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BME688

Digital low power gas, pressure, temperature & humidity sensor with AI

BME688 – Datasheet

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BME688

Digital low power gas, pressure, temperature & humidity sensor with AI

The BME688 is the first gas sensor with Artificial Intelligence (AI) and integrated high-linearity and high-accuracy pressure, humidity and temperature sensors. It is housed in a robust yet compact 3.0 x 3.0 x 0.9 mm³ package and especially developed for mobile & connected applications where size and low power consumption are critical requirements. The gas sensor can detect Volatile Organic Compounds (VOCs), volatile sulfur compounds (VSCs) and other gases such as carbon monoxide and hydrogen in the part per billion (ppb) range.

Additionally to all features of the BME680, the BME688 has a gas scanner function. In standard configuration, the presence of VSCs is being detected as indicator for e.g. bacteria growth. And the gas scanner can be customized with respect to sensitivity, selectivity, data rate and power consumption as well. The BME AI-Studio tool enables customers to train the BME688 gas scanner on their specific application, like in home appliances, IoT products or Smart Home.

Typical applications

- Indoor air quality measurement
- Bad breath or spoiled food detection based on the measurement of volatile sulfur compounds, which are an indicator of bacteria growth
- Detection of unusual gases and smells, which might indicate for instance a leakage
- Diaper state detection, e.g. for baby care
- Early detection of odors & bad smells

Target Devices

- Handsets such as mobile phones, tablet PCs, GPS devices
- Wearables e.g. smart watches or connected sensors
- Mobile / care devices like toothbrushes or breath checkers
- Smart home devices, e.g. smart speakers, connected sensors or lamps
- Room climate sensors
- Home appliances
- Gaming, e.g. flying toys
- Connected devices, for instance for asset tracking or surveillance
- Sensor networks / sensor nodes

Videos, further documents & software is available online:

- BME688: https://www.bosch-sensortec.com/products/environmental-sensors/gas-sensors/bme688/
- Software: https://www.bosch-sensortec.com/software-tools/software/bme688-software/

Key features

- Package — 3.0 mm x 3.0 mm x 0.93 mm metal lid LGA
- Digital interface — I²C (up to 3.4 MHz) and SPI (3 and 4 wire, up to 10 MHz)
- Supply voltage — V_{DD} main supply voltage range: 1.71 V to 3.6 V; V_{DDIO} interface voltage range: 1.2 V to 3.6 V
- Current consumption — 2.1 µA at 1 Hz humidity and temperature; 3.1 µA at 1 Hz pressure and temperature; 3.7 µA at 1 Hz humidity, pressure and temperature; 90 µA at ULP mode for p/h/T & air quality; 0,9 mA at LP mode for p/h/T & air quality; 3,9 mA in standard gas scan mode; 0.09–12 mA for p/h/T/gas in customized operation modes; 0.15 µA in sleep mode
- Operating range — -40–+85 °C, 0–100% r.H., 300–1100 hPa
- The product is RoHS compliant, halogen-free, MSL1

Key parameters for gas sensor

- F1 score for H_2S scanning — 0.94
- Standard scan speed — 10.8 s / scan
- Electric charge for standard scan — 0.18 mAh (5 scans ~ 1 min)
- Power consumption — < 0.1 mA in ultra-low power mode
- Output data processing — Major direct outputs: Index for Air Quality (IAQ), bVOC- & CO_2-equivalents (ppm), Gas scan result (%) & Intensity level (all listed in Table 20: BSEC outputs)

Key parameters for humidity sensor

- Response time ($\tau_{0-63\%}$) — ~8 s
- Accuracy tolerance — ±3% r.H.
- Hysteresis — ±1.5% r.H.

Key parameters for pressure sensor

- RMS Noise — 0.12 Pa, equiv. to 1.7 cm
- Offset temperature coefficient — ±1.3 Pa/K, equiv. to ±10.9 cm at 1 °C temperature change

Key parameters for temperature sensor

- Absolute accuracy — ±0.5 °C (0 - 65°C)

Key hardware & software tools for the BME688

- BME688 Development Kit & App for mobile devices
- BME AI-Studio Desktop & Server software for use-case testing & development
- BSEC 2.x library for system µC w/ integration code examples
- Sensor API (driver) w/ code examples

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1. Specification

If not stated otherwise,

- all values are valid over the full voltage range,
- all minimum/maximum values are given for the full accuracy temperature range
- minimum/maximum values of drifts, offsets and temperature coefficients are ±3σ values over lifetime,
- typical values of currents and state machine timings are determined at 25 °C,
- minimum/maximum values of currents are determined using corner lots over complete temperature range, and
- minimum/maximum values of state-machine timings are determined using corner lots over 0–+65 °C temperature range.

Besides the general electrical specifications, the following tables are separated for the gas, pressure, humidity and temperature functions of the BME688.

1.1 General Electrical Specification

Table 1: Electrical parameter specification

OPERATING CONDITIONS BME688						
Parameter	**Symbol**	**Condition**	**Min**	**Typ**	**Max**	**Unit**
Supply Voltage Internal Domains[1]	V_{DD}	ripple max. 50 mVpp	1.71	1.8	3.6	V
Supply Voltage I/O Domain	V_{DDIO}		1.2	1.6	3.6	V
Sleep current	I_{DDSL}			0.15	1	µA
Standby current (inactive period of normal mode)	I_{DDSB}			0.29	0.8	µA
Current during humidity measurement	I_{DDH}	Max value at 85 °C		340	450	µA
Current during pressure measurement	I_{DDP}	Max value at -40 °C		714	849	µA
Current during temperature measurement	I_{DDT}	Max value at 85 °C		350		µA
Start-up time	$t_{startup}$	Time to first communication after both V_{DD} > 1.58 V and V_{DDIO} > 0.65 V			2	ms
Power supply rejection ratio (DC)	PSRR	full V_{DD} range			±0.01 ±5	%r.H./V Pa/V
Standby time accuracy	$\Delta t_{standby}$			±5	±25	%

[1] The power efficiency, performance and heat dissipation scales with the applied supply voltage. The BME688 is optimized for 1.8 V.

1.2 Gas sensor specification

The tables 2-5 list the gas sensor specification. All the parameters are deduced from lab measurements under controlled environmental conditions, which are chosen according to the ISO16000-29 standard “Test methods for VOC detectors”. The detailed procedure to measure the gas sensor is available in the application notes AN012 (“Measurement Instructions for Lab Environment”) or AN016 (“handbook”).

Referring to chapter 4, a software solution (BSEC: Bosch Software Environmental Cluster) is available for the BME688. The software is carefully engineered to seamlessly work with the 4 integrated sensors inside the BME688. Based on intelligent algorithms, the BSEC provides numerous useful outputs (see Table 20), e.g. an Index for Air Quality (IAQ), bVOC- & CO_2-equivalents (ppm) and Gas scan results (%). The IAQ output is an index that can have values between 0 and 500 with a resolution of 1 to indicate or quantify the quality of the air available in the surrounding. Table 3 lists the IAQ system specification. The detailed classification and colour coding of the IAQ index is described in Table 6. Furthermore, the BSEC solution supports different operation modes (see Table 19) for the gas sensor to address the necessary power budget and update rate requirements of the end-application.
Unless mentioned otherwise, the specifications are deduced from new sensors that have been operated for at least five days mainly in ambient air and consequently have the same history (i.e. same power mode and exposed to the same environment).

The sensors are tested especially with hydrogen sulfide (H_2S), ethanol (“EtOH”), carbon monoxide (CO) and breath-VOCs (“b-VOC”). The b-VOC mixture, as listed in Table 7, represents the most important compounds in an exhaled breath of healthy humans. The values are derived from several publications on breath analysis studies. The composition does not contain species which would chemically react to ensure that the mixture is stable for at least 6 months. Furthermore, the composition is also limited to species which can be manufactured in one mixture.

Table 2: Gas sensor parameter specification

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operational range[1]			-40		85	°C
			10		95	% r.H.
Supply Current during heater operation	I_{DD}	Heater target temperature 320 °C, constant operation (V_{DD} ≤ 1.8 V, 25°C)	9	12	13	mA
Peak Supply Current	I_{Peak}	occurs within first ms of switching on the hotplate	15	17	18	mA
Average Supply Current (V_{DD} ≤ 1.8 V, 25°C)	$I_{DD,IAQ}$	Ultra-low power mode		0.09		mA
		Low power mode		0.9		mA
		Continuous mode		12		mA
Response time[2] (brand-new sensors)	$\tau_{33-63\%}$	Ultra-low power mode		92		s
	$\tau_{33-63\%}$	Low power mode		1.4		s
	$\tau_{33-63\%}$	Continuous mode		0.75		s
Resolution of gas sensor resistance measurement			0.05	0.08	0.11	%
Noise in gas sensor resistance (RMS)	N_R			1.5		%

[1] The sensors are electrically operable within this range. Actual performance may vary.
[2] Response time of unsoldered, brand-new sensors extracted from the sensors’ resistance change in response to a 0.6–60 ppm step of EtOH and a 0.5–15 ppm step of b-VOC at 20 °C, 50% r.H. and atmospheric pressure.

Table 3: IAQ system parameter specification[3]

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Accuracy status[4]	AX_{IAQ}	Android compatible	0		3	
IAQ Resolution	IAQ_{rs}			1		
IAQ Range	IAQ_{rg}		0		500	
Sensor-to-sensor deviation[5]	IAQ_{S2S}	All operation modes		±15% ±15		
Durability to siloxanes[6,7,8]	IAQ_{S2S}	Sensor-to-sensor deviation		±15% ±15		
	IAQ_{drift}	Drift at low & high concentrations		±1% ±4		

[3] IAQ parameters only apply for the combination of BME688 together with the Bosch Software Environmental Cluster (BSEC) solution (available for download, see chapter 4)
[4] The accuracy status is equal to zero during the power-on stabilization times of the sensor and is equal to 3 when the sensor achieves best performance
[5] Tested with 0.6–90 ppm of EtOH at 5–40 °C, 20–80% r.H. and atmospheric pressure. Condition is valid after the calibration period of the BSEC algorithm.
[6] Siloxanes are present in a typical indoor environment and can in principle perturb the metal-oxide-based gas sensor performance.
[7] 220 hours of 700 mg/m³ of octamethylcyclotetrasiloxane (D4) in ambient conditions (i.e. 20 °C and 50% r.H.) simulates the amount of siloxanes in a typical indoor environment over more than 10 years.
[8] Tested with 0.5–15 ppm of b-VOC at 20 °C and 50% r.H. using continuous operation mode for 220 hours of 700 mg/m³ of octamethylcyclotetrasiloxane (D4).

Table 4: Standard gas scanner mode for H_2S selectivity[9]

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Average Supply Current (V_{DD} ≤ 1.8 V, 25°C)	$I_{DD,IAQ}$	Gas scanner standard mode consists of 5 scan cycles and 10 sleeping cycles		3.96		mA
Gas scanning power consumption in ampere hours	Ah_{scan}	Electric charge for one scanning phase (5 scan cycles in standard gas scanner mode)		0.18		mAh
Duty cycle of standard gas scanner mode	$t_{standard\ scan}$	Duration of gas scanning phase		54		s
	$f_{standard\ scan}$	ODR during scanning phase		1/10.8		1/s
	$t_{standard\ sleep}$	Duration of sleeping phase		108		s
	$f_{standard\ sleep}$	ODR during sleeping phase		0		1/s
Gas scan cycle	$t_{standard\ cycle}$	Duration of gas scan cycle		10.8		s
Selectivity to H_2S	P_{H2S}	Probability of H_2S and non H_2S class	0		1	
		Resolution of probability		0.01		
	S_{H2S}	Sensitivity (recall) of H_2S classification		0.95		
	$F1_{H2S}$	F1 score of H_2S classification		0.94		
	$D_{S/F1}$	Average long-term drift[10] of Sensitivity / F1 score		0.012		/year
IAQ	IAQ_{rg}		0		500	

[9] The classification performance for VSCs was developed based on comprehensive lab tests with H_2S concentrations between 100 and 500 ppb (i.e. 0.1 – 0.5 ppm) as representative for sulfur compounds and tested at 5–40 °C, 20–80% r.H. and atmospheric pressure. The selectivity was approved by testing against the presence of bVOCs up to 15 ppm, Ethanol up to 15 pm and Carbon monoxide up to 50 ppm. The specification is based on BSEC 2.2.0.0.

[10] Typical value for operation in normal room air temperature/humidity range derived from JEDEC standard JESD22-A108D. Software-compensated on sensor component level by considering the performance of aged sensors. Other environment conditions or contaminations (e.g. outgassing, adhesives or packaging materials) might lead to different values. Please see the Handling, Soldering and Mounting Instructions (HSMI) for details.

Table 5: Customization of gas scanner mode[11]

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Classification		Number of Classes	2		4	
Number of temperature steps				10		
Duration of gas scan cycle				10 to 30		sec

Table 6: Index for Air Quality (IAQ) classification and color-coding[12]

IAQ Index	Air Quality	Impact (long-term exposure)	Suggested action
0 – 50	Excellent	Pure air; best for well-being	No measures needed
51 – 100	Good	No irritation or impact on well-being	No measures needed
101 – 150	Lightly polluted	Reduction of well-being possible	Ventilation suggested
151 – 200	Moderately polluted	More significant irritation possible	Increase ventilation with clean air
201 – 250	Heavily polluted	Exposition might lead to effects like headache depending on type of VOCs	optimize ventilation
251 – 350	Severely polluted	More severe health issue possible if harmful VOC present	Contamination should be identified if level is reached even w/o presence of people; maximize ventilation & reduce attendance
> 351	Extremely polluted	Headaches, additional neurotoxic effects possible	Contamination needs to be identified; avoid presence in room and maximize ventilation

Table 7: bVOC mixture with Nitrogen as carrier gas

Molar fraction	Compound	Production tolerance	Certified accuracy
5 ppm	Ethane	20 %	5 %
10 ppm	Isoprene /2-methyl-1,3 Butadiene	20 %	5 %
10 ppm	Ethanol	20 %	5 %
50 ppm	Acetone	20 %	5 %
15 ppm	Carbon Monoxide	10 %	2 %

[11] For customization we recommend to use the BME AI-Studio software with comprehensive documentation (see Table 18: Software components).

[12] According to the guidelines issued by the German Federal Environmental Agency, exceeding 25 mg/m^3 of total VOC can lead to headaches and further neurotoxic impact on health. The BSEC software auto-calibrates the low and high concentrations applied during testing to IAQ of 50 and 200, respectively.

1.3 Humidity sensor specification

Table 8: Humidity parameter specification

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operating Range[13]			-40	25	85	°C
			0		100	% r.H.
Full accuracy range			0		65	°C
			10		90	% r.H.
Supply Current	$I_{DD,H}$	1 Hz forced mode, temperature and humidity measurement		2.1	2.8	µA
Absolute Accuracy	A_H	20 - 80 % r.H., 25 °C, including hysteresis		±3		% r.H.
Hysteresis[14]	H_H	10→90→10 % r.H., 25°C		±1.5		% r.H.
Nonlinearity[15]	NL_H	10→90 % r.H., 25°C		1.7		% r.H.
Response time to complete 63% of step[16]	$\tau_{0\text{-}63\%}$	N_2 (dry) → 90 % r.H., 25°C		8		s
Resolution	R_H			0.008		% r.H.
Noise in humidity (RMS)	N_H	Highest oversampling		0.01		% r.H.
Long-term stability	ΔH_{stab}	10 - 90 % r.H., 25°C		0.5		% r.H./ year

[13] When exceeding the operating range (e.g. for soldering), humidity sensing performance is temporarily degraded and reconditioning is recommended as described in Section 7.7. Operating range only for non-condensing environment.
[14] For hysteresis measurement the sequence 0→10→30→50→70→90→70→50→30→10 % r.H. is used. The hysteresis is defined as the maximum difference between measurements at of the same humidity up / down branch and the averaged curve of both branches.
[15] Non-linear contributions to the sensor data are corrected during the calculation of the relative humidity by the compensation formulas described in Section 3.5 and following.
[16] The air-flow in direction to the vent-hole of the device has to be dimensioned in a way that a sufficient air exchange inside to outside will be possible. To observe effects on the response time-scale of the device an air-flow velocity of approximately 1 m/s is needed.

1.4 Pressure sensor specification

Table 9: Pressure parameter specification

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operating temperature range	T_A	operational	-40	25	85	°C
		full accuracy	0		65	
Operating pressure range	P	full accuracy	300		1100	hPa
Supply current	$I_{DD,LP}$	1 Hz forced mode, pressure and temperature, lowest power		3.1	4.2	µA
Temperature coefficient of offset[17]	TCO_P	25 - 40 °C, 900 hPa		±1.3		Pa/K
				±10.9		cm/K
Absolute accuracy pressure	$A_{p,\ full}$	300 - 1100 hPa 0 - 65°C		±0.6		hPa
Relative accuracy pressure	A_{rel}	700 – 900 hPa, 25 - 40 °C, at constant humidity		±0.12		hPa
	A_{rel}	900 – 1100 hPa 25 - 40 °C, at constant humidity		±0.12		hPa
Resolution of pressure output data	R_P	Highest oversampling		0.18		Pa
Noise in pressure	$N_{P,fullBW}$	Full bandwidth, highest oversampling		1.4		Pa
				11		cm
		Reduced bandwidth, highest oversampling		0.2		Pa
				1.7		cm
Solder drift		Minimum solder height 50 µm	-0.5	1.2	+2.0	hPa
Long-term stability[18]	P_{stab}	per year		±1.0		hPa
Possible sampling rate	f_{sample_P}	Lowest oversampling, see chapter 3.6.2	157	182		Hz

[17] When changing temperature from 25 °C to 40 °C at constant pressure / altitude, the measured pressure / altitude will change by ($15 \times TCO_P$).
[18] Long-term stability is specified in the full accuracy operating pressure range 0–65 °C

1.5 Temperature sensor specification

Table 10: Temperature parameter specification

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Operating temperature range	T_A	operational	-40	25	85	°C
Supply current	$I_{DD,T}$	1 Hz forced mode, temperature measurement only		1.0		µA
Absolute accuracy temperature[19]	A_T	0 - 65 °C		±0.5		°C
Output resolution	R_T	API output resolution		0.01		°C
RMS noise	N_T	Lowest oversampling		0.005		°C

[19] Temperature measured by the internal temperature sensor. This temperature value depends on the PCB temperature, sensor element self-heating and ambient temperature and is typically above ambient temperature.

2. Absolute maximum ratings

The absolute maximum ratings are determined over the complete temperature range using corner lots. The values are provided in Table 11.

Table 11: Absolute maximum ratings

Parameter	Condition	Min	Max	Unit
Voltage at any supply pin	V_{DD} and V_{DDIO} pin	-0.3	4.25	V
Voltage at any interface pin		-0.3	V_{DDIO} + 0.3	V
Storage temperature	≤ 65% r.H.	-45	+85	°C
Pressure		0	20 000	hPa
ESD	HBM, at any pin		±2	kV
	Machine model		±200	V

3. Sensor usage

3.1 Use cases

The key features of the BME688 hardware-software system are:

- Selectivity to target gas classes
- Provision for custom usecase develpment
- Calculation of index for air quality (IAQ) level outside of the device
- Calculation of ambient air temperature outside of the device (e.g. phone)
- Calculation of ambient relative humidity outside of the device

3.2 Selectivity

Selectivity to target gas classes will enable wide variety of use cases for customers. From a gas sensing perspective selectivity is the ability to classify different gas compositions (with different combinations and concentrations of gases) that occur in different situations. Operating the metal oxide layer of the gas sensor at different temperatures enable measuring with different sensitivities and can create a unique fingerprint for numerous gas compositions. The standard heater profile is as shown below figure is executed in sensor ASIC which consists of 10 heater temperature steps. Features interpreted by AI based software brings selectivity feature.

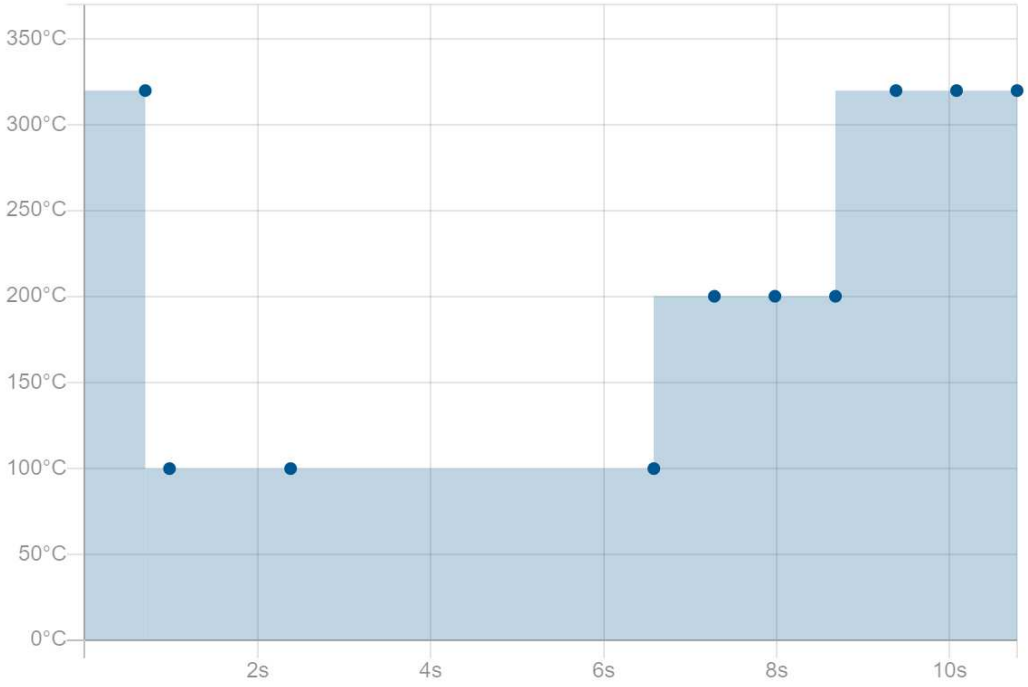


Figure 1: Standard Heater profile

3.3 Indoor-air-quality

The BME688 is a metal oxide-based sensor that detects gases by adsorption (and subsequent oxidation/reduction) on its sensitive layer. The intensity of the signal typically scales with the chemical reactivity of the gases. The BME688 reacts to most volatile compounds as well as many other gases polluting indoor air (exceptions are very few gases which are chemically pretty inert, e.g. N_2 and CO_2). In contrast to sensors selective for one specific component, the BME688 is capable of measuring the sum of VOCs/contaminants in the surrounding air. This enables the BME688 to detect e.g. outgasing from paint, furniture and/or garbage, high VOC levels due to cooking, food consumption, exhaled breath and/or sweating.

As a raw signal, the BME688 will output the gas sensor resistance values and its changes due to varying VOC concentrations (the higher the concentration of reducing VOCs, the lower the resistance and vice versa). Since this raw signal is influenced by parameters other than VOC concentration (e.g. humidity level), the raw values are transformed to an index for air quality (IAQ) by smart algorithms inside BSEC.

The IAQ scale ranges from 0 (clean air) to 500 (heavily polluted air). During operation, the algorithms automatically calibrate and adapt themselves to the typical environments where the sensor is operated (e.g., home, workplace, inside a car, etc.). This automatic background calibration ensures that users experience consistent IAQ performance. The calibration process considers the recent measurement history (typ. up to four days, configurable) to ensure that IAQ ~ 50 corresponds to “typical good” air and IAQ ~ 200 indicates “typical polluted” air.

3.4 Sensor modes

The sensor supports low-level power modes: sleep, parallel and forced mode. These modes can be selected using the *mode<1:0>* control register (see Section 5.3.1.3). The key differences between the modes are summarized in Table 12. Measurement cycle is abbreviated as TPHG (Temperature, Pressure, Humidity and Gas) in the following descriptions.

After a power-up sequence, the sensor automatically starts in sleep mode. If the device is currently performing a measurement, execution of mode switching commands is delayed until the end of the currently running measurement period**.** It is important to note that, further mode change commands or other write commands to the control registers are ignored until the mode change command has been executed. All control registers should be set to the desired values before writing to the mode register.

Table 12: Low-level operation modes

Operation mode	mode<1:0>	Key features
Sleep	00	▶ No measurements are performed ▶ Minimal power consumption
Forced mode	01	▶ Single TPHG cycle is performed ▶ Sensor automatically returns to sleep mode afterwards ▶ Gas sensor heater only operates during gas measurement
Parallel mode	10	▶ Multiple TPHG cycles are performed ▶ Sensor will not automatically returns to sleep mode ▶ Gas sensor heater operates in parallel to TPH measurement

In forced mode, temperature, pressure, humidity and gas conversion are performed sequentially for 1 heater temperature step and heating duration. In parallel mode, TPH measurements and gas conversion are performed parallelly. Hence in parallel mode at least one of T,P,H is expected to be enabled. Up to 10 temperature steps and heating durations for the gas sensor hot plate can be stored in the sensor registers and can be executed as heater profile. Heater profiles can be repeated without host support. In the Figure 1, heater steps and the corresponding measurements are identified as G_0 – G_9.

Figure 2 illustrates the handling of these measurement sequences and the gas sensor hot plate is heated for the forced mode and parallel mode.

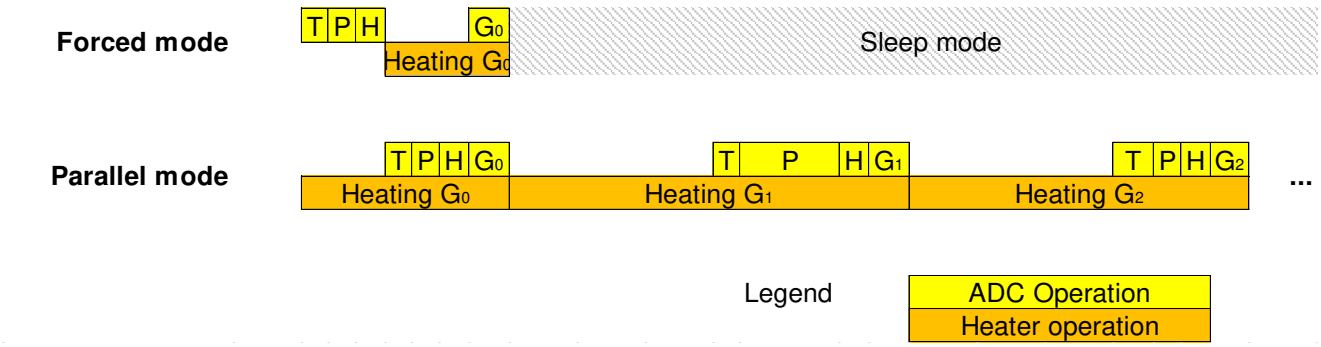


Figure 2: Sequence of ADC and gas sensor heater operation

3.5 Sensor configuration

3.5.1 Quick start – Forced mode

The sensor is configured by writing to a set of control registers (see Chapter 5 for a detailed list of all available registers and their descriptions). This section illustrates, with the help of a basic step-by-step example, how to configure the sensor for simple forced mode measurements with a single heater step. For a more detailed description of the measurement flow, please refer to Section 3.6.

In this example, the sensor will be configured to use 2x oversampling for its temperature measurements, 16x oversampling for the pressure signal, and 1x oversampling for humidity. Moreover, the gas sensor hot plate will be configured to be heated for 100 ms at 300 °C before the gas measurement is performed.

First, the user must configure the oversampling settings for temperature, pressure and humidity by setting the control registers *osrs_t<2:0>* and *osrs_h<2:0>*, respectively. Supported settings range from 16x oversampling down to 0x, which is equivalent to skipping the corresponding sub-measurement. See Section 5.3.3 for further details.

1. Set humidity oversampling to 1x by writing 0b001 to *osrs_h<2:0>*
2. Set temperature oversampling to 2x by writing 0b010 to *osrs_t<2:0>*
3. Set pressure oversampling to 16x by writing 0b101 to *osrs_p<2:0>*

It is highly recommended to set first *osrs_h<2:0>* followed by *osrs_t<2:0>* and *osrs_p<2:0>* in one write command (see Section 3.6).

Next, the user shall set at least one gas sensor hot plate temperature step and heating duration. Up to 10 heating duration can be configured through the control registers *gas_wait_x<7:0>,* where x ranges from 0 to 9. See Section 5.3.4 for definition of register content. The corresponding heater step are stored in the registers *res_heat_x<7:0>*. Section 3.6.5 explains how to convert the target heater temperature, e.g. 300 °C, into a register code. For forced mode operation, the used heater step is selected by setting the control register *nb_conv<3:0>* to the heater profile to be used, e.g. to use *gas_wait_0<7:0>* and *res_heat_0<7:0>*, *nb_conv<3:0>* shall be set to 0x0. Finally, gas functionality shall be enabled by setting the *run_gas_h* bit to 1.

4. Set *gas_wait_0<7:0>* to 0x59 to select 100 ms heat up duration
5. Set the corresponding heater step by writing the target heater resistance to res_heat_0<7:0>
6. Set *nb_conv<3:0>* to 0x0 to select the previously defined heater settings
7. Set *run_gas_h* to 1 to enable gas measurements

Now, a single forced mode measurement with the above settings can be triggered by writing 0b01 to *mode<1:0>*. For more details on data readout, please see Section 5.3.1.3.

8. Set *mode<1:0>* to 0b01 to trigger a single measurement.

Please find abstracted example code using BME68x-Sensor-API in https://github.com/BoschSensortec/BME68x-Sensor-API/blob/master/examples/forced_mode/forced_mode.c

3.5.2 Sensor configuration flow – Forced mode

Figure 3 illustrates which control registers must be set. For details on the individual control registers, please refer to Chapter 5. Moreover, details on the measurement flow for the individual modes can be found in Section 3.6.

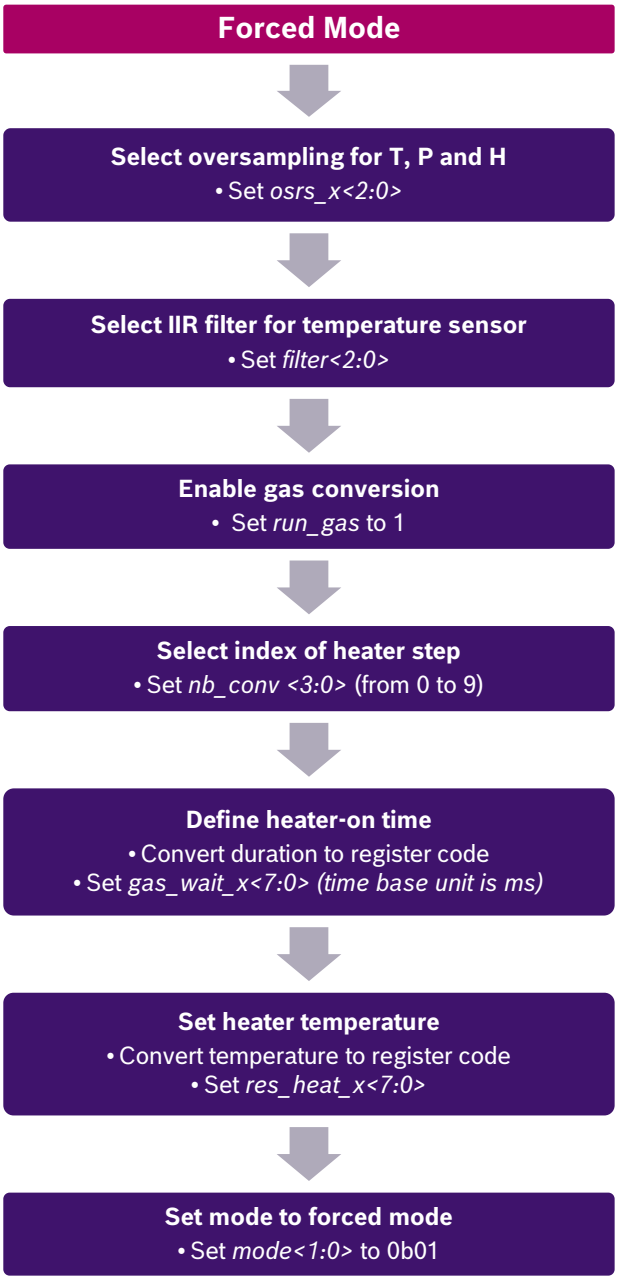


Figure 3: Sensor configuration flow in Forced Mode

3.5.3 Quick start – Parallel mode

Please find abstracted example code using BME68x-Sensor-API in https://github.com/BoschSensortec/BME68x-Sensor-API/tree/master/examples/parallel_mode

3.5.4 Sensor configuration flow – Parallel mode

Figure 3 illustrates which control registers must be set. For details on the individual control registers, please refer to Chapter 5. Moreover, details on the measurement flow for the individual modes can be found in Section 3.6.

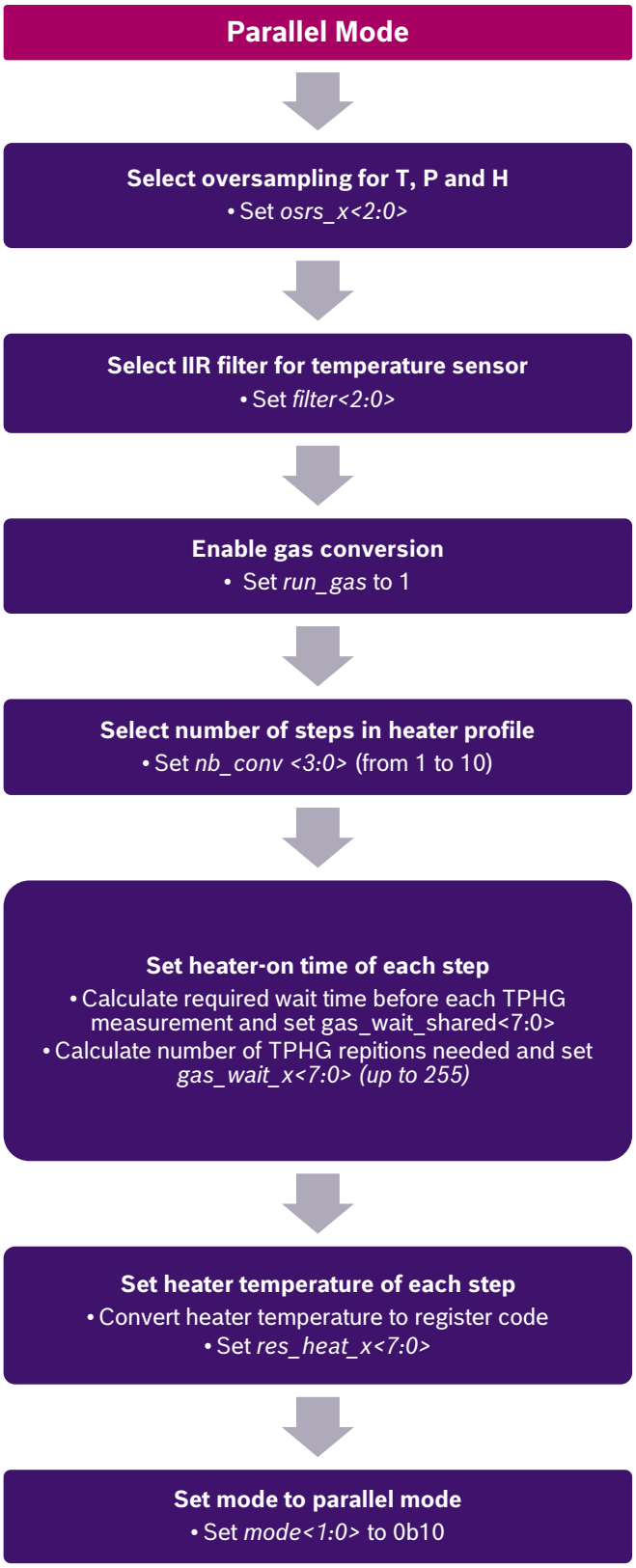


Figure 4: Sensor configuration flow in Parallel Mode

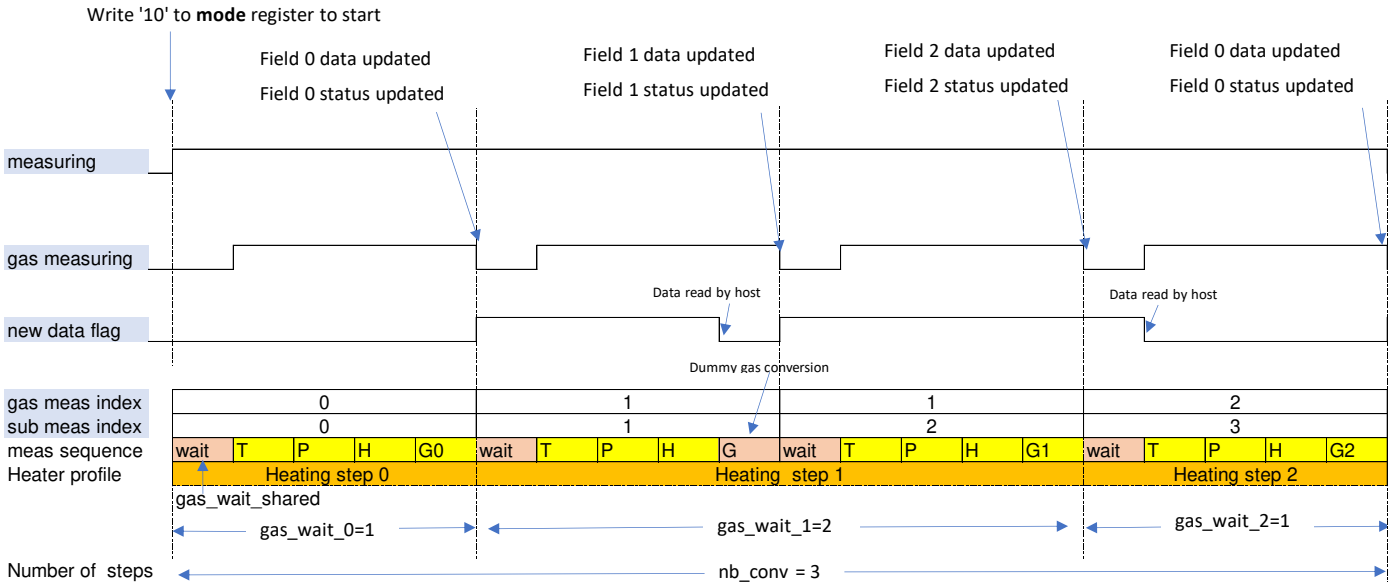


Figure 5: Illustration of parallel measurement mode, an example with 3 step heater profile

3.6 Measurement flow

Referring to Figure 2, the BME688 measurement period consists of a temperature, pressure and humidity measurement with selectable oversampling. Moreover, it contains a heating phase for the gas sensor hot plate as well as a measurement of the gas sensor resistance. In parallel mode there are 3 data registers naming Field 0, Field 1 and Field 2 which will be filled in first in first out order.

After the measurement period, the pressure and temperature data can be passed through an optional IIR filter, which removes short-term fluctuations. For humidity and gas, such a filter is not needed and has not been implemented.

3.6.1 Temperature measurement

Temperature measurement can be enabled or skipped. Skipping the measurement is typically not recommended since temperature information is used to compensate temperature influences in the other parameters. When enabled, several oversampling options exist. The temperature measurement is controlled by the *osrs_t<2:0>* setting which is detailed in Section 5.3.3.2. For the temperature measurement, oversampling is possible to reduce the noise. The resolution of the temperature data depends on the IIR filter (see Section 5.3.3.4) and the oversampling setting:

- When the IIR filter is enabled, the temperature resolution is 20 bit
- When the IIR filter is disabled, the temperature resolution is 16 + (*osrs_t* – 1) bit, e.g. 18 bit when *osrs_t* is set to '3'

Using the variables listed in Table 13, the following code will calculate the compensated temperature value (in degrees Celsius). It is, however, recommended to use the sensor API available on github (Chapter 0) for a friendlier user experience.

Floating point:

```
var1 = (((double)temp_adc / 16384.0) - ((double)par_t1 / 1024.0)) * (double)par_t2;
var2 = ((((double)temp_adc / 131072.0) - ((double)par_t1 / 8192.0)) *
         (((double)temp_adc / 131072.0) - ((double)par_t1 / 8192.0))) *
         ((double)par_t3 * 16.0);
t_fine = var1 + var2;
temp_comp = t_fine / 5120.0;
```

Integer:

```
var1 = ((int32_t)temp_adc >> 3) - ((int32_t)par_t1 << 1);
var2 = (var1 * (int32_t)par_t2) >> 11;
var3 = ((((var1 >> 1) * (var1 >> 1)) >> 12) * ((int32_t)par_t3 << 4)) >> 14;
t_fine = var2 + var3;
temp_comp = ((t_fine * 5) + 128) >> 8;
```

where

- *par_t1*, *par_t2* and *par_t3* are calibration parameters,
- *temp_adc* is the raw temperature output data, *see 5.3.5.2*
- *temp_comp* is the compensated temperature output data in degrees Celsius.

Table 13: Variable names and register addresses for *temp_comp* calculation

Variable name	Register address (LSB / MSB)
par_t1	0xE9 / 0xEA
par_t2	0x8A / 0x8B
par_t3	0x8C
temp_adc	Field 0 - 0x24<7:4> / 0x23 / 0x22 Field 1 - 0x35<7:4> / 0x34 / 0x33 Field 2 - 0x46<7:4> / 0x45 / 0x44

3.6.2 Pressure measurement

Pressure measurement can be enabled or skipped. When enabled, several oversampling options exist. The pressure measurement is controlled by the osrs_p<2:0> setting which is detailed in Section 5.3.3. For the pressure measurement, oversampling is possible to reduce noise. The resolution of the pressure data depends on the IIR filter (see Section 5.3.3.4) and the oversampling setting:

- When the IIR filter is enabled, the pressure resolution is 20 bit
- When the IIR filter is disabled, the pressure resolution is 16 + (*osrs_p* – 1) bit, e.g. 18 bit when *osrs_p* is set to '3'

Using the variables listed in Table 14 the following code will calculate the compensated pressure value (in Pascal). It is, however, recommended to use the sensor API available on github for a friendlier user experience.

Floating point:

```
var1 = ((double)t_fine / 2.0) - 64000.0;
var2 = var1 * var1 * ((double)par_p6 / 131072.0);
var2 = var2 + (var1 * (double)par_p5 * 2.0);
var2 = (var2 / 4.0) + ((double)par_p4 * 65536.0);
var1 = ((((double)par_p3 * var1_p * var1) / 16384.0) +
         ((double)par_p2 * var1_p)) / 524288.0;
var1 = (1.0 + (var1 / 32768.0)) * (double)par_p1;
press_comp = 1048576.0 - (double)press_adc;
press_comp = ((press_comp - (var2_p / 4096.0)) * 6250.0) / var1;
var1 = ((double)par_p9 * press_comp * press_comp) / 2147483648.0;
var2 = press_comp * ((double)par_p8 / 32768.0);
var3 = (press_comp / 256.0) * (press_comp / 256.0) *
         (press_comp / 256.0) * (par_p10 / 131072.0);
press_comp = press_comp + (var1_p + var2_p + var3_p +
              ((double)par_p7 * 128.0)) / 16.0;
```

Integer:

```
var1 = ((int32_t)t_fine >> 1) - 64000;
var2 = ((((var1 >> 2) * (var1 >> 2)) >> 11) * (int32_t)par_p6) >> 2;
var2 = var2 + ((var1 * (int32_t)par_p5) << 1);
var2 = (var2 >> 2) + ((int32_t)par_p4 << 16);
var1 = (((((var1 >> 2) * (var1 >> 2)) >> 13) *
            ((int32_t)par_p3 << 5)) >> 3) + (((int32_t)par_p2 * var1) >> 1);

var1 = var1 >> 18;
var1 = ((32768 + var1) * (int32_t)par_p1) >> 15;
press_comp = 1048576 - press_raw;
press_comp = (uint32_t)((press_comp - (var2 >> 12)) * ((uint32_t)3125));
if (press_comp >= (1 << 30))
    press_comp = ((press_comp / (uint32_t)var1) << 1);
else
    press_comp = ((press_comp << 1) / (uint32_t)var1);
var1 = ((int32_t)par_p9 * (int32_t)(((press_comp >> 3) *
            (press_comp >> 3)) >> 13)) >> 12;
var2 = ((int32_t)(press_comp >> 2) * (int32_t)par_p8) >> 13;
var3 = ((int32_t)(press_comp >> 8) * (int32_t)(press_comp >> 8) *
            (int32_t)(press_comp >> 8) * (int32_t)par_p10) >> 17;
press_comp = (int32_t)(press_comp) +
            ((var1 + var2 + var3 + ((int32_t)par_p7 << 7)) >> 4);
```

where

- *par_p1*, *par_p2*, ..., *par_p10* are calibration parameters,
- *press_adc* is the raw pressure output data, *see 5.3.5.1*
- *press_comp* is the compensated pressure output data in Pascal.

Table 14: Variable names and register addresses for *press_comp* calculation

Variable name	Register address (LSB / MSB)
par_p1	0x8E / 0x8F
par_p2	0x90 / 0x91
par_p3	0x92
par_p4	0x94 / 0x95
par_p5	0x96 / 0x97
par_p6	0x99
par_p7	0x98
par_p8	0x9C / 0x9D
par_p9	0x9E / 0x9F
par_p10	0xA0
press_adc	Field 0 - 0x21<7:4> / 0x20 / 0x1F Field 1 - 0x32<7:4> / 0x31 / 0x30 Field 2 - 0x43<7:4> / 0x42 / 0x41

3.6.3 Humidity measurement

The humidity measurement can be enabled or skipped. When enabled, several oversampling options exist. The humidity measurement is controlled by the *osrs_h<2:0>* setting, which is described in detail in Section 5.3.3.1. For the humidity measurement, oversampling is possible to reduce noise. The resolution of the humidity measurement is fixed at 16 bit ADC output.

Using the variables listed in Table 15, the following code will calculate the compensated humidity value (in percent). It is, however, recommended to use the sensor API available on github for a friendlier user experience.

Floating point:

```
var1 = hum_adc - (((double)par_h1 * 16.0) + (((double)par_h3 / 2.0) * temp_comp));
var2 = var1 * (((double)par_h2 / 262144.0) * (1.0 + (((double)par_h4 / 16384.0) *
            temp_comp) + (((double)par_h5 / 1048576.0) * temp_comp * temp_comp)));
var3 = (double)par_h6 / 16384.0;
var4 = (double)par_h7 / 2097152.0;
hum_comp = var2 + ((var3 + (var4 * temp_comp)) * var2 * var2);
```

Integer:

```
temp_scaled = (int32_t)temp_comp;
var1 = (int32_t)hum_adc - (int32_t)((int32_t)par_h1 << 4) –
        (((temp_scaled * (int32_t)par_h3) / ((int32_t)100)) >> 1);
var2 = ((int32_t)par_h2 * (((temp_scaled *
        (int32_t)par_h4) / ((int32_t)100)) +
        (((temp_scaled * ((temp_scaled * (int32_t)par_h5) /
        ((int32_t)100))) >> 6) / ((int32_t)100)) + ((int32_t)(1 << 14)))) >> 10;
```

```
var3 = var1 * var2;
var4 = (((int32_t)par_h6 << 7) +
        ((temp_scaled * (int32_t)par_h7) / ((int32_t)100))) >> 4;
var5 = ((var3 >> 14) * (var3 >> 14)) >> 10;
var6 = (var4 * var5) >> 1;
hum_comp = (var3 + var6) >> 12;
hum_comp = (((var3 + var6) >> 10) * ((int32_t) 1000)) >> 12;
```

where

- *par_h1*, *par_h2*, ..., *par_h7* are calibration parameters,
- *hum_adc* is the raw humidity output data, *see 5.3.5.3*
- *hum_comp* is the compensated humidity output data in percent.

Table 15: Variable names and register addresses for *hum_comp* calculation

Variable name	Register address (LSB / MSB)
par_h1	0xE2<3:0> / 0xE3
par_h2	0xE2<7:4> / 0xE1
par_h3	0xE4
par_h4	0xE5
par_h5	0xE6
par_h6	0xE7
par_h7	0xE8
hum_adc	Field 0 - 0x26 / 0x25 Field 1 - 0x37 / 0x36 Field 2 - 0x48 / 0x47

3.6.4 IIR filter

The environmental pressure is subject to many short-term changes, caused external disturbances. To suppress disturbances (e.g. slamming of door or wind blowing into the sensor) in the output data without causing additional interface traffic and processor work load, the BME688 features an internal IIR filter (see Section 5.3.3.4). It effectively reduces the bandwidth of the temperature and pressure output signals and increases the resolution of the output data to 20 bit, noting that the humidity and gas values inside the sensor does not fluctuate rapidly and does not require low pass filtering. The output of a next measurement step is filtered using the following formula:

$$x_{filt}[n] = \frac{x_{filt}[n-1] \cdot (c-1) + x_{ADC}}{c}$$

$x_{filt}[n-1]$ is the data coming from the current filter memory, and x_{ADC} is the data coming from current ADC acquisition. $x_{filt}[n]$ denotes the new value of filter memory and the value that will be sent to the output registers.

The IIR filter can be configured to different filter coefficients, which slows down the response to the sensor inputs. Note that the response time with enabled IIR filter depends on the number of samples generated, which means that the data output rate must be known to calculate the actual response time.

When writing to the register *filter*, the filter is reset. The next ADC values will pass through the filter unchanged and become the initial memory values for the filter. If temperature or pressure measurements are skipped, the corresponding filter memory will be kept unchanged even though the output registers are set to 0x80000. When the previously skipped measurement is re-enabled, the output will be filtered using the filter memory from the last time when the measurement was not skipped. If this is not desired, please write to the filter register in order to re-initialize the filter.

3.6.5 Gas sensor heating and measurement

The operation of the gas sensing part of BME688 involves two steps:

1. Heating the gas sensor hot plate to a target temperature (typically between 200 °C and 400 °C) and keep that temperature for a certain duration of time.
2. Measuring the resistance of the gas sensitive layer.

Up to 10 different hot plate temperature set points can be configured by setting the registers *res_heat_x<7:0>*, where x = 0...9 .The internal heater control loop operates on the resistance of the heater structure. Hence, the user first needs to convert the target temperature into a device specific target resistance before writing the resulting register code into the sensor memory map.
Using the variables listed in Table 16, the following code will calculate register code that to be written to *res_heat_x<7:0>*. It is, however, recommended to use the sensor API available on github (Chapter 0) for a friendlier user experience.

Floating point:

```
var1 = ((double)par_g1 / 16.0) + 49.0;
var2 = (((double)par_g2 / 32768.0) * 0.0005) + 0.00235;
var3 = (double)par_g3 / 1024.0;
var4 = var1 * (1.0 + (var2 * (double) target_temp));
var5 = var4 + (var3 * (double)amb_temp);
res_heat_x = (uint8_t)(3.4 * ((var5 * (4.0 / (4.0 + (double)res_heat_range)) * (1.0/(1.0 +
((double)res_heat_val * 0.002)))) - 25));
```

Integer:

```
var1 = (((int32_t)amb_temp * par_g3) / 10) << 8;
var2 = (par_g1 + 784) * (((((par_g2 + 154009) * target_temp * 5) / 100) + 3276800) / 10);
var3 = var1 + (var2 >> 1);
var4 = (var3 / (res_heat_range + 4));
var5 = (131 * res_heat_val) + 65536;
res_heat_x100 = (int32_t)(((var4 / var5) - 250) * 34);
res_heat_x = (uint8_t)((res_heat_x100 + 50) / 100);
```

where

- *par_g1*, *par_g2*, and *par_g3* are calibration parameters,
- *target_temp* is the target heater temperature in degree Celsius,
- *amb_temp* is the ambient temperature (hardcoded or read from temperature sensor),
- *var5* is the target heater resistance in Ohm,
- *res_heat_x* is the decimal value that needs to be stored in register, where '*x*' corresponds to the temperature profile number between 0 and 9,
- *res_heat_range* is the heater range stored in register address 0x02 <5:4>, and
- res_heat_val is the heater resistance correction factor stored in register address 0x00 (signed, value from -128 to 127).

Table 16: Variable names and register addresses for *res_heat_x* calculation

Variable name	Register address (LSB / MSB)
par_g1	0xED
par_g2	0xEB/0xEC
par_g3	0xEE
res_heat_range	0x02 <5:4>
res_heat_val	0x00

For each of the 10 temperature steps, the heating duration must be specified. Referring to Figure 2, the heating phase starts after the temperature, pressure and humidity measurements are complete. This means there is no heating in parallel to these measurements, which is desirable to minimize undesired cross-influences between the various sensor components.

The heating duration is specified by writing to the corresponding *gas_wait_x<7:0>* control register. Heating durations between 1 ms and 4032 ms can be configured. In practice, approximately 20–30 ms are necessary for the heater to reach the intended target temperature.

3.7 Data readout

The procedure goes as follows, the *new_data* bit (see Section 5.3.6.1) can be checked to see if a new data is generated. If gas measurements are performed the *gas_valid_r* (see Section 5.3.6.5) and *heat_stab_r* (see Section 5.3.6.6) status bits of the respectively field should be checked to ensure that the gas measurement was successful. If *heat_stab_r* is zero, it indicates that either the heating time was not enough to allow the sensor to reach to configured target temperature or that the target temperature was too high for the sensor to reach.

After the uncompensated values of temperature, pressure and humidity have been read, the actual humidity, pressure and temperature need to be calculated using the compensation parameters stored in the device. Please refer to the BME68x-Sensor-API for more details.

3.7.1 Gas resistance readout

Readout of gas resistance ADC value and calculation of gas resistance consists of 2 steps

1. Read gas ADC value (*gas_adc*) and gas ADC range (*gas_range*) (see Section 5.3.5)
2. Convert ADC value into gas resistance in ohm

Using the variables listed in Table 17, the conversion is done as follows:

Floating point:

```
uint32_t var1 = UINT32_C(262144) >> gas_range;
int32_t var2 = (int32_t) gas_adc - INT32_C(512);
var2 *= INT32_C(3);
var2 = INT32_C(4096) + var2;
gas_res = 1000000.0f * (float)var1 / (float)var2;
```

Integer:

```
uint32_t var1 = UINT32_C(262144) >> gas_range;
int32_t var2 = (int32_t) gas_adc - INT32_C(512);
var2 *= INT32_C(3);
var2 = INT32_C(4096) + var2;
/* multiplying 10000 then dividing then multiplying by 100 instead of multiplying by 1000000 to prevent
overflow */
```

```
calc_gas_res = (UINT32_C(10000) * var1) / (uint32_t)var2;
gas_res = calc_gas_res * 100;
```

where

- *gas_adc* is the raw gas resistance output data (i.e. ADC value), see 0
- *gas_range* is the ADC range of the measured gas resistance, see 5.3.5.5
- *gas_res i*s the compensated gas resistance output data in Ohms.

Table 17: Variable names and register addresses for *gas_res* calculation

Variable name	Register address (LSB / MSB)
gas_adc	Field 0 - 0x2D<7:6> / 0x2C Field 1 - 0x3E<7:6> / 0x3D Field 2 - 0x4F<7:6> / 0x4E
gas_range	Field 0 - 0x2D<3:0> Field 1 - 0x3E<3:0> Field 2 - 0x4F<3:0>

4. Software

4.1 BME software components

Table 18: Software components

Software component	Type	Function	Link
BME68x sensor API	C code	Provide software interfaces to get compensated raw data from sensor via SPI/I2C interface	BME68x-Sensor-API
BSEC	C static library	Provides fused sensor outputs and AI interpreter for classifcation of gas classes	BME688-Software
BME AI Studio	PC application	AI toolchain to develop, verify and deploy custom gas classification use cases	

4.2 BME software library - BSEC software

BME688 sensor is intended to be used together with Bosch Software Environmental Cluster (BSEC) solution and BME6xy sensor API to unlock its full potential. The BSEC software features intelligent algorithms which enable use cases such as indoor-air-quality monitoring using the BME688. Moreover, the software algorithms handle humidity compensation, baseline as well as long-term drift correction of the gas sensor signal.

Bosch Sensortec BSEC software is available as a closed source binary which will be made available via a Software License Agreement (SLA) on the Bosch Sensortec website.

Different power modes for the gas sensor and corresponding data rates are supported by the software solution:

- **Gas Scan mode (scan)** is designed for interactive applications where selectivity of traget gases are needed in addition in indoor airquality monitoring. The standard heater profile has an update rate of 10.8 s and can be finetuned for use-cases using BME AI Studio.
- **Ultra low power (ULP)** mode is designed for battery-powered and/or frequency-coupled devices over extended periods of time. This mode features an update rate of 300 seconds and an average current consumption of <0.1 mA
- **Quick Ultra-low power (q-ULP)** has a 3 s data rate for Temprature, pressure and humidity w/o significantly increasing the power consumption compared to ULP.
- **Low power (LP)** mode that is designed for interactive applications where the air quality is tracked and observed at a higher update rate of 3 seconds with a current consumption of <1 mA
- **Continuous (CONT)** mode provides an update rate of 1 Hz and shall only be used short-term for use cases that incorporate very fast events or stimulus.

Table 19: BSEC gas sensor power-modes

BSEC power mode	Update rate	Average current consumption
Standard gas scan mode (scan)	1/10.8 s	3.96 mA
Ultra-low power mode (ULP)	3.3 mHz	0.09 mA
quick Ultra-low power mode (q-ULP)	0.33 Hz (T, p, h) / 3.3 mHz (IAQ)	0.1 mA
Low power mode (LP)	0.33 Hz	0.9 mA
Continuous mode (for testing purposes only)	1 Hz	12 mA

The following table describes the available outputs of BSEC. Full descriptions of the outputs and the available interfaces are available in the integration guide shipped together with the BSEC software.

Table 20: BSEC outputs

Output	Description
Raw pressure	Raw data from sensor API bypassed to BSEC output
Raw temperature	Raw data from sensor API bypassed to BSEC output
Raw relative humidity	Raw data from sensor API bypassed to BSEC output
Raw gas resistance	Raw data from sensor API bypassed to BSEC output
Sensor-compensated temperature (°C)	Temperature which is compensated for internal cross-influences caused by the BME sensor
Sensor-compensated relative humidity (%)	Relative humidity which is compensated for internal cross-influences caused by the BME sensor
Sensor-compensated gas resistance (Ohm)	Raw gas resistance compensated by temperature and humidity influences.
Ambient temperature (°C)	Ambient temperature after compensating the influence of device (where BME688 is integrated in) heatsources
Ambient relative humidity (%)	Ambient relative humidity after compensating influence of device (where BME688 is integrated in) heatsources
IAQ (0-500)	Index for Air Quality, especially recommended for mobile devices, since the auto-trim algorithm automatically adopts to different environments.
Static IAQ (“s-IAQ”)	“Static” Index for Air Quality, especially recommended for stationary devices (w/ o auto-trimming algorithm)
CO_2 equivalents (ppm)	Estimation of the CO_2 level in ppm. The sensor does not directly measure CO_2, but derives this from the average correlation between VOCs and CO_2 in human’s exhaled breath.
b-VOC equivalents (ppm)	Conversion into breath-VOC equivalents in ppm concentration. The scaling is derived from lab tests with the b-VOC gas mixture described in Table 7.
Accuracy status (0-3)	Accuracy status of IAQ
Stabilization time status	Indicates if the sensor is undergoing initial stabilization during its first use after production
Run in status	Indicates when the sensor is ready after after switch-on
Gas (%)	Alternative indicator for air pollution which rates the current raw gas resistance value based on the individual sensor history: 0% = “lowest air pollution ever measured” 100% = “highest air pollution level ever measured”
Gas scan result (%)	The gas scan result is given in % for each of the used classes. In standard scan mode, the probability of H_2S and non H_2S class is provided by the variables GAS_ESTIMATE_1 & GAS_ESTIMATE_2 respectively. A maximum of 4 classes can be used by configuring using BME AI-Studio.

5. Global memory map and register description

5.1 General remarks

Communication with the device is performed by reading from and writing to registers. Registers have a width of 8 bits. If I^2C is used, 8-bit addressing is utilized. If SPI is used, 7-bit address is only available for register access. For details on the interface, consult Chapter 0.

In SPI mode complete memory map is accessed using page 0 and page 1. Register *spi_mem_page* is used for page selection. After power-on, *spi_mem_page* is in its reset state and page 0 (0x80 to 0xFF) will be active. Page 1 (0x00 to 0x7F) will be active on setting *spi_mem_page* to 1.

Global memory map consists of calibration registers, control registers, data registers, status registers and reserved registers. There are, however, several registers which are reserved. Accordingly, they should not be written to and no specific value is guaranteed when they are read.

Table 21: Memory map page selection

Digital Interface	Register address range	Register *spi_mem_page*	Memory Page
I^2C	0x00 to 0xFF	Not Applicable	Not Applicable
SPI	0x80 to 0xFF	0 (default; power on state)	Page 0
SPI	0x00 to 0x7F	1	Page 1

5.2 Memory map

The memory map is given in Table 22, noting that not all reserved registers are depicted.

Table 22: Memory map

Register name	I²C	SPI		Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit2	Bit 1	Bit 0	Reset state
	Adr	Adr	Pg									
Status	73h	73h	1				spi_mem_page					01h
Variant_Id	F0h	70h	0	variant_id<7:0>								01h
Reset	E0h	60h	0	reset<7:0>								00h
Chip_Id	D0h	50h	0	chip_id<7:0>								61h
Config	75h	75h	1				filter<2:0>				spi_3w_en	00h
Ctrl_meas	74h	74h	1	osrs_t<2:0>			osrs_p<2:0>			mode<1:0>		00h
Ctrl_hum	72h	72h	1		spi_3w_int_en				osrs_h<2:0>			00h
Ctrl_gas_1	71h	71h	1			run_gas		nb_conv<3:0>				00h
Ctrl_gas_0	70h	70h	1					heat_off				00h
Gas_wait_shared	6Eh	6Eh	1	gas_wait_shared<7:0>								00h
Gas_wait_x	6Dh...64h	6Dh...64h	1	gas_wait_9<7:0> downto gas_wait_0<7:0>								00h
Res_heat_x	63h...5Ah	63h...5Ah	1	res_heat_9<7:0> downto res_heat_0<7:0>								00h
Idac_heat_x	59h...50h	59h...50h	1	idac_heat_9<7:0> downto idac_heat_0<7:0>								00h
gas_r_lsb [2]	4Fh	4Fh	1	gas_r<1:0>		gas_valid_r	heat_stab_r	gas_range_r				00h
gas_r_msb [2]	4Eh	4Eh	1	gas_r<9:2>								00h
hum_lsb [2]	48h	48h	1	hum_lsb<7:0>								00h
hum_msb [2]	47h	47h	1	hum_msb<7:0>								80h
temp_xlsb [2]	46h	46h	1	temp_xlsb<7:4>				0	0	0	0	00h
temp_lsb [2]	45h	45h	1	temp_lsb<7:0>								00h
temp_msb [2]	44h	44h	1	temp_msb<7:0>								80h
press_xlsb [2]	43h	43h	1	press_xlsb<7:4>				0	0	0	0	00h
press_lsb [2]	42h	42h	1	press_lsb<7:0>								00h
press_msb [2]	41h	41h	1	press_msb<7:0>								80h
sub_meas_index [2]	40h	40h	1	sub_meas_index_2<7:0>								00h
meas_status [2]	3Fh	3Fh	1	new_data	gas_measuring	measuring		gas_meas_index_2<3:0>				00h
gas_r_lsb [1]	3Eh	3Eh	1	gas_r<1:0>		gas_valid_r	heat_stab_r	gas_range_r				00h
gas_r_msb [1]	3Dh	3Dh	1	gas_r<9:2>								00h

hum_lsb [1]	37h	37h	1	hum_lsb<7:0>												00h
hum_msb [1]	36h	36h	1	hum_msb<7:0>												80h
temp_xlsb [1]	35h	35h	1	temp_xlsb<7:4>				0	0	0	0					00h
temp_lsb [1]	34h	34h	1	temp_lsb<7:0>												00h
temp_msb [1]	33h	33h	1	temp_msb<7:0>												80h
press_xlsb [1]	32h	32h	1	press_xlsb<7:4>				0	0	0	0					00h
press_lsb [1]	31h	31h	1	press_lsb<7:0>												00h
press_msb [1]	30h	30h	1	press_msb<7:0>												80h
sub_meas_index [1]	2Fh	2Fh	1	sub_meas_index_1<7:0>												00h
meas_status [1]	2Eh	2Eh	1	new_data	gas_measuring	measuring		gas_meas_index_1<3:0>								00h
gas_r_lsb [2]	2Dh	2Dh	1	gas_r<1:0>		gas_valid_r	heat_stab_r	gas_range_r								00h
gas_r_msb [0]	2Ch	2Ch	1	gas_r<9:2>												00h
hum_lsb [0]	26h	26h	1	hum_lsb<7:0>												00h
hum_msb [0]	25h	25h	1	hum_msb<7:0>												80h
temp_xlsb [0]	24h	24h	1	temp_xlsb<7:4>				0	0	0	0					00h
temp_lsb [0]	23h	23h	1	temp_lsb<7:0>												00h
temp_msb [0]	22h	22h	1	temp_msb<7:0>												80h
press_xlsb [0]	21h	21h	1	press_xlsb<7:4>				0	0	0	0					00h
press_lsb [0]	20h	20h	1	press_lsb<7:0>												00h
press_msb [0]	1Fh	1Fh	1	press_msb<7:0>												80h
sub_meas_index [0]	1Eh	1Eh	1	sub_meas_index_0<7:0>												00h
meas_status [0]	1Dh	1Dh	1	new_data	gas_measuring	measuring		gas_meas_index_0<3:0>								00h

Registers	Color/Type
Reserved	Do not change
Status register	Read only
Data register	Read only
Control register	Read/write

5.3 Register description

5.3.1 General control registers

5.3.1.1 *SPI 3 wire interrupt enable – spi_3w_int_en*

Register Name	Address	Content<bit position>	Description
ctrl_hum	0x72	spi_3w_int_en <6>	New data interrupt can be enabled if the device is in SPI 3 wire mode and *pi_3w_int_en=1*. The new data interrupt is then indicated on the SDO pad.

5.3.1.2 *SPI 3 wire enable – spi_3w_en*

Register Name	Address	Content<bit position>	Description
config	0x75	*spi_3w_en<0>*	Enable SPI 3 wire mode

5.3.1.3 *Mode Selection – mode*

The operation modes of the sensor can be controlled by the register mode as specified below.

Register Name	Address	Content<bit position>	Description
ctrl_meas	0x74	*mode<1:0>*	Select sensor power mode as shown in the following table

mode<1:0>	Mode
00	Sleep mode
01	Forced mode
10	Parallel mode

5.3.1.4 *SPI memory map page selection – spi_mem_page*

In SPI mode complete memory page is accessed using page 0 & page 1. Register *spi_mem_page* is used for page selection. After power-on, *spi_mem_page* is in its reset state and page 0(0x00 to 0x7F) will be active. Page1 (0x7F to 0xFF) will be active on setting *spi_mem_page*. Please refer Table 21 for better understanding.

Register Name	Address	Content<bit position>	Description
status	0x73(Page 0/1)	*spi_mem_page <4>*	Selects memory map page in SPI mode

5.3.1.5 *Reset – reset*

Writing 0xB6 to this register initiates a soft-reset procedure, which has the same effect like power-on reset. The default value stored in this register is 0x00.

Register Name	Address	Content<bit position>	Description
reset	0x60 (Page 0 in SPI mode) 0xE0 in I^2C	*reset<7:0>*	Resets the device

5.3.2 Sensor identification registers

5.3.2.1 *Variant Id – Variant_Id*

Register Name	Address	Content<bit position>	Description
Variant_Id	0x70(Page 0 in SPI mode) 0xF0 in I^2C	*variant_id<7:0>*	Variant Id of the sensor For BME688 - 0x01h

5.3.2.2 *Chip id – chip_id*

Register Name	Address	Content<bit position>	Description
Chip_Id	0x50(Page 0 in SPI mode) 0xD0 in I^2C	*chip_id<7:0>*	Chip id of the device

5.3.3 Temperature, pressure and relative humidity control registers

5.3.3.1 *Humidity sensor over sampling control – osrs_h*

Register Name	Address	Content<bit position>	Description
ctrl_hum	0x72	*osrs_h<2:0>*	Controls over sampling setting of humidity sensor as described in the following table

osrs_h<2:0>	Humidity oversampling
000	Skipped (output set to 0x8000)
001	oversampling ×1
010	oversampling ×2
011	oversampling ×4
100	oversampling ×8
101, Others	oversampling ×16

5.3.3.2 *Over sampling setting – Temperature data – osrs_t*

Register Name	Address	Content<bit position>	Description
ctrl_meas	0x74	*osrs_t<7:5>*	Temperature oversampling settings as shown in the following table

osrs_t<2:0>	Temperature oversampling
000	Skipped (output set to 0x8000)
001	oversampling ×1
010	oversampling ×2
011	oversampling ×4
100	oversampling ×8
101, Others	oversampling ×16

5.3.3.3 *Over sampling setting – Pressure data – osrs_p*

Register Name	Address	Content<bit position>	Description
ctrl_meas	0x74	osrs_p<4:2>	Pressure oversampling settings as shown in the following table

osrs_p<2:0>	Pressure oversampling
000	Skipped (output set to 0x8000)
001	oversampling ×1
010	oversampling ×2
011	oversampling ×4
100	oversampling ×8
101, Others	oversampling ×16

5.3.3.4 *IIR filter control – filter*

IIR filter applies to temperature and pressure data but not to humidity and gas data. The data coming from the ADC are filtered and then loaded into the data registers. The temperature and pressure result registers are updated together at the same time at the end of the measurement. IIR filter output resolution is 20 bits. The result registers are reset to value 0x80000 when the temperature and/or pressure measurements have been skipped (*osrs_x*="000"). The appropriate filter memory is kept unchanged (the value from the last measurement is kept). When the appropriate OSRS register is set back to nonzero, then the first value stored to the result registers are filtered.

Register Name	Address	Content<bit position>	Description
config	0x75	filter<4:2>	IIR filter settings as shown in the following table

filter<2:0>	Filter coefficient
000	0
001	1
010	3
011	7
100	15
101	31
110	63
111	127

5.3.4 Gas control registers

The sensor can have 10 programmable gas sensor heater steps. Each heater step consists of a target heater resistance corresponding to heater temperature, heater-on time and optionally an initial heater current.

5.3.4.1 *Heater current - idac_heat_x*

BME688 contains a heater control block that will inject enough current into the heater resistance to achieve the requested heater temperature. There is a control loop which periodically measures heater resistance value and adapts the value of current injected from a DAC.

The heater operation could be speeded up by setting an initial heater current for a target heater temperature by using register *idac_heat_x<7:0>*. This step is optional since the control loop will find the current after a few iterations anyway. The current injected to the heater in mA can be calculated by: (*idac_heat_7_1* + 1) / 8, where idac_heat_7_1 is the decimal value stored in *idac_heat<7:1>* (unsigned, value from 0 to 127).

Heater steps	Register name	Address	Content	Description
0...9	idac_heat_x *x is from 0 to 9*	0x50...0x59	idac_heat_x<7:0> *x is from 0 to 9*	idac_heat of particular heater set point

5.3.4.2 *Target heater resistance - res_heat_x*

Target heater resistance is programmed by user through *res_heat_x<7:0>* registers. The definition of *res_heat_x* is given in Section 3.6.5.

Heater step	Register name	Address	Content	Description
0...9	res_wait_x *x is from 0 to 9*	0x5A...0x63	res_heat_x<7:0> *x is from 0 to 9*	Decimal value that needs to be stored for achieving target heater resistance

5.3.4.3 *Gas Sensor heater-on time in Forced mode - gas_wait_x*

Referring to Figure 2, the time between the beginning of the heat phase and the start of gas sensor resistance measurement depends on *gas_wait_x* setting as mentioned below.

Heater step	Register name	Address	Content	Description
0...9	gas_wait_x x is from 0 to 9	0x64...0x6D	gas_wait_x<5:0> x is from 0 to 9	64 timer values with 1 ms step sizes, all zeros means no wait
0...9	gas_wait_x x is from 0 to 9	0x64...0x6D	gas_wait_x<7:6> x is from 0 to 9	Timer multiplication factor as shown in below table

gas_wait_x<7:6>	Gas sensor wait time multiplication factor
00	1
01	4
10	16
11	64

5.3.4.4 *Gas Sensor heater-on time in parallel mode -- gas_wait_x & gas_wait_shared*

Referring to 3.5.4, total heater-on time depends on number of TPHG sequence, time taken for TPHG measurement and wait phase of each TPHG sequence. gas_wait_x<7:0> sets number of times TPHG sequence needs to be repeated.
The number of TPHG sub-measurement sequences within the one Gas conversion for one target temperature resistance is defined by gas_wait_X(7:0) settings. The duration of measurement is calculated as follows: Duration = gas_wait_X × (wait time defined by gas_wait_shared + TTPHG_duration)

Heater step	Register name	Address	Content	Description
0...9	gas_wait_x x is from 0 to 9	0x64...0x6D	gas_wait_x<7:0> x is from 0 to 9	255 values with 1 LSB corresponds to 1 TPHG sequence, all zeros means gas_wait_shared is fully skipped and one TPHG sequence is executed.

gas_wait_shared<7:0> sets wait time before each TPHG measurement sequence with duration as configured below. This is common for the whole gas measurement sequence in parallel mode.

Register Name	Address	Content<bit position>	Description
gas_wait_shared	0x6E	gas_wait_shared<5:0>	64 timer values with 0.477ms step sizes, all zeros means no wait. gas_wait_shared=0x00 is treated as if gas_wait_shared=0x01.

gas_wait_shared <7:6>	Gas sensor wait time multiplication factor
00	1
01	4
10	16
11	64

5.3.4.5 *Heater off - heat_off*

Register Name	Address	Content<bit position>	Description
ctrl_gas_0	0x70	heat_off <3>	Turn off current injected to heater by setting bit to one

5.3.4.6 *Heater profile selection- nb_conv*

nb_conv set heater profile of the sensor.

Register Name	Address	Content<bit position>	Description
ctrl_gas_1	0x71	nb_conv<3:0>	Forced mode: Indicates index of heater step that will be used in forced mode as describe in below table Parallel mode: Indicates sequence of up to 10 heater steps as describe in below table

In forced mode:

nb_conv<3:0>	Heater step
0000	0
0001	1
0010	2
0011	3
0100	4
0101	5
0110	6
0111	7
1000	8
1001	9

In parallel mode:

nb_conv<3:0>	Length of heater profile
0000	No conversion
0001	Heater step 0
0010	Heater step 0-1
0011	Heater step 0-2
0100	Heater step 0-3
0101	Heater step 0-4
0110	Heater step 0-5
0111	Heater step 0-6
1000	Heater step 0-7
1001	Heater step 0-8
1010 to 1111	Heater step 0-9

Each heater step in profile has specific heater temperature and heater-on time and gas_meas_index register (see 5.3.6.4) stores index of heater step (up to 10 steps numbered from 0 to 9) corresponding to TPHG data.

5.3.4.7 *Run Gas - run_gas*

Register Name	Address	Content<bit position>	Description
ctrl_gas_1	0x71	*run_gas*<5>	The gas conversions are started only in appropriate mode if run_gas = '1'

5.3.5 Data registers

In this section, the data registers for the temperature, pressure, humidity and gas sensors are explained. Shadowing registers are utilized to buffer the data and to ensure stable data in case an update of the data registers occurs simultaneously with the serial interface reading out.

3 fields store TPHG data, status bits and time indexes:

- In forced mode only field 0 is used,
- In parallel mode, fields are filled from 0 to 2 and overwritten if more than 3 heater steps have been selected (5.3.4.6).

5.3.5.1 *Pressure data*

Register Name [Field]	Address	Content<bit position>	Description
press_msb [0] press_msb [1] press_msb [2]	0x1F 0x30 0x41	press_msb<7:0>	Contains the MSB part [19:12] of the raw pressure measurement output data.
press_lsb [0] press_lsb [1] press_lsb [2]	0x20 0x31 0x42	press_lsb<7:0>	Contains the LSB part [11:4] of the raw pressure measurement output data
press_xlsb [0] press_xlsb [1] press_xlsb [2]	0x21 0x32 0x43	press_xlsb<7:4>	Contains the XLSB part [3:0] of the raw pressure measurement output data. Contents depend on pressure resolution controlled by oversampling setting.

5.3.5.2 *Temp data*

Register Name [Field]	Address	Content<bit position>	Description
temp_msb [0] temp_msb [1] temp_msb [2]	0x22 0x33 0x44	temp_msb<7:0>	Contains the MSB part [19:12] of the raw temperature measurement output data.
temp_lsb [0] temp_lsb [1] temp_lsb [2]	0x23 0x34 0x45	temp_lsb<7:0>	Contains the LSB part [11:4] of the raw temperature measurement output data.
temp_xlsb [0] temp_xlsb [1] temp_xlsb [2]	0x24 0x35 0x46	temp_xlsb<7:4>	Contains the XLSB part [3:0] of the raw temperature measurement output data. Contents depend on temperature resolution controlled by oversampling setting.

5.3.5.3 *Humidity data*

Register Name [Field]	Address	Content<bit position>	Description
hum_msb [0] hum_msb [1] hum_msb [2]	0x25 0x36 0x47	hum_msb<7:0>	Contains the MSB part [15:8] of the raw humidity measurement output data.
hum_lsb [0] hum_lsb [1] hum_lsb [2]	0x26 0x37 0x48	hum_lsb<7:0>	Contains the LSB part [7:0] of the raw humidity measurement output data.

5.3.5.4 *Gas resistance data*

Register Name [Field]	Address	Content<bit position>	Description
gas_r_msb [0] gas_r_msb [1] gas_r_msb [2]	0x2C 0x3D 0x4E	gas_r<7:0>	Contains the MSB part gas resistance [9:2] of the raw gas resistance.
gas_r_lsb [0] gas_r_lsb [1] gas_r_lsb [2]	0x2D 0x3E 0x4F	gas_r<7:6>	Contains the LSB part gas resistance [1:0] of the raw gas resistance.

5.3.5.5 *Gas resistance range*

Register Name [Field]	Address	Content<bit position>	Description
gas_r_lsb [0] gas_r_lsb [1] gas_r_lsb [2]	0x2D 0x3E 0x4F	gas_range_r<3:0>	Contains ADC range of measured gas resistance.

5.3.6 Status registers

The measured data are stored into the output data registers at the end of each TPHG conversion phase along with status flags and index of measurement

5.3.6.1 *New data status*

Register Name [Field]	Address	Content<bit position>	Description
meas_status [0] meas_status [1] meas_status [2]	0x1D 0x2E 0x3F	new_data<7>	New data flag indicate that data field contains a new data, not already read-out.

5.3.6.2 *Gas measuring status*

Measuring bit is set to 1 only during gas measurements, goes to 0 as soon as measurement is completed and data transferred to data registers. The registers storing the configuration values for the measurement (*gas_wait_shared*, *gas_wait_x*, *res_heat_x*, *idac_heat_x*, image registers) should not be changed when the device is measuring.

Register Name [Field]	Address	Content<bit position>	Description
meas_status [0] meas_status [1] meas_status [2]	0x1D 0x2E 0x3F	gas_measuring<6>	Gas measuring status flag

5.3.6.3 *Measuring status*

Measuring status will be set to '1' whenever a conversion (temperature, pressure, humidity and gas) is running and back to '0' when the results have been transferred to the data registers.

Register Name [Field]	Address	Content<bit position>	Description
meas_status [0] meas_status [1] meas_status [2]	0x1D 0x2E 0x3F	measuring<5>	Measuring status flag

5.3.6.4 *Gas Measurement Index*

User can trigger a heater profile of up to 10 heater steps by setting *nb_conv<3:0>(see 5.3.4.6)*.
Each heater step in profile has specific heater temperature and heater-on time and gas_meas_index register stores index of heater step (up to 10 steps numbered from 0 to 9) corresponding to TPHG data

Register Name [Field]	Address	Content<bit position>	Description
meas_status [0] meas_status [1] meas_status [2]	0x1D 0x2E 0x3F	gas_meas_index_0<3:0>	Gas measurement index

5.3.6.5 *Gas valid status*

In each TPHG sequence in parallel mode contains a gas measurement slot, either a real one which result is used or a dummy one to keep a constant sampling rate and predictable device timing. A real gas conversion (i.e., not a dummy one) is indicated by the *gas_valid_r* status register.

Register Name [Field]	Address	Content<bit position>	Description
gas_r_lsb [0] gas_r_lsb [1] gas_r_lsb [2]	0x2D 0x3E 0x4F	gas_valid_r<5>	Gas valid bit

5.3.6.6 *Heater Stability Status*

Heater temperature stability for target heater resistance is indicated *heat_stab_x* status bits and updated with data registers.The heater stability flag behavior depends on the current device mode:
- Forced mode: Stability is monitored only during the auto ranging sequences for gas measurements.
- Parallel mode: Stability is monitored from the beginning of the last one TPHG sequence (the on containing the real gas measurements) to the end of the gas measurement.

Register Name [Field]	Address	Content<bit position>	Description
gas_r_lsb [0] gas_r_lsb [1] gas_r_lsb [2]	0x2D 0x3E 0x4F	heat_stab_r<4>	Heater stability bit

5.3.6.7 *Sub Measurement Index*

Indicates current TPHG sequence number on operating sensor on parallel mode, which are incremented for each TPHG measurement. These status bytes form “virtual time sensor” and contain a snapshot of the internal 8 bit conversion counter since the last change of device mode.

Register Name [Field]	Address	Content<bit position>	Description
sub_meas_index [0] sub_meas_index [1] sub_meas_index [2]	0x1E 0x2F 0x40	sub_meas_index<7:0>	TPHG measurement sequence number

6. Digital interfaces

The sensor supports the I²C and SPI digital interfaces, where it acts as a slave for both protocols. The I²C interface supports the Standard, Fast and High Speed modes. The SPI interface supports both SPI mode '00' (CPOL = CPHA = '0') and mode '11' (CPOL = CPHA = '1') in 4-wire and 3-wire configuration.

The following transactions are supported:

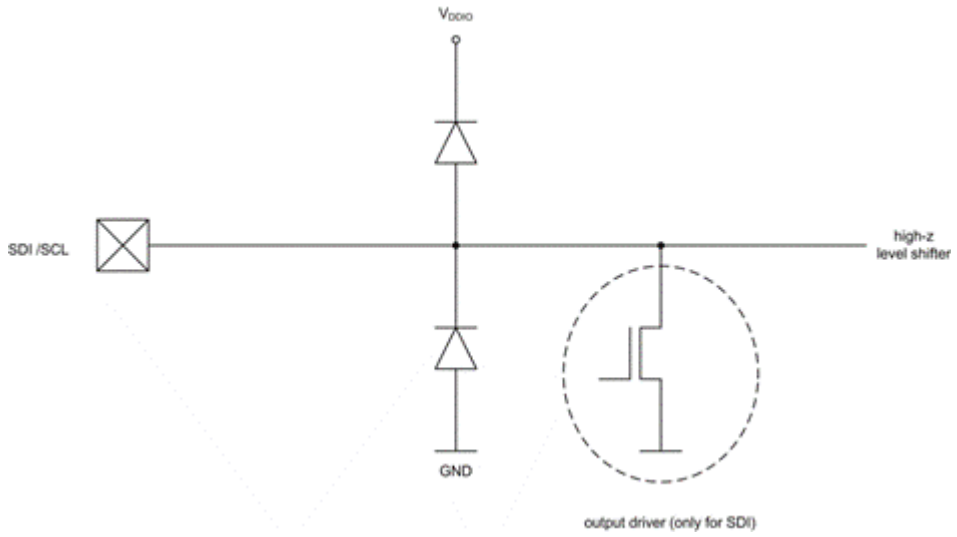
- Single byte write
- multiple byte write (using pairs of register addresses and register data)
- single byte read
- multiple byte read (using a single register address which is auto-incremented)

6.1 Interface selection

Interface selection is done automatically based on CSB (chip select) status. If CSB is connected to V_{DDIO}, the I²C interface is active. If CSB is pulled down, the SPI interface is activated. After CSB has been pulled down once (regardless of whether any clock cycle occurred), the I²C interface is disabled until the next power-on-reset. This is done in order to avoid inadvertently decoding SPI traffic to another slave as I²C data. Since the device startup is deferred until both V_{DD} and V_{DDIO} are established, there is no risk of incorrect protocol detection because of the power-up sequence used. However, if I²C is to be used and CSB is not directly connected to V_{DDIO} but is instead connected to a programmable pin, it must be ensured that this pin already outputs the V_{DDIO} level during power-on-reset of the device. If this is not the case, the device will be locked in SPI mode and not respond to I²C commands.

6.2 I²C Interface

For detailed timings, please review Table 24 . All modes (standard, fast, high speed) are supported. SDA and SCL are not pure open-drain. Both pads contain ESD protection diodes to VDDIO and GND. As the devices does not perform clock stretching, the SCL structure is a high-Z input without drain capability.



Picture 6: SDI/SCK ESD schematic

The 7-bit device address is 111011x. The 6 MSB bits are fixed. The last bit is changeable by SDO value and can be changed during operation. Connecting SDO to GND results in slave address 1110110 (0x76); connection it to V_{DDIO} results in slave address 1110111 (0x77), which is the same as BMP280's I²C address. The SDO pin cannot be left floating; if left floating, the I²C address will be undefined.

The I²C interface uses the following pins:

- SCK: serial clock (SCL)
- SDI: data (SDA)
- SDO: Slave address LSB (GND = '0', V_{DDIO} = '1')

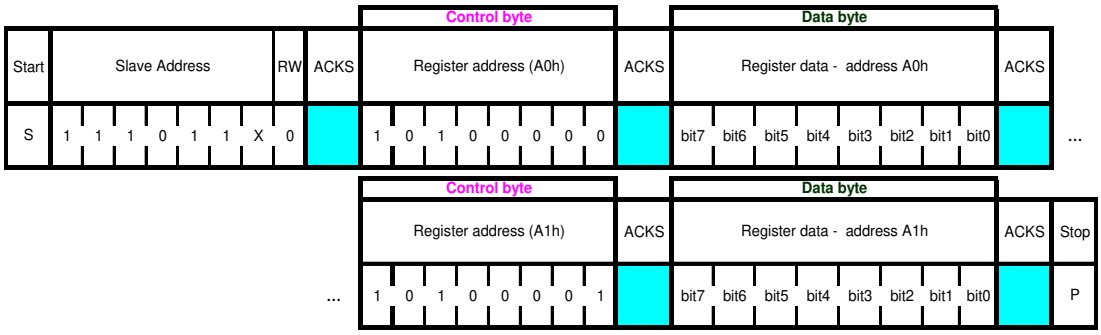
CSB must be connected to V_{DDIO} to select I²C interface. SDI is bi-directional with open drain to GND: it must be externally connected to V_{DDIO} via a pull up resistor. Refer to Chapter 7 for connection instructions.

The following abbreviations will be used in the I²C protocol figures:

- S Start
- P Stop
- ACKS Acknowledge by slave
- ACKM Acknowledge by master
- NACKM Not acknowledge by master

6.2.1 I²C write

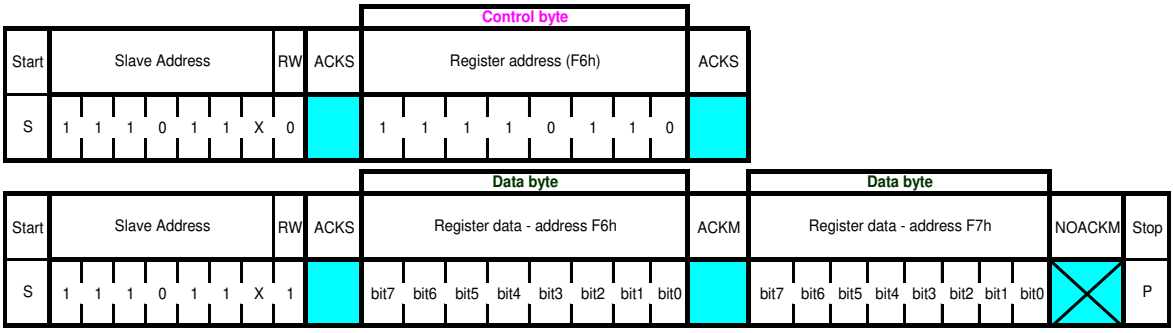
Writing is done by sending the slave address in write mode (RW = '0'), resulting in slave address 111011X0 ('X' is determined by state of SDO pin. Then the master sends pairs of register addresses and register data. The transaction is ended by a stop condition. This is depicted in Picture 7.



Picture 7: I²C multiple byte write (not auto-incremented)

6.2.2 I²C read

To be able to read registers, first the register address must be sent in write mode (slave address 111011X0). Then either a stop or a repeated start condition must be generated. After this the slave is addressed in read mode (RW = '1') at address 111011X1, after which the slave sends out data from auto-incremented register addresses until a NOACKM and stop condition occurs. This is depicted in Picture 8, where register 0xF6 and 0xF7 are read.



Picture 8: I²C multiple byte read

6.3 SPI interface

The SPI interface is compatible with SPI mode ‘00’ (CPOL = CPHA = ‘0’) and mode ‘11’ (CPOL = CPHA = ‘1’). The automatic selection between mode ‘00’ and ‘11’ is determined by the value of SCK after the CSB falling edge.

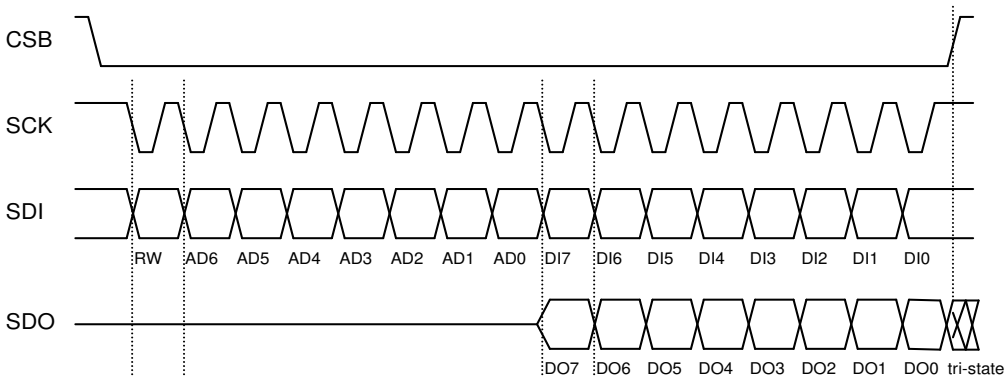
The SPI interface has two modes, namely 4-wire and 3-wire mode. However, the protocol is the same for both. The 3-wire mode is selected by setting ‘1’ to the register spi3w_en. The pad SDI is used as a data pad in 3-wire mode.

The SPI interface uses the following pins:

- CSB: chip select, active low
- SCK: serial clock
- SDI: serial data input; data input/output in 3-wire mode
- SDO: serial data output; hi-Z in 3-wire mode

For more connection instructions, please refer to Chapter 7.

CSB is active low and has an integrated pull-up resistor. Data on SDI is latched by the device at SCK rising edge and SDO is changed at SCK falling edge. Communication starts when CSB goes to low and stops when CSB goes to high; during these transitions on CSB, SCK must be stable. The SPI protocol is shown in It is important to note that Picture 9. For timing details, please review Table 25.



Picture 9: SPI protocol (shown for mode ‘11’ in 4-wire configuration)

It is important to note that in the SPI mode, only 7 bits of the register addresses are used; the MSB of register address is not used and replaced by a read/write bit (RW = ‘0’ for write and RW = ‘1’ for read). For example, address 0xF7 is accessed by using SPI register address 0x77. On the one hand, the byte 0x77 is transferred for write access, and on the other hand, the byte 0xF7 is transferred for read access.

6.3.1 SPI write

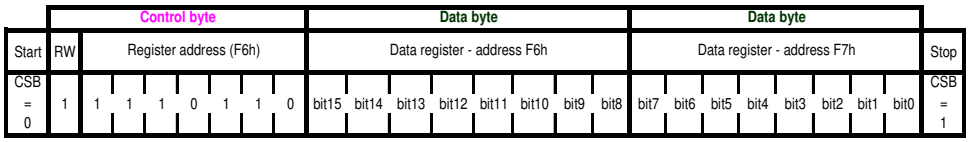
Writing is done by lowering CSB and sending pairs control bytes and register data. The control bytes consist of the SPI register address (= full register address without bit 7) and the write command (bit7 = RW = ‘0’). Several pairs can be written without raising CSB. The transaction is ended by a raising CSB. The SPI write protocol is depicted in Picture 10.

	Control byte								Data byte								Control byte								Data byte								
Start	RW	Register address (F4h)								Data register - address F4h								RW	Register address (F5h)								Data register - adress F5h								Stop
CSB = 0	0	1	1	1	0	1	0	0		bit7	bit6	bit5	bit4	bit3	bit2	bit1	bit0	0	1	1	1	0	1	0	1		bit7	bit6	bit5	bit4	bit3	bit2	bit1	bit0	CSB = 1

Picture 10: SPI multiple byte write (not auto-incremented)

6.3.2 SPI read

Reading is done by lowering CSB and first sending one control byte. The control bytes consist of the SPI register address (= full register address without bit 7) and the read command (bit 7 = RW = '1'). After writing the control byte, data is sent out of the SDO pin (SDI in 3-wire mode); the register address is automatically incremented. The SPI read protocol is depicted in Picture 11.



Picture 11: SPI multiple byte read

6.4 Interface parameter specification

6.4.1 General interface parameters

Table 23: Interface parameters

Parameter	Symbol	Condition	Min	Typ	Max	Unit
Input low level	V_{il_si}	V_{DDIO}=1.2 V to 3. 6V			20	%V_{DDIO}
Input high level	V_{ih_si}	V_{DDIO}=1.2 V to 3.6 V	80			%V_{DDIO}
Output low level I^2C	V_{ol_SDI}	V_{DDIO}=1.62 V, I_{ol}=3 mA			20	%V_{DDIO}
Output low level I^2C	$V_{ol_SDI_1.2}$	V_{DDIO}=1.20 V, I_{ol}=3 mA			23	%V_{DDIO}
Output low level SPI	V_{ol_SDO}	V_{DDIO}=1.62 V, I_{ol}=1 mA			20	%V_{DDIO}
Output low level SPI	$V_{ol_SDO_1.2}$	V_{DDIO}=1.20 V, I_{ol}=1 mA			23	%V_{DDIO}
Output high level	V_{oh}	V_{DDIO}=1.62 V, I_{oh}=1 mA (SDO, SDI)	80			%V_{DDIO}
Output high level	$V_{oh_1.2}$	V_{DDIO}=1.20 V, I_{oh}=1 mA (SDO, SDI)	60			%V_{DDIO}
Pull-up resistor	R_{pull}	Internal CSB pull-up resistor to V_{DDIO}	70	120	190	kΩ
I^2C bus load capacitor	C_b	On SDI and SCK			400	pF

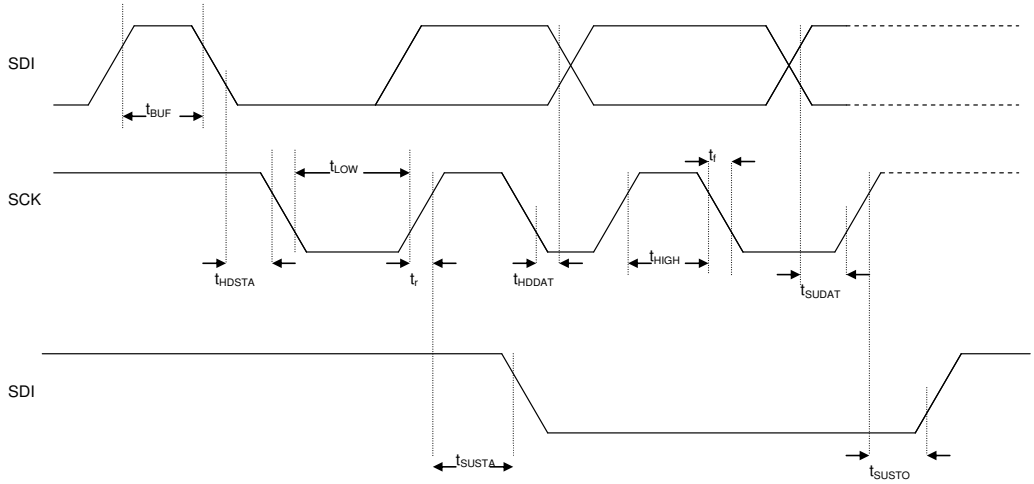
6.4.2 I²C timings

For I²C timings, the following abbreviations are used:

- “S&F mode” = standard and fast mode
- “HS mode” = high speed mode
- C_b = bus capacitance on SDA line

All other naming refers to I²C specification 2.1 (January 2000).

The I²C timing diagram is in Picture 12. The corresponding values are given in Table 24



Picture 12: I²C timing diagram

Table 24: I²C timings

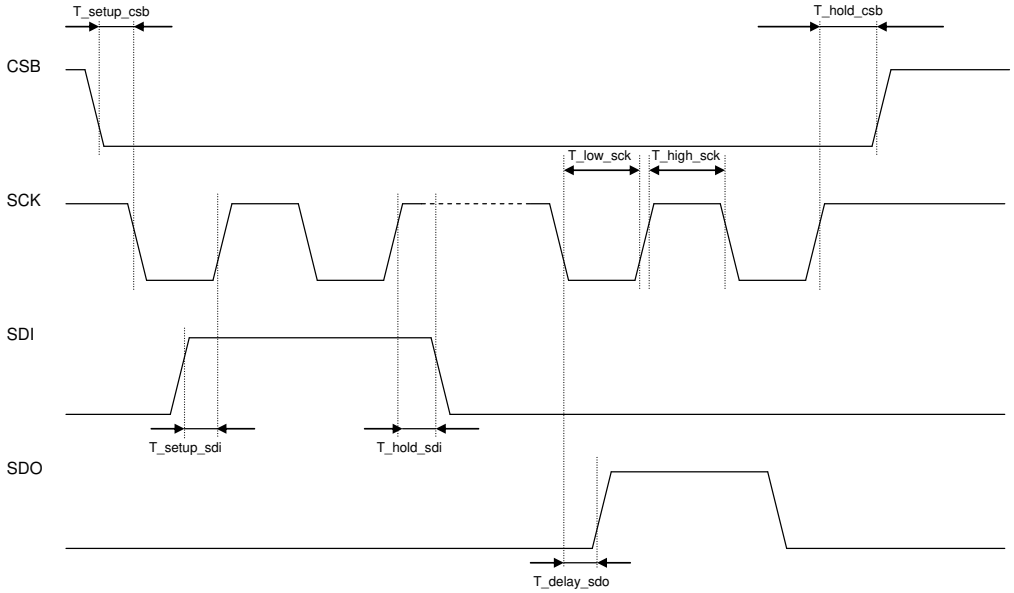
Parameter	Symbol	Condition	Min	Typ	Max	Unit
SDI setup time	$t_{SU;DAT}$	S&F Mode	160			ns
		HS mode	30			ns
SDI hold time	$t_{HD;DAT}$	S&F Mode, C_b≤100 pF	80			ns
		S&F Mode, C_b≤400 pF	90			ns
		HS mode, C_b≤100 pF	18		115	ns
		HS mode, C_b≤400 pF	24		150	ns
SCK low pulse	t_{LOW}	HS mode, C_b≤100 pF V_{DDIO} = 1.62 V	160			ns
SCK low pulse	t_{LOW}	HS mode, C_b≤100 pF V_{DDIO} = 1.2 V	210			ns

The above-mentioned I²C specific timings correspond to the following internal added delays:

- Input delay between SDI and SCK inputs: SDI is more delayed than SCK by typically 100 ns in Standard and Fast Modes and by typically 20 ns in High Speed Mode.
- Output delay from SCK falling edge to SDI output propagation is typically 140 ns in Standard and Fast Modes and typically 70 ns in High Speed Mode.

6.4.3 SPI timings

The SPI timing diagram is in Picture 13, while the corresponding values are given in Table 25. All timings apply both to 4- and 3-wire SPI.



Picture 13: SPI timing diagram

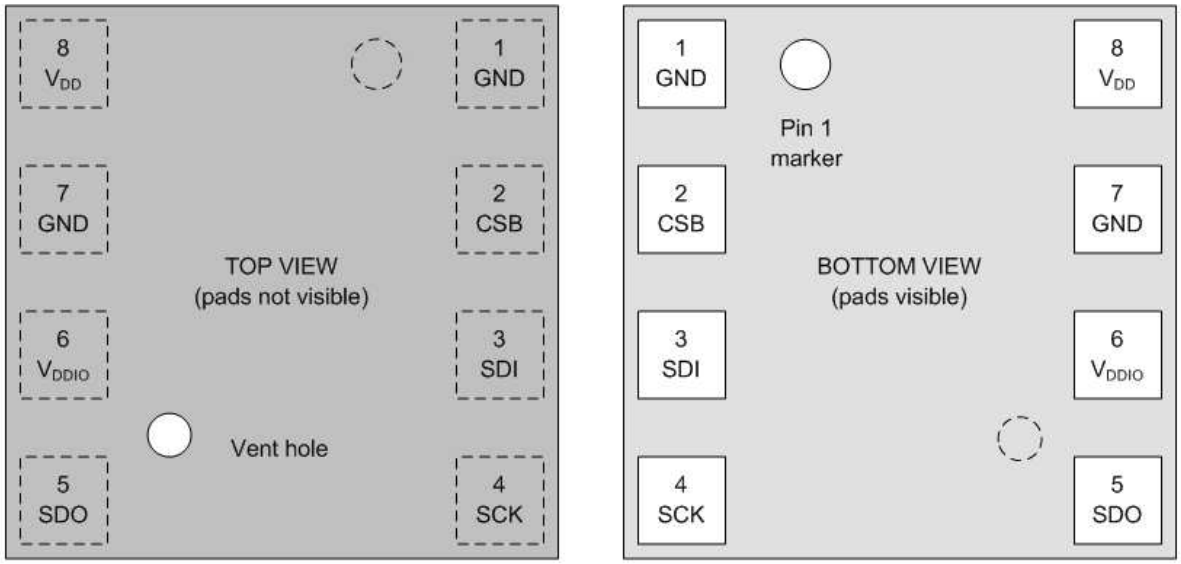
Table 25: SPI timings

Parameter	Symbol	Condition	Min	Typ	Max	Unit
SPI clock i/p frequency	F_spi		0		10	MHz
SCK low pulse	T_low_sck		20			ns
SCK high pulse	T_high_sck		20			ns
SDI setup time	T_setup_sdi		20			ns
SDI hold time	T_hold_sdi		20			ns
SDO output delay	T_delay_sdo	25 pF load, V_{DDIO}=1.6 V min			30	ns
SDO output delay	T_delay_sdo	25 pF load, V_{DDIO}=1.2 V min			40	ns
CSB setup time	T_setup_csb		20			ns
CSB hold time	T_hold_csb		20			ns
SPI clock input frequency	F_spi		0		10	MHz

7. Pin-out and connection diagram

7.1 Pin-out

The pin numbering of BME688 is performed in the untypical clockwise direction when seen in top view and counter-clockwise when seen in bottom view. Picture 14 and Table 26 give a detailed description and illustration of the input/output pins.



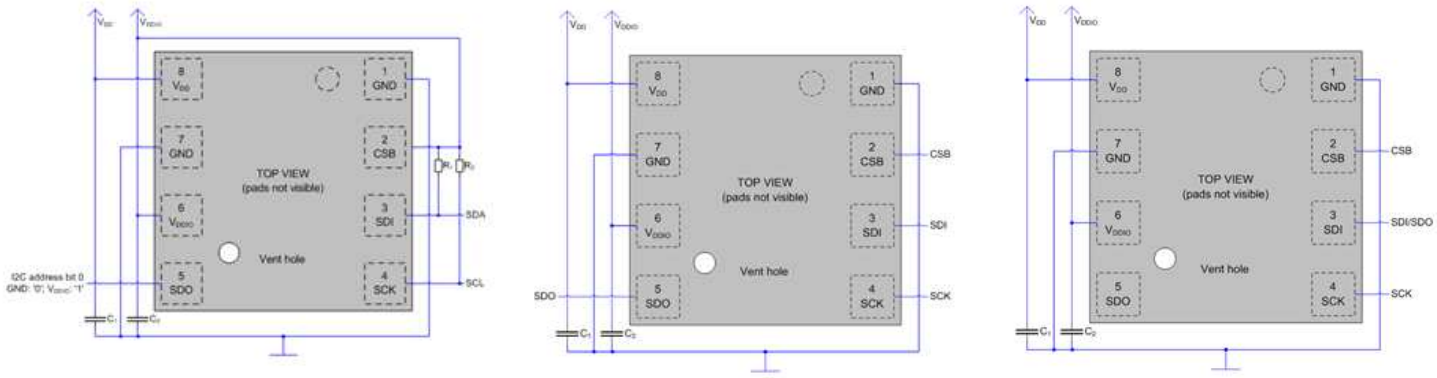
Picture 14: Top (left) and bottom (right) views of the chip with input/output pins

Table 26: Pin description

Pin	Name	I/O type	Description	Connection		
				SPI 4W	**SPI 3W**	**I²C**
1	GND	Supply	Ground	GND		
2	CSB	In	Chip select	CSB	CSB	V_{DDIO}
3	SDI	In/Out	Serial data input	SDI	SDI/SDO	SDA
4	SCK	In	Serial clock input	SCK	SCK	SCL
5	SDO	In/Out	Serial data output	SDO	DNC	GND for default address
6	V_{DDIO}	Supply	Digital / Interface supply	V_{DDIO}		
7	GND	Supply	Ground	GND		
8	V_{DD}	Supply	Analog supply	V_{DD}		

7.2 Connection diagrams

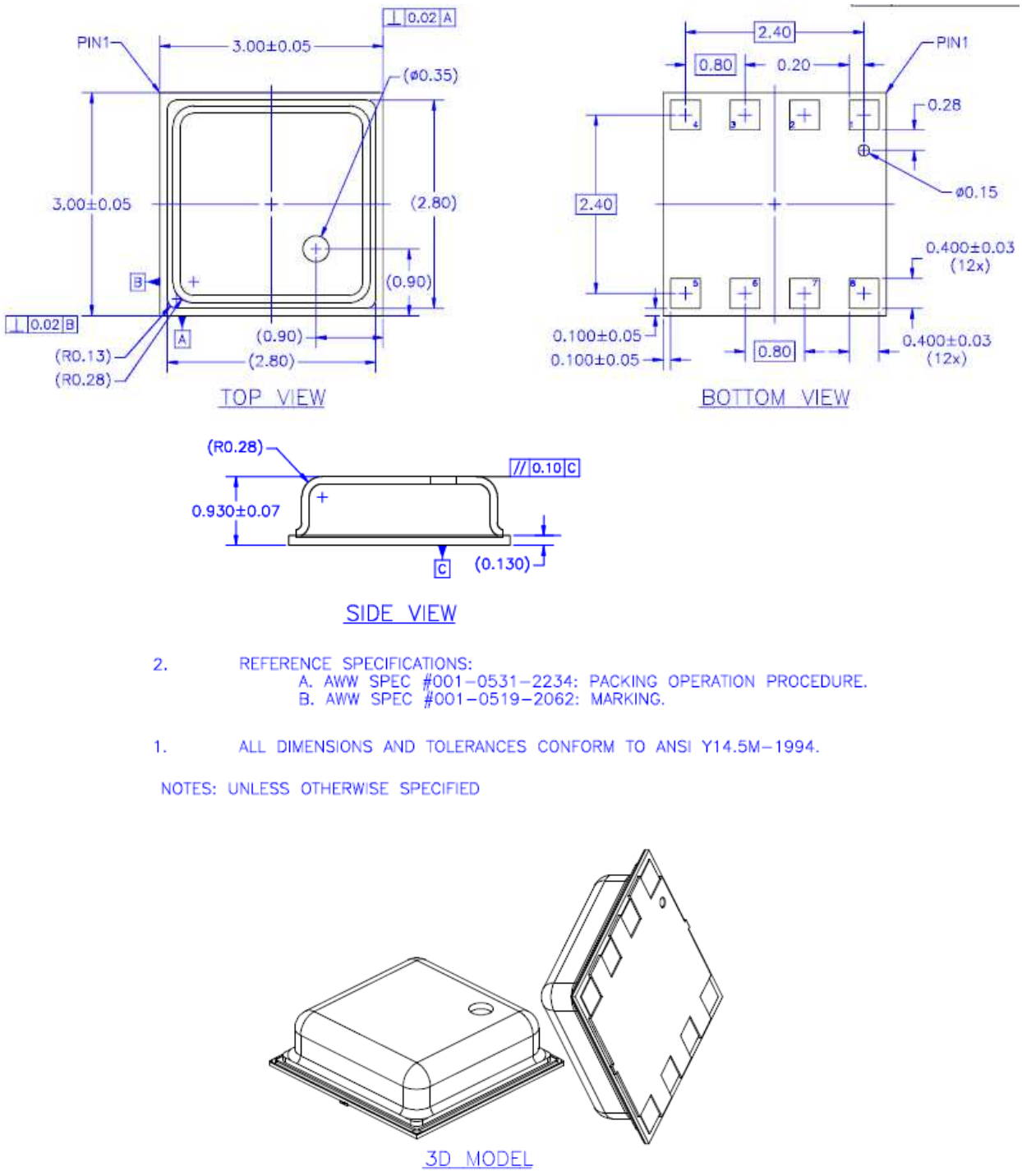
For the I²C connection, it is recommended to use 100 nF for C_1 and C_2. Moreover, the value for the pull-up resistors R_1 and R_2 should be based on the interface timing and the bus load; a normal value is 4.7 kΩ. Finally, a direct connection between CSB and V_{DDIO} is required. Similarly for the 4- and 3-wire SPI connections, it is suggested to use 100 nF for C_1 and C_2.



(a) (b) (c)

Picture 15: Connection diagrams for (a) I²C, (b) 4-wire SPI, and (c) 3-wire SPI

7.3 Package dimensions

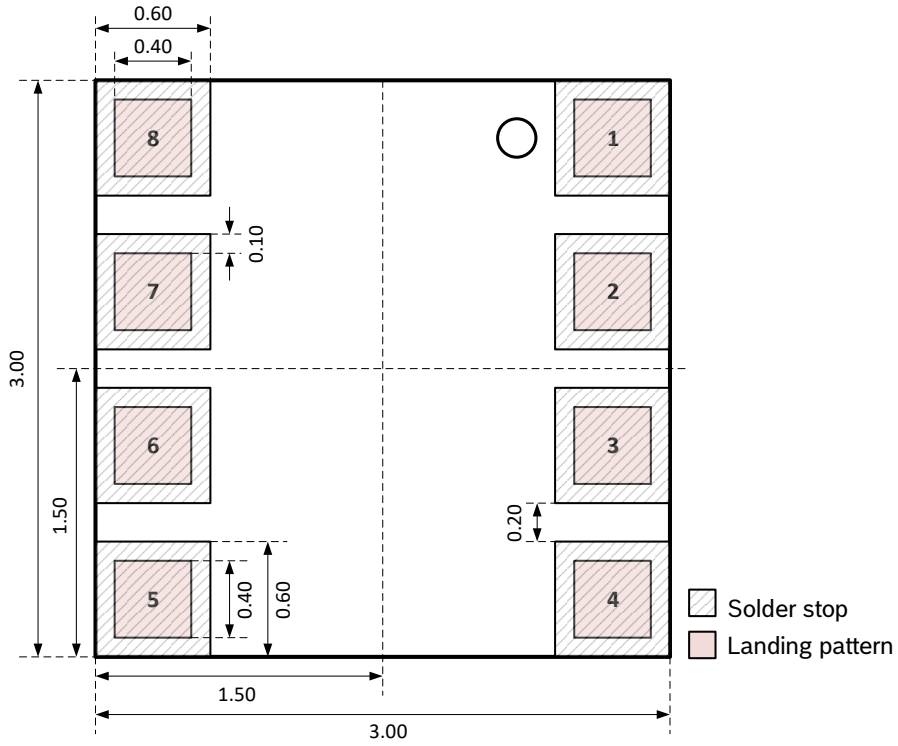


Picture 16: Package dimensions for top, bottom and side view

7.4 Landing pattern recommendation

For the design of the landing pattern, the dimensions shown in Picture 17: Recommended landing pattern (top view; dimensions are in millimeters) are recommended. It is important to note that areas marked in red are exposed PCB metal pads.

- In case of a solder mask defined (SMD) PCB process, the land dimensions should be defined by solder mask openings. The underlying metal pads are larger than these openings.
- In case of a non-solder mask defined (NSMD) PCB process, the land dimensions should be defined in the metal layer. The mask openings are larger than these metal pads.

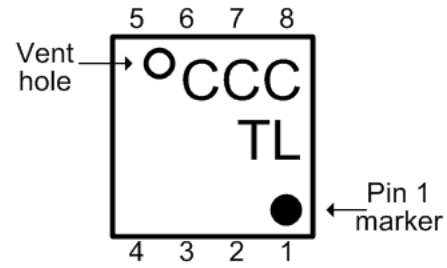


Picture 17: Recommended landing pattern (top view; dimensions are in millimeters)

7.5 Marking

7.5.1 Mass production devices

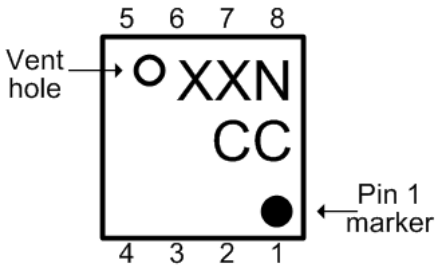
Table 27: Marking of mass production parts

Marking	Symbol	Description
	CCC	Lot counter: 3 alphanumeric digits, variable to generate mass production trace-code
	T	Product number: 1 alphanumeric digit, fixed to identify product type. “T” identifies the BME688 w/ the part no. 0 273 017 016
	L	Sub-contractor ID: 1 alphanumeric digit, variable to identify sub-contractor (L = “P”)

Note: The product numbers “S” and “E” identify the BME680.

7.5.2 Engineering samples

Table 28: Marking of engineering samples

Marking	Symbol	Description
	XX	Sample ID: 2-3 alphanumeric digits, variable to generate trace-code
	N	Eng. Sample ID: 1 alphanumeric digit, fixed to identify engineering sample, N = “ * ” or “e” or “E”
	CC	Counter ID: 2-3 alphanumeric digits, variable to generate trace-code

Note: Early engineering samples (e.g. w/ marking “688E HR1”) did not yet have a flashed *variant_id* as described in chapter 5.3.2.1. Consequently, they are not automatically recognized by the API. In order to ensure correct function, the API needs to be manually modified according to the used variant.

7.6 Soldering guidelines and reconditioning recommendations

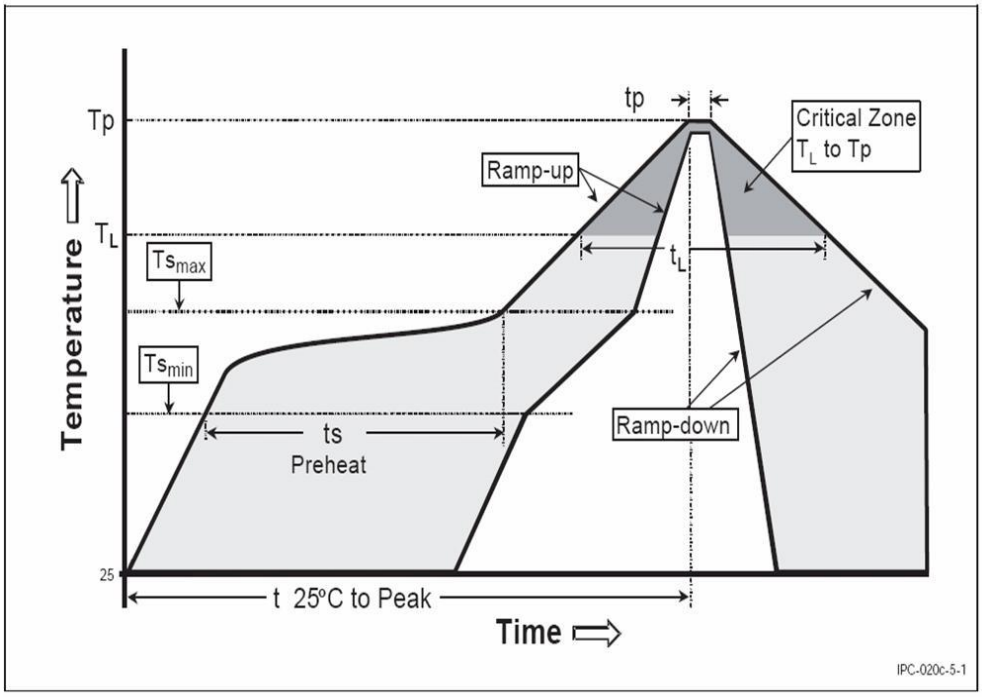
The moisture sensitivity level of the BME688 sensors corresponds to JEDEC Level 1, see also:

- IPC/JEDEC J-STD-020C "Joint Industry Standard: Moisture/Reflow Sensitivity Classification for non-hermetic Solid State Surface Mount Devices"
- IPC/JEDEC J-STD-033A "Joint Industry Standard: Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices"

The sensor fulfils the lead-free soldering requirements of the above-mentioned IPC/JEDEC standard, i.e. reflow soldering with a peak temperature up to 260°C. The minimum height of the solder after reflow shall be at least 50 µm. This is required for good mechanical decoupling between the sensor device and the printed circuit board (PCB).

Profile Feature		Pb-Free Assembly
Average Ramp-Up Rate (Ts_{max} to Tp)		3° C/second max.
Preheat – Temperature Min (Ts_{min}) – Temperature Max (Ts_{max}) – Time (ts_{min} to ts_{max})		150 °C 200 °C 60-180 seconds
Time maintained above: – Temperature (T_L) – Time (t_L)		217 °C 60-150 seconds
Peak/Classification Temperature (Tp)		260 °C
Time within 5 °C of actual Peak Temperature (tp)		20-40 seconds
Ramp-Down Rate		6 °C/second max.
Time 25 °C to Peak Temperature		8 minutes max.

Note 1: All temperatures refer to topside of the package, measured on the package body surface.



Picture 18: Soldering profile

7.7 Mounting and assembly recommendations

This HSMI-document provides all the necessary instructions to handle, solder and mount the environmental sensor BME688. Following the reported guidelines is very important to prevent the damage of the sensor and the resultant loss of warranty.

7.8 Environmental safety

7.8.1 RoHS

The BME688 sensor meets the requirements of the EC restriction of hazardous substances (RoHS) directive, see also:

Directive 2011/65/EU and its amendments, including the amendment 2015/863/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment.

7.8.2 Halogen content

The BME688 is halogen-free. For more details on the analysis results please contact your Bosch Sensortec representative.

7.8.3 Internal package structure

Within the scope of Bosch Sensortec's ambition to improve its products and secure the mass product supply, Bosch Sensortec qualifies additional sources (e.g. 2nd source) for the packaging and processing of the BME688.

While Bosch Sensortec took care that all of the technical packages parameters are described above are 100% identical for all sources, there can be differences in the chemical content and the internal structural between the different package sources.

However, as secured by the extensive product qualification process of Bosch Sensortec, this has no impact to the usage or to the quality of the BME688 product.

8. Legal disclaimer

8.1 Engineering samples

Engineering Samples are marked with an asterisk (*), (E) or (e). Samples may vary from the valid technical specifications of the product series contained in this data sheet. They are therefore not intended or fit for resale to third parties or for use in end products. Their sole purpose is internal client testing. The testing of an engineering sample may in no way replace the testing of a product series. Bosch Sensortec assumes no liability for the use of engineering samples. The Purchaser shall indemnify Bosch Sensortec from all claims arising from the use of engineering samples.

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Bosch Sensortec products are developed for the consumer goods industry. They may only be used within the parameters of this product data sheet. They are not fit for use in life-sustaining or safety-critical systems. Safety-critical systems are those for which a malfunction is expected to lead to bodily harm, death or severe property damage. In addition, they shall not be used directly or indirectly for military purposes (including but not limited to nuclear, chemical or biological proliferation of weapons or development of missile technology), nuclear power, deep sea or space applications (including but not limited to satellite technology).

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The purchaser accepts the responsibility to monitor the market for the purchased products, particularly with regard to product safety, and to inform Bosch Sensortec without delay of all safety-critical incidents

8.3 Application examples and hints

With respect to any examples or hints given herein, any typical values stated herein and/or any information regarding the application of the device, Bosch Sensortec hereby disclaims any and all warranties and liabilities of any kind, including without limitation warranties of non-infringement of intellectual property rights or copyrights of any third party. The information given in this document shall in no event be regarded as a guarantee of conditions or characteristics. They are provided for illustrative purposes only and no evaluation regarding infringement of intellectual property rights or copyrights or regarding functionality, performance or error has been made.

9. Document history and modifications

Rev.	Chapter	Description of modifications	Date
1.0		Initial release	April 2021
1.1	1.2 1.5 5.2 5.3.4.7	• Sensitivity (S_{H2S}) & F1-score ($F1_{H2S}$) improved by updated BSEC 2.2.0.0 software (Table 4) • Typical IAQ range updated according to BSEC 2.2.0.0 software improvements (Table 6) • Temperature accuracy (A_T) improved (Table 10) • Memory Map for ctrl_gas_1 updated (Table 22) • Bit position updated for ctrl_gas_1	July 2022
1.2	General	Updated Typical Applications and Target Devices	February 2024
1.3	2	Removed condensation parameter from table 11	February 2024

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