FGD-03F

Floating Gate Dosimeter (FGDOS®)

FEATURES

FGDOS® radiation sensor with digital output

Total Ionizing Dose (TID) radiation up to 500 Gy

Chip Serial Number

Interface for microcontroller applications

Internal +18V Charge Pump for Sensor Recharging

Programmable Sensitivity 10 kHz/Gy or to 70 kHz/Gy

Standby Mode by pin

Passive detection mode (zero power consumption)

Temperature monitor integrated on-chip

5V supply voltage

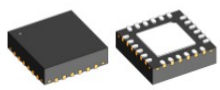
APPLICATIONS

Radiation sensor

Space

Particle Physics Facilities

PACKAGE



QFN32 5x5m (2 sensors)

GENERAL DESCRIPTION

FGD-03F is a high TID digital radiation sensor based in FGDOS® principle.

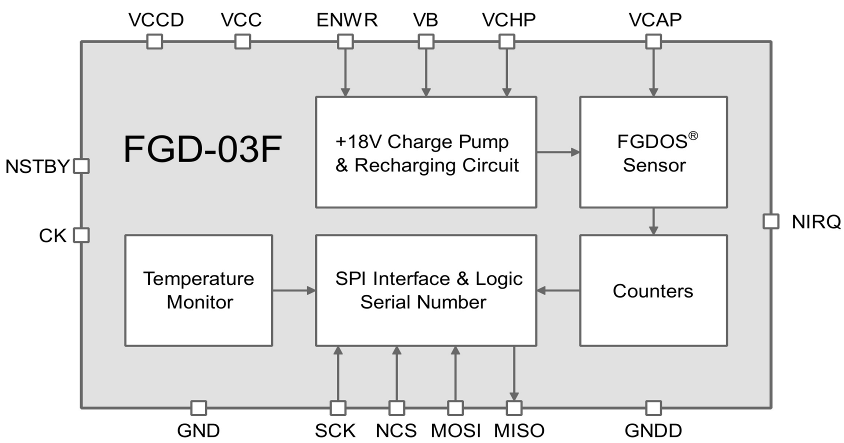
Sensor output is a frequency modulated pulse train proportional to radiation dose. Internal counters allow radiation dose digital value to be read via SPI Interface.

Chip serial number is provided for sensor tracking

In passive mode, the chip is still sensing the accumulated radiation dose even when there is no power supply.

Internal +18V Charge Pump allows FGDOS® sensor recharging from a single 5V supply.

On-chip temperature sensor and reference channel are provided for extended precision applications, via digital post-processing .



FUNCTIONAL BLOCK DIAGRAM

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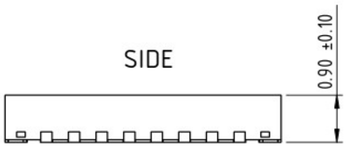
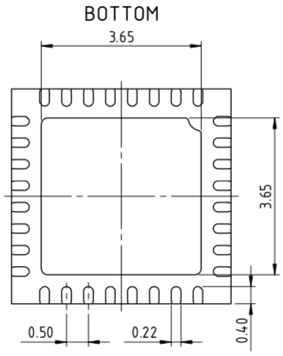
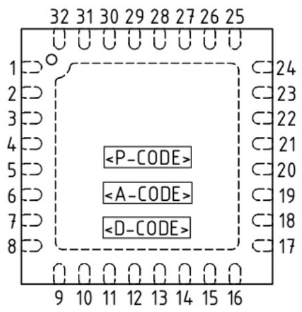
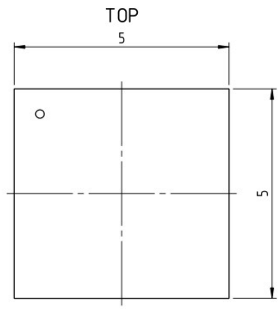
PACKAGING INFORMATION AND DIMENSIONS









Pin configuration QFN32-5x5 (top view)
The *Thermal Pad* is to be connected to a Ground Plane on the PCB.
Only pin 1 marking on top or bottom defines the package orientation

All dimensions given in mm
Tolerances according to JEDEC MO-220.
The approximated chip weight is 2 g

Pin	Name	Function	Pin	Name	Function
1	MISO-1	Serial Data Output *SENSOR-1*	17	MISO-2	Serial Data Output *SENSOR-2*
2	NCS-1	Chip Select, level low *SENSOR-1*	18	NCS-2	Chip Select, level low *SENSOR-2*
3	MOSI-1	Serial Data Input *SENSOR-1*	19	MOSI-2	Serial Data Input *SENSOR-2*
4	VCAP-1	VCAP *SENSOR-1*	20	VCAP-2	VCAP *SENSOR-2*
5	VCHP-1	Charge Pump Output *SENSOR-1*	21	VCHP-2	Charge Pump Output *SENSOR-2*
6	N.C.	Not Connected	22	N.C.	Not Connected
7	NIRQ-1	Interrupt Request, level low *SENSOR-1*	23	NIRQ-2	Interrupt Request, level low *SENSOR-2*
8	VCCD-1	Dig. Power Supply *SENSOR-1*	24	VCCD-2	Dig. Power Supply *SENSOR-2*
9	GND-1	Ground *SENSOR-1*	25	GND-2	Ground *SENSOR-2*
10	VB-1	Recharge Voltage *SENSOR-1*	26	VB-2	Recharge Voltage *SENSOR-2*
11	VCC-1	Power Supply *SENSOR-1*	27	VCC-2	Power Supply *SENSOR-2*
12	GNDD-1	Digital Ground *SENSOR-1*	28	GNDD-2	Digital Ground *SENSOR-2*
13	SCK-1	Serial Clock *SENSOR-1*	29	SCK-2	Serial Clock *SENSOR-2*
14	CK-2	Window Clock *SENSOR-2*	30	CK-1	Window Clock *SENSOR-2*
15	ENWR-2	Enable Write *SENSOR-2*	31	ENWR-1	Enable Write *SENSOR-1*
16	NSTBY-2	Standby, level low *SENSOR-2*	32	NSTBY-1	Standby, level low *SENSOR-1*

ABSOLUTE MAXIMUM RATINGS

These ratings do not imply permissible operating conditions; functional operation is not guaranteed. Exceeding these ratings may damage the device

Item	Symbol	Parameter	Conditions			Unit
No.				**Min**	**Max**	
G001	VB	Permissible Voltage at VB			25	V
G002	V()	Voltage at NIRQ, VCCD, VCC, SCK, NCS, ENWR, NSTBY, MISO, NCS, MOSI, CK	Referenced to GND		5.5	V
G003	Vd()	ESD Susceptibility at all pins			TBD (*)	kV
G004	Tj	Junction Temperature		-40	150	ºC
G005	Ts	Storage Temperature Range		-40	150	ºC

(*) Electrostatic discharges may vary the charge stored in **FGDOS**®

THERMAL DATA

These ratings do not imply permissible operating conditions; functional operation is not guaranteed.
Exceeding these ratings may damage the device

Item	Symbol	Parameter	Conditions				Unit
No.				**Min**	**Typ**	**Max**	
T01	Ta	Operating Ambient Temperature Range		-40		85	ºC
T02	Rthja	Thermal Resistance Chip/Ambient	Mounted on PCB		25		K/W
T03	RthjTP	Thermal Resistance Chip/Thermal Pad			4		K/W

ELECTRICAL CHARACTERISTICS

Operating Conditions: VB=18V, VCC=4.5V .. 5.5V, VCCD = VCC, Tj=-40 .. 85 ºC, Rad. source = Co60, TID=0Gy unless otherwise stated. Target Specification, limits not guaranteed.

Item No.	Symbol	Parameter	Conditions	Min	Typ	Max	Unit
Total Device							
001	VB	Permissible Programmer Voltage at VB	Referenced to GND	15		20	V
002	VCAP	Permissible Programmer Voltage at VCAP	Referenced to GND			24	V
003	I(VB)	Recharge current at VB	Recharge Disabled Recharge Enabled			1 100	µA
004	VCC	Permissible Supply Voltage at VCC	Referenced to GND	4.5		5.5	V
005	I(VCC)	Supply current at VCC	NSTBY = 1 NSTBY = 0			10 100	mA µA
006	VCCD	Permissible Supply Voltage at VCCD	Referenced to GND	4.5		5.5	V
007	I(VCCD)	Supply current at VCCD	NSTBY = 1 NSTBY = 0			2 TBD	mA µA
008	Vc(lo)	Clamp Voltage at VB,VCC, VCCD, MISO, NIRQ, ENWR, NCS, SCK, MOSI, CK	I()=10mA	-1.5		-0.6	V
009	f(CK)	Recommended CK frequency	ENGATE=0		32.768		kHz
Digital Input/Outputs							
100	Isc()lo	Short Circuit Current lo at NIRQ, MISO		-40		-4	mA
101	Isc()hi	Short Circuit Current hi at NIRQ, MISO		4		40	mA
102	Vs()lo	Saturation Voltage lo at NIRQ, MISO	I()=2mA	-0.4			V
103	Vs()hi	Saturation Voltage hi at NIRQ, MISO	I()=-2mA			0.4	V
104	Vt()hi	Input Threshold Voltage hi at ENWR, NCS, SCK, MOSI, NSTBY, CK				2	V
105	Vt()lo	Input Threshold Voltage lo at ENWR, NCS, SCK, MOSI, NSTBY, CK		0.8			V
106	I()pd	Pull down Current at ENWR, NCS, SCK, MOSI, NSTBY. CK		1		50	µA
107	Fsck	Max allowed SPI clock frequency				5	MHz
108	Tncslo	Min NCS low time before first SCK pulse		100			ns
Sensor Output							
200	PSRR()	Power supply rejection Ratio	High Sensitivity Configuration		TBD		Hz/mV
202	∆Fs()R	Frequency sensitivity	(*) High Sensitivity Conf. Low Sensitivity Conf.		70 10		kHz / Gy
203	RGmax	Maximum Gamma Dose (TID)			400		Gy
204	RPMax	Maximum Proton Dose (TID)			TBD		Gy
205	∆Fs()An	Annealing Frequency variation after first recharge	(*) Measured 5 Days after		4		kHz
206	Fs()Noise	Sensor Frequency noise	Constant temperature,no radiation applied, 250ms window		+-75		Hz

207	LinG()	Gamma linearity response	Sensor within 20 kHz linear range		99		%
208	LinP()	Protons linearity response	Sensor within 20 kHz linear range		TBD		%
209	Fs()Temp	Frequency dependency to Temperature	High Sensitivity Configuration Low Sensitivity Configuration		300 1000		Hz/ºC
Reference Output							
300	Fr()	Reference Frequency	E2V = 0 Low Sensitivity Configuration High Sensitivity Configuration		 180 90		kHz
301	Fr()Noise	Reference Frequency noise	Constant temperature,no radiation applied, 250ms window		+-75		Hz
302	Fr()Temp	Frequency dependency to Temperature	Low Sensitivity Configuration High Sensitivity Configuration		400 800		Hz/ºC
Window Measurement Gate							
400	Tcklmin	Minimum CK low time between Sensor and Reference measurements	ENGATE=1			20	µs
Charge Pump							
500	V()ChP	Output voltage by internal charge pump	SET(2:0)=000 SET(2:0)=001 SET(2:0)=010 SET(2:0)=011 SET(2:0)=100 SET(2:0)=101 SET(2:0)=110 SET(2:0)=111		14.5 15.0 15.5 16.0 16.5 17.0 17.5 18.0		V
501	I()out	Maximum output current				1	µA
502	C()max	Capacitor at VCHPx				100	pF
Temperature Monitor							
601	Trange	Temperature Measurement Range		-40		125	ºC
602	Tresol	Temperature Measurement Resolution			1		ºC
603	Reading	Temperature Value Ranges	Tj = 125 ºC Tj = -40 ºC	200 40		230 60	Digits
(*) Based on statistics measured with Co60 15 rad(Si) dose at 30 rad(Si)/h. Each sensor must be individually characterized							

PRINCIPLE OF OPERATION

The **FGDOS**® principle of detection is based on a Floating Gate (FG) capacitor. Charge is pre-stored in the FG using an on-chip recharging system. This charge is stored indefinitely, unless ionizing radiation is applied. When this occurs, the pre-stored charge at FG discharges. Thus, monitoring the charge at the FG capacitor, radiation dose can be measured.

FGDOS® working principle is based on three basic steps, as shown in Figure 1:

1. Initial charge action of the FG up to target value (Zone A). In this step, the FG sensor core is evaluated and it is a factory procedure.
2. The FG discharges due to applied ionizing radiation (Zone B). The discharging rate of the sensor is highly linear with radiation dose.
3. Recharge is triggered when FG charge reaches the threshold value (Zone C).
4. The measured radiation dose can be obtained by reading the sensor output data, calculating the sensor value decrease and counting the number of recharges been triggered.

Following these basic steps, **FGDOS**® ensures working in a very linear zone of detection, keeping the charge in the FG between target and threshold value.

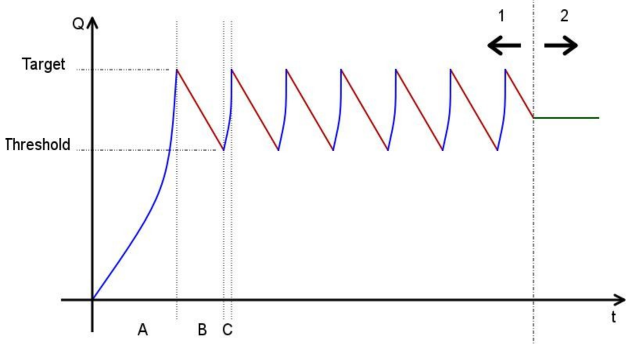


Figure 1. Working principle of **FGDOS**®

Note: More detailed information on the **FGDOS**® principle of operation, can be found at the following scientific publications:

1. *S. Danzeca, J. Cesari, M. Brugger, L. Dusseau, A. Masi, A. Pineda, G. Spiezia, "Characterization and Modeling of a Floating Gate Dosimeter with gamma and protons at various energies", November 2014 IEEE Transactions on Nuclear Science, vol. 61, no. 6, pp 3451 – 3457, 2014.*
2. *J. Cesari, A. Barbancho, A. Pineda, G. Ruy and H. Moser "Floating Gate Dosimeter Measurements at 4M Lunar Flyby Mission", The Nuclear and Space Radiation Effects Conference (NSREC) Radiation Effects Data Workshop (REDW), Boston, July 2015.*

QUICK SET-UP AND OPERATION EXAMPLE

This section provides, as an example, the steps for a quick set-up of **FGD-03F** working with the most common features:

- 250 ms-long *Sensor* and *Reference* measurements
- High Sensitivity Mode (HS)
- Automatic recharging

These are the required configuration steps:

A) Power-on the device

1. Apply a 32.768 kHz clock at **CK** pin.
2. Apply supply voltage and wait 100 µs

B) Configure FGD-03-F for HS mode, automatic recharging mode, 250 ms-long *Measurement Window* and recharge using the internal charge pump.

Addr. 0x0B = b11001000 = 0xC8h

Addr. 0x0C = b01111001 = 0x79h

Addr. 0x0E = b00000100 = 0x04h

C) Configure FGD-03F linear zone ranges and charge pump output voltage (Pins VCHP and VB must be shorted)

1. Disconnect Recharging System and configure **SET(2:0)** to 000 (14.5 V)

   Addr. 0x0D = b00000000 = 0x00h

2. Configure **TARGET(4:0)** to 90 kHz

   Addr. 0x09 = b00001011 = 0x0Bh

3. Configure **THRESHOLD(4:0)** to 50 kHz

   Addr. 0x0A = b00000110 = 0x06h

> *Note:*
> *FGD-03F is pre-charged in factory to a nominal, approximated value of 90kHz.*
> *However, it is possible the sensor suffers some discharge during soldering, or accidental exposure to radiation during transportation.*
> *In that cases, it may be desirable to force an initial recharge to ensure initial sensor value to be as close as possible to reference frequency, around 90kHz.*
>
> *To do so, configure* **THRESHOLD(4:0)=TARGET(4:0)** *for the first time the sensor is used.*
> *This initial recharge operation is finished when register RECHEV=0.*
>
> *Then, configure* **THRESHOLD(4:0)** *with equivalent 50 kHz nominal value*

4. Enable Recharging System

   Addr. 0x0D = b01000000 = 0x40h

D) Read Measured Data

1. Wait 2.2 seconds, in order to have new data in **F1S(17:0)** and **F1R(17:0)** registers
2. If a recharge is ongoing: **RECHEV** = 1. Disregard *Sensor* value. Go back to point D.1 and wait for next data.

E) Calculate Radiation value

1. Convert **F1S(17:0)** to frequency
2. Calculate radiation measured.

$$Radiation = \frac{f(Sensor)n - f(Sensor)n-1}{Sensitivity}$$

3. In case it is necessary, apply temperature compensation (see section DATA POST-PROCESSING)

BASIC OPERATION OVERVIEW

FGD-03F contains an **FGDOS®** sensor (*Sensor*) that discharges with radiation dose. The output is encoded in frequency and it decreases as the sensor discharges.

When the sensor value goes below a predefined value, it is possible to recharge the sensor and continue with the radiation dose measurement (see RECHARGING SYSTEM chapter).

FGD-03F also includes a reference oscillator (*Reference*), which provides a reference frequency for temperature compensation of the sensor. The value of *Reference* is not affected by radiation dose.

The typical operation procedure of **FGD-03F** can be summarize as follows:

1. *Sensor* is charged to a predefined target value. This value should be as close as possible to the value of *Reference.*
2. The chip measures *Sensor* and *Reference*, each during a specific time window (see MEASUREMENT WINDOW SETTING chapter).
3. *Sensor* and *Reference* are read. The *Sensor* value drop is proportional to the radiation dose.
4. The value of *Reference* can be used for compensating temperature effects (see DATA POST-PROCESSING chapter).
5. If the sensor goes below a predefined threshold value, it is recharged to the original value (see RECHARGING SYSTEM chapter).

OPERATION DESCRIPTION

The operation of **FGD-03F** consists on alternating consecutive measurements of the *Sensor* and the *Reference*. The duration of the measurement is called *Measurement Window*. During the *Measurement Window*, **FGD-03F** counts *Sensor* and *Reference* pulses alternatively*.* The duration of a *Measurement Window* is equal for the *Sensor* and the *Reference* and it is configurable.

Reading Sensor and Reference

The values of the *Sensor* and the *Reference* are available at internal registers **F1S(17:0)** (*Sensor*) and **F1R(17:0)** (*Reference*) as 18-bit registers (see Table 3 and Table 4).

F1S(17:0) and **F1R(17:0)** can be read via SPI interface. They are updated after each corresponding *Measurement Window* has elapsed. Therefore, it is recommended to wait always at least two Me*asurement Windows* (plus an additional safety time of 10% *Measurement Window*) between two consecutive read commands.

DNEWR and **DNEWS** bits indicate if a new value is available since last individual bit check (see Table 8 and Table 9). They are cleared automatically after read.

FGD-03F generates an interrupt signal at **NIRQ** pin after both *Sensor* and *Reference Measurement Windows* are finished. **NIRQOC** bit allows configuring the output interruption as open collector or push-pull (see Table 25).

MEASUREMENT WINDOW SETTING

The *Measurement Window* is the total time that **FGD-03F** keeps counting *Sensor* and *Reference* pulses. Short windows allow higher measuring rates, while long windows can be used for filtering the measured values.

The *Measurement Window* is governed by pin **CK** and bit **ENGATE** (see Table 11):

- If **ENGATE** = 0 the *Measurement Window* is determined by a specific amount of pulses at **CK** pin.
- If **ENGATE** = 1 the *Measurement Window* determined by the duration of an external pulse at **CK** pin.

Measurement Window as amount of CK pulses

With bits **WINDOW(1:0)** there are four possible **CK** amount of pulses to be selected (see Table 10). E.g., if **WINDOW(1:0)** = 11, the *Measurement Window* will be active during 4096 pulses at pin **CK**.

Knowing the frequency from the signal at **CK**, it is easy to calculate the *Sensor* frequency:

$$Sensor\ Frecuency = \frac{F1S(17:0)}{Window\ Pulses\ amount} \times f(CK)\quad [\text{Hz}]$$

Similarly, the *Reference* frequency can be calculated.

In order to minimize noise effects, in this mode it is recommended to discard measurements during SPI communication. This is achieved by setting EDIRT bit to '1' (See Table 12).

Measurement Window gating at CK

In this configuration, the Measurement *Window* is active as long as **CK** pin is set high. Knowing the duration of **CK** pulse, *Sensor* frequency can be calculated:

$$Sensor\ Frecuency = \frac{F1S(17:0)}{CK\ pulse\ duration}\quad [\text{Hz}]$$

Similarly, the *Reference* frequency can be calculated.

Figure 2 shows a timing diagram example of using *Measuring Window* gating at CK. CK must remain low a minimum time, $tckl_{min}$ (***El. Char. No. 400***), between a *Sensor* and a *Reference* measurement. **DNEWS** (see Table 9) is set when *Sensor* measurement is finished, and **DNEWR** is set after a *Reference* measurement (see Table 8). When interrupt pin **NIRQ** goes low, the data is ready to be read by serial communication. **DNEWS** and **DNEWR** are cleared automatically after read.

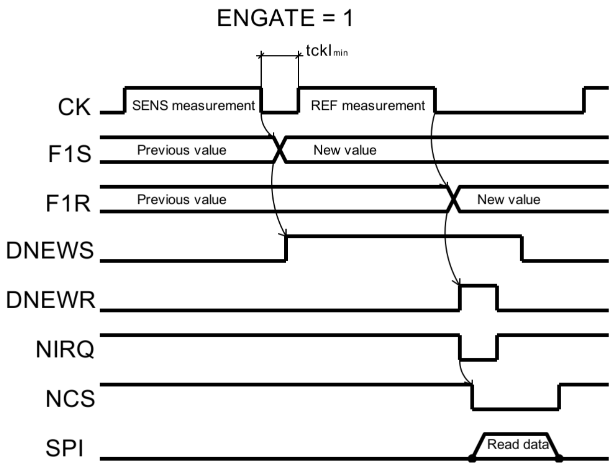


Figure 2: Sensor and Reference measurement with window gating

Count Overflow

F1S(17:0) and **F1R(17:0)** are 18-bit registers. If the selected *Measurement Window* is too long or the *Sensor* recharging value is too high, the registers might overflow. This event is flag through bits **F1SOVF** and **F1ROVF** (See Table 6 and Table 7).

SENSITIVITY CONFIGURATION

The *Sensor* offers two different sensitivity configurations, selected by bits **SENS(2:0)** (see Table 24):

- If **SENS(2:0)** = 100, Low Sensitivity configuration (LS) is selected. The *Sensor* linear range goes typically from 140 kHz to 180 kHz. The sensitivity of the *Sensor* is lower, while the TID needed for triggering a recharge is higher.
- If **SENS(2:0)** = 001, High Sensitivity configuration (HS) is selected. The *Sensor* linear range goes typically from 50 kHz to 90 kHz. The sensitivity of the *Sensor* is higher, while the TID needed for triggering a recharge is lower.

	kHz / Gy	Gy / Cycle
High Sensitivity	70	0.67
Low Sensitivity	10	4

Table 1: Sensitivity configuration

RECHARGING SYSTEM

The *Sensor* should be kept working within its linear range. This range depends on the sensitivity configuration selected:

- High Sensitivity (HS): Typically from 50 kHz to 90 kHz.
- Low Sensitivity (LS): Typically from 140 kHz to 180 kHz.

The *Reference* should be configured to the maximum value of the linear range. This is achieved using **E2V** bit (See Table 5).

If the *Sensor* value is discharged below the linear range, a recharging system allows recharging it back to the original value. **This value should be as close as possible to the *Reference* value**. The supply voltage for the recharging system can be generated either internally or externally:

1. Using the internal charge pump, no external voltage is needed. In this configuration pins **VB** and **VCHP** have to be shorted together. The following bits need to be configured accordingly:

   NCHP = 0
   EVBCHP = 1

   Furthermore, **SET(2:0)** will select the charge pump output voltage. Higher **SET(2:0)** values will yield faster recharging process. However, there is the risk of overcharging the sensor if **SET(2:0)** value is too high. It is recommended to calibrate the system to select the optimal **SET(2:0)** value.

2. Using an external supply voltage between 15 V and 20 V at pin **VB** (***El. Char. No. 001***). In this configuration, **NCHP** bit must be configured to disable the internal charge pump.

   NCHP = 1

Two registers are available to define the upper and lower limits of the linear working range:

- **TARGET(4:0)** defines the maximum value (See Table 15). This value should be as close as possible to the Reference value, which typically is:
  - 90 kHz in HS
  - 180 kHz in LS
- **THRESHOLD(4:0)** defines the minimum value (see Table 16). The recommended values are:
  - 50 kHz in HS
  - 140 kHz in LS

Configuring Target and Threshold

TARGET(4:0) and **THRESHOLD(4:0)** are 5-bit registers, while **F1S(17:0)** is 18-bit long. To compare the *Sensor* with the target and threshold, only the 5 MSB of the sensor register are compared, **F1S(17:13)**. This means 1 single count in **TARGET(4:0)** or **THRESHOLD(4:0)** registers correspond to 13 bits of **F1S(17:0)** register, i.e. 8192 counts.

To configure **TARGET(4:0)**, the following expression can be used:

$$TARGET(4:0) = FS_T \times \frac{T_I}{LSB_{COUNTS}}$$

FS_T is the target Sensor frequency in Hz. It should be as close as possible to Reference frequency, typically 90 kHz.

T_I is the integration time. Depending on the Measurement Window selected:

- If ENGATE = 0 $\longrightarrow$ $T_I = \frac{WINDOW(1:0)}{F_{CK}}$
- If ENGATE = 1 $\longrightarrow$ $T_I = T_{CK}$

F_{CK} is the frequency of the external clock, and T_{CK} is the duration of the external CK pulse.

LSB_{COUNTS} is the number of counts in **F1S(17:0)** that correspond to 1 count in **TARGET(4:0)**, i.e. 8192. This quantity can be reduced if desired by setting bit **TDIV**. If **TDIV**=1, only 10 bits of **F1S(17:0)**, i.e. 1024 counts, correspond to 1 count of **TARGET(4:0). Table 2 summarizes** how to configure **TARGET(4:0)** depending on configuration bits **TDIV** and **ENGATE.**

	TDIV = 0	TDIV = 1
ENGATE = 0	$FS_T \times \frac{WINDOW(1:0)}{F_{CK} \cdot 8192}$	$FS_T \times \frac{WINDOW(1:0)}{F_{CK} \cdot 1024}$
ENGATE = 1	$FS_T \times \frac{T_{CK}}{8192}$	$FS_T \times \frac{T_{CK}}{1024}$

Table 2: TARGET(4:0) configuration depending on TDIV and ENGATE bits.

The same expression can be used to configure **THRESHOLD(4:0)**, but instead of FS_T, the desired threshold sensor frequency should be introduced, typically 50 kHz for HS mode.

There are two main recharging modes, depending on bit **EAWR** (see Table 13):

- Manual Recharge
- Automatic Recharge

Independent of the recharging mode, to enable recharges the global bit **ECH** must be set high (see Table 14).

Automatic Recharge

If **EAWR** = 1 the recharging system works automatically.

- When **F1S(17:10)** goes below **THRESHOLD(7:0)** a recharge start.
- When **F1S(17:10)** goes above **TARGET(7:0)** the recharge is stopped.

Bits **RCHCNT(6:0)** count the number of recharges carried out (see Table 21). They allow working with long periods between each data read. A read must be carried out before **RCHCNT(6:0)** reaches maximum value and it must be cleared manually by performing a write operation on address 0x01.

Bit **RCHEV** is a safety flag bit that indicates if a recharge is process (see Table 17).

Manual Recharge

In *Manual Recharge* the user controls the start and stop of the *Sensor* recharge. It can be controlled either by external pin or by internal bit:

- By internal bit. Bit **FCH** and bit **EPWR** must both be set to 1, while global enable charge bit **ECH** bit is also set to 1 (see Table 20).
- By external pin. Pin **ENWR** must be pulled high and bit **EPWR** must be set to 1, while **ECH** bit is also set to 1.

In *Manual Recharge* it is not necessary to use **TARGET(4:0)** and **THRESHOLD(4:0)**. To detect if the *Sensor* is within the linear range, **F1S(17:0)** must be polled. To relate the **F1S(17:0)** to the Sensor frequency the following expression can be used:

$$FS=\frac{F1S(17:0)}{T_I}¿$$

FS is the sensor frequency and T_I is the integration time. Depending on the *Measurement Window* selected:

Depending on the Measurement Window selected:

- If ENGATE = 0 $\longrightarrow$ $T_I=\frac{WINDOW(1:0)}{F_{CK}}$
- If ENGATE = 1 $\longrightarrow$ $T_I=T_{CK}$

F_{CK} is the frequency of the external clock, and T_{CK} is the duration of the external CK pulse.

In manual recharge, the recharge counter is increased every time the user triggers a new recharge.

STANDBY MODE AND PASSIVE DETECTION

FGD-03F features two different modes for low and even zero power consumption: Standby and Passive Detection Mode.

Both in Passive Detection and Standby Mode, the core of the sensor is still sensing and recording the received radiation dose.

For data reading, **FGD-03F** must be fully powered-one (Normal Operation). Once data reading operation is finished, it can be switched back to Passive Detection or Standby Mode.

Standby Mode

By pulling **NSTBY** pin low, **FGD-03F** consumption is reduced to a minimum value (***El. Char. No. 005 and 007***).

Passive Detection Mode

FGDOS® can measure radiation dose with no supply voltage, acting as a passive radiation detector. Consumption of **FGD-03F** can be reduced to zero by switching off **VCC** and **VCCD** power supplies.

For data reading, **FGD-03F** must be powered-on. Once read, it can be switched back to passive detection mode.

INTERNAL TEMPERATURE MONITOR

FGD-03F includes an 8-bit temperature monitor with a range going from -40 °C to 125 °C and a resolution of 1 °C/LSB. The internal temperature can be obtained by reading **TEMP(7:0)** register, which is a read-only register (see Table 26).

Absolute read values may differ from one chip to another. An individual initial calibration of the temperature monitor is recommended.

The temperature monitor can be used to compensate temperature effects on the *Sensor*. The microcontroller can use a look-up table combined with the temperature value measured through **TEMP(7:0)** register.

SERIAL ID NUMBER

FGD-03F provides a 3 bytes-long unique individual serial number that can be read at address 0x10 to 0x12.

SERIAL PHERIPHERAL INTERFACE (SPI)

SPI slave interface

The SPI slave interface uses pins **NCS**, **SCLK**, **MISO** and **MOSI**. Pin **NCS** is the chip select pin and must be set lo by the SPI master in order to start communication. Pins **MISO** and **MOSI** are the data communication lines and pin **SCLK** is the clock line generated by the SPI master (E.g. microcontroller).

The SPI protocol frames are shown in Figure 3. A communication frame consists of one address byte and at least one data byte. Bits 7:6 of the address byte is the opcode used for selecting a read operation (set to "10") or a write (set to "01") operation. The remaining 6 bits are used for register addressing.

It is possible to transmit several bytes consecutively, if the **NCS** signal is not reset and **SCLK** keeps clocking. The address is internally incremented after each transmitted byte. Once the address reaches the last register (0x14h), it is reset back to 0x00.

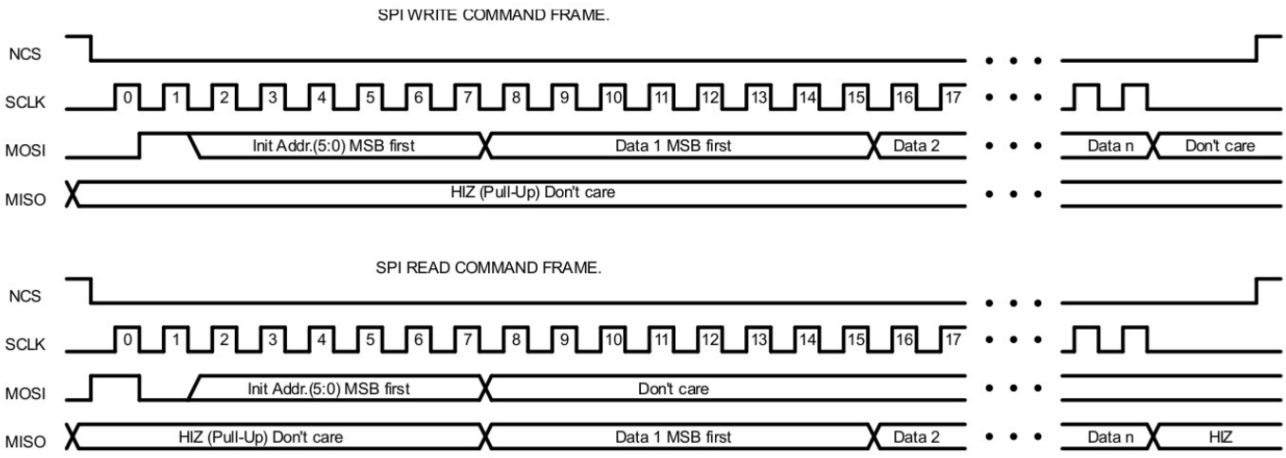


Figure 3: SPI Read and Write commands

DATA POST-PROCESSING

Background

The accuracy of **FGDOS®** is improved if the effects of operating temperature are compensated. This can be achieved by post-processing the sensor data through an external microcontroller or FPGA.

A single measurement of **FGDOS®** consists of a reference frequency (*FR*) and a sensor frequency (*FS*) pair. Both sensor and reference dependencies should be compensated to improve **FGDOS®** accuracy.

Typical values for FS and FR temperature dependence (see ***El. Char. No. 209 and 302***).

Compensating for the FS and FR temperature dependence

FGDOS® has to be characterized in temperature after the sensor has been charged for the first time. This temperature characterization must be carried out under no radiation.

The relation of FS and FR is very linear with temperature variation. Assuming this linearity, the equation of a line can be extracted by measuring two pairs of FS and FR at different temperatures, T_{RT} and T_1:

$$FS_{RAD0}(T_{RT}),FR_{RAD0}(T_{RT})$$

$$FS_{RAD0}(T_1),FR_{RAD0}(T_1)$$

where $FS_{RAD0}(T_{RT})$ is the sensor frequency with no radiation at room temperature. This line is shown in Figure 4. The resulting equation is:

$$FS_{RAD0}=m \cdot FR_{RAD0}+a \qquad (1)$$

Once the FS_{RAD0} is obtained, radiation can be applied to **FGDOS®**. When radiation RAD_1 is applied to the sensor, the line relating FS and FR is modified, but it can be assumed that the slope remains constant. Figure 5 shows the effect of applying radiation. When a pair of FR and FS is measured under radiation RAD_1 and a random temperature T_3, the following pair is obtained:

$$FS_{RAD1}(T_3),FR_{RAD1}(T_3)$$

With $FR_{RAD1}(T_3)$ and formula (1), $FS_{RAD0}(T_3)$ can be obtained. From Figure 4 it can be seen that:

$$FS_{RAD0}(T_3)–FS_{RAD0}(T_{RT}) = FR_{RAD1}(T_3)–FS_{RAD1}(T_{RT})$$

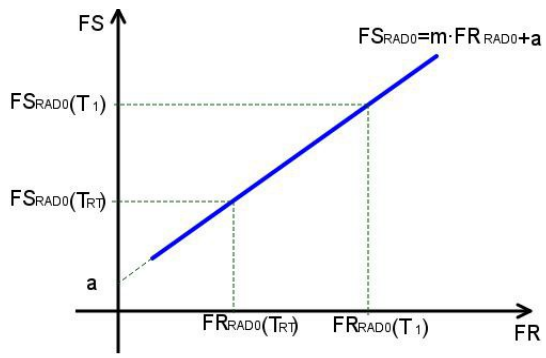


Figure 4: Variation of FS and FR with temperature

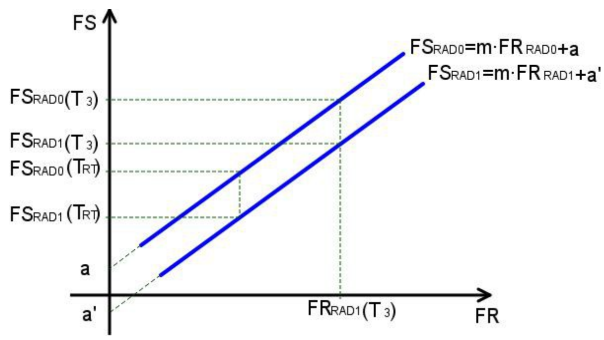


Figure 5: Effect of applying radiation

The radiation increase with respect to $FS_{RAD0}(T_{RT})$ is therefore:

$$FS_{RAD1}(T_{RT}) = FR_{RAD1}(T_3) – FS_{RAD0}(T_3)$$

This value is temperature compensated and is given in frequency. Applying the Frequency Sensitivity factor (***El. Char. No. 202***), the radiation value in Gy is obtained.

This compensation technique assumes linear behavior of the relation of FR and FS with temperature, as well as constant slope of this relation when radiation is applied.

This is a possible approach, however **it is possible to improve even more the accuracy if these assumptions are not considered and instead a look-up table is used for temperature compensation**.

FLOATING GATE MANUAL DISCHARGE

FGD-03F includes the possibility of emulating the effect of radiation by electrically discharging the floating gate through pin VCAP. This can be done with either external or internal voltage.

External discharge

Discharging the sensor externally requires applying an external voltage (18V to 25V) at pin **VCAP** during a certain period of time. **F1S(17:0)** must be monitored during the discharging process, until the desired value is reached.

Both the required voltage and time may be variable from sample to sample, so this process is recommended to be carried out under user supervision, at least during the first time it is performed over an specific sample.

When a voltage is applied to **VCAP**, this voltage is linearly superposed to the floating-gate sensor. This means that sensor output **FSENS** will show a very high frequency value (close to saturation or even saturated) as long as high-voltage is applied to **VCAP**. Thus, it is not possible to monitor the floating-gate discharge while high-voltage is applied to **VCAP**. To monitor how much discharge it has been produced, high-voltage must be disconnected from n. Then, the following iterative procedure must be carried out:

1. Connect high-voltage to **VCAP** (18V to 25V). The higher voltage, the faster discharge rate.
2. Wait some time (*). During this time **FSENS** is saturated to its maximum value (or close) and gives no relevant info about the floating-gate status.
3. Remove high-voltage from **VCAP** (if possible, connect it to **GND**) and check the floating-gate new value through **FSENS**.
4. Repeat this process until **FSENS** has been lowered to the desired value. Both wait time (step2) and **VCAP** voltage can be adjusted to get faster or slower discharge if necessary.

(*) This time can be variable from sample to sample. It is recommended to start with no more than 30 seconds. In case that no discharge is appreciated or it is smaller than required, this time can be increased progressively. It is possible that time required for significant discharge is in the order of 10 minutes or even more. Also, using higher voltage at **VCAP** it will lead to faster discharge rate.

Internal discharge

It is possible to use the same **FGD-03F** charge-pump to generate the high-voltage to be applied at **VCAP** pin. For such a purpose, use the following register configuration:

- **SET(2:0)** = 111 (Charge-Pump set to maximum value, 18V typ.)
- **ENDCH** = 1
- **ECH** = 1
- **EPWR** = 0
- **EVBCH** = 0
- Pins **VB** and **VCHP** must be shorted together.
- Pin **VCAP** must be left floating.

DO NOT CONNECT VCAP TO GND OR ANY OTHER VOLTAGE SOURCE DURING THIS PROCEDURE

Then, by setting bit **ECH** = 1, **VCAP** will be set to 18V typ. and the discharge process is initiated. Please, refer to the steps described in **External**

discharge section for more information about the discharge procedure. Since maximum applied voltage though the charge pump is 18 V, a higher required discharging time is expected for internal discharge process.
Setting **ECH**=1 and **ECH**=0 is equivalent to connect and disconnect the high-voltage source to/from **VCAP** pin. It is recommended to check at least once that pin **VCAP** is effectively at approximately 18 V when **ECH**=1. However, once this check has been made, it is recommended not leaving any multimeter or voltage measuring device connected to **VCAP** to avoid potential loading of the charge pump.

REGISTER DESCRIPTION

Sensor and Reference

F1S	Addr. 0x06/07/08	Bits 17:0	R 0x0000
0x00000	Minimum sensor counter value		
0x3FFFF	Maximum sensor counter value		

Table 3: Sensor Counter

F1R	Addr. 0x03/04/05	Bits 17:0	R 0x0000
0x00000h	Minimum reference counter value		
0x3FFFFh	Maximum reference counter value		

Table 4: Reference Counter

E2V	Addr. 0x0D	Bit 3	R/W 0
0	Reference set high		
1	Reference set low		

Table 5: Reference frequency configuration

F1ROVF	Addr. 0x05	Bit 2	R 0
0	No Reference overflow		
1	Reference overflow		

Table 6: Reference counter overflow

F1SOVF	Addr. 0x08	Bit 2	R 0
0	No Sensor overflow		
1	Sensor overflow		

Table 7: Sensor counter overflow

DNEWR	Addr. 0x05	Bit 3	R 0
0	No new reference data is ready		
1	New reference data is ready		

Table 8: Reference data new value

DNEWS	Addr. 0x08	Bit 3	R 0
0	No new sensor data is ready		
1	New sensor data is ready		

Table 9: Sensor data new value

Measurement Window bits

WINDOW	Addr. 0x0B	Bit 3:2	R/W 00
00	32,768 CK pulses per window		
01	16,384 CK pulses per window		
10	8,192 CK pulses per window		
11	4,096 CK pulses per window		

Table 10: Window length selection

ENGATE	Addr. 0x0E	Bit 0	R/W 0
0	Meas. Window by counts at CK		
1	Meas. Window by gating at CK		

Table 11: Enable window gating

EDIRT	Addr. 0x0E	Bit 2	1
0	Measurements during SPI allowed		
1	Measurements during SPI discarded		

Table 12: Measurements during SPI enable bit

Recharging System bits

EAWR	Addr. 0x0B	Bit 7	R/W 0
0	Automatic recharging mode disabled		
1	Automatic recharging mode enabled		

Table 13: Charge Mode Selection

ECH	Addr. 0x0D	Bit 6	R/W 0
0	Recharge not allowed		
1	Recharge allowed		

Table 14: Enable Recharging

TARGET	Addr. 0x09	Bits 4:0	R/W 0x00
0x00	Minimum Frequency		
0x1F	Maximum Frequency		

Table 15: Upper level target frequency

THRES	Addr. 0x0A	Bits 4:0	R/W 0x00
0x00	Minimum Frequency		
0x1F	Maximum Frequency		

Table 16: Lower level threshold frequency

RCHEV	Addr. 0x01 Bit 7 R 0
0	Recharge not in progress
1	Recharge in progress

Table 17: Recharge event flag

EVBCHP	Addr. 0x0B Bit 6 R/W 0
0	Internal charge pump not at VB pin
1	Internal charge pump at VB pin

Table 18: Internal charge pump connection to VB pin

NCHP	Addr. 0x0B Bit 5 R/W 1
0	Recharge by internal charge pump
1	Recharge by external voltage at VB

Table 19: Recharge source

FCH	Addr. 0x0C Bit 7 R/W 0
0	FG charging stopped
1	FG charging started

Table 20: Force charge in Manual Recharging mode

Sensitivity Configuration

SENS(2:0)	Addr. 0x0C Bit 2:0 R/W 000
xxx	Reserved
001	High Sensitivity Selected
xxx	Reserved
100	Low Sensitivity Selected
xxx	Reserved

Table 24: Sensitivity Configuration

Interrupt request

NIRQOC	Addr. 0x0E Bit 1 R/W 0
0	NIRQ interruption push-pull
1	NIRQ interruption open collector

Table 25: Interrupt output

Temperature Monitor

TEMP	Addr. 0x00 Bits 7:0 R 0x00
0x00	Minimum temperature value
0xFF	Maximum temperature value

Table 26: Temperature monitor

RCHCNT(6:0)	Addr. 0x01 Bit 6:0 R/W 0x00
0x00	No recharges since last clear
0x7F	At least 127 rech. since last clear

Table 21: Recharge counter

SET(2:0)	Addr. 0x0D Bits 2:0 R/W 100
000	Min. charge pump output voltage
111	Max. charge pump output voltage

Table 22: Charge pump output voltage

TDIV	Addr. 0x0B Bit 0 R/W 0
0	13 LSB bits for TARGET and THR.
1	10 LSB bits for TARGET and THR.

Table 23: Divider for Target and Threshold

Serial Number and Chip Version

SN	Addr. 0x10/11/12 Bits 23:0 R 0x000000
0x000000	Minimum serial number value
0xFFFFFF	Maximum serial number value

Table 27: Serial Number

CHIPID	Addr. 0x13 Bits 7:0 R 0x01
0x01	FGD-03F version 1
0x81	FGD-03F version Z, Z1

Table 28: Chip Identification Number

REGISTER MAP

OVERVIEW

Addr	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0x00 R	**TEMP(7:0)**							
0x01 R	**RECHEV**	**RCHCNT(6:0)**						
0x02	**Not implemented**							
0x03 R	**F1R(7:0)**							
0x04 R	**F1R(15:8)**							
0x05 R	**0**	**0**	**0**	**0**	**DNEWR**	**F1ROVF**	**F1R(17:16)**	
0x06 R	**F1S(7:0)**							
0x07 R	**F1S(15:8)**							
0x08 R	**0**	**0**	**0**	**0**	**DNEWS**	**F1SOVF**	**F1S(17:16)**	
0x09	**0***	**0***	**0***	**TARGET(4:0)**				
0x0A	**0***	**0***	**0***	**THRESHOLD(4:0)**				
0x0B	**EAWR**	**EVBCHP**	**NCHP**	**ENDCH (**)**	**WINDOW(1:0)**		**0**	**TDIV**
0x0C	**FCH**	**1***	**1***	**1***	**1***	**SENS(2:0)**		
0x0D	**0***	**ECH**	**EPWR**	**NEASNR (**)**	**E2V**	**SET(2:0)**		
0x0E	**0**	**0**	**0**	**0**	**0***	**EDIRT**	**NIRQOC**	**ENGATE**
0x0F	**Not implemented**							
0x10	**SN(7:0)**							
0x11	**SN(15:8)**							
0x12	**SN(23:15)**							
0x13 R	**CHIPID(7:0)**							
0x14	**0**	**0**	**0**	**0**	**Reserved**			

R: Read-only register
(*) : Reserved. Must be set to specified value
(**) : ENDCH and NEASNR are internal debugging bits and must be set to 0.

EXTENDED BIT DESCRIPTION

The information in previous chapters allows working with the sensor in default mode. However, some additional bits are available a deeper control of the device is desired.

REGISTER DESCRIPTION

ENDCH	Addr. 0x0B	Bit 4	0
0	VB not connected to VCAP		
1	VB connected to VCAP		

Table 29: Enable FG discharge bit

E9S	Addr. 0x0C	Bit 0	1
0	Low sensitivity FG arrangement		
1	High sensitivity FG arrangement		

Table 30: Sensitivity FG arrangement bit

SNRF	Addr. 0x0C	Bit 1	
0	Automatic control SENS/REF meas. swapping.		
1	Manual control SENS/REF meas. swapping.		

Table 31: Sensor/Reference measurement swapping bit

NEIDCM	Addr. 0x0C	Bit 2	0
0	DC current compensated (HS)		
1	DC current not compensated (LS)		

Table 32: DC current compensation bit

ENOSC	Addr. 0x0C	Bit 3	1
0	Disable measurement oscillators		
1	Enable measurement oscillators		

Table 33: Measurement oscillator enable bit

NELF	Addr. 0x0C	Bit 4	1
0	Low Frequency range measurement		
1	Normal Frequency range measurement		

Table 34: Frequency Range measurement bit

ENTEMP	Addr. 0x0C	Bit 5	1
0	Digital thermometer disabled		
1	Digital thermometer enabled		

Table 35: Digital thermometer enable bit

NEBUF	Addr. 0x0C	Bit 6	0
0	Output buffers for external frequency measurement enabled		
1	Output buffers for external frequency measurement disabled		

Table 36: Output buffers for external frequency bit

ENMC	Addr. 0x0D	Bit 7	0
0	External compensation mode disabled		
1	External compensation mode enabled		

Table 37: External compensation mode enable bit

LOWN	Addr. 0x0E	Bit 3	0
0	Default Finite State Machine oscillator timebase		
1	Special Finite State Machine oscillator timebase		

Table 38: Finite State Machine oscillator timebase selection bit

EXTENDED BIT REGISTER MAP

Addr	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
0x00 R	TEMP(7:0)							
0x01 R	RECHEV	RCHCNT(6:0)						
0x02	Not implemented							
0x03 R	F1R(7:0)							
0x04 R	F1R(15:8)							
0x05 R	0	0	0	0	DNEWR	F1ROVF	F1R(17:16)	
0x06 R	F1S(7:0)							
0x07 R	F1S(15:8)							
0x08 R	0	0	0	0	DNEWS	F1SOVF	F1S(17:16)	
0x09	0*	0*	0*	TARGET(4:0)				
0x0A	0*	0*	0*	THRESHOLD(4:0)				
0x0B	EAWR	EVBCHP	NCHP	ENDCH	WINDOW(1:0)		0	TDIV
0x0C	FCH	NEBUF	ENTEMP	NELF	ENOSC	NEIDCM	SNRF	E9S
0x0D	ENMC	ECH	EPWR	NEASNR	E2V	SET(2:0)		
0x0E	0	0	0	0	LOWN	EDIRT	NIRQOC	ENGATE
0x0F	Not implemented							
0x10	SN(7:0)							
0x11	SN(15:8)							
0x12	SN(23:15)							
0x13 R	CHIPID(7:0)							
0x14	0	0	0	0	Reserved			

R: Read-only register

DESIGN REVIEW: Notes On Chip Functions

FGD-03F Z		
No.	**Function, Parameter/Code**	**Description and Application Notes**
1	Standby Mode	Standby Mode is not supported
2	Measurement window as Gating	In Gating mode (ENGATE = 1) reference value F1R(17:0) may not always be updated
3	Chip Revision Number	For FGD-03F chip releases, see Table 28

FGD-03F Z1		
No.	**Function, Parameter/Code**	**Description and Application Notes**
1	Measurement window as Gating	In Gating mode (ENGATE = 1) reference value F1R(17:0) may not always be updated
2	Chip Revision Number	Chip ID not updated, value points to Z version instead of Z1, see Table 25.
3	Standby Mode	Standby Mode is not supported
4	Charge-pump	In internal recharging mode (EVBCHP=1), if voltage at VB is high enough, the sensor can be unintentionally recharged even at values above Target. VB pin should be kept low capacitive to ensure fast charge-pump voltage decay after a recharge process.

DATASHEET REVISION HISTORY

Rel.	Rel. Date	Chapter	Modification	Page
A0.1	29/05/2018		Initial Version	
A0.2	31/10/2018	All	Changed to Sealicon Trademark. Overall document design adapted.	All
A0.3	18/12/2018	Features	TID = 400 Gy	1/23
		BLOCK DIAGRAM, PACKAGING INFORMATION	NIRQ function on FREQB pin	1,3/23
		OPERATION DESCRIPTION	Additional information on Interrupt function at NIRQ	10/23
		MEAS. WINDOW SETTING	Figure 2 updated.	11/23
		FLOAT. GATE DISCH.	Chapter added regarding manual discharge of the floating gate	15/23
		REGISTER DESCRIPTION	NEASNR bit, Table 11 ENDCH bit, Table 27	19/23 21/23
A0.4	13/02/2019	All	VCAP, FREQA, FREQB, NRES pins not specified	All
		ABS. MAX. RATINGS	G003 ESD Susceptibility TBD	4/21
		ELECTRICAL CHAR.	005, 007; I(VCC) I(VCCD) in NSTBY TBD 203 Gamma TID max 400 Gy	5/21
		ELECTRICAL CHAR.	Charge Pump characteristics added	6/21
		OPERATION DESCRIPTION	Removed reference to MINTOC bit	9/21
		MEAS. WINDOW SETTING	Figure 2 updated	10/21
		RECHARGING SYSTEM	Removed reference to TDIV bit	12/21
		STANDBY MODE	Power saving mode changed to Standby mode	13/21
		FLOAT. GATE DISCH.	Chapter removed	13/21
		REGISTER DESCRIPTION	NEASNR bit Table removed TDIV, EPWR, ENDCH bit Tables removed	17/21 18/21
		REGISTER MAP	TDIV, NEASNR and ENDCH bits as debug bits	19/21
		DESIGN REVIEW	Chapter added	20/21
A0.5	12/06/2019	ORDERING INFORMATION	Only RTC Evaluation Boards available, Chip version updated	21/21
A0.6	25/06/2019	BLOCK DIAGRAM	VCAP pin added	1/22
		PACKAGING INFORMATION	VCAP pins 4, 20	3/22
		ELECTRICAL CHAR.	005, 007, Supply current in Standby mode	5/22

Rel.	Rel. Date	Chapter	Modification	Page
		ELECTRICAL CHAR.	502, max Charge Pump Capacitor 100 pF	6/22
		RECHARGING SYSTEM	Removed need of external capacitor at VB	11/22
		FLOAT. GATE DISCH. DESIGN REVIEW REVISION HISTORY	Chapter added for manual discharge through VCAP Version Z, Z1 separated. Error list updated. Info from previous datasheet versions included	16/22 20/22 21/22
A0.7	08/10/2019	RECHARGING SYSTEM ELECTRICAL CHAR. REGISTER DESCRIPTION	Formulas updated for clearer understanding 007; I(VCCD) in NSTBY TBD Table 27 updated	13/22 01/05/22 19/23
A0.8	29/10/2019	Disclaimer ELECTRICAL CHAR. Datasheet Datasheet ORDERING INFO	 005; I(VCC) in NSTBY=1 and NSTBY=0 Changed from “Confidential” to “Preliminary” Changed contact info Removed FGD-03F_Z1 TC	24/24 05/24 24/24
A0.9	01/04/20	EXTENDED BIT DESCRIPTION FLOATING GATE MANUAL DISCHARGE MEASUREMENT WINDOW SETTING REGISTER MAP OVERVIEW REGISTER DESCRIPTION QUICK SETUP AND OPERATIONAL EXAMPLE	Added Chapter Additional info to internal/external sensor discharge Figure 2. Removed mention to MNREV. Mention to EDIRT for noise rejection Bit 0x0E bit 2 = EDIRT EDIRT (Table 12) added 0x0E = 0b00000100 = 0x04h	23/27 17/27 10/27 21/27 19/27 08/27
A0.10	06/05/20	ELECTRICAL CHAR.	Noise figures updated based on experimental results.	6
		ELECTRICAL CHAR.	MDD figures removed.	
		ELECTRICAL CHAR.	SPI requirements for NCS and SCK added	5
		ELECTRICAL CHAR.	Frequency sensitivity updated	5
A0.11		TABLE	Table 1 updated	
		RECHARGING SYSTEM	Mention to **SET(2:0)** configuration and overshoot risk	11/29
		Notes on chip functions	Undesired sensor recharge due to high voltage at VB	25/29
		QUICK SET-UP	Recommended SET(2:0) value = 000	8/29

SOLDERING CONSIDERATIONS

The temperature applied to **FGD-03F** throughout the soldering process can lead to charges recombination on FGDOS® sensor. Consequently, **it is recommended to trigger a new charging process after soldering.**

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ORDERING INFORMATION

Product	Description
FGD-03F_Z1	FGD-03F_Z1 sensor, non-characterized, QFN32
FGD-03F_Z1 RTC	FGD-03F_Z1 sensor, radiation and temperature characterized, QFN32
FGD-03F EVAL RTC	Evaluation board with FGD-03F_Z1 sensor, radiation and temperature characterized

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