_bytes = gp21_read_2byte_status();

          if((TOF_status_bytes & 0x1E00)!=0)
            {
              if((TOF_status_bytes & 0x0600)!=0)
              { // Timeout Error routine
              }
              else
              { // Sensor error routine
              }
            }
           else
            {
               // Config reg 1 - Calculate 2nd hit start
               GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_RESET); // Deactivating Reset
               while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}

               SPI_I2S_SendData(SPI2, 0x0081);  // RAM WR OPCODE+ADDRESS

               while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
               SPI_I2S_SendData(SPI2, 0x0031);    // DATA BYTE HIGH - 1

               while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
               SPI_I2S_SendData(SPI2, 0x0044);   // DATA BYTE HIGH - 2

               while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
               GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_SET); // Activating Reset
            }
   }
   break;
 case 2:
   {
          // Config reg 2 - Calculate 2nd hit start
          GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_RESET); // Deactivating Reset
          while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}

          SPI_I2S_SendData(SPI2, 0x0081);  // RAM WR OPCODE+ADDRESS

          while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
```

```
          SPI_I2S_SendData(SPI2, 0x0041);   // DATA BYTE HIGH - 1

          while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
          SPI_I2S_SendData(SPI2, 0x0044);   // DATA BYTE HIGH - 2

          while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
          GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_SET); // Activating Reset
     }
    break;
  case 3:
    {
      //.............RES_0 : Result0 word = 4 Byte.....................

            Result0 = gp21_read_4bytes(0xB0);
      //.............RES_1 : Result1 word = 4 Byte.....................

            Result1 = gp21_read_4bytes(0xB1);
      //.............RES_2 : Result2 word = 4 Byte.....................

            Result2 = gp21_read_4bytes(0xB2);
      //...............................................................
    }
    break;
  default:
     break;
  }// switch statement

      hit_count++;

}// while loop with hit_count

// Calculation of TOF
  if(upstream==FALSE)
  {
    average_Result_down = (Result0 + Result1 + Result2) /3;

  // RECONFIG & INIT FOR UPSTREAM MEASUREMENT
  //---------------- Reinitializing Config reg 1  --------------------------------
      gp21_wr_config_reg(0x81, 0x21444512); // Config reg 1
      gp21_send_1byte(0x70);                // Opcode INIT to GP21

      upstream = TRUE;
```

```
         hit_count = 1;
         Result0 = 0;
         Result1 = 0;
         Result2 = 0;
    }
    else
    {
      average_Result_up   = (Result0 + Result1 + Result2) /3;
      Time_of_flight      = ((average_Result_up- average_Result_down)/65536) * 0.25; //
This gives result in us ; 2^16=65536
    }

stream_count++;
} // while loop with stream_count

} //main

//...........................................................................
//.......................SUBROUTINES........................................
//...........................................................................

/**************************************************************************
 * Function Name: Dly100us
 * Parameters: u32 Dly
 * Return: none
 * Description: Delay Dly * 100us
 **************************************************************************/
void Dly100us(void *arg)
{
u32 Dely = (u32)arg;
 while(Dely--)
 {
   for(int i = LOOP_DLY_100US; i; i--);
 }
}

void Simple_delay_750ns(void *arg) // With arg 1, gives 750ns delay
{
u32 Dely = (u32)arg;
   for(int i = Dely; (i!=0); i--);
}
//***********************************************************************
/**************************************************************************
```

```
 * Function Name: gp21_send_1byte
 * Parameters: Opcode byte
 * Return: none
 * Description: Writes the Opcode to GP21
 *************************************************************************/
void gp21_send_1byte (uint8_t gp21_opcode_byte)
{
     GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_RESET); // Deactivating Reset
     SPI_I2S_SendData(SPI2, gp21_opcode_byte);     // OPCODE TO GP21
     while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}

     GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_SET);   // Reset to GP21
}
//*********************************************************************

/*************************************************************************
 * Function Name: gp21_wr_config_reg
 * Parameters: Address byte, 4 bytes of Configuration
 * Return: none
 * Description: Writes the config.reg. specified in GP21 with the data
 *************************************************************************/
void gp21_wr_config_reg (uint8_t opcode_address, uint32_t config_reg_data)
{

   uint8_t Data_Byte_Lo    = config_reg_data;
   uint8_t Data_Byte_Mid1  = config_reg_data>>8;
   uint8_t Data_Byte_Mid2  = config_reg_data>>16;
   uint8_t Data_Byte_Hi    = config_reg_data>>24;

GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_RESET); // Deactivating Reset
      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}

      SPI_I2S_SendData(SPI2, opcode_address);  // RAM WR OPCODE+ADDRESS

      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
      SPI_I2S_SendData(SPI2, Data_Byte_Hi);  // DATA BYTE HIGH

      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
       SPI_I2S_SendData(SPI2, Data_Byte_Mid2);  // DATA MID - 2

      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
       SPI_I2S_SendData(SPI2, Data_Byte_Mid1);  // DATA MID - 1
      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}
```

```
       SPI_I2S_SendData(SPI2, Data_Byte_Lo);  // DATA LOW

      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==0) {}

      GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_SET);
}
//*********************************************************************

/*************************************************************************
 * Function Name: gp21_read_2byte_status
 * Parameters: none
 * Return: 2 bytes of status
 * Description: Read 2 bytes of status from GP21
 ************************************************************************/
uint16_t gp21_read_2byte_status(void)
{
  uint16_t Status_bytes=0;

    GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_RESET);
    SPI_I2S_SendData(SPI2, 0x00B4);  // READ OPCODE+Address 4

    while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==RESET);

//Compulsory reads to DR and SR to clear OVR, so that next incoming data is saved
    SPI_I2S_ReceiveData(SPI2);                     // To clear OVR
    SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE);// To clear OVR

//Reading byte1
    SPI_I2S_SendData(SPI2, 0x00FF);  // DUMMY WRITE

// Wait until the RX buffer is not empty, then read the received data
    while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_RXNE)==0){}
    Status_bytes = Status_bytes | SPI_I2S_ReceiveData(SPI2); // actual Read
    Status_bytes = Status_bytes<<8;

//Reading byte2
    SPI_I2S_SendData(SPI2, 0x00FF);  // DUMMY WRITE

// Wait until RX buffer is not empty, then read the received data
    while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_RXNE)==0) {}
    Status_bytes = Status_bytes | SPI_I2S_ReceiveData(SPI2); // actual read
    GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_SET);     // Reset to GP21
```

```
    return Status_bytes;
}

/*************************************************************************
 * Function Name: gp21_read_4bytes
 * Parameters: none
 * Return: 4 bytes from the specified read address
 * Description: Reads 4 bytes from an address in GP21
 *************************************************************************/
uint32_t gp21_read_4bytes(uint8_t read_opcode_addr)
{
    uint32_t Result_read=0;

     //.............. Result  word = 4 Byte = 32  bits......................
      GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_RESET);

      SPI_I2S_SendData(SPI2, read_opcode_addr);  // READ OPCODE + Address 1

      while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE)==RESET);

       //Compulsory reads to DR and SR to clear OVR, so next incoming data is saved
       SPI_I2S_ReceiveData(SPI2);                     // To clear OVR
       SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_TXE); // To clear OVR

       //Reading byte1
       SPI_I2S_SendData(SPI2, 0x00FF);  // DUMMY WRITE

       // Wait until the RX buffer is not empty, then read the received data
       while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_RXNE)==0){}
       Result_read |= SPI_I2S_ReceiveData(SPI2); //  Read
       Result_read = Result_read<<8;

       //Reading byte2
       SPI_I2S_SendData(SPI2, 0x00FF);  // DUMMY WRITE

       // Wait until RX buffer is not empty, then read the received data
       while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_RXNE)==0) {}
       Result_read |= SPI_I2S_ReceiveData(SPI2); //  Read
       Result_read = Result_read<<8;

       //Reading byte3
       SPI_I2S_SendData(SPI2, 0x00FF);  // DUMMY WRITE
```

```
       // Wait until the RX buffer is not empty, then read the received data
       while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_RXNE)==0){}
       Result_read |= SPI_I2S_ReceiveData(SPI2); //  Read
       Result_read = Result_read<<8;

       //Reading byte4
       SPI_I2S_SendData(SPI2, 0x00FF);  // DUMMY WRITE

       // Wait until the RX buffer is not empty, then read the received data
       while (SPI_I2S_GetFlagStatus(SPI2, SPI_I2S_FLAG_RXNE)==0){}
       Result_read |= SPI_I2S_ReceiveData(SPI2); //  Read

       GPIO_WriteBit(GPIOB, GPIO_Pin_12, Bit_SET);     // Reset to GP21

       return Result_read;
}
//***********************************************************************

/*************************END OF FILE**********************/
```

7 Literature References

acam-messelectronic gmbh - “TDC-GP21 Datasheet“
http://www.acam.de/download-center/time-to-digital converters

acam-messelectronic gmbh - “GP2 to GP21 migration guide“
http://www.acam.de/download-center/time-to-digital converters

acam-messelectronic gmbh - “Temperature port investigations of TDC-GP2“
http://www.acam.de/download-center/time-to-digital converters

8 Revision History

19.10.2011 Chapters 5 & 6 revised.

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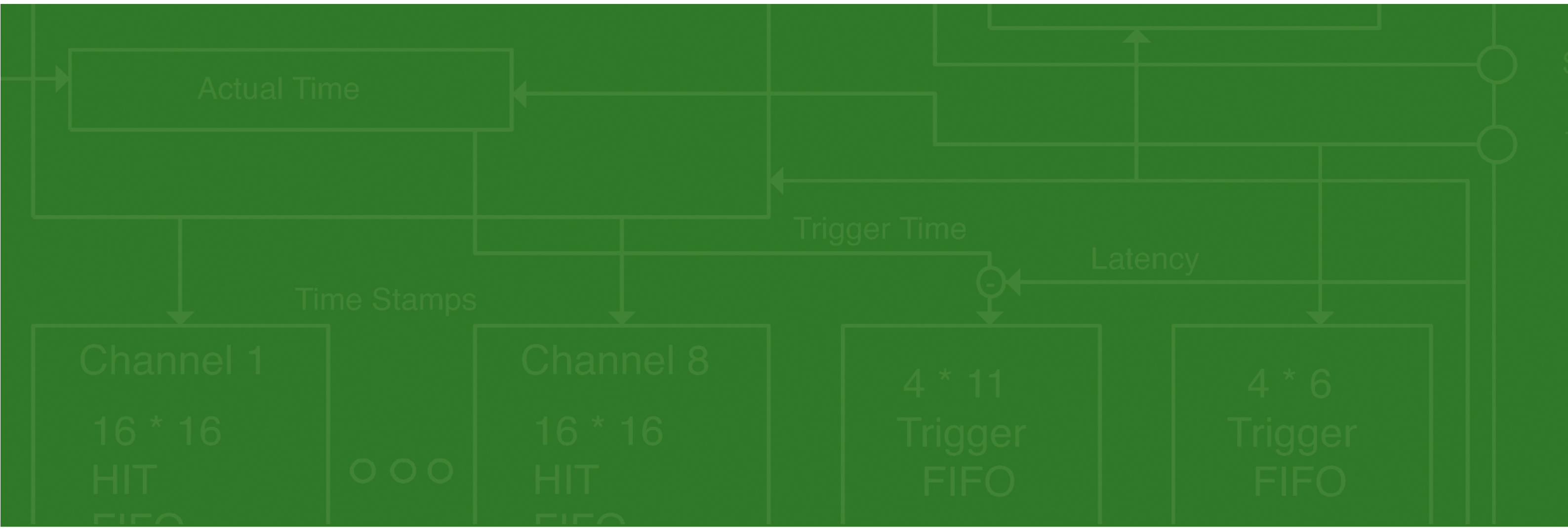

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