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Time-to-**D**igital-**C**onverter

Preliminary Datasheet

TDC-GP21

**Universal 2-Channel
Time-to-Digital Converter**

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TDC-GP21

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1 Overview

1.1 Features

TDC-GP21 is next generation's upgrade for TDC-GP2. It offers pin-to-pin and functional compatibility, several feature improvements and an extended functionality. Analog elements like a chopper stabilized comparator and analog switches simplify external circuits in a significant manner. In parallel, measurement quality is improved and operating current is reduced. The firepulse generator is extended, a new low-power 32 kHz oscillator driver is implemented and the temperature measuring unit is further improved. All in all, the TDC-GP21 is perfectly suited to design ultra-compact and low-cost ultrasonic flow meters and heat meters. If the integrated analog elements of the TDC-GP21 are used, the avarage operating current of a typical heatmeter application can be reduced to 2.2 µA

Measure Mode 2

- 1 channel with typ. 90 ps resolution
- Double resolution mode with 45 ps, Quad resolution mode with 22 ps resolution
- Measurement range 500 ns to 4 ms
- 2 x CLKHS pulse-pair resolution with 3-fold multihit capability
- Each of the 3 events can be assigned to an adjustable measuring window with 10 ns resolution

Analog Input Circuit

- Chopper-stabilized low-offset comparator
- 2 analog switches for input selection
- External circuit is reduced to 2 resistors and 2 capacitors

Special Functions

- Fire pulse generator, up to 127 pulses
- Trigger to rising and/or falling edge
- Precise stop enable by windowing
- Low-power 32 kHz oscillator (500 nA)
- Clock calibration unit
- 7x32 Bit EEPROM

Temperature Measurement Unit

- 2 or 4 sensors
- PT500/PT1000 or higher
- Schmitt trigger integrated
- Very high resolution:
  16-Bit eff. with external Schmitt-trigger (0.004 °C resolution for platinum sensors), 17.5-Bit eff. with integrated low noise Schmitt-trigger (0.0015 °C resolution for platinum sensors)
- Ultra low current (0.08 µA when measuring every 30 seconds)

Measure Mode 1

- 2 channels with typ. 90 ps resolution
- 1-channel double resolution with typ. 45 ps
- Range 3.5 ns (0 ns) to 2.5 µs
- 20 ns pulse-pair resolution, 4-fold multihit
- Up to 1 million measurements per second im measure mode 1

General

- 4-wire SPI interface
- 1 MHz continuous data rate max.
- I/O voltage 2.5 V to 3.6 V
- Core voltage 2.5 V to 3.6 V
- Temperature range – 40 °C to +85 °C
- QFN 32 package

1.2 Blockdiagram
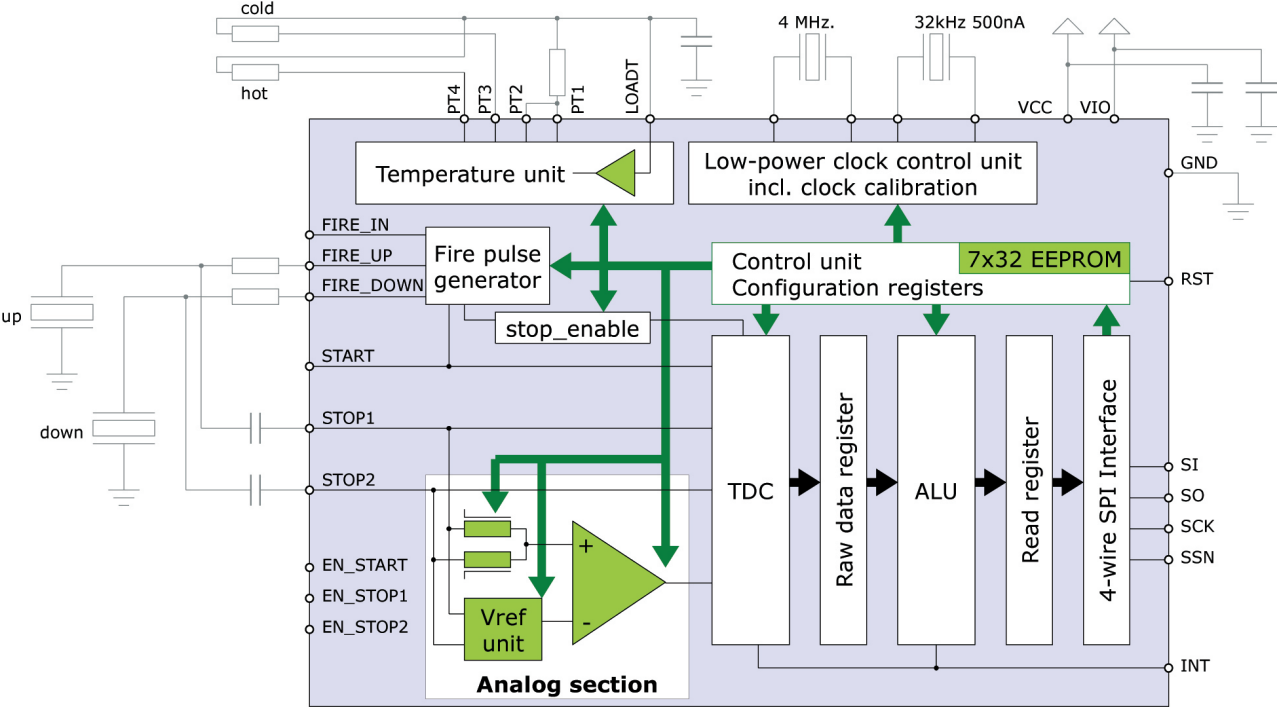
2   Characteristics & Specifications

2.1   Electrical Characteristics

Absolute Maximum Ratings

Supply voltage

Vcc vs. GND	- 0.3 to 4.0	V
Vio vs. GND	- 0.3 to 4.0	V

Vin	- 0.5 to Vcc + 0.5	V
Storage temperature (Tstg)	- 55 to 150	°C
ESD rating (HBM), each pin	> 2	kV
Junction temperature (Tj)	max. 125	°C

Recommended Operating Conditions

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
Vcc	Core supply voltage*	Vio > Vcc	2.5		3.6	V
Vio	I/O supply voltage		2.5		3.6	V
tri	Normal input rising time				200	ns
tfa	Normal input falling time				200	ns
tri	Schmitt trigger rising time				5	ms
tfa	Schmitt trigger falling time				5	ms
Ta	Ambient temperature	Tj must not exceed 125°C	-40		125	°C

*including the oscillator pins XIN, XOUT, Clk32In, Clk32Out

DC Characteristics (Vio = Vcc = 3.0 V, Tj = -40 to +85°C)

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
I32	Current 32 kHz	Icc + Iio, only 32kHz oscillator running		1.0		µA
Ihs	Current 4 Mhz oscillator	3.6V 3.0V off		200 130 < 1		µA µA nA
Itmu	Current time measuring unit	only during active time measurement		4		mA
Iddq	Quiescent current	all clocks off, @ 85 °C		< 0.1		µA
Il	Input leakage current					µA
Voh	High level output voltage	Ioh= tbd mA Vio=Min.	0.8Vio			V
Vol	Low level output voltage	Iol = tbd mA, Vio=Min			0.2Vio	V
Vih	High level input voltage	LVTTL Level, Vio = Max.	0.7Vio			V
Vil	Low level input voltage	LVTTL Level, Vio = Min.			0.3Vio	V
Vth	High level Schmitt trigger voltage		0.7Vio			V

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
Vtl	Low level Schmitt trigger voltage				0.3Vio	V
Vh	Schmitt trigger hysteresis			0.28		V

Terminal Capacitance

Symbol	Terminal	Condition	Rated Value			Unit
			Min.	Typ.	Max.	
Ci	Digital input	measured @ Vcc = Vio, f = 1 MHz, Ta = 25°C		7		pF
Co	Digital output					
Cio	Bidirectional			9		
	PT ports			t.b.d.		
	Analog in			t.b.d.		

Analog Frontend

Symbol	Terminal	Condition	Rated Value			Unit
			Min.	Typ.	Max.	
	Comparator input offset voltage (chopper stabilized)			< 1	2	mV
	Rdson Analog switch			200		Ohm

2.2 Converter Specification

Time Mesuring Unit

Symbol	Terminal	Condition	Rated Value			Unit
			Min.	Typ.	Max.	
LSB	Resolution (BIN-Size)	Measure Mode 1 & 2: DOUBLE_RES = 0 DOUBLE_RES = 1		90 45		ps
		Measure mode 2: QUAD_RES = 1		22		ps
σ	Standard deviation	Measure Mode 1 & 2: DOUBLE_RES = 0 DOUBLE_RES = 1		t.b.d		ps
		Measure mode 2: QUAD_RES = 1		t.b.d		ps
t_m	Measuring range	Measure mode 1	3.5 ns		2.4 µs	
		Measure mode 2	500 ns		4 ms	
INL	Integral Non-linearity			< 0.1		LSB
DNL	Differential Non-linearity			< 0.8		LSB

Temperature Measuring Unit[1]

Symbol	Terminal		Internal Schmitt-Trigger		external Schmitt-Trigger[2]		Unit
			PT500	PT1000	PT500	PT1000	
	Resolution RMS		17.5	17.5	16.0	16.0	Bit
	SNR		105	105	96	96	dB
	Absolute Gain[3]		0.9912	0.9931	0.9960	0.9979	
		3.6 V	0.9923	0.9940	0.9962	0.9980	
	Absolute Gain vs. Vio[3]	3.0 V	0.9912	0.9931	0.9960	0.9979	
		2.5 V	0.9895	0.9915	0.9956	0.9979	
	Gain-Drift vs. Vio		0,25	0.23	0.06	0.04	%/V
	max. Gain Error (@ dθ = 100 K)		0,05%	0,05%	0,02%	< 0.01%	
	Gain-Drift vs. Temp		0.022	0.017	0.012	0.0082	%/10 K
	Gain-Drift vs. Vio				0,08		%/V
	Initial Zero Offset		< 20	<10	< 20	< 10	mK
	Offset Drift vs. Temp		< 0.05	< 0.03	< 0,012	< 0.0082	mK/ °C
	PSRR				>100		dB

[1] All values measured at Vio = Vcc = 3.0 V, Cload = 100 nF for PT1000 and 200 nF for PT500 (COG-type)
[2] measured with external 74AHC14 Schmitt-trigger
[3] compared to an ideal gain of 1

2.3   Timings

At Vcc = 3.0 V $\pm$ 0.3 V, ambient temperature -40 °C to +85 °C unless otherwise specified

Oscillator

Symbol	Parameter	Min.	Typ.	Max.	Unit
Clk32	32 kHz reference oscillator		32,768		kHz
t32st	32 kHz oscillator start-up time after power-up		3		s
ClkHS	High-speed reference oscillator	2	4	8	MHz
toszst	Oscillator start-up time with ceramic resonator		100		µs
toszst	Oscillator start-up time with crystal oscillator		3		ms

Serial Interface

Symbol	Parameter	Max. @ Vio =		Unit
		2.5 V	**3.3 V**	
fclk	Serial clock frequency	15	20	MHz

Symbol	Parameter	Max. @ Vio =		Unit
		2.5 V	**3.3 V**	
tpwh	Serial clock, pulse width high	30	25	ns
tpwl	Serial clock, pulse width low	30	25	ns
tsussn	SSN enable to valid latch clock	40	10	ns
tpwssn	SSN pulse width between write cycles	50	40	ns
thssn	SSN hold time after SCLK falling	40	25	ns
tsud	Data set-up time prior to SCLK falling	5	5	ns
thd	Data hold time before SCLK falling	5	5	ns

Symbol	Parameter	Max. @ Vio =		Unit
		2.5 V	**3.3 V**	
tvd	Data valid after SCLK rising	20	16	ns

Serial Interface (SPI compatible, Clock Phase Bit =1, Clock Polarity Bit =0):
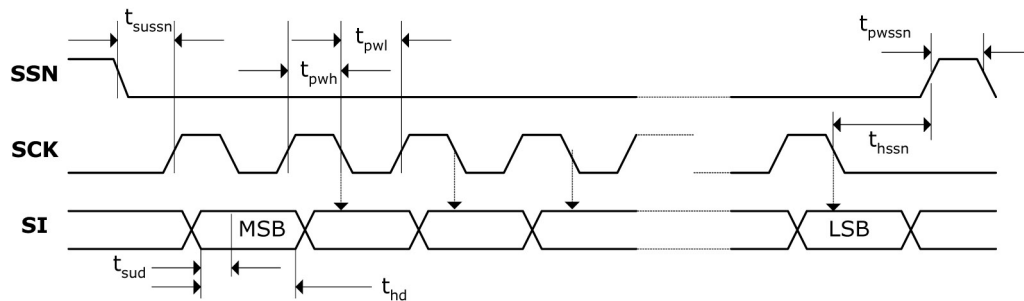
Figure 2.1: SPI Write

Figure 2.2: SPI Read
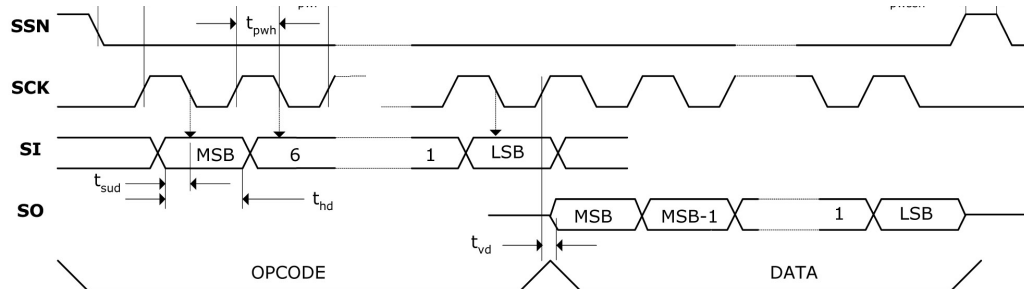
Disable Timings

Figure 2.3:
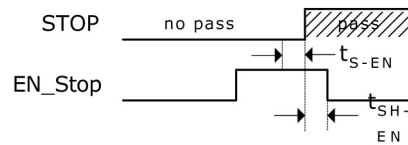
Spec	Description	Min (ns)	Max (ns)
tS-EN	Enable Setup Time	t.b.d. ns	-
tSH-EN	Enable Hold Time	t.b.d. ns	-

Reset Timings

Figure 2.4:
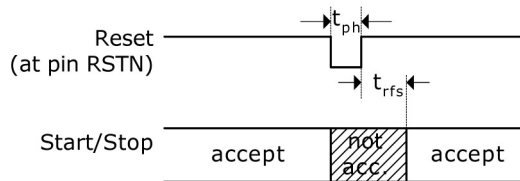
Spec	Description	Min (ns)	Max (ns)
tph	Reset pulse width	t.b.d. ns	-
trfs	Time after rising edge of reset pulse before hits are accepted	t.b.d. µs	-

Note: After power-on reset it is necessary to wait minimum 500 us to settle the analog part.

2.4   Pin Description
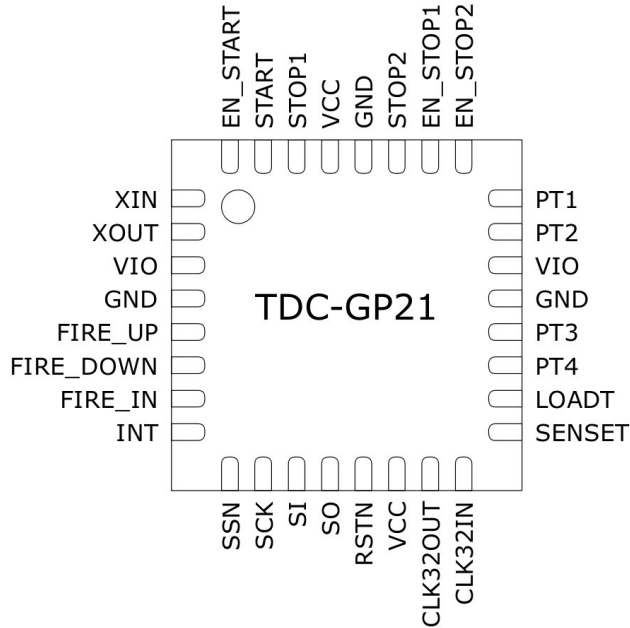
No.	Name	Description	Buffer type	Value	If not used
1	XIN	Oscillator driver in			GND
2	XOUT	Oscillator driver out			
3	VIO	I/O – supply voltage			
4	GND	Ground			
5	FIRE_UP	Fire pulse generator output 1	48 mA		
6	FIRE_DOWN	Fire pulse generator output 2	48 mA		
7	FIRE_IN	Signal input for quasi "Sing Around"			GND
8	INTN	Interrupt flag	4 mA	LOW active	
9	SSN	Slave select		LOW active	
10	SCK	Clock serial interface			
11	SI	Data input serial interface			
12	SO	Data output serial interface	4 mA tristate		
13	RSTN	Reset input		LOW active	
14	VCC	Core supply voltage			
15	CLK32OUT	Output 32 kHz clock generator			n. c.
16	CLK32IN	Input 32 kHz clock generator			GND
17	SENSET	Sense input temperature measurement	Schmitt trigger		GND
18	LOADT	Load output temperature measurement	24 mA		n.c.
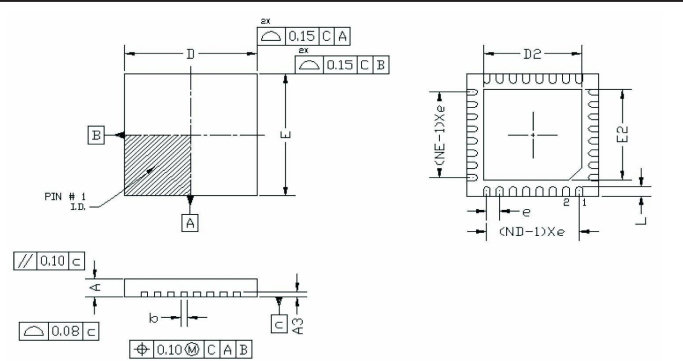
No.	Name	Description	Buffer type	Value	If not used
19	PT4*	Port 4 temperature measurement	> 96 mA open drain		
20	PT3*	Port 3 temperature measurement	> 96 mA open drain		
21	GND	Ground			
22	VIO	I/O – supply voltage			
23	PT2*	Port 2 temperature measurement	> 96 mA open drain		
24	PT1*	Port 1 temperature measurement	> 96 mA open drain		
25	EN_STOP2	Enable pin stop input 2		HIGH active	Vio
26	EN_STOP1	Enable pin stop input 1		HIGH active	Vio
27	STOP2	Stop input 2			GND
28	GND	Ground			
29	VCC	Core supply voltage			
30	STOP1	Stop input 1			GND
31	START	Start input			
32	EN_START	Enable pin start input		HIGH active	Vio

* R_{DSON} temperature ports: typ. 1.8 Ω @ 3.0 V

2.5   Package Drawings

Suitable socket: Plastronics 32QN50S15050D

Symbol	Dimension in Millimeters		
	Min.	Nom.	Max.
D	-	5	-
E	-	5	-
A	-	-	1
A1	0	-	-
b	0.17	-	0.3
e	-	0.5	-
L	0.3	-	0.5
G		3.24	

Caution: Center pad is internally connected to GND.

Thermal resistance

Roughly 40 K/W at 0 m/s air flow, 37 K/W at 1 m/s air flow, 35 K/W at 2m/s air flow (values just for reference).

Soldering Temperature Profile

The temperature profile for infrared reflow furnace (in which the temperature is the resin's surface temperature) should be maintained within the range described below.

Maximum temperature

The maximum temperature requirement for the resin surface, given 260°C as the peak temperature of the package body's surface, is that the resin surface temperature must not exceed 250°C for more than 10 seconds. This temperature should be kept as low as possible to reduce the load caused by thermal stress on the package, which is why soldering for short periods only is recommended. In addition to using a suitable temperature profile, we also recommend that you check carefully to confirm good soldering results.
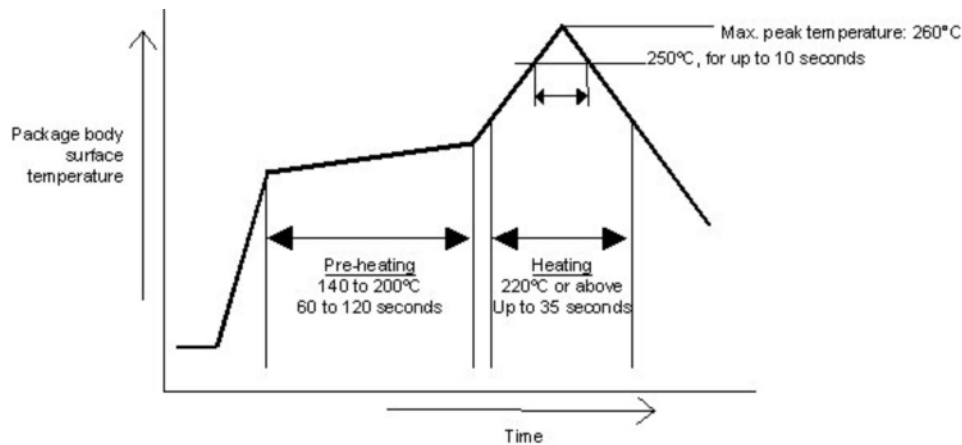
2.6   **Power Supply**

Supply voltage

TDC-GP21 is a high end mixed analog/digital device. To reach full performance of the chip a good power supply is mandantory. It should be high capacitive and of low inductance.

The TDC-GP21 provides two pairs of power supply terminals:

Vio   - I/O supply voltage

Vcc   - Core supply voltage

All ground pins should be connected to a ground plane on the printed circuit board. Vio and Vcc should be provided by a battery or fixed linear voltage regulator. Do not use switched regulators to avoid disturbances caused by the I/O supply.

The measurement quality of a time-to-digital converter depends on a good power supply. The chip sees mainly pulsed current and therefore a sufficient bypassing is mandatory:

Vcc	47 μF	(minmum 22 μF)
Vio	100 μF	(minimum 22 μF)

The supply voltage should be provided through analog regulators. We strongly recommend not to use switch mode power supplies.

Current consumption

The current consumption is the sum from different parties (all data for Vio = Vcc = 3.0V):

I_{ddq} < 5 nA typ.@3.0V, 25°C   Quiescent current, no 32 kHz oscillator running

I_{32} typ. 1.0 μA   Standby current with active 32 kHz oscillator (GP21 waiting for command).

I_{hs} typ. 130 μA/s * (active runtime)   Current into the high speed oscillator at 3.0 V Vio.
Example: In ultrasonic flow-meters the high-speed oscillator is on for about 2ms only. The average current consumption is 130 μA/s * 2 ms = 0.26 μA

I_{tmu} typ. 4 mA/s * (active measuring time)   Current into the time measuring unit, In measurement range 1 the time measuring unit is active for the start-stop time inter val plus the calibration time interval of 2 periods of the refe rence clock per measurement.
In measurement range 2 the time measuring unit is on for average 4 periods of the reference clock per measurement, two for the time measurement and two for calibration.
Example: With 10 measurements per second in measurement range 2 and a 4 MHz reference clock the time measuring unit is active for only about 10 μs.
The average current is 4 mA/s * 10 μs = 0.040 μA.

I_{alu} typ. 7 nA per calculation   Current into ALU during data proccesing including a calibration calculation.
Example: At 1000 measurements per second with 3 stops per start the ALU average current is 7 nA * 3000 = 21 μA.

I_T typ. 2.5 µAs * measure rate   The current for a full temperature measurement is typ.2.5µAs. In heat-meters the temperature is measured typically once every 30 seconds. The average current is about 0.085 µA

I_{ana} typ. 0.8 mA   Current consuption of the integrated analog part of TDC-GP21during a Time-of-flight (ToF) measurement. The analog part is active for a duration of 250 µs + ToF.

In a typical ultrasonic heat meater application, the flow is measured twice per second. The temperature is measured every 30 seconds. With TDC-GP21 the current consumption of the complete flow and temperature measuring unit, including the analog part, the transducers and PT sensors, is as low as 2.2 µA typically.

3 Registers & Communication

3.1 Configuration registers

The TDC-GP21 has 6 configuration registers with 32 bit. The upper 24 bit are used for configuration and are write only. They are used to setup the TDC-GP21 operating mode. The lowest 8 bit can be used e.g. as an ID and can be read back. As the read/write operations start with the MSB communication will be compatible with TDC-GP2.

For communication test please write to register 1 and read back the highest 8 bit from address 5.

Note:

The write registers of TDC-GP21 are fully upwards compatible with TDC-GP2. A given configuration of TDC-GP2 can directly be used one-to-one in TDC-GP21. The TDC-GP21 than works as a TDC-GP2. The add-on functionality can be selected in register 6 and reg1 Bits 7:0 which are not used in GP2. For proper work of TDC-GP21, a power-up reset via pin or SPI command is necessary after the power-up of the circuit.

3.1.1 Alphanumeric listing of configuration parameters

Parameter	Old name (TDC-GP2)	Register	Bits	Default value	New or modified
ANZ_FAKE	No_Fake	0	15	0	
ANZ_FIRE	Fire#	6 0	28-31 8-10	2	×
ANZ_PER_CALRES	CALRES#	6	22,23	0	
ANZ_PORT	PORT#	0	17	1	
CALIBRATE	calibrate	0	13	1	
Conf Fire	CONF_FIRE	5	28-31	0	
CURR32K		1	15	1	×
CYCLE_TEMP		6	18,19	0	×
CYCLE_TOF		6	16,17	0	×
DELVAL1	DELVAL1	2	8-23	0	
DELVAL2	DELVAL2	3	8-23	0	
DELVAL3	DELVAL3	4	8-23	0	
DIS_PHASSHIFT	Dis_PhaseNoise	5	27	0	
DIV_CLKHS	ClkHSDiv	0	20,21	0	
DIV_FIRE	DIV_FIRE	0	24-27	2	
DOUBLE_RES		6	12	0	×
EN_ANALOG		6	31	0	×
EN_ERR_VAL	EN_ERR_VAL	3	29	0	
EN_Fast_Init	EN_FAST_INIT	1	23	0	
EN_INT	EN_INT	2 6	29-31 21	1	×
EN_STARTNOISE	EN_STARTNOISE	5	28	0	

Parameter	Old name (TDC-GP2)	Register	Bits	Default value	New or modified
FIREO_DEF		6	14	0	×
HIT1	HIT1	1	24-27	5	
HIT2	HIT2	1	28-31	5	
Hitin1	HITIN1	1	16-18	0	
Hitin2	HITIN2	1	19-21	0	
HZ60		6	15	0	×
IDO		0	0-7	0	×
ID1		1	0-7	0	×
ID2		2	0-7	0	×
ID3		3	0-7	0	×
ID4		4	0-7	0	×
ID5		5	0-7	0	×
ID6		6	0-7	0	×
MESSB2	MRange2	0	11	1	
NEG_START	NEG_START	0	8	1	
NEG_STOP_TEMP		6	30	0	×
NEG_STOP1	NEG_STOP1	0	9	1	
NEG_STOP2	NEG_STOP2	0	10	1	
NO_CAL_AUTO	DisAutoCal	0	12	0	
PHFIRE	Phase_Fire	5	8-23	0	
QUAD_RES		6	13	0	×
REPEAT_FIRE	REPEAT_FIRE	5	24-26	0	
RFEDGE1	RFEDGE1	2	27	0	
RFEDGE2	RFEDGE2	2	28	0	
SEL_ECLK_TMP	SelClkT	0	14	1	
SEL_START_FIRE		1	14	0	×
SEL_TIMO_MB2	SEL_TIMO_MR2	3	27,28	3	
SEL_TSTO1		1	8-10	0	×
SEL_TSTO2		1	11-13	0	×
START_CLKHS	START_ClkHS	0 6	18,19 20	1	×
TCYCLE	TCycle	0	16	0	
TEMP_PORTDIR		6	11	0	×
TW2		6	22,23	0	×

3.1.2 List of configuration registers

Bit number →	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
parameter →			param1				k.d.									
Default value →							1	1	0	0	1	0	1	0	1	0

k.d. = keep default values

Register 0 (address 0):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
ANZ_FIRE				DIV_FIRE																				IDO
0	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0	1	1	0	1	0	0	0	0

Bit labels (left to right): ANZ_PER_CALRES, DIV_CLKHS, START_CLKHS, ANZ_PORT, TCYCLE, ANZ_FAKE, SEL_ECLK_TMP, CALIBRATE, NO_CAL_AUTO, MESSB2, NEG_STOP2, NEG_STOP1, NEG_START

Parameter (Old GP2 name)	Description	Settings
ANZ_FIRE (FIRE#)	Sets number of pulses generated by fire pulse generator. Additional 3 bits are set in register 6. For values ANZ_FIRE > 15 the phase setting (PHFIRE) can not be used.	0 = off 1 = 1 pulse 2 = 2 pulses … 127 = 127 pulses
DIV_FIRE	Sets predivider for internal clock signal of fire pulse generator	0 = not permitted 1 = divided by 2 2 = divided by 3 3.= divided by 4 … 15 = divided by 16
ANZ_PER_CALRES (CALRES#)	Sets number of periods used for calibrating the ceramic resonator	0 = 2 periods = 61.035 µs 1 = 4 periods = 122.07 µs 2 = 8 periods = 244.14 µs 3 = 16 periods = 488.281 µs
DIV_CLKHS (ClkHSDiv)	Sets predivider for CLKHS	0 = divided by 1 1 = divided by 2 2 = divided by 4 3 = divided by 4
START_CLKHS[1:0]	Defines the time interval the chip waits after switching on the oscillator before making a measurement. **Note**: The highest bit to adjust START_CLKS is located in register 6, bit 20. This has to be set to 1 for settling times of 2.44 ms and 5.14 ms.	0 = Oscillator off 1 = Oscillator continuously on 2 = settling time 480 µs 3 = settling time 1.46 ms 4 = settling time 2.44 ms 5 to 7 = settling time 5.14 ms
ANZ_PORT (PORT#)	Sets number of ports used for temperature measurement	0 = 2 temperature ports (PT1 and PT2) 1 = 4 temperature ports
TCYCLE	Sets cycle time for temperature measurement	0 = 128 µs cycle time @ 4 MHz 1 = 512 µs cycle time @ 4 MHz (recommended)
ANZ_FAKE (FAKE#)	Number of dummy cycles at the beginning of a tempera-ture measurement	0 = 2 Fake measurements 1 = 7 Fake measurements

SEL_ECLK_TMP (SelClkT)	Select reference signal for internal cycle clock for tem-perature measurement	0 = use 32.768 kHz as cycle clock 1 = use 128 * CLKHS as period for cycle clock (32µs with 4 MHZ high speed clock signal)
CALIBRATE	Enables/disables calibration calculation in the ALU	0 = calibration off (allowed only in mode 1) 1 = calibration on (recommended)
NO_CAL_AUTO (DisAutoCal)	Enables/disables auto-calibration run in the TDC	0 = auto-calibration after measurement 1 = auto-calibration disabled
MESSB2 (MRange2)	Switch to measurement range 2	0 = measurement range 1 1 = measurement range 2
NEG_STOP2	Negation stop 2 input	0 = non-inverted input signal – rising edge 1 = inverted input signal – falling edge
NEG_STOP1	Negation stop 1 input	0 = non-inverted input signal – rising edge 1 = inverted input signal – falling edge
NEG_START	Negation start input	0 = non-inverted input signal – rising edge 1 = inverted input signal – falling edge
ID0	Free bits, e.g. to be used as identification or version number	

Register 1 (address 1):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
HIT2				HIT1						HITIN2			HITIN1					SEL_TSTO2			SEL_TSTO1			ID1
0	1	0	1	0	1	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

Bits: EN_FAST_INIT, k.d., CURR32K, SEL_START_FIRE

Parameter	Description	Settings	
HIT2	Defines operator for ALU data post-processing Measure mode 1: HIT1-HIT2 Measure mode 2: HIT2-HIT1	MRange1: 0 = Start 1 = 1. Stop Ch1 2 = 2. Stop Ch1 3 = 3. Stop Ch1 4 = 4. Stop Ch1 5 = no action 6 = Cal1 Ch1 7 = Cal2 Ch1 9 = 1. Stop Ch2 A = 2. Stop Ch2 B = 3. Stop Ch2 C = 4. Stop Ch2	MRange2: 2 = 1. Stop Ch1 3 = 2. Stop Ch1 4 = 3. Stop Ch1

HIT1	Defines operator for ALU data post-processing MRange1: HIT1-HIT2 MRange2: HIT2-HIT1	MRange1: 0 = Start 1 = 1. Stop Ch1 2 = 2. Stop Ch1 3 = 3. Stop Ch1 4 = 4. Stop Ch1 5 = no action 6 = Cal1 Ch1 7 = Cal2 Ch1 9 = 1. Stop Ch2 A = 2. Stop Ch2 B = 3. Stop Ch2 C = 4. Stop Ch2	MRange2: 1 = Start
EN_FAST_INIT	Enables fast init operation	0 = Fast init mode disabled 1 = Fast init mode enabled	
HITIN2	Number of expected hits on channel 2	0 = stop channel 2 disabled 1 = 1 hit 2 = 2 hits 3 = 3 hits 4 = 4 hits 5 to 7 = not permitted	
HITIN1	Number of expected hits on channel 1	0 = stop channel 1 disabled 1 = 1 hit 2 = 2 hits 3 = 3 hits 4 = 4 hits 5 to 7 = not permitted	
CURR32K	Low current option for 32 kHz oscillator. Basically there is no need to use high current option (1). Low current (0) also guarantees oscillation.	0 = low current (recommended) 1 = high current (GP2 compatibility)	
SEL_START_FIRE	Firepulse is used as TDC start. The START input is disabled.	0 = TDC-GP2 behaviour 1 = Use FIRE as Start	
SEL_TSTO2	Defines functionality of EN_START pin. Besides the GP2 functionality this üin can act as output for various signals. If SEL_TSTOP2 > 0 then EN_START = HIGH internally.	0 = GP2 functionality, Fire_in input for sing arround 1 = START_TDC output 2 = STOP1 TDC output 3 = STOP2 TDC output 4 = Stop Tempearture measurement output 5 = EN_STOP by DELVAL output 6 = n.c. 7 = 4 kHz (32 kHz/8) clock	

SEL_TSTO1	Defines functionality of FIRE_IN pin. Besides the GP2 functionality this üin can act as output for various signals. If SEL_TSTO1 >1 the FIRE_IN iscoonected to GND internally.	0 = GP2 functionality, Fire_in input for sing arround 1 = START_TDC output 2 = STOP1 TDC output 3 = STOP2 TDC output 4 = Start Tempearture measurement output 5 = TOF=UP, =1 when TOF_UP measurement is active 6 = RUN_HA, =1 when hardmacro is active 7 = 32 kHz clock
ID1	Free bits, e.g. to be used as identification or version number	

Register 2 (address 2):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
EN_INT					DELVAL1																			ID2
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Bit 28 = RFEDGE2, Bit 27 = RFEDGE1

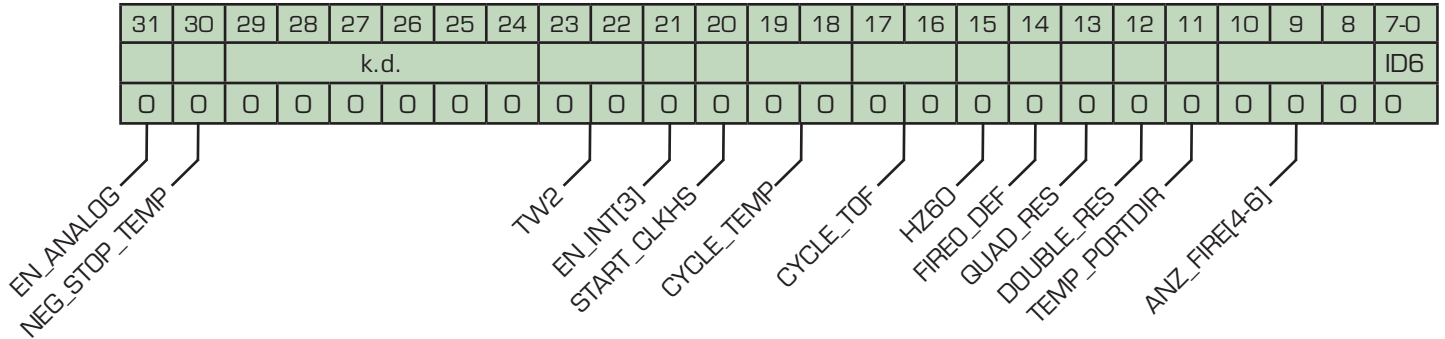| Parameter	Description	Settings
EN_INT	Activates interrupt sources wired by OR. Additional bit in register 6 (see there, too)	Bit 31 = Timeout interrupt enable Bit 30 = End Hits interrupt enable Bit 29 = ALU interrupt enable Reg6, BIT21 = End of EEPROM action
RFEDGE2	Edge sensitivity channel 1	0 = rising or falling edge 1 = rising and falling edge
RFEDGE1	Edge sensitivity channel 1	0 = rising or falling edge 1 = rising and falling edge
DELVAL1	Delay value for internal stop enable unit, hit 1 channel 1. Fixed point number with 14 integer and 5 fractional digits in multiples of Tref	DELVAL1 = 0 to 16383.96875
ID2	Free bits, e.g. to be used as identification or version number	

Register 3 (address 3):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
k.d.				DELVAL2																				ID3
0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

EN_ERR_VAL
SEL_TIMO_MB2
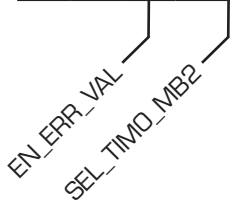
Parameter	Description	Settings
EN_ERR_VAL	Timeout forces ALU to write 0xFFFFFFFF into the output register	0 = disabled 1 = enabled
SEL_TIMO_MB2	Select predivider for timeout in measurement range 2	0 = 64 µs 1 = 256 µs 2 = 1024 µs 3 = 4096 µs @ 4 MHz ClkHS
DELVAL2	Delay value for internal stop enable unit, hit 2 channel 1. Fixed point number with 14 integer and 5 fractional digits in multiples of Tref	DELVAL1 = 0 to 16383.96875
ID3	Free bits, e.g. to be used as identification or version number	

Register 4 (address 5):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
k.d.					DELVAL3																			ID4
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Parameter	Description	Settings
DELVAL3	Delay value for internal stop enable unit, hit 3 channel 1. Fixed point number with 14 integer and 5 fractional digits in multiples of Tref	DELVAL1 = 0 to 16383.96875
ID4	Free bits, e.g. to be used as identification or version number	

Register 5 (address 5):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
								PHFIRE																ID5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

CONF_FIRE
EN_STARTNOISE
DIS_PHASESHIFT
REPEAT_FIRE
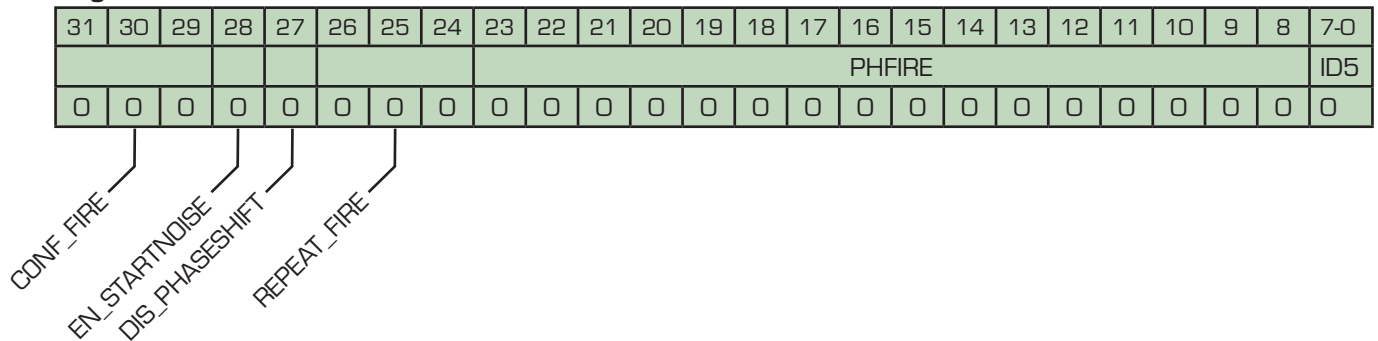
Parameter	Description	Settings
CONF_FIRE	Output configuration for pulse generator	Bit 31 = 1: FIRE_BOTH (inverts FIRE_DOWN) Bit 30 = 1: disable output FIRE_UP Bit 29 = 1: disable output FIRE_DOWN
EN_STARTNOISE	Enables additional noise for start channel	1 = switch on noise unit
DIS_PHASESHIFT (DIS_PHASENOISE)	Phase noise unit. Improves statistijcs and should be enabled if start pulse generation is derived from the GP2 reference clock (e. g. with fire pulse generator).	1 = disables phase noise 0 = enables phase noise unit
REPEAT_FIRE	Number of pulse sequnce repetition for "quasi-sing-arround"	0 = no signal repetition 1 = 1 signal repetition 2 = 2 signal repetition … 7 = 7 signal repetition
PHASE_FIRE	Enables phase reversing for each pulse of a sequence of up to 15 possible pulses	0 = no inversion 1 = inversion
ID5	Free bits, e.g. to be used as identification or version number	

New register:

Register 6 (address 6):

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7-0
				k.d.																				ID6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

EN_ANALOG
NEG_STOP_TEMP
TW2
EN_INT[3]
START_CLKHS
CYCLE_TEMP
CYCLE_TOF
HZ60
FIREQ_DEF
QUAD_RES
DOUBLE_RES
TEMP_PORTDIR
ANZ_FIRE[4-6]

Parameter	Description	Settings
EN_ANALOG	Activates the analog part for the ultrasonic flow measurement is. If active, this section is powered only for the duration of the measurement to save current. STOP1 and STOP2 are analog inputs now and automatically selected by the internal multiplexer.	0 = STOP1 and STOP2 are digital inputs (TDC-GP2 compatibility) 1 = The analog section is used.
NEG_STOP_TEMP	Inverts the SenseT input signal. This is mandatory when the internal comparator is used instead of the external one like in TDC-GP2	0 = external 74HC14 is used (TDC-GP2 compatibility) 1 = internal Schmitt trigger is used
TW2	Timer to charge up the capacitor of the recommend RC network when the internal analog part is used.	Charge time: 0 = 90 µs 1 = 120 µs 2 = 150 µs 3 = 300 µs
EN_INT	Additional interrupt source. See also register 2 for the lwoer 3 bits of EN_INT. The various sources are wired by an OR. An EEPROM action, e.g EEPROM_COMPARE, is managed by the TDC-GP21 and especially the EEPROM wirte may last up to 130ms. Indicating the end will be helpful.	1 = end of EEPROM action

START_CLKHS[2]	Highest bit to set the settling time for the high speed oscillator. The lower bits are set in register 0, bit 20 and 21.	0 = off 1 = continously on 2 = 480 µs delay 3 = 1.46 ms 4 = 2.44 ms 5 to 7 = 5.14 ms
CYCLE_TEMP	Selects timer for triggering the second temperature measurement in multiples of 50/60Hz	0 = 1 1 = 1.5 2 = 2 3 = 2.5
CYCLE_TOF	Selects timer for triggering the second ToF measurement in multiples of 50/60Hz	0 = 1 1 = 1.5 2 = 2 3 = 2.5
HZ60	TDC-GP21 can make complete up and down flow measurement and also two temperature measurements in series. The time interval between 2 measurements is based on 50 or 60 Hz.	0 = 50 Hz base, 20 ms 1 = 60 Hz base, 16.67ms
FIRE0_DEF	Specifies the default level of the inactive fire buffer. Example: if FIRE_UP is active then the FIRE_DOWN buffer is connected to the default level. Setting 1 is mandatory when using the integrated analog section.	0 = High-Z (as in GP2) 1 = LOW
QUAD_RES	Option to improve the resolution by factor 4 from 90 ps to 22 ps. Can be used only in measure mode 2.	0 = off (TDC-GP2 mode) 1 = on
DOUBLE_RES	Doubles the resolution from 90 ps to 45 ps. In measure mode 1 this option limits the number of stop inputs to one (Stop1)	0 = off (TDC-GP2 mode) 1 = on
TEMP_PORTDIR	Ports for temperature measurement are measured in the opposite order.	0 = PT1 > PT2 > PT3 > PT4 1 = PT4 > PT3 > PT2 > PT1
ANZ_FIRE[6:4]	Highest 3 bits of the number of fire pulses. See also register 0. If ANZ_FIRE > 15 then PHFIRE is no longer active.	0 = off 1 = 1 pulse 2 = 2 pulses … 127 = 127 pulses

TDC-GP21

3.2 Read registers

The result and status registers can be read by means of opcode 0xBX. The opcode is followed by 4, 2 or 1 bytes, depending ond the address.

The ID register bits in the configuration registers can be read back by means of opcode 0xB7. This opcode is followed by 7 bytes in the order ID0, ID1 … ID6, each byte with the MSB first.

ADR	Symbol	Bits	Description									
0	RES_0	32	Measurement result 1, fixed-point number with 16 integer and 16 fractional digits 2^{15} $2^0,2^{-1}$ 2^{-16}									
1	RES_1	32	Measurement result 2, fixed-point number with 16 integer and 16 fractional digits									
2	RES_2	32	Measurement result 3, fixed-point number with 16 integer and 16 fractional digits									
3	RES_3	32	Measurement result 4, fixed-point number with 16 integer and 16 fractional digits									
4	STAT	16	15	14	13	12	11	10	9	8 - 6	5 - 3	2 - 0
			EEPROM_eq_CREG	EEPROM_DED	EEPROM_Error	Error short	Error open	Timeout Precounter	Timeout TDC	# of hits Ch2	# of hits Ch1	Pointer result register
5	REG_1	8	Content of highest 8 Bits of write register 1, to be used for testing the communication									

The data structure and the occupancy of the result registers depend on the operation mode and whether calibrated or non-calibrated data are stored. Several cases must be distinguished:

- Only in measure mode 1 negative results are possible.
- In measure mode 2 only positive results are possible, given as unsigned numbers.
- A non-calibrated measure is possible only in measure mode 1.
- In measure mode 1 with calibrated data (ALU) the time intervals that have to be measured can not exceed twice the period of the calibration clock. When measuring bigger time intervals an ALU - overflow will occur and 0xFFFFFFFF is written in the appropriate result register.

a. Measure mode 1 with calibrated data (Calibrate = 1)

The results are given in multiples of the internal reference clock (= external reference clock divided by 1, 2 or 4 (DIV_CLKHS)). Calibrated data are 32 bit fixed point numbers with 16 integer bits and 16 fractional bits. Any calibrated result covers therefore 1 result register. The serial output begins with the highest bit (2^{15}) and ends with the lowest one (2^{-16}). The numbers are available in complements of 2.

$$Time = RES\_X * T_{ref} * 2^{ClkHSDiv} = RES\_X * T_{ref} * N \text{ , with N = 1, 2 or 4}$$

$$Time < 2 * T_{ref} * 2^{ClkHSDiv}$$

b. Measure mode 1 without calibration (Calibrate = 0)

Non-calibrated data are of the type ‚Signed Integer' and are stored as a 16 bit value in the high word of the result registers. The bits of the low word are set to zero. The result is represented as number of LSB and is available in complements of 2.

$$Time = RES\_X * LSB \sim RES\_X * 90 \text{ ps}$$

c. Measure mode 2

In measure mode 2 the TDC-GP21 only supports calibrated measurement. The results are given in multiples of the internal reference clock (= external reference clock divided by 1, 2 or 4 (DIV_CLKHS)). Calibrated data are 32 bit fixed point numbers with 16 integer bits and 16 fractional bits. Any calibrated result covers therefore 1 result register. The serial output begins with the highest bit (2^{15}) and ends with the lowest one (2^{-16}). The numbers are available in complements of 2.

$$Time = RES\_X * T_{ref} * 2^{ClkHSDiv} = RES\_X * T_{ref} * N \text{ , with N = 1, 2 or 4}$$

d. Temperature measurement

Discharge time in the same format as in c., measure mode 2.

3.2.3   Status register

Bits	Name	Description	Values
2 – 0	Pointer result register	Pointer to the next free result register	
5 – 3	# of hits Ch 1	Number of hits registered on channel 1	
8 – 6	# of hits Ch 2	Number of hits registered on channel 2	
9	Timeout TDC	Indicates an overflow of the TDC unit	1 = overflow
10	Timeout Precounter	Indicates an overflow of the 14 bit precounter in MR 2	1 = overflow
11	Error open	Indicates an open sensor at temperature measurement	1 = open
12	Error short	Indicates a shorted sensor at temperature measurement	1 = short
13	EEPROM_eq_CREG	Indicates whether the content of the configuration registers equals the EEPROM	1 = equal
14	EEPROM_DED	Double error detection. A multiple error has been detected whcich can not be corrected.	1 = multiple error
15	EEPROM_Error	Single error in EEPROM which has been corrected	1 = error

3.3 EEPROM

The TDC-GP21 has a 7x32 bit EEPROM. This EEPROM can be used to store the configuration data together with the ID or version number. Only the following three actions are possible:

- Write configuration register content into the EEPROM
- Transfer the EEPROM content into the configuration registers
- Compare the configuration registers' content with the EEPROM content

Besides the ID it is not possible to read back the EEPROM. This gives customers the possibility to program the chips by themselves and prohibit other to read back the configuration.

For verification it is possible to compare the configuration register may be compare with the EEPROM. Bit EEPROM_eq_CREG in the status register indicates whether the content is eaul or not.

The EEPROM has an internal error correction (Hamming code). It is possible
- to detect and correct single bit errors,
- to detect multi-bit errors without correction

Errors are indicated in the status register, bits EEPROM_Error (single bit) and EEPROM_DED (double error detection).

The data retention of the EEPROM is > 10 years @ 85 °C without single or multiple errors.

3.4   SPI-interface

The serial interface is compatible with the 4-wire SPI standard. It needs the SerialSelectNot (SSN) and can not operated as 3-wire interface.

SSN   - Slave Select

SCK   - SPI Clock

SI   - SPI Data In

SO   - SPI Data Out

The TDC-GP21 does only support the following SPI mode:

          Clock Phase Bit = 1

          Clock Polarity Bit = 0

The timings are shown in fiures setion 2.2.

SSN as Reset

The SerialSelectNot (SSN) line is the HIGH-active reset for the serial interface. After SSN is set to LOW different operations can be addressed, not depending on the status of the interface before the reset.

Note:

It is mandatory to set the SSN – line to High-state for at least 50 ns between each Read-/Write sequence.

OPCodes

Hex	MSB							LSB	Description	Followed by	New
h8x	1	0	0	0	0	A2	A1	A0	Write into address A	24 bit or 32 bit data	
hBx	1	0	1	1	0	A2	A1	A0	Read from address A	8, 16 or 32 bit data	
hB7	1	0	1	1	0	1	1	1	Read ID bits	56 bits ID's	×
hC0	1	1	0	0	0	0	0	0	Write configuration registers into EEPROM		×
hF0	1	1	1	1	0	0	0	0	Transfer EEPROM content into configuration registers		×
hC5	1	1	0	0	0	1	1	0	Compare configuration registers with EEPROM		×

Hex	MSB							LSB	Description	Followed by	New
h70	0	1	1	1	0	0	0	0	Init		
h50	0	1	0	1	0	0	0	0	Power On Reset		
h01	0	0	0	0	0	0	0	1	Start_TOF (old name: Start_Cycle)		
h02	0	0	0	0	0	0	1	0	Start_Temp		
h03	0	0	0	0	0	0	1	1	Start_Cal_Resonator		
h04	0	0	0	0	0	1	0	0	Start_Cal_TDC		
h05	0	0	0	0	0	1	0	1	Start_TOF_Restart		×
h06	0	0	0	0	0	1	1	0	Start_Temp_Restart		×

The transfer starts with the MSB and is finished sending the LSB. The transfer is done bytewise. Data transfer can be stopped after each byte, sending a LOW-HIGH-LOW on the SSN line.

Example:

h80 + 3 bytes will write configuration register 0 in the TDC-GP2 compatible mode.

h80 + 4 bytes will write configuration register 0 including ID0 (TDC-GP21 only).

It is not possible to do incremental writing. Each register must be addressed separately.

3.4.4   Opcode Explanations

- hC0, hF0, hC5 all refer to EEPROM operations. Those may last up 130 ms, especially the EE-PROM write. Therefore, the EN_INT bit 3 in register 6 indicates the end of the EEPROM operation. This can be used to adjust microprocessor actions.

- h01, Start_TOF: triggers a sequence for a single time-of-flight measurement. First, the 4 MHz oscillator is switched on. After the delay set to settle the oscillator (START_CLKHS), the comparator and the reference voltage are switched on. The receiver capacitor is charged up th Vref while inactive fire buffer is pulled down to GND. After the delay set to charge up the capacitor (TW2), the fire buffer sends the fire pulses. After the delay set in DELVAL the TDC stop channel is open. At the end of the measurement the analog section and the 4 MHz are switched off and the current consumption drops down to near zero. The interrupt is set, pin INTN = LOW.

- h05, Start_TOF_Restart: This new opcode runs the Start_TOF sequence twice, in up and down direction as it is typical in ultrasonic flow meters. The interrupt is set, pin INTN = LOW, when the

time measurement for each direction is finished. So, for one Start_TOF_Restart command the microprocessor sees two interrupts and has to read twice. The time interval between the up and down measurement is set by configuration parameter CYCLE_TOF in multiples of 50 Hz or 60 Hz. The right selection of the delay between the two measurements suppresses 50/60 Hz noise.

CYCLE_TOF	factor	HZ60 = 0(50Hz)	HZ60 = 1(60Hz)
0	1	20 ms	16.67 ms
1	1.5	30 ms	25.00 ms
2	2	40 ms	33.33 ms
3	2.5	50 ms	41.67 ms

- h02, Start_Temp: triggers a single temperature measurement sequence. It begins with the fake measurements (ANZ_FAKE) on port PT0. Then it measures ports PT0 > PT1 > PT2 > PT4. If TEMP_PORTDIR is set one then the sequence of ports is inverted, starting with the fake measurements at port PT4.

- h06, Start_Temp_Restart: This opcode runs the Start_Temp sequence twice. The time interval between the up and down measurement is set by configuration parameter CYCLE_TEMP in multiples of 50 Hz or 60 Hz. The right selection of the delay between the two measurements suppresses 50/60 Hz noise.

CYCLE_TEMP	factor	HZ60 = 0	HZ60 = 1
0	1	20 ms	16.67 ms
1	1.5	30 ms	25.00 ms
2	2	40 ms	33.33 ms
3	2.5	50 ms	41.67 ms

- h03, Start_Cal_Resonator: Triggers a calibration measurement of the high speed oscilator. The TDC measures a time interval between 61 μs and 488 μs, specified in ANZ_PER_CALRES. The end of the measurement is indicated by the interrupt. The result, in multiples or the high speed clock period, is stored in result register 0. Dividing this by the theoretical value gives the correction factor.

- h04, Start_Cal_TDC: This command starts a measurement of 2 periods of the reference clock. It is used to update the calibration raw data. Typically, the chip is configured for auto-calibration and this command is not necessary.

4 Converter Frontend

4.1 TDC - Measure Mode 1

4.1.1 General Description

- Measurement range 3.5 ns to 2.4 µs (0 to 2.4 µs between stop channels)
- 2 stop channels referring to one start channel each of typ. 90 ps resolution
- 1 stop channel referring to one start channel with typ. 45 ps resolution
- 20 ns pulse pair resolution
- 4-fold multihit capability for each stop channel
- Selectable rising/falling edge sensitivity for each channel
- Enable pins for windowing functionality
- The possibility to arbitrarily measure all events against each other
- Typical application: Laser ToF, RF ToF, ATE

Digital TDCs use internal propagation delays of signals through gates to measure time intervals with very high precision. Figure 5 clarifies the principal structure of such an absolute-time TDC. Intelligent circuit structures, redundant circuitry and special methods of layout on the chip make it possible to reconstruct the exact number of gates passed by the signal. The maximum possible resolution strongly depends on the maximum possible gate propagation delay on the chip.

Figure 4.1
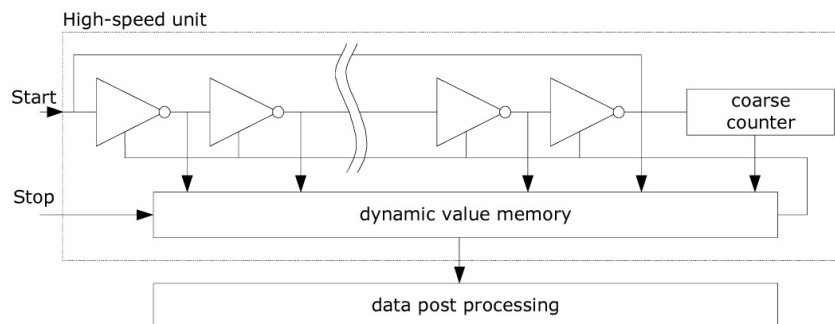
The measuring unit is triggered by a START signal and stopped by a STOP signal. Based on the position of the ring oscillator and the coarse counter the time interval between START and STOP is calculated with a 20 Bit measurement range.

The BIN size (LSB) is typically 90 ps at 3.3 V and 25 °C ambient temperature. The RMS noise is about 60 ps (0.7 LSB). The gate propagation delay times strongly depend on temperature and voltage. Usually this is solved doing a calibration. During such a calibration the TDC measures 1 and 2 periods of the reference clock.

The measurement range is limited by size of the counter:

$$t_{yy} = BIN \times 26224 \sim 90 \text{ ps} \times 26224 = 2.4 \text{ µs}$$

	Time (Condition)	Description
tph	2,5 ns (min.)	Minimum pulse width
tpl	2,5 ns (min.)	Minimum pulse width
tss	3.5 ns ns (min) 2.4 µs (max.)	Start to Stop
trr	20 ns (typ.)	Rising edge to rising edge
tff	20 ns (typ.)	
tva	t.b.d. uncalibrated t.b.d. calibrated	Last hit to data valid
txx	No timing limits	
tyy	2.4 µs (max)	Max. measuring range
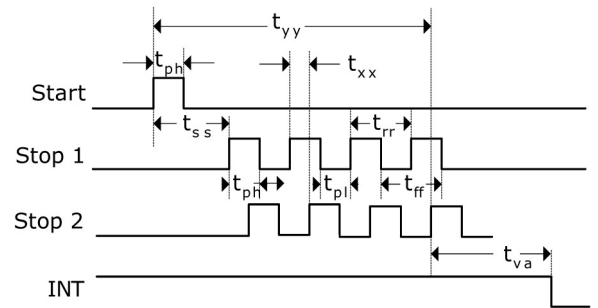
Figure 4.2

Input circuitry

Each input separately can be set to be sensitive to rising or falling edge or both edges. This is done in register 0, bits 8 to 10. (NEG_START, NEG_STOP1, NEG_STOP2) and register 2, bit 27&28, RFEDGEx.

Furthermore all Start/Stop-inputs support a high active enable pin.

4.1.2   Measurement Flow

Figure 4.3
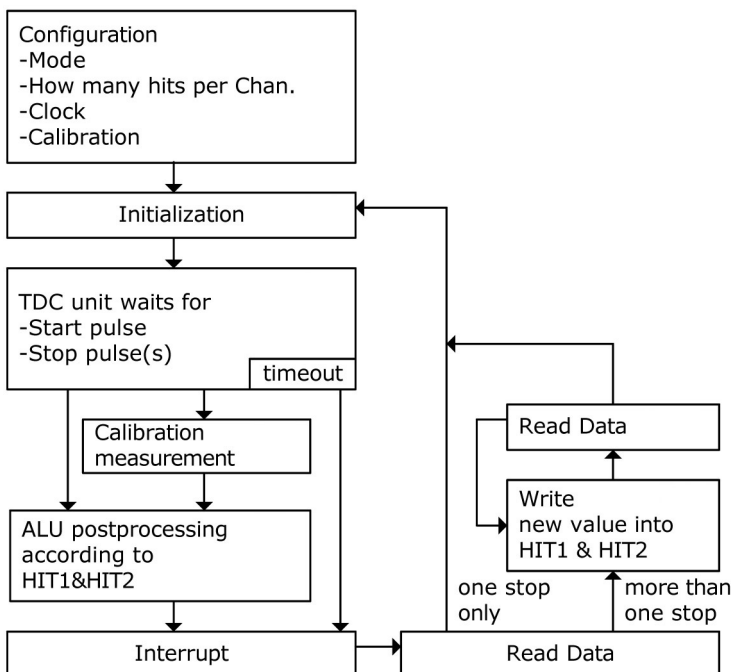
Configuration

At the beginning the TDC-GP21 has to be configured. The main settings for measurement range 1 are:

a. Select measure mode 1

Set register 0, bit 11, MESSB2 = 0.
Register 6, bit 12, DOUBLE_RES = 1 selects double resolution.With this bit set the resolution is typ. 45 ps instead of 90 ps, but only one STOP channel is available.

b. Select the reference clock

(see also section 5.1)
Register 0, bits 18 & 19 and register 6,

bit 20 , START_CLKHS defines the switch-on behavior of the high-speed clock. If only the 32kHz is used it should be „0". If only the high-speed clock is used it should be „1" (continuously on).

Register 0, bits 20 & 21, DIV_CLKHS sets an additional internal divider for the reference clock (1,2 or 4). This is important for calibrated measurements in measurement range 1 because the ALU works correctly only if 2*Tref(intern) is bigger than the maximum time interval to be measured. Otherwise the ALU output is 0xFFFFFFFF.

Make also sure that 2*Tref(intern) < 2.4 µs to avoid a timeout during calibration.

c. Set the number of expected hits

In register 1, bits 16 to 18 and 19 to 21, HITIN1 and HITIN2 the user has to define the number of hits the TDC-GP21 has to wait for. A maximum of 4 on each channel is possible. The TDC-GP21 measures until the set number of hits is registered or a timeout occurs.

d. Select calibration

As the BIN size varies with temperature and voltage the TDC-GP21 ALU can internally calibrate the results. This option is switched on by setting register 0, bit13, CALIBRATE = „1". It is recommended to do this.

For the calibration the TDC measures 1 and 2 cycles of the reference clock. The two data are stored as Cal1 and Cal2.

There are two ways to update the calibration data Cal1 and Cal2:
- Separate calibration by sending opcode Start_Cal_TDC via the SPI interface
- Automatic update by setting register 0, bit 12, NO_CAL_Auto = „0". In most applications this will be the preferred setting.

e. Define ALU data processing

While the TDC unit can measure up to 4 hits on each channel the user is free in his definition what the ALU shall calculate. The settings are done in register 1, bits 16 to 19 and 20 to 23, HIT1 and HIT2. Both parameters can be set to:

0 = Start
1 = 1. Stop Ch1   9 = 1. Stop Ch2
2 = 2. Stop Ch1   A = 2. Stop Ch2

3 = 3. Stop Ch1   B = 3. Stop Ch2

4 = 4. Stop Ch1   C = 4. Stop Ch2

6 = Cal1 Ch1

7 = Cal2 Ch1

The ALU calculates Hit1 - Hit2.

Examples:

Reg1 = 0x01xxxx - 1st Stop Ch1-Start

Reg1 = 0x2Bxxxx - 3rd Stop Ch2-2nd Stop Ch1

Reg1 = 0x06xxxx - Cal1

In case calibration is active the ALU does the full calibration calculation (except when reading the calibration values. In this case the ALU writes the Cal1/Cal2 raw data to the output register).

$$RES\_X = \frac{(HIT1 - HIT2)}{Cal2 - Cal1}$$

$$Cal2 - Cal1 = gradient$$

$$Time = RES\_X \times T_{ref} \times 2^{ClkHSDiv} = RES\_X \times T_{ref} \times N$$

N = 1, 2 or 4.

Figure 4.4
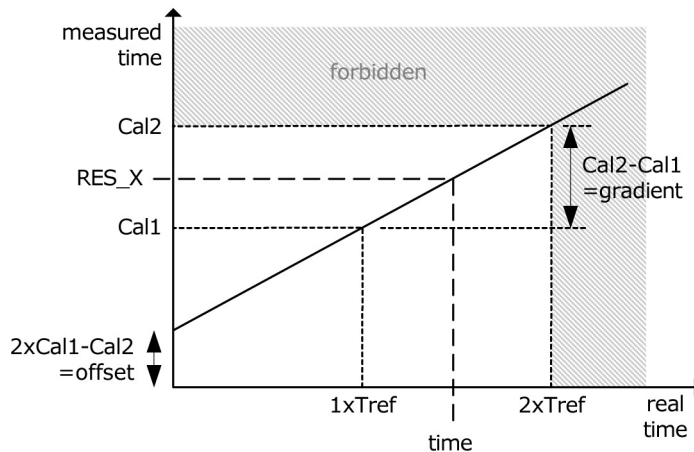
f. Select input sensitivity

In register 2, bits 27 & 28, RFEDGE1 and RFEDGE2, the user can select whether the stop inputs are sensitive to either rising or falling edges (RFEDGE = „0") or to both rising and falling edges (RFEDGE = „1").

In register 0, bits 8 to 10 the user can add an internal inverter to each input, Start, Stop1 and Stop2. With RFEDGE = „0" this is the same as rising edge (NEG_X = „0") or falling edge (NEG_X = „1").

g. Interrupt behavior

The interrupt pin 8, INT can have different sources. They are selected in register 2, bits 29 to 31, EN_INT and register 6, bit 21.

Reg 2 bit 29 = 1   ALU ready

Reg 2 bit 30 = 1   The set number of hits is there

Reg 2 bit 31 = 1   Timeout of the TDC unit

Reg 6 bit 21 = 1   End of EEPROM action

The different options are wired by OR to enable more than one source.

There are further configuration options that will be described later in this chapter.

After the configuration the user has to initialize the TDC-GP21 by sending opcode „Init" so that the TDC accepts Start and Stop hits.

Measurement

After an initialization the TDC unit will start with the first pulse on the Start input. It will run until:

- the set number of hits has been seen (maximum 4 on both stop channels in mode 1)
- or until a timeout occurs at the end of the measurement range (at about 2.4 µs in mode 1).

The time measurement raw data are internally stored. The number of hits can be seen from the status register, bits 3 to 8. In case calibration is active the TDC now measures one and two periods of the internal reference clock (Tref * 1, 2 or 4). The calibration raw data Cal1 and Cal2 are also internally stored.
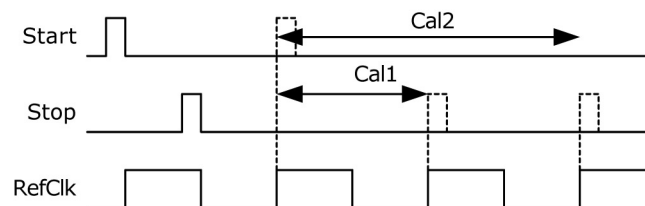
Figure 4.5

Data Processing

At the end of the measurement the ALU starts to process the data according to the HIT1, HIT2 settings and transfers the result to the output register. In case calibration is off the ALU transfers the 16 bit raw data to the output register. With calibration the ALU calculates according to 3.1.1.d and transfers the 32 bit fixed point number to the output register.

The ALU can be switched off configuring HIT1=HIT2=5.

The time it takes the ALU depends on whether calibration is on or not and the supply voltage.

Table 3.1: ALU timings

	un-calibrated	calibrated
3.3 V	t. b. d.	t. b. d.
2.5 V	t. b. d.	t. b. d.

As soon as the data is available from the output register the interrupt flag is set (assumed that the ALU interrupt is enabled, see reg 2, EN_INT). Further the load pointer of the output register is increased by 1 and points to the next free memory. The actual position of the load pointer can be seen in the status register, Bits 0 to 2.

Reading Data

Now the user can read the data sending the opcode 10110ADR. With the next 16 clock cycles (un-calibrated data) or 32 clock cycles (calibrated data) the TDC-GP21 will send the result, beginning with the most significant Bit (MSB).

a. Un-calibrated data format:

16 Bit Signed integer in complements of 2. 1BIN = uncalibrated gate delay is about 90 ps at 3.3 V and 25 °C.

Time = RES_X x 90 ps

b. Calibrated data format:

32 Bit fixed-point number in complements of 2. Given in multiples of the reference clock.

Time = RES_X * T_{ref} * N, N = 1, 2 or 4

The measured time interval may not exceed , otherwise the ALU will go into overflow and will write the data 0xFFFFFFFF to the output register.

The configuration of the ALU allows only one hit calculation at the time. In case more than one hit has been measured it is necessary to write new commands to HIT1/HIT2 to instruct the ALU for calculating the other hits. After writing to HIT1/HIT2 it is necessary to wait for minimum t.b.d. µs (calibrated data) or t.b.d. ns (uncalibrated data) before reading or writing again to HIT1/HIT2.

Example:
configuration
…
write reg1=0x014400   4 hits on channel 1, calculate 1st Stop -Start
…
Initialize
…
while(Check interrupt flag)
write reg1=0x024400   calculate 2nd -Start
wait(4.6µs)
write reg1=0x034400   calculate 3rd-Start
wait(4.6µs)
write reg1=0x044400   calculate 4th-Start
wait(4.6µs)
Now all Hit data are available from registers 0 to 3. The load pointer value is 4.

At the end the TDC-GP21 has to be initialized again to be ready for the next measurement. This is done by sending the opcode „Init" so that the TDC accepts new Start and Stop hits.

4.2   TDC - Measure Mode 2

4.2.1   General Description

- 1 stop channels referring to one start channel
- Typical 22 ps / 45 ps / 90 ps resolution
- Measurement range 2 x Tref to 4 ms @ 4MHz
- 2 x Tref pulse pair resolution
- 3-fold multihit capability
- Selectable rising/falling edge sensitivity
- Integrated programmable windowing for each single stop with 10 ns precision
- Typical application: Ultrasonic flow & heat meter

Digital TDCs use internal propagation delays of signals through gates to measure time intervals with very high precision (see also measurement range 1, section 4).

In measurement range 2 the maximum time interval is extended using a pre-divider. The resolution in LSB remains unchanged by that. In this mode the high-speed unit of the TDC does not measure the whole time interval but only time intervals from START and STOP to the next rising edge of the reference clock (fine-counts). In between the fine-counts the TDC counts the number of periods of the reference clock (coarse-count).

Figure 4.6

$$time = Tref \times (Cc + (Fc1 - Fc2)/(Cal2 - Cal1))$$
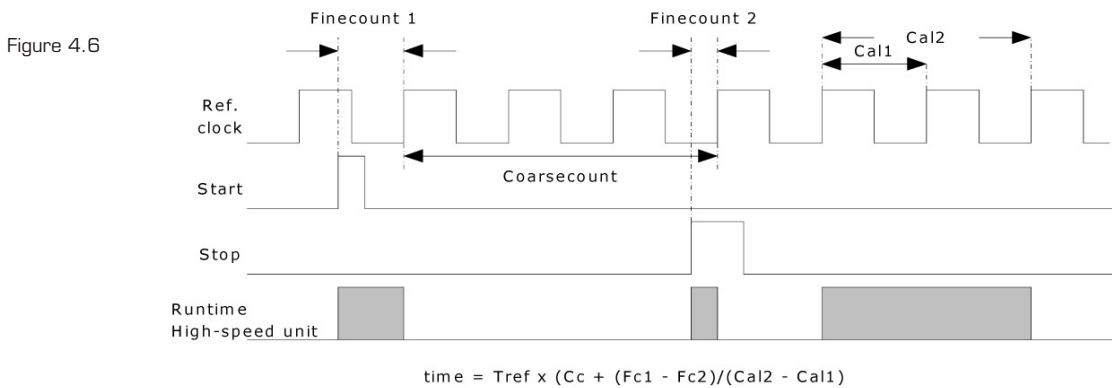
The BIN size (LSB) is typically 90 ps at 3.3 V and 25 °C ambient temperature. The RMS Noise is approx. 60 ps (0.7 LSB). The gate propagation delay times strongly depend on temperature and voltage. In measuring range 2 the result is the sum of different fine and coarse-count results. Therefore it is necessary in measuring range 2 to make a calibration. During a calibration the TDC measures 1 and 2 periods of the reference clock.

A calibrated result does not depend on temperature or supply voltage.

The measurement range is limited by size of the coarse counter:

$$tyy = Tref \times 2^{14} = 4.1ms @ 4MHz$$

The time interval between START and STOP is calculated with a 26 bit measurement range.

Figure 4.7
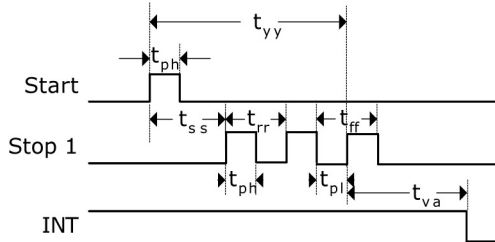
	Time (Condition)	Description
tph	2,5 ns (min.)	Minimum pulse width
tpl	2,5 ns (min.)	Minimum pulse width
tss	2*Tref	Start to Stop @ Dis_Phasenoise=1
trr	2*Tref	Rising edge to rising edge
tff	2*Tref	Falling edge to falling edge
tva	4.6 µs (max.)	ALU start to data valid
tyy	4 ms (max)	Max. measuring range

Input circuitry

Each input separately can be set to be sensitive to rising or falling edge. This is done in register 0, Bits 0 to 2. (NEG_START, NEG_STOP1).

Further all Start/Stop-inputs support a high active enable pin.

Note:

In case the Start-Stop interval is less than the lower limit tzz the TDC will ignore more and more events the smaller it is. In no case there will be wrong results.

4.2.2   Measurement Flow

Figure 4.8
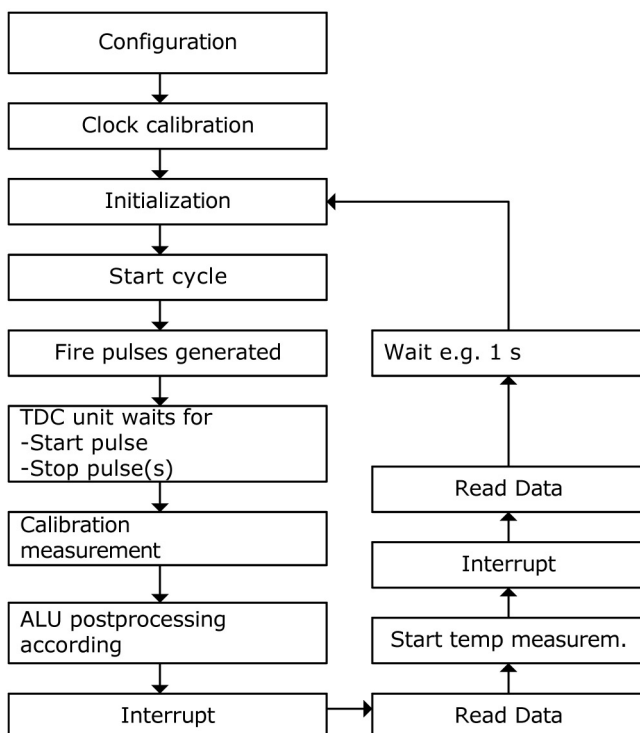
Configuration

At the beginning the TDC-GP21 has to be configured. The main settings for measurement range 2 are:

a. Select measurement range2

setting register 0, Bit11, MRange2 = 1.

b. Select the reference clock

(see also section 5.1)

In measurement range 2 the TDC-GP21 needs the high-speed clock for the time measurement. In case of low-power applications this clock can be switched of in between measurements. The a 32.768 kHz clock is necessary for the timing control during the oscillator power-on.

Register 0, Bits 18&19, START_CLKHS defines the switch-on behavior of the high-speed clock. If only the high-speed clock is used this is be set to „1"(continuously on). In case both oscillators are used for current saving reasons this should be set to „2" for ceramic oscillators and to „3" for quartz oscillators".

Register 0, Bits 20&21, ClkHSDiv sets an additional internal divider for the reference clock (1,2 or 4). The choice has an influence on the minimum time interval

$$t_{min} = 2 * T_{ref} * 2^{ClkHDiv}$$

and the maximum time interval

$$t_{max} = 2^{14} * T_{ref} * 2^{ClkHDiv}$$

Further, it is necessary that

$$2 * T_{ref} * 2^{ClkHDiv} < 2.4 \; \mu s.$$

Otherwise the ALU will go into an overflow during calibration and write 0xFFFFFFFF as output data.

Please note:

The resulting clock after the predivider has to be in the allowed range of 2 MHz to 8 Mhz in single and double resolution and from 2 MHz .... 6 MHz in quad resolution.

c. Set the number of expected hits

In register 0, Bits 16 to 18, HITIN1 the user has to define the number of hits the TDC-GP21 has to wait for. A maximum of 3 on channel 1 is possible. The number HITIN1 always has to be higher by 1 than the number of expected hits. The reason is that the Start is also counted as a hit. The TDC-GP21 measures until the set number of hits is registered or a timeout occurs. register 0, Bits 11 to 13, HITIN2 have to be set to „0".

Example:

2 stop pulses are expected:

HITIN1 = 3, HITIN2 = 0

---

d. Select calibration

The calibration is switched on by setting register 0, Bit13, Calibrate = „1". It is mandatory to do this.

For the calibration the TDC measures 1 and 2 cycles of the reference clock. The two data are stored as Cal1 and Cal2.

There are two ways to update the calibration data Cal1 and Cal2:

▪ Separate calibration by sending opcode Start_Cal_TDC via the SPI interface

▪ Automatic update by setting register 0, Bit 12, NO_AUTO_CAL = „0". In most applications this will be the preferred setting.

e. Define ALU data processing

While the TDC unit can measure up to 3 hits the ALU can calculate only one hit at once. The settings are done in register 1, Bits 24 to 27 and 28 to 31, HIT1 and HIT2. The Start pulse is internally handled like a Stop pulse because of the special measuring method in measurement range 2.

Reg1 = 0x21xxxx = Calculate 1st Stop Ch1-Start
Reg1 = 0x31xxxx = Calculate 2nd Stop Ch1-Start
Reg1 = 0x41xxxx = Calculate 3rd Stop Ch1-Start

The ALU calculates the time interval as:

$$RES\_X = CoarseCount + \frac{(HIT1 - HIT2)}{Cal2 - Cal1}$$

Time = RES_X * T_{ref} * $2^{ClkHSDiv}$

f. Select input sensitivity

In register 2, Bits 27 & 28, RFEDGE1 and RFEDGE2, the user can select whether the stop inputs are sensitive to either rising or falling edges (RFEDGE = „0") or to both rising and falling edges (RFEDGE = „1"). In register 0, Bits 8 to 10 the user can add an internal inverter to each input, Start, Stop1 and Stop2. With RFEDGE = „0" this is the same as rising edge (NEG_X = „0") or falling edge (NEG_X = „1").

g. Interrupt behavior

The INT pin can have various sources, to be selected in register 2, Bits 21 to 23, EN_INT, , and register 6 Bit 21 EN_INT.

EN_INT =   no bits set   no Interrupt source
            reg2 Bit29   ALU ready
            reg2 Bit30   The set number of hits is there
            reg2 Bit31   Timeout of the TDC unit
            reg6 Bit21   EEPROM action has finished

The different options are wired by OR.

After the configuration the user has to initialize the TDC-GP21 by sending opcode „Init" so that the TDC accepts Start and Stop hits.

Measurement

After an initialization the TDC unit will start with the first pulse on the Start input. It will run until:

- the set number of hits has been seen (maximum 3 on channel 1 in measurement range 2)
- or until a timeout occurs. The timeout can be programmed in multiples of the reference clock setting Reg 3, Bits 27&28, SEL_TIMO_MR2. At 4 MHz the values are:

SEL_TIMO_MR2 (@ 4 MHz, ClkHSDiv = 0)

= 0	= 64 µs
= 1	= 256 µs
= 2	= 1024 µs
= 3	= 4096 µs

At the end of the time measurement the TDC measures 2 periods of the reference clock for calibration.

Data processing

At the end of the measurement the ALU starts to process the data according to the HIT1, HIT2 settings and transfers the result to the output register. The ALU calculates according to 4.2.2.e and transfers the 32 bit fixed point number to the output register.

The time it takes the ALU depends on the supply voltage:

Table 4-2: ALU timings

	calibrated
3.3 V	2.3 µs
2.5 V	2.8 µs

As soon as the data is available from the output register the interrupt flag is set (assumed that the ALU interrupt is enabled, see reg 2, EN_INT). Further the load pointer of the output register is increased by 1 and points to the next free memory. The actual position of the load pointer can be seen in the status register, Bits 0 to 2.

Reading Data

Now the user can read the data sending the opcode 10110ADR. With the next 32 cycles (calibrated data) the TDC-GP21 will send the result, beginning with the main significant bit (MSB).

The 32 bit fixed-point numbers in complements of 2 represent the time interval in multiples of the reference clock.

$$Time = RES\_X * T_{ref} * 2^{ClkHSDiv}$$

The configuration of the ALU allows only one hit calculation at the time. In case more than one hit has been measured it is necessary to write new commands to HIT1/HIT2 to instruct the ALU for calculating the other hits. After writing to HIT1/HIT2 it is necessary to wait for minimum 3.1 µs before reading or writing again to HIT1/HIT2.

```
Example:
configuration
…
write reg1=0x214400        3 hits on channel 1, calculate Hit1-Start
…
Initialize
…
while(Check interrupt flag)
write reg1=0x314400        calculate Hit2-Start
wait(4.6µs)
write reg1=0x414400        calculate Hit3-Start
wait(4.6µs)


Now all hit data are available from registers 0 to 2. The load pointer value is 3.
```

At the end the TDC-GP21 has to be initialized again to be ready for the next measurement. This is done by sending the opcode „Init" so that the TDC accepts new Start and Stop hits.

4.2.3   Stop Masking

The TDC-GP21 can set time-based masking windows for each of the 3 hits on Stop1 input when no hits are accepted. The masking refers to the start event and has an accuracy of less than 10 ns. The internal enable unit is connected to the external enable pin by a logical AND. The external enable

pin must be set to "1" to use the internal masking unit. The configuration settings are made in registers 2 to 4, DELVAL1, DELVAL2 and DELVAL3:

- DELVAL1 … DELVAL3 are fixed point numbers with 14 bit integer and 5 bit fractional digits, in multiples of the internal reference clock

$$\text{Delay}_{min} = \text{DELVALX} / 2^5 * T_{ref} * 2^{ClkHSDiv}$$

- The minimum mask size is 3 clock cycles
- The mask values must have an ascending order. Each mask value must be 3 clock cycles bigger than the previous value

It is mandatory that if not all registers are used the mask values that are not required are set to "0". When all DELVAL registers are set to 0, the complete unit is disabled.

Example:

4 Mhz reference, ClkHSDiv = 1

DELVAL1 = 0x3200   1st Stop not accepted before 200 µs after Start
$(128000/32 * 250ns * 2^1 = 200 \text{ µs})$

DELVAL2 = 0x3300   2nd Stop not accepted before 204 µs after Start
$(13056/32 * 250ns * 2^1 = 204 \text{ µs})$

DELVAL1 = 0x3400   3rd Stop not accepted before 208 µs after Start
$(13312/32 * 250ns * 2^1 = 208 \text{ µs})$

4.3   Analog Input Section

Compared to TDC-GP2, the TDC-GP21 got an additional analog input section which can be used alter-natively to the pure digital inputs. Especially the design of ultrasonic flow and heat meters is greatly simplified by this new option. The external circuit of the ultrasonic part is reduced to just two resis-tors and capacitors additional to the piezo transducers.

The ultrasonic signals will be packages of 50 to 200 sinusoidal oscillations with a several 100 mV amplitude. The signals are coupled to the inputs by means of a highpass filter as the comparator can not handle GND as threshold. The threshold of the comparator is set to 1/3 VCC. An analog multiplexer selects the input according to the active measurement direction. The comparator is chopper stabilized to guarantee a low offset voltage in the range of < 2 mV. This is mandatory for a good measurement quality. The input offset voltage of the comparator is frequently corrected by an internal chopper circuit. If temperature or supply voltage changes over time, the offset voltage is automatically adapted and hold at < 2 mV.

Figure 4.9:
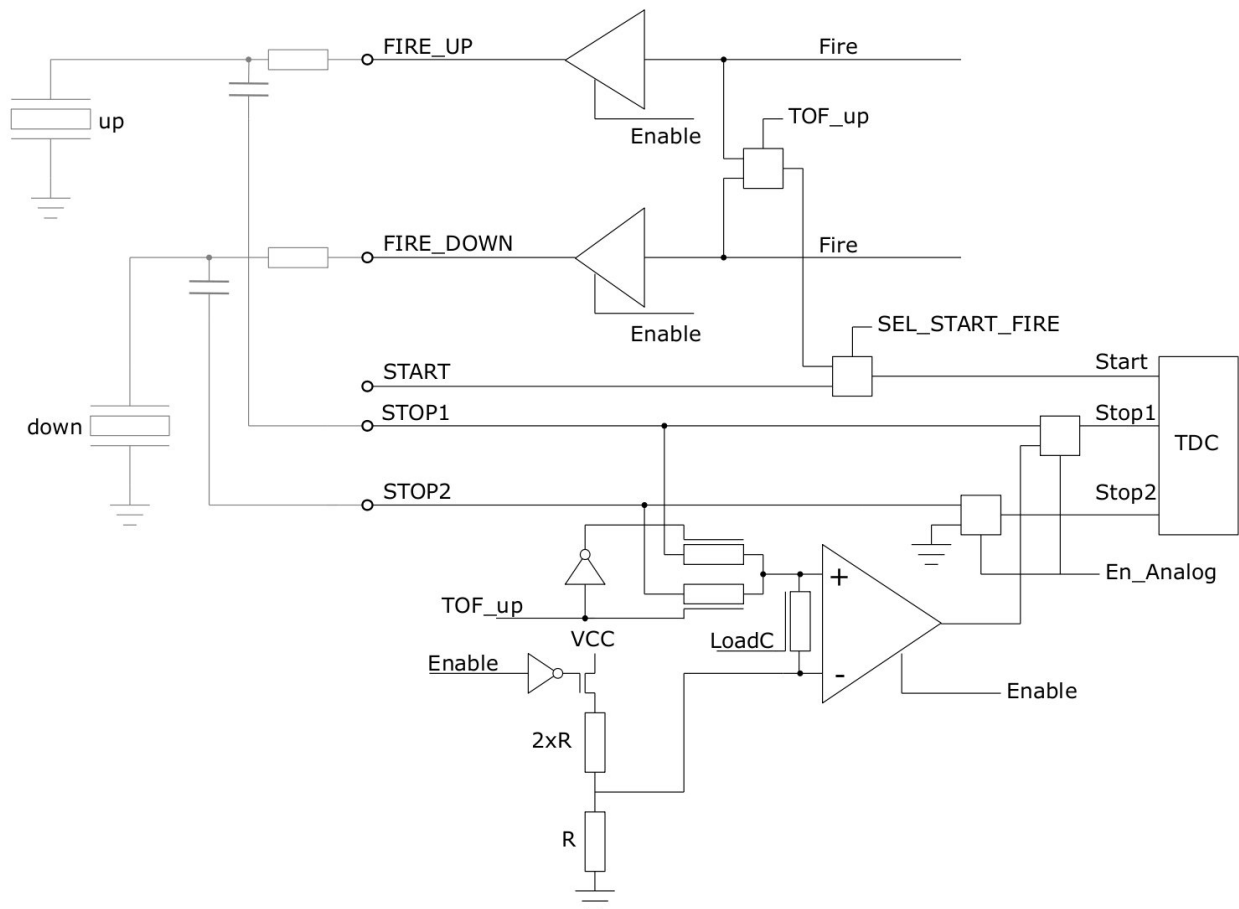
All elements are controlled by the TDC-GP21 control unit. They are powered only during the measurement to keep down the power consumtion.

A measurement sequence, triggered by command Start_TOF_Restart looks like the following procedure, starting with the up flow measurement:

- The 4 MHz oscillator is switched on. The chips waits for the programmed delay to give enought time for the oscillator to reach the full amplitude.
- The comparator, the reference voltage and the analog switches get powered.
- The capacitor of the transmitting path (STOP1) is connected to GND.
- The fire down buffer (FIRE_DOWN) is connected to GND.
- The capacitor of the receiving path (STOP2) is charged up to Vref. The TDC waits the delay set in TW2.
- The analog switch selects STOP2 input as input to the comparator.
- FIRE_UP is selected as TDC START signal.
- The set number of pulses is sent through the fire up buffer, pin FIRE_UP.
- The analog signal at STOP2 passes the comparator converted to a digital signal that is connected to the STOP input of the TDC unit.
- When the delay of the stop masking unit (DELVAL) expired the TDC is ready to measure. It can measure up to 3 stops.
- At the end of the measurement the control unit switches off the comparator, the reference the analog switches and the 4 MHz. The current is reduced to close zero. The interrupt flag is set.
- The control unit waits a period, given in multiples of 50Hz/60Hz. During this this the processor has to read the results.
- After the delay the same procedure is started but in the opposite direction.

4.4   Temperature Measurement

Especially for heat meter applications the TDC-GP21 has a PICOSTRAIN based temperature measu-
ring unit that offers high resolution and very low current consumption.

The measurement is based on measuring discharge times. Therefore, a capacitor is discharged
alternately through the sense resistors and the reference resistors. As an improvement compared to
TDC-GP2, the TDC-GP21 has the comparator already integrated.

Figure 4.10
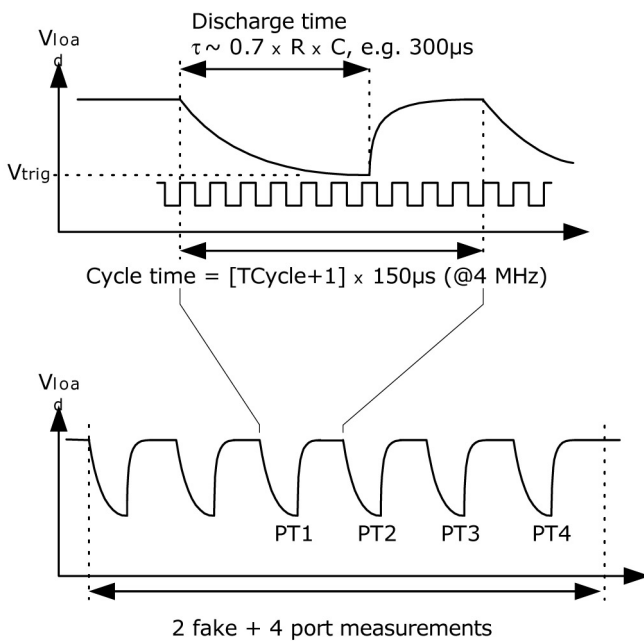
Figure 4.11: With internal Schmitt trigger
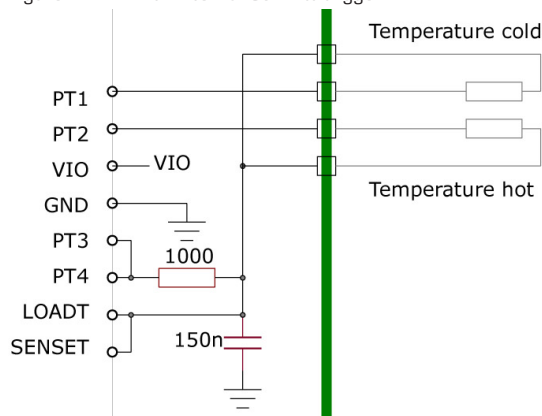
Figure 4.12: GP2 compatible with external trigger
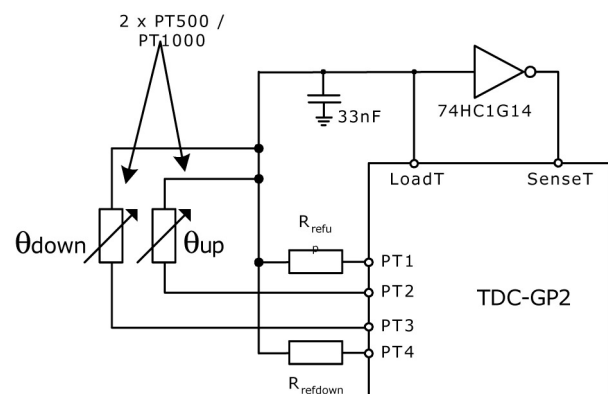
The unit has 4 resistor ports, two of them to be used for the temperature sensors for hot water (up) and cold water (down). The other two ports are used for reference resistors. Basically, on reference resistor connected to both ports is sufficient.

The temperature sensors should have a minimum resistance of 500 Ohm. The cable length should not exceed 3 m. TDC-GP21 can measure 2-wire sensors only. It is not possible to use 4-wire sensors. The precision of the temperature measurement is far within the limits of the standard for heat meters when PT500 or PT1000 are used. In combimation with PT500 or PT1000 temperature sensors there is no need for two reference resistors. A typical setup with with one fixed reference is shown in figure 5-8.

With some loss in temperature stability the GP21 is also capable of temparature measurement with PT100 sensors. In that case we recommend to use two reference resistors instead of one, as shown inm figure 5-9. This helps to (partly) overcome the increasing gain drift by means of a two point temperature calibration over the full temperature range.

Figure 4.13: PT500 / PT1000 temperature measurement with one refrence resistor
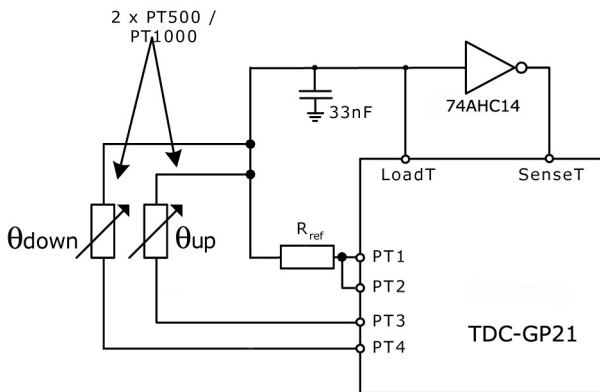
Figure 4.14: PT100 temperature measurement with two reference resistors
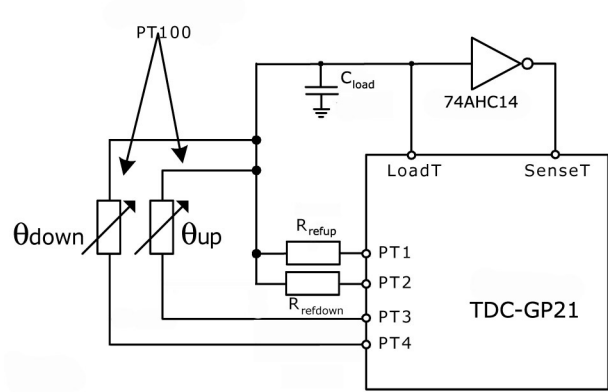
The temperature measurement is fully automated. It is triggered by the µC sending the opcodes Start_Temp or Start_Temp_Restart. With Start_Temp_Restart the TDC-GP21 measures the temperature twice, with a delay given in multiples of the 50 Hz/60 Hz period. This will be of help to reduce 50Hz/60Hz noise.

For a measurement, the TDC-GP21 starts with 2 or 8 dummy measurements at port PT1 before it makes the real four measurements in the order PT1 > PT2 > PT3 > PT4. After the 4 measurements have finished the interrupt flag is set. TDC-GP21 has the possibility to inverse the order, making the dummy measurements at port PT4.

The four data are found in registers 0 to 3. From Res_2/RES_1 and RES_3/RES_4 the microcont-

roller can calculate the ratio Rtemp/Rref. By means of a look-up table it can calculate the temperature for the special type of sensor in use.

Configuration

Register 0, bit 15, ANZ_FAKE sets the number of dummy measurements at the beginning of a temperature measurement. This is necessary to overcome mechanical effects of the load capacitor.

ANZ_FAKE = 0   2 dummy measurements

ANZ_FAKE = 1   8 dummy measurements

Register 0, bit 16, TCYCLE sets the cycle time for the temperature measurement.

TCYCLE = 0   128 µs cycle time @ 4MHz

TCYCLE = 1   512 µs cycle time @ 4MHz

Register 0, bit 17, ANZ_PORTS sets the number of ports that will be used.

ANZ_PORTS = 0   2 ports = 1 sensor

ANZ_PORTS = 1   4 ports = 2 sensors

Register 6, bit 11, TEMP_PORTDIR sets the order of the port measurements

TEMP_PORTDIR = 0   PT1 > PT2 > PT3 > PT4

TEMP_PORTDIR = 1   PT4 > PT3 > PT2 > PT1

Register 6, bit 15, HZ60 sets the base frequency for the delay between the up and down measurements for commands Start_TOF_Restart and Start_Temp_Restart.

HZ60   = 0   50 Hz base

HZ60   = 1   60 Hz base

Register 6, bits 18,19, CYCLE_TEMP, selects the factor timer for triggering the second temperature measurement in multiples of 50/60Hz.

CYCLE_TEMP   = 0   1

                 = 1   1.5

                 = 2   2

                 = 3   2.5

Register 6, bit 30, NEG_STOP_TEMP inverts ths signal at the SenseT path. This is mandatory when the internal comparator is used. Without inversion the unit is compatible to TDC-GP2 operation with an external Schmitt trigger

| NEG_STOP_TEMP | = 0 | No inversion, TDC-GP2 compatible |
| | = 1 | Inversion, mandatory when the internal comparator is used |

Recommended Capacitor Values

The discharge time should be about 150 µs. Therefore the capacitor should have the following value:

PT500:   220 nF

PT1000:   100 nF

Please set Tcycle = 1 to avoid timeout error.

Recommended Capacitor Type

To get accurate results we recommend capacitor types with very low dC/dU. We recommend:

COG types or CfCap Series from Tayo Yuden

For heatmeter application please do note use X7R or similar capacitors.

Current consumption

By means of the TDC technology the temperature measurement needs an extremely low current, much less than an A/D converter does.

A full temperature measurement with 2 sensors, 2 references am PT1000 sensor type, including all calculations takes less than 2.5 µAs. With one temperature measurement in 30 seconds (typical for heatmeters) the average current consumption is 0.08 µA only. This is about 50 times less than other solutions. A PT500 sensor doubles the current.

Note: During temperature measurement the start input has to be enabled.

Error detection

Additionally the temperature unit checks the plausibility of the results. It is able to detect a short circuit of the sensor or an open sensor. The TDC-GP21 provides in the relevant output register an error code instead of a measurement value.

1. Short circuit: equivalent to a very short time interval (< 8 x Tref = 2 µs @ 4 MHz). The TDC-GP21 writes a 0x0 to the output register of the shorted sensor.

2. Broken sensor: equivalent to no stop signal or timeout. The TDC-GP21 writes a 0xFFFFFFFF into the output register of the open sensor.

Table 4.3: Analog specification

Symbol	Terminal		Internal Schmitt-Trigger		external Schmitt-Trigger[2]		Unit
			PT500	PT1000	PT500	PT1000	
	Resolution RMS		17.5	17.5	16.0	16.0	Bit
	SNR				96	96	dB
	Absolute Gain[3]		0.9912	0.9931	0.9960	0.9979	
	Absolute Gain vs. Vio[3] (gain factor)	3.6 V	0.9923	0.9940	0.9962	0.9980	
		3.0 V	0.9912	0.9931	0.9960	0.9979	
		2.5 V	0.9895	0.9915	0.9956	0.9979	
	Gain-Drift vs. Vio		0,25	0.23	0.06	0.04	%/V
	max. Gain Error (@ dθ = 100 K)		0,05%	0,05%	0,02%	< 0.01%	
	Gain-Drift vs. Temp		0.022	0.017	0.012	0.0082	%/10 K
	Gain-Drift vs. Vio				0,08		%/V
	Initial Zero Offset		< 20	<10	< 20	< 10	mK
	Offset Drift vs. Temp		< 0.05	< 0.03	< 0,012	< 0.0082	mK/ °C
	PSRR				>100		dB

[1] All values measured at Vio = Vcc = 3.0 V, Cload = 100 nF for PT1000 and 200 nF for PT500 (COG-type)
[2] measured with external 74AHC14 Schmitt-trigger
[3] compared to an ideal gain of 1

Gain error and its mathematical correction

The GP21 temperature measurement is based on acam's PICOSTRAIN technology. Here the resistance variation of an RTD is digitized by means of a high accurate time interval measurement. According to that, the Schmitt-trigger's delay time introduces a considerable gain error that results in a gain reduction compared to an ideal output value. This gain reduction can be mathematically described as a deviation from an ideal straight line. Hence, a simple mathematical correction by adding a correction factor compensates for this deviation from the ideal gain. It is calculated as follows:

$$T_{corr} = T_{uncorr}/\text{gainfactor}$$

with

T_{corr}: gain corrected temperature result

T_{uncorr}: uncorrected temperature result

gainfactor: gain correction factor, compensates the deviation from an ideal gain of 1

By means of this compensation, the effect of the Schmitt-trigger's delay time can be reduced to a residual gain error of 0.05% of F. S. with the internal Schmitt-trigger, or even less in combination with an external 74AHC14 Schmitt-trigger.

Three main parameters have to be considered, to select the correct gain factor:

- base resistance of the temperature sensor (e. g. PT500, PT1000)
- used Schmitt-Trigger (GP21-internal, external 74AHC14)
- GP21 supply voltage

The appropriate gain correction factors are provided in table 4-3 ("Absolute gain vs. Vio").

Import note:

The gain correction factors for the external Schmitt-trigger exclusively refer to the 74AHC14 Schmitt trigger. Other types (e. g. 74HC14) require different gain factors, in order to ensure a correct compensation. According to that, we strongly recommend to use a 74AHC14 as external Schmitt trigger.

Example 1:

Application with PT1000 Sensor, GP21 internal Schmitt trigger and 3.0 V supply voltage. According to table 4.3 a gain factor of 0.9931 has to be selected. The gain corrected result is calculated then by the following equation:

$$T_{corr}=T_{uncorr}/0.9931$$

Example 2:

Application with PT500 Sensor, external 74AHC14 Schmitt trigger and 3.6 V supply voltage. Table 4-3 now specifies a gain factor of 0.9980. The gain corrected result is calculated as follows:

$$T_{corr} = T_{uncorr}/0.9980$$

5   Details and Special Functions

5.1   Oscillator

The TDC-GP21 uses up to 2 clock signals depending on the operating mode:

- High-speed clock, typically 4 MHz, for calibration and as a predivider for the TDC measuring unit in measure mode 2 and for the EEPROM
- 32 kHz clock signal used for internal timer functions.

5.1.1   High-Speed Oscillator

Generally, the TDC-GP21 needs a high-speed clock for calibration. The recommed value is 4 MHz, the possible range is 2 to 8 MHz (2 to 6 MHz in QUAD_RES mode). When running in measure mode 2 the TDC-GP21 needs the high-speed clock signal also as a part of the time measuring unit. Finally the EEPROM operations need the high speed clock, too.

The oscillator takes an average current of 200 µA when running all the time. But as it is needed only during the time measurement, the TDC-GP21 has the capability to control the on-time by itself. The settings are done with parameter START_CLKHS. With START_CLKHS > 1 the oscillator is switched on after sending opcodes Start_TOF, Start_TOF_Restart, Start_Temp and Start_Temp_Restart for the duration of the measurement. A delay between starting the oscillator and starting the measurement guarantees sufficient time for the oscillation to settle at full amplitude.

START_CLKHS

= 0	Oscillator off
= 1	Oscillator continuously on
= 2	The measurement is started with 480 µs delay.
= 3	same as '2', but with 1.46 ms delay
= 4	same as '2', but with 2.44 ms delay
= 5 to 7	same as '2', but with 5.14 ms delay
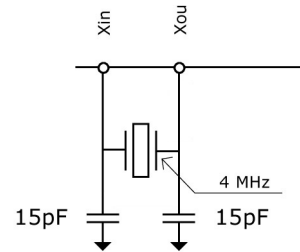
Figure 5.1

The programmable delay guarantees that the oscillator has settled before the measurement starts. For ceramic resonators 480 µs will be sufficient.

By this measure the average current consumption can be drastically reduced.

Example:

At one ToF measurement in an ultrasonic flowmeter (forth/back) per second the high-speed oscillator is active only for about 2 ms. The average current consumption is 130 µAs * 2 ms = 0.26 µA.

5.1.2 32.768 kHz Oscillator

The TDC-GP21 needs a 32.768 kHz reference for the start-up control of the high-speed clock and the clock calibration. It therefore offers a an integrated low-power driver. The 32.768 kHz oscillator is permanently running and has a current consumption of only about 0.5 µA at 3.0 V. The settling time of this oscillator is about 3 s after power-up. The 32.768 kHz oscillator cannot be switched off. Without a 32kHz clock pin CLK32In has to be connected to GND.
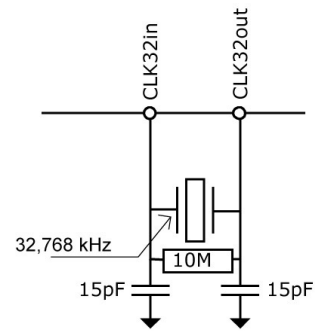
Figure 5.2

The low-power clock can be internally forwarded to an output pin to be available for an external microprocessor. The possible settings are:

SEL_TSTO1 = 7: 32 kHz output at pin FIRE_IN

SEL_TSTO2 = 7: 4 kHz (32kHz/8) output at pin EN_START

It is also possible to provide an external low-frequency rectangular clock at the CLK32Out pin (3.6 V max.).

5.1.3 Calibrating a Ceramic High-speed Oscillator

Using a ceramic oscillator for the 2 to 8 MHz clock will be attractive because it is of low cost and has a fast settling time. Unfortunately it has a poor tolerance of 0.3 to 0.5 % and shows a temperature drift. For this reason the TDC-GP21 allows to execute a calibration measurement that allows to compensate this behavior. This measurement is based on the very precise 32.768 kHz clock. The TDC-GP21 generates start/stop pulses from the 32.768 kHz and measures this time interval with its TDC unit. The result is stored in the result register and the interrupt flag is set. The frequency error of the ceramic resonator can be calculated by the microprocessor. The calibration is configured by setting register 0, ANZ_PER_CALRES and is started with „START_Cal_Resonator" - instruction by the microprocessor.

The time interval to be measured is set by ANZ_PER_CALRES which defines the number of periods of the 32.768kHz clock:

ANZ_PER_CALRES = 0 2 periods = 61.035 µs

= 1 4 periods = 122.07 µs

= 2 8 periods = 244.14 µs

= 3 16 periods = 488.281µs

The results is given in multiples of the high-speed clock and (divided by 1, 2 or 4 (DIV_CLKHS)) as 32 bit fixed point numbers with 16 integer bits and 16 fractional bits.

The microcontroller can compare this measured value to the theoretical value and calculate the cor-

rection factor RES_X/REStheor.

> Example:
>
> The system shall work with a 4 MHz resonator. With CLKHSDIV=0 and CALRES#=1 the theoretical result is 122.0703125µs/250ns = 488.28125 (RES_0 = 0x01E84800). If the ceramic resonator in use is not exactly at 4MHz but only 3.98MHz the calibration measurement will show 485,83984375 (RES_0 = 1E5D700). The correction factor for the microcontroller is 1.005.

Note:

During clock calibration the start input has to be enabled.

5.1.4 How to use Clock Calibration

a. Application

This option is dedicated especially to ultrasonic flow and heat meters. In those applications the use of ceramic oscillators shows two main advantages: lower cost and less current consumption. Mainly because of the short oscillation start-up time of the ceramic oscillator the operating current can be reduced by several µA. Referring to 10 years of operation this saves several 100 mAh in battery capacitance. There is no negative effect on the resolution when using this option the correct way.

b. Jitter of the 32 kHz clock and consequences

The 32 kHz clock is very precise in frequency with only a few ppm error. However, the phase jitter is about 3 to 5 ns peak-peak. For this reason also a calibration measurement (Start_Cal_Resonator) has this error. When multiplying a measurement result with the calibration result, the jitter of the calibration is transferred to the result by the ratio calibration measurement time (see CALRES#) to measurement time. Using a permanently updated calibration value will add a considerable jitter to the measurement result.

c. Application of this option in ultrasonic flow meters

A measurement result is always made of two single time-of-flight measurements in ultrasonic flow meters, with and against the flow direction. The difference between those measurements is a measure for the flow. To avoid an influence of the calibration jitter on this measurement result it is necessary only to use the same calibration for both ToF measurements. Following this, the difference between the two ToF measurements will be free of the jitter of the clock calibration measurement. The clock can be calibrated only between measurements that are not directly substracted from each other.

5.2 Fire-pulse Generator
5.2.1 General Description

The fire-pulse generator generates a sequence of pulses which is highly programmable in frequency, phase and number of pulses. The high-speed oscillator frequency divided by the factor selected for CLKHS_DIV is used as the basic frequency. This frequency is internally doubled and can freely be divided by a factor of 2 to 15. It is possible to generate 1 to 127 pulses. If maximum 15 pulses are sent the phase for each pulse can be adjusted per register configuration. The fire-pulse generator is activated by sending opcode Start_Cycle. The firepulse maybe used directly for the START of the TDC.

The fire-pulse generator provides 2 outputs, FIRE_UP and FIRE_DOWN. The driver strength of each output is 48mA @5V. These 2 outputs can be paralleled to increase the driver strength up to 96 mA. Furthermore, FIRE_DOWN output signal can be inverted to double the signal amplitude. The outputs can be set individually high-Z. Alternately, the default level of the inactive buffer can be set to GND.

The fire-pulse generator allows to generate and send pulse sequences multiple times for use in a quasi "sing-around" method. Using this feature the received pulse sequence is fed into TDC-GP21 FIRE_IN input. It is digitally amplified and directly forwarded to the output buffer for an immediate re-emittance without any clock delay. This option can not be used with the internal analog section.

5.2.2 Configuration

Number of pulses:

|		
ANZ_FIRE	= 0	Switch off fire-pulse generator
	= 1	1 pulse
	= 2	2 pulses
	…	…
	= 127	127 pulses
SEL_START_FIRE	= 1	Fire pulse is used as TDC START
FIRE_DEFAULT	= 0	Default level High_Z (GP2 compatible)
	= 1	Default level GND. Mandatory if the internal analog circuit and the recommended circuit with external R and C is used.

Phase:

The phase of each pulse can be defined in register 5, Bits 0 to 15, PHFIRE, if not more than 15 pulses are sent. „0" stands for HIGH-LOW and „1" for LOW-HIGH. The pulse sequence begins with the LSB and ends with the MSB

Example:

Fire# = 7, PHFIRE = 0x0055

| 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
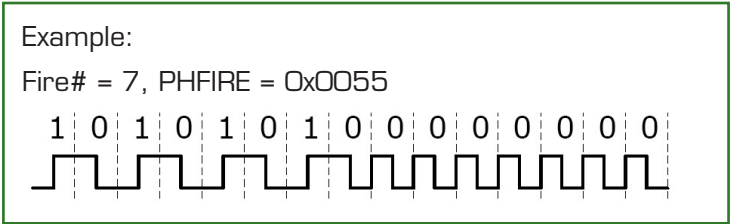
Fire-pulse frequency:

The input signal fireclk1 for the fire pulse generator is derived from the high speed clock CLKHS and the selected value for the high speed clock divider DIV_CLKHS.

Figure 5.3
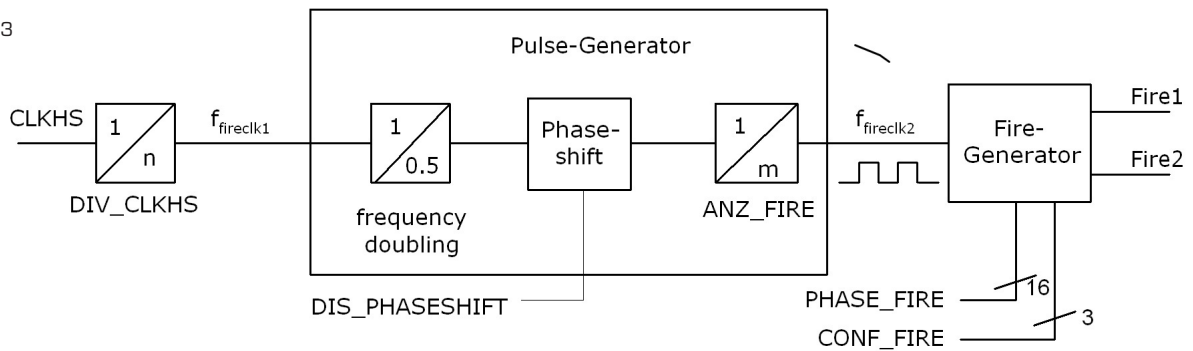
This Signal is internally doubled and divided by DIV_FIRE.

DIV_FIRE =   0   not permitted

                1   divided by 2

                2   divided by 3

                …   …

                15   divided by 16

Register 5, Bit 19, DIS_PHASESHIFT actives the phase shift, which introduces additional noise to improve statistical behaviour when averaging.

DIS_PHASESHIFT = 0 Phase shift on

DIS_PHASESHIFT = 1 Phase shift off

$$f_{fireclk2} = f_{fireclk1} \times \frac{2}{DIV\_FIRE + 1}$$

fireclk2 is used as reference signal for the FIRE_UP / FIRE_DOWN - signal which is emitted by the output buffers FIRE_UP / Fire 2 of the fire pulse generator.

Figure 5.4
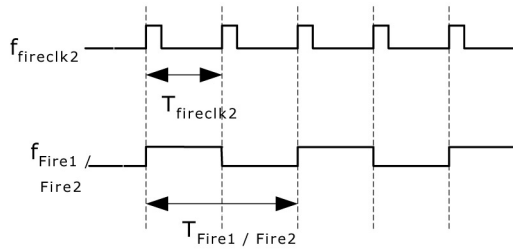
As shown in Figure 16 at least 2 clock periods $T_{fireclk2}$ are required to send one Fire_Pulse. One for the high phase and one for the low phase of the FIRE_UP/FIRE_DOWN output signal.

> Example:
>
> CLKHS = 4 MHz, DIV_CLKHS = 1, DIV_FIRE = 1
>
> $$f_{fireclk2} = f_{fireclk1} \times \frac{2}{DIV\_FIRE + 1} = 2\,MHz$$
>
> Max. frequency of the FIRE_UP / FIRE_DOWN output signal:
>
> $$f_{Fire1/Fire2} = \tfrac{1}{2} \times f_{fireclk2} = 1\,MHz$$

Driver outputs:

The output drivers are configured in register 5, Bits 21 to 23, CONF_FIRE:

Bit 31 = 1   FIRE_BOTH (Inverted output on FIRE_DOWN)

Bit 30 = 1   FIRE_DOWN disabled (High-Z)

Bit 29 = 2   FIRE_UP disabled (High-Z)

Pulse-burst repetition (quasi sing-around):

In register 5, Bits 16 to 18, REPEAT_FIRE the number of repetitions of the pulse sequence is defined.

REPEAT_FIRE   = 0   no repetition

               = 1   1 repetition

               …   …

               = 7   7 repetitions

Only the number of pulses set under FIRE# will be repeated. With a period of 5 µs without a pulse the TDC-GP21 detects the end of a pulse sequence.

Note:

This option can not be used with the internal analog section. It is strongly recommend that the summarized time of flight of the up to 7 repetitions does not exceed the measurement range of the GP21 !!!

5.3 Fast Initialization

In measurement range 1 the TDC-GP21 offers the possibility of a fast initialization. Activated by setting register 1, Bit 15, EN_FAST_INIT = „1" the interrupt flag automatically initializes the TDC. So the TDC is already prepared for the next measurement while the data can be read out. This mode is for highest speed applications only. It is most reasonable for un-calibrated measurements with only one stop.

5.4 Noise Unit

In case the user wants to improve the measuring results by averaging it is necessary that the values do not always display exactly the same time difference. Instead the user should provide some ‚noise' so that different quantization steps of the characteristic curve of the TDC are involved. This can not happen with very constant time differences. One would constantly hit the same LSB.

The noise unit enables the use of weighted averaging even for constant time differences. The noise unit adds a random offset to the start. It is dedicated to applications where the TDC gets a dummy start and measures the time difference between STOP1 and STOP2 (e.g. laser range finders).

The noise unit is switched on by setting register 5, Bit 20, EN_STARTNOISE = „1"

6 Applications

6.1 Ultrasonic Heatmeter

The TDC-GP21 is perfectly suited for low-cost ultrasonic heatmeter designs. Thanks to the implemented functionality, including precision temperature measurement, fire pulse generation, analog switches, comparator, windowing and clock calibration, it is sufficient to add a simple microprocessor (without A/D converter).

The final circuit reaches a unknown level in compactness and small size. The following diagram shows the front end section of a typical ultrasonic heat meter as it might look like when TDC-GP21 is used.

Figure 6.1
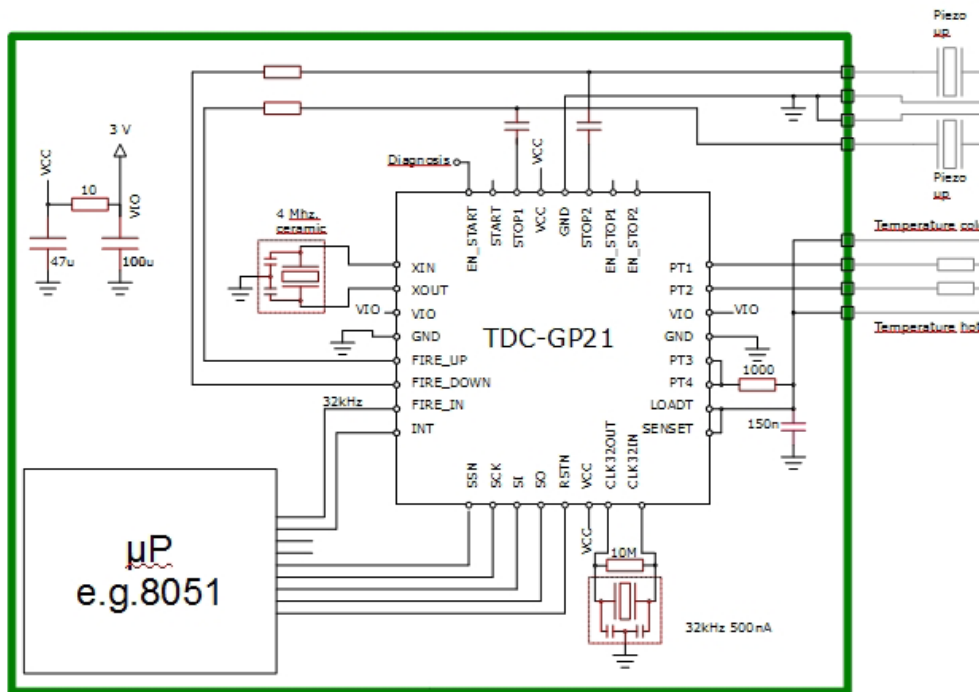
The red parts illustrate the external components needed. The number is reduced to a minimum:

- In the ultrasonic path, the piezo transducers are connected through pairs of R and C.
- In the temperature path only a temperature stable reference resistor and a capacitor
- As oscillators take a 32.768 kHz and a ceramic 4 MHz oscillator. The FIRE_IN pin can be used as output driver for the 32.768 kHz clock, so the µP does not need a low power oscillator.
- For the power supply use separate bypass capacitors of sufficient size to block VCC and VIO. Separate both by a small resistor.

In total 11 low-cost elements only are needed for the measurement.

Register	Value	Typical example configuration
Register 0	hF3CB6810	ANZ_FIRE = 31 (see register 6, too) DIV_FIRE = 3, fire pulse freuqency = 4 MHz/4 = 1.0 MHz ANZ_PER_CALRES = 3, the 4 MHz is calibrated by a 488.81µs measurement DIV_CLKHS = 0, the 4 MHz ceramic oscillator is internally used as it is START_CLKHS = 2, the ceramic oscillator has 480 µs to settle ANZ_PORT = 1, use all 4 ports for the temperature measurement TCYCLE = 1, 512 µs cycle time for the temperature measurement ANZ_FAKE = 0, 2 fake measurements SEL_ECLK_TMP = 1, use 4 MHz for the temperature measurement cycle definition CALIBRATE = 1, mandatory in measure mode 2 to be on NO_CAL_AUTO = 0, mandatory in measure mode 2 to have auto-calibration MESSB2 = 1, switch on measure mode 2 for measuring > 2 µs. NEG_STOP/NEGSTART = 0, all set to rising edges ID0 = h10, together with ID1 this could be interpreted as configuration version 1.0.1.2
Register 1	h21445712	HIT2 = 2, HIT1 = 1: calculate 1. Stop - Start in measure mode 2 EN_FAST_Init = 0, off HITIN2 = 0 HITIN1 = 4, measure 3 stops (in measure mode 2 this includes the start, 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 = 2, comparator out signal can be seen at pin EN_START SEL_TSTO1 = 7, The FIRE_IN pin is used as output and provides the 32.768 kHz to the microcontroller ID1 = h12
Register 2	hA0320012	EN_INT = b1101, interrupt given by time_out, ALU ready or end of EEPROM action (see also register 6) RFEDGE1 = RFEDGE2 = 0, use only rising edges DELVAL1 = 400, the first stop is accepted after 100 µs ID2 = h12, could be part of a serial number h1234567890

Register 3	h08330034	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 = 408, the first stop is accepted after 104 µs
		ID3 = h34, could be part of a serial number h1234567890
Register 4	h20340056	DELVAL3 = 416, the first stop is accepted after 108 µs
		ID4 = h56, could be part of a serial number h1234567890
Register 5	h00000078	CON_FIRE = 0, FIRE_UP and FIRE_DOWN are used alternately for up and down flow measurements
		EN_STARTNOISE = 0, switch off
		DIS_PHASESHIFT = 0, phase noise unit is active to improve the statistical behaviour
		REPEAT_FIRE = 0, no sing-arround
		PHASE_FIRE = 0, no phse change in the fire pulse sequence
		ID5 = h78, could be part of a serial number h1234567890
Register 6	hC0645190	EN_ANALOG = 1, use the internal analog circuit
		NEG_STOP_TEMP = 1, use the internal Schmitt trigger for the temperature measurment
		TW2 = 1, 120 µs delay to charge up the capacitors of the highpass
		EN_INT = b1101, interrupt given by time_out, ALU ready or end of EEPROM action (see also register 6)
		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 measurments
		CYCLE_TOF = 0, use factor 1.0 for the delay between two TOF measurements
		HZ60 = 0, 50 Hz base
		FIRE0_DEF = 1, mandatory when using the internal analog circuit
		QUAD_RES = 0
		DOUBLE_RES = 1, use 45 ps resolution
		TEMP_PORTDIR = 0, standard order for T measurement
		ANZ_FIRE = 31 (see register 0, too)
		ID6 = h90, could be part of a serial number h1234567890

Measurement flow:

Power-on reset:

Send SO = 0x50

Load configuration from EEPROM to configuration registers:

Send SO = 0x50

Check-loop INTN = 0? for end of EEPROM action

Calibrate Clock:

Send SO = 0x03 Start_Cal_Resonator

Check-loop INTN = 0?

Send SO = 0xB0, Read SI = RES_0

Correction factor = 488.28125/RES_0

Measurement loop:

Temperature measurement every 30 seconds:

Send SO = 0x06 Start_Temp_Restart

Check-loop INTN = 0?

Send SO = 0xB4, Read SI = STAT

STAT&0x1E00 > 0: -> Error routine

Send SO = 0xB0, Read SI = RES_0

Send SO = 0xB1, Read SI = RES_1

Send SO = 0xB2, Read SI = RES_2

Send SO = 0xB3, Read SI = RES_3

Rhot/Rref = RES_0/RES_1

Rcold/Rref = RES_3/RES_2

Check-loop INTN = 0?

Send SO = 0xB4, Read SI = STAT

STAT&0x1E00 > 0: -> Error routine

Send SO = 0xB0, Read SI = RES_0

Send SO = 0xB1, Read SI = RES_1

Send SO = 0xB2, Read SI = RES_2

Send SO = 0xB3, Read SI = RES_3

Rhot/Rref = RES_0/RES_1

Rcold/Rref = RES_3/RES_2

Calculate the average of the two measurements.

Go to look-up table to get the temperatures

Time-of-flight measurement every half second:

Send SO = 0x70 Initialize TDC

Send SO = 0x05 Start_TOF_Restart

Check-loop INTN = 0? (up TOF)

Send SO = 0xB4, Read SI = STAT

STAT&0x0600 > 0: -> Error routine

Send SO = 0x81314000 calculate HIT2-Start

Wait for 4.6µs (ALU time)

Send SO = 0x81414000 calculate HIT3-Start

Wait for 4.6µs (ALU time)

Send SO = 0xB0, Read SI = RES_0

Send SO = 0xB1, Read SI = RES_1

Send SO = 0xB2, Read SI = RES_2

Check-loop INTN = 0? (down TOF)

Send SO = 0xB4, Read SI = STAT

STAT&0x0600 > 0: -> Error routine

Send SO = 0x81314000 calculate HIT2-Start

Wait for 4.6µs (ALU time)

Send SO = 0x81414000 calculate HIT3-Start

Wait for 4.6µs (ALU time)

Send SO = 0xB0, Read SI = RES_0

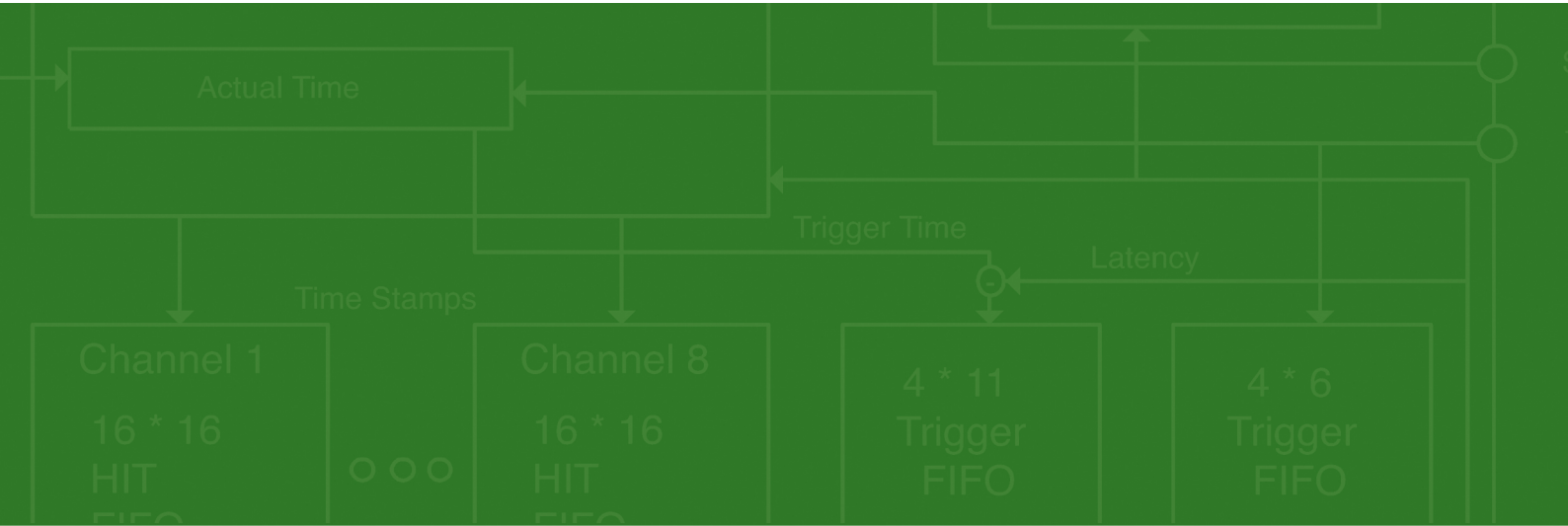Send SO = 0xB1, Read SI = RES_1

Send SO = 0xB2, Read SI = RES_2

µP can now start the data post-processing and calculate the flow and the heat.

7   Miscellaneous

7.1   Bug Report

7.2   Last Changes

27.05.2010	Target Specification, draft version
28.07.2010	Version 0.1 for release
13.08.2010	Version 0.2 slight changes
08.11.2010	Version 0.3 released
24.11.2010	Version 1.0 relesed, revision of section 4
17.01.2010	Version 1.1 released, several corrections in the whole document