

# BOS1211 Scalable Piezo Haptic Controller with Waveform Synthesizer

## 1 Features

- AEC-Q100 Grade 2 Qualified
- Scalable Low Power Piezo Controller
  - Designed for TDK PowerHap 120 V Actuator Portfolio
  - Drives up to 4  $\mu$ F
  - Energy Recovery
  - Small Solution Footprint
- Integrated Digital Front End with SPI
  - 1024-Samples Internal FIFO
  - 2-kB RAM Waveform Memory
  - Waveform Synthesizer
  - 1.8 V to 5.0 V Digital I/O Supply
- Piezo Sensing Interface
- Multi-Actuator Synchronization
- Fast Start-Up Time of 500  $\mu$ s
- Connects to 12 V Power Bus
- Offered in a Wettable Flank QFN-24 Package

## 2 Applications

- Display Haptics
- Button Replacement
- Human Machine Interface

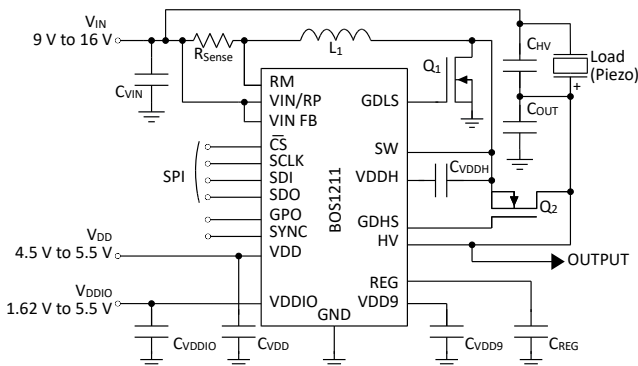


Figure 1: Simplified schematic

## 3 Description

The BOS1211 is a scalable piezo haptic controller based on our patented CapDrive™ technology. It can drive TDK's PowerHap 120 V piezo actuators or similar loads with up to 120 V HD haptic low distortion waveforms and operates from a 12 V supply voltage. The BOS1211 integrates a digital interface, low-side and high-side NMOS gate drivers for buck-boost conversion and piezo sensing capability.

The BOS1211 plays waveforms through its digital front-end and SPI interface. A flexible deep FIFO interface enables the user to continuously stream the digital waveform data for playback or to transmit burst data. The interface also integrates a waveform synthesizer and 2-kB RAM waveform memory to generate HD haptic waveforms with minimum communication bandwidth enabling two waveform generation modes: RAM playback and RAM synthesis.

The digital front-end gives access to many internal registers to optimize performance. The BOS1211 features a piezo sensing interface that can detect a pressure applied on the piezo actuator, play automatic haptic waveform feedback, and notify the host of the event.

The high-speed SPI enables the device to share a common communication bus for a multi-actuator system. The pin SYNC synchronizes multiple controllers in the same system to have waveforms phase delay within less than 2  $\mu$ s.

Safety systems protect the device from damage in case of a fault.

Table 1: Product information

| PART NUMBER | DESCRIPTION           |
|-------------|-----------------------|
| BOS1211AQ   | QFN 24L 4.0mm x 4.0mm |

See section 10 for ordering information.

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## 4 Pins Configuration and Functions

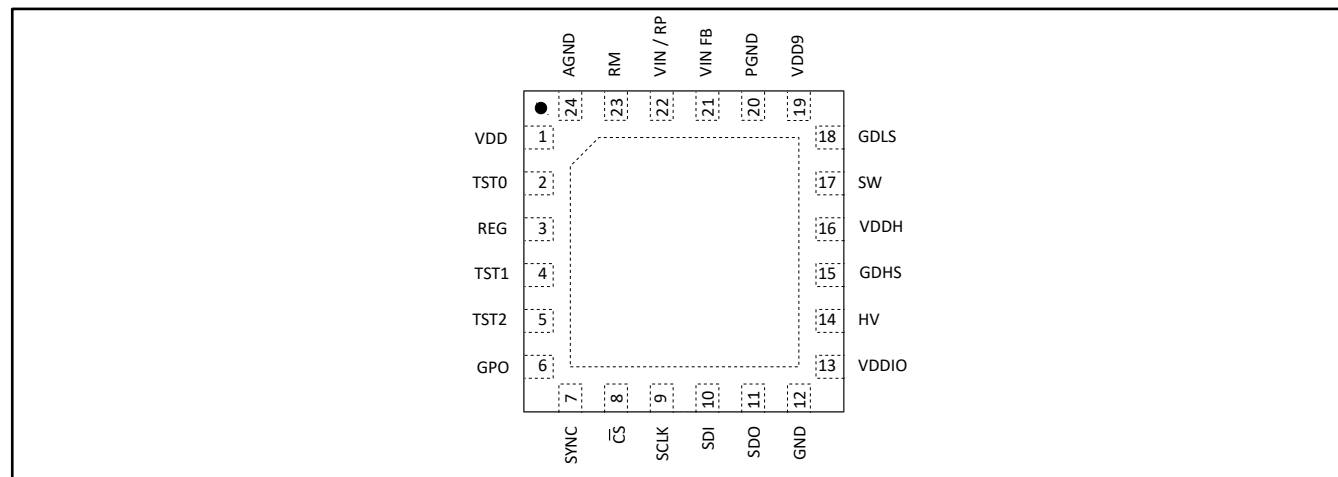


Figure 2: QFN 24L 4.0mm x 4.0 mm package with exposed thermal pad (TOP VIEW; NOT TO SCALE)

Table 2: QFN 24L 4.0mm x 4.0mm pin description

| PIN NO. | PIN NAME        | TYPE         | DESCRIPTION  |
|---------|-----------------|--------------|--|
| 1       | VDD             | Power        | Main controller supply                                     |
| 2       | TST0            | -            | Factory test pin: must be kept floating                    |
| 3       | REG             | Power        | Internal 1.8 V regulator output                            |
| 4       | TST1            | -            | Factory test pin: must be kept floating                    |
| 5       | TST2            | Input        | Factory test pin: must be connected to GND                 |
| 6       | GPO             | Output       | Configurable output  |
| 7       | SYNC            | Input/Output | Multi-chip synchronizing pin                               |
| 8       | $\overline{CS}$ | Input        | SPI chip select  |
| 9       | SCLK            | Input        | SPI clock  |
| 10      | SDI             | Input        | SPI serial data in   |
| 11      | SDO             | Output       | SPI serial data out  |
| 12      | GND             | Power        | Power supply ground  |
| 13      | VDDIO           | Power        | Power supply for digital IO                                |
| 14      | HV              | Input        | Voltage sense of high-voltage piezo signal                 |
| 15      | GDHS            | Output       | Gate driver output to high side NMOS switch                |
| 16      | VDDH            | Output       | Floating supply for high side gate driver                  |
| 17      | SW              | Input        | Power converter switch pin                                 |
| 18      | GDLS            | Output       | Gate driver output to low side NMOS switch                 |
| 19      | VDD9            | Power        | 9 V internal gate driver supply                            |
| 20      | PGND            | Power        | Power supply ground connection to the low-side gate driver |
| 21      | VIN FB          | Input        | Voltage sense of low voltage piezo signal                  |
| 22      | VIN/RP          | Power/Input  | 12 V Supply /Current sense positive input                  |
| 23      | RM              | Input        | Current sense negative input                               |
| 24      | AGND            | Power        | Power supply ground  |

## 5 Specifications

### 5.1 Absolute Maximum Ratings

Table 3: Absolute maximum ratings<sup>‡</sup>

|   | SYMBOL           | PARAMETER                                | MIN  | NOM | MAX | UNIT |
|---|------------------|--|------|-----|-----|------|
| 1 |                  | Voltage at pins HV, GDHS, GDLS, VDDH, SW | -0.3 |     | 140 | V    |
| 2 |                  | Voltage at pins RM, VIN/RP, VIN FB       | -0.3 |     | 28  | V    |
| 3 |                  | Voltage at all other pins                | -0.3 |     | 7   | V    |
| 4 | T <sub>stg</sub> | Storage temperature                      | -65  |     | 150 | °C   |
| 5 | T <sub>J</sub>   | Junction temperature                     | -40  |     | 150 | °C   |

<sup>‡</sup>Exceeding these values may cause permanent damage. Functional operation under these conditions is not guaranteed.

### 5.2 Package Thermal Information

Table 4: Package thermal information

|   | SYMBOL          | PARAMETER                              | PACKAGE               | MIN | NOM  | MAX | UNIT |
|---|-----------------|--|-----------------------|-----|------|-----|------|
| 1 | Θ <sub>JA</sub> | Junction-to-ambient thermal resistance | QFN 24L 4.0mm x 4.0mm |     | 28.8 |     | °C/W |

### 5.3 Recommended Operating Conditions

Table 5: Recommended operating conditions

|   | SYMBOL                             | PARAMETER                          | TEST CONDITIONS                                     | MIN  | NOM | MAX  | UNIT |
|---|------------------------------------|------------------------------------|---|------|-----|------|------|
| 1 | T <sub>A</sub>                     | Operating Temperature              | Operating free-air temp.                            | -40  |     | 105  | °C   |
| 2 | V <sub>IN</sub>                    | Actuator input supply voltage      |   | 9    |     | 16   | V    |
| 3 | V <sub>DD</sub>                    | Supply voltage                     |   | 4.5  |     | 5.5  | V    |
| 4 | V <sub>DDIO</sub> <sup>(1)</sup>   | I/O Supply voltage                 |   | 1.62 |     | 5.5  | V    |
| 5 | C <sub>ISS-Q2</sub> <sup>(2)</sup> | Gate capacitance of Q <sub>2</sub> |   |      |     | 2    | nf   |
| 6 | C <sub>Load</sub>                  | Load capacitance                   | f <sub>sig</sub> = 300 Hz, V <sub>OUT</sub> = 120 V |      |     | 4    | μF   |
| 7 | L <sub>1</sub>                     | Inductance                         |   |      | 10  |      | μH   |
| 8 | R <sub>sense</sub> <sup>(3)</sup>  | Sense resistor                     |   | 30   |     | 1000 | mΩ   |
| 9 | f <sub>OUT</sub>                   | Output frequency                   |   | 3.9  |     | 1000 | Hz   |

(1) Digital I/O voltage (V<sub>DDIO</sub>) must match with controller SPI interface voltage (MCU).

(2) C<sub>ISS-Q2</sub> and C<sub>VDDH</sub> determine the voltage at GDHS pin. See section 7.4.5 and 7.4.6 for more information.

(3) See section 7.4.3 for R<sub>sense</sub> selection.

## 5.4 Electrical Characteristics

Table 6: Electrical characteristics. Conditions:  $T_A = -40^{\circ}\text{C}$  to  $105^{\circ}\text{C}$ ,  $V_{DD} = 5\text{ V}$ ,  $V_{IN} = 12\text{ V}$  (unless otherwise noted)

|    | SYMBOL        | PARAMETER   | TEST CONDITIONS   | MIN                   | NOM            | MAX              | UNIT          |
|----|---------------|---|---|-----------------------|----------------|------------------|---------------|
| 1  | $V_{REG}$     | Voltage at REG pin  |   | 1.75                  | 1.80           | 1.85             | V             |
| 2  | $V_{DD9}$     | Voltage at VDD9 pin   |   |                       | 9.6            |                  | V             |
| 3  | $V_{IL}$      | Digital low-level input voltage <sup>(1)</sup>              |   |                       |                | 0.5              | V             |
| 4  | $V_{IH}$      | Digital high-level input voltage <sup>(1)</sup>             |   | $V_{DDIO} \times 0.7$ |                | $V_{DDIO} + 0.3$ | V             |
| 5  | $V_{OL}$      | Digital low-level output voltage <sup>(1)</sup>             |   |                       |                | 0.4              | V             |
| 6  | $V_{OH}$      | Digital high-level output voltage <sup>(1)</sup>            |   | $V_{DDIO} \times 0.8$ |                |                  |               |
| 7  | $V_{OUT(FS)}$ | Full-scale OUTPUT voltage (at HV pin) <sup>(1)</sup>        |   | 117.5                 | 120            | 122.5            | V             |
| 8  | $I_{Q\_VIN}$  | $V_{IN}$ supply quiescent current                           | SLEEP<br>IDLE, <a href="#">OE</a> bit = 0x0<br>IDLE, <a href="#">OE</a> bit = 0x1   |                       | 6<br>14<br>350 |                  | $\mu\text{A}$ |
| 9  | $I_{Q\_VDD}$  | $V_{DD}$ supply quiescent current                           | SLEEP <sup>(1)</sup>  |                       | 1              | 10               | $\mu\text{A}$ |
|    |               |   | IDLE, <a href="#">OE</a> bit = 0x0<br>IDLE, <a href="#">OE</a> bit = 0x1  |                       | 1<br>2         | 3.5<br>4         | mA            |
| 10 | $I_{VIN,AVG}$ | Average $V_{IN}$ supply current during operation            | $f_{sig} = \text{DC}$ <sup>(2)</sup><br>$V_{OUT} = 120\text{ V}$<br>$C_{Load} = 4\text{ }\mu\text{F}$<br>$V_{IN} = 12\text{ V}$ |                       | 3              |                  | mA            |
|    |               |   | $f_{sig} = 300\text{ Hz}$<br>$V_{OUT} = 120\text{ V}$<br>$C_{Load} = 4\text{ }\mu\text{F}$<br>$V_{IN} = 12\text{ V}$            |                       | 250            |                  | mA            |
| 11 | $I_{GATELS}$  | Max. peak transient current at GDLS pin                     | Source, <a href="#">SLS</a> = 0x3<br>Sink, <a href="#">SLS</a> = 0x3  |                       | 1200<br>850    |                  | mA            |
| 12 | $I_{GATEHS}$  | Max. peak transient current at GDHS pin                     | Source, <a href="#">SHS</a> = 0x3<br>Sink, <a href="#">SHS</a> = 0x3  |                       | 1100<br>800    |                  | mA            |
| 13 | $V_{GATELS}$  | Voltage at GDLS pin activating Q <sub>1</sub>               |   |                       | 8.6            |                  | V             |
| 14 | THD+N         | Total Harmonic Distortion + Noise <sup>(1)</sup>            | $f_{sig} = 300\text{ Hz}$<br>$V_{OUT} = 120\text{ V}$<br>$C_{Load} = 4\text{ }\mu\text{F}$                                      |                       |                | 1                | %             |
| 15 | $f_s$         | Sampling rate for waveform playback <sup>(3)</sup>          | 25°C, <a href="#">PLAY[2:0]</a> = 0x0<br>25°C, <a href="#">PLAY[2:0]</a> = 0x7  | 998<br>7.8            | 1024<br>8      | 1050<br>8.2      | ksp/s         |
| 16 | DHL           | Sensing Detection to Haptic feedback latency <sup>(1)</sup> | Time from sensing detection event to automatic playback   |                       |                | 100              | $\mu\text{s}$ |

(1) Specification is assured by design and characterization data.

(2) [PARCAP\[7:0\]](#) bits can be adjusted to reduce power consumption for DC output.

(3) See Figure 12 for output frequency variation as a function of temperature.

## 5.5 Timing Characteristics (SPI)

Table 7: Timing characteristics. Conditions:  $T_A = -40^{\circ}\text{C}$  to  $105^{\circ}\text{C}$ ,  $V_{DDIO} = 3.3\text{ V}$  to  $5.5\text{ V}$ ,  $SDO\text{ load} = 20\text{ pF}$ . Specifications are assured by design and characterization data.

|    | SYMBOL      | PARAMETER  | MIN | NOM | MAX | UNIT |
|----|-------------|--|-----|-----|-----|------|
| 1  | $t_{clk}$   | Clock period <sup>(1)</sup>  | 28  |     |     | ns   |
| 2  | $t_{clkL}$  | Clock Low period   | 15  |     |     | ns   |
| 3  | $t_{clkH}$  | Clock High period  | 10  |     |     | ns   |
| 4  | $t_L$       | Time between $\overline{CS}$ falling edge and SCLK rising edge           | 18  |     |     | ns   |
| 5  | $t_H$       | Time between SCLK last falling edge and rising edge of $\overline{CS}$   | 15  |     |     | ns   |
| 6  | $t_{CS}$    | $\overline{CS}$ High time between two transmissions <sup>(2)</sup>       | 150 |     |     | ns   |
| 7  | $t_{SDI,S}$ | Input data setup time  | 4.5 |     |     | ns   |
| 8  | $t_{SDI,H}$ | Input data hold time   | 3.5 |     |     | ns   |
| 9  | $t_{SDO}$   | $\overline{CS}$ or SCLK falling edge to data output valid <sup>(1)</sup> |     |     | 14  | ns   |
| 10 | $t_{oz}$    | $\overline{CS}$ rising edge to SDO high impedance                        |     |     | 14  | ns   |

(1) Specification depend on  $V_{DDIO}$  and  $SDO$  load, see Table 8.

(2) A minimum delay of 400 ns is required if the first transaction is used to set [BC\[4:0\]](#) bits and the second transaction is used for data reading.

Table 8: Maximum SPI frequency vs.  $V_{DDIO}$  and  $SDO$  load.

|   | $V_{DDIO}$ | MAXIMUM SPI FREQUENCY ( $1/t_{clk}$ ) |                                  | UNIT |
|---|------------|---------------------------------------|----------------------------------|------|
|   |            | $SDO\text{ load} = 20\text{ pF}$      | $SDO\text{ load} = 80\text{ pF}$ |      |
| 1 | 1.8 V      | 13                                    | 10                               | MHz  |
| 2 | 2.5 V      | 28                                    | 20                               | MHz  |
| 3 | 3.3 V      | 35                                    | 30                               | MHz  |
| 4 | 5.5 V      | 35                                    | 30                               | MHz  |

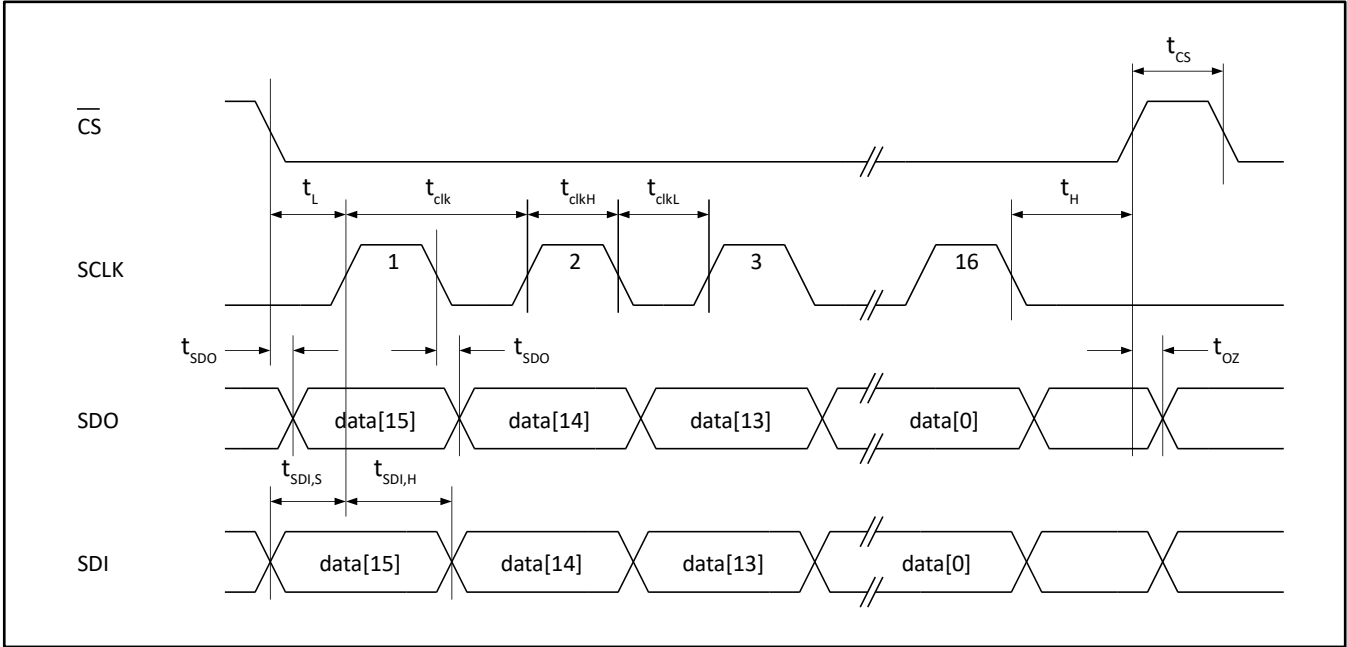


Figure 3: SPI timing diagram

## 5.6 Typical Performance Characteristics

Typical performance characteristics for the following conditions:  $T_A = 25^\circ\text{C}$ ,  $V_{IN} = 12\text{ V}$ ,  $C_{OUT} = 4\text{ }\mu\text{F}$ ,  $V_{OUT} = 120\text{ V}_{pk-pk}$  and  $f_{OUT} = 300\text{ Hz}$  (unless otherwise noted).

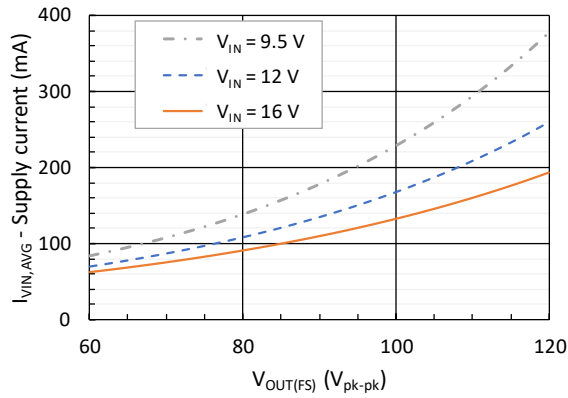


Figure 4:  $V_{IN}$  supply current vs output voltage

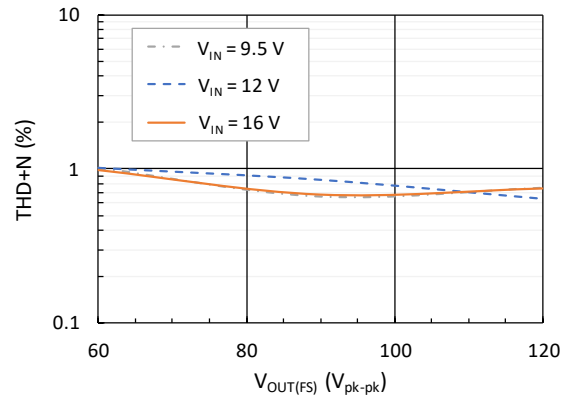


Figure 5: Total harmonic distortion + noise vs output voltage

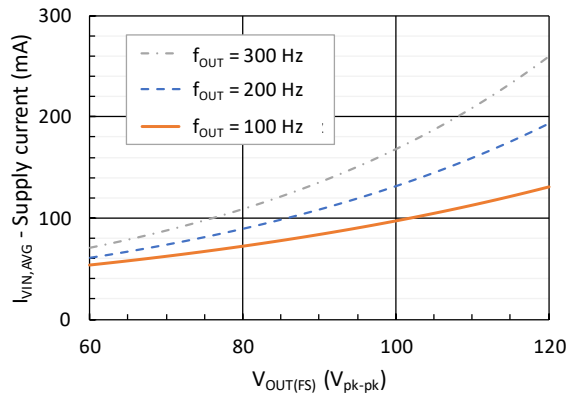


Figure 6:  $V_{IN}$  supply current vs output voltage

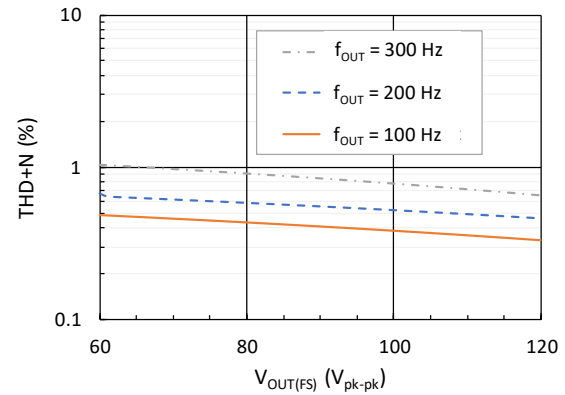


Figure 7: Total harmonic distortion + noise vs output voltage

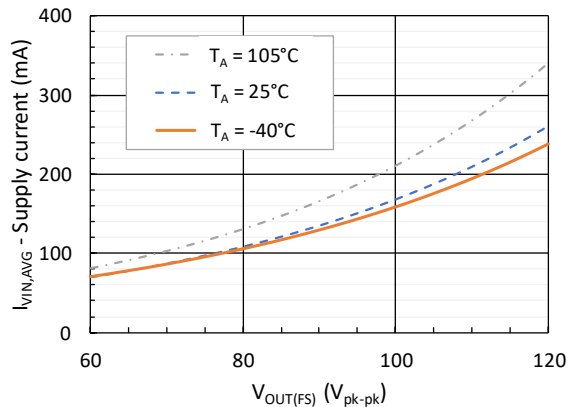


Figure 8:  $V_{IN}$  supply current vs operating free-air temperature

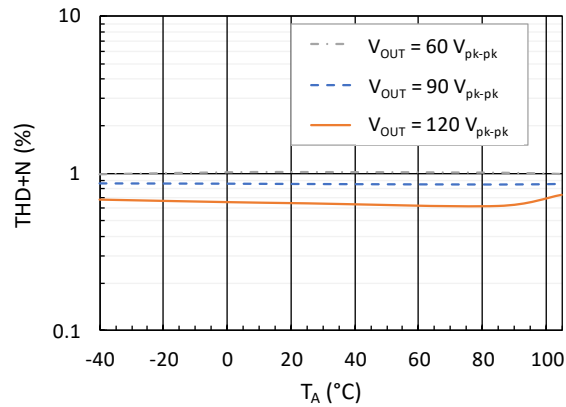


Figure 9: Total harmonic distortion + noise vs operating free-air temperature



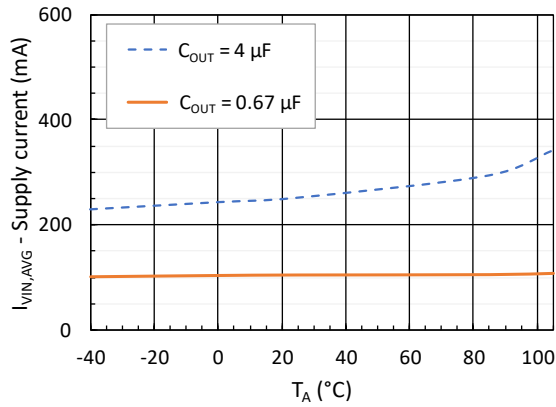


Figure 10:  $V_{IN}$  supply current vs operating free-air temperature

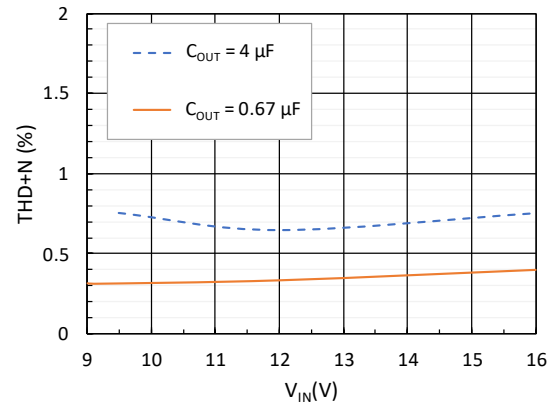


Figure 11: Total harmonic distortion + noise vs input voltage<sup>2</sup>

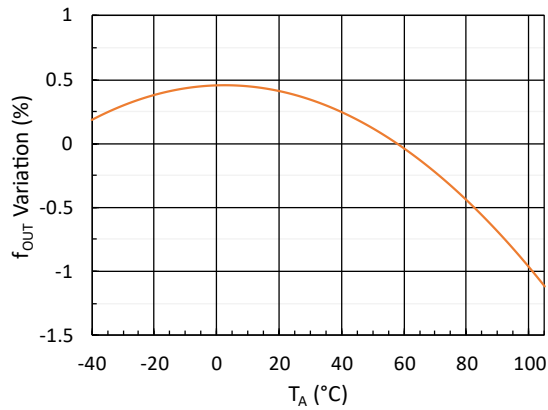


Figure 12: Output frequency variation vs operating free-air temperature

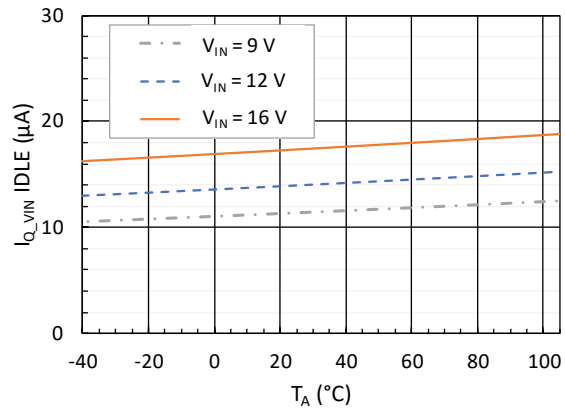


Figure 13:  $V_{IN}$  supply quiescent current in IDLE state vs operating free-air temperature

<sup>2</sup> Data for a load of 4  $\mu F$  starts at a  $V_{IN}$  of 9.5 V because playing a waveform while having a  $V_{IN}$  lower than 9.5 V triggers the [UVLO12](#) error flag.

## 6 Functional Description

### 6.1 Overview

The BOS1211 is a scalable haptic piezo actuator controller with integrated digital front end, including a FIFO and a Waveform Synthesizer (WFS). The BOS1211 implements a dynamic buck-boost conversion with energy recovery, based on Boreas's patented CapDrive™ Technology. The BOS1211 integrates a low-side and high-side NMOS gate drivers. The controller is compatible with 12 V systems. It can generate HD haptic waveforms with amplitude up to 120 V for a wide range of piezo actuators including TDK PowerHap 120 V portfolio. Interpolation between samples is done to smooth the haptic waveform. The digital interface enables the user to stream the waveforms data from any MCU with an SPI port. A flexible FIFO interface enables the user to continuously stream the digital waveform data for playback or to transmit burst data. Data from the FIFO can be read at different sample rates. The digital front-end also integrates a Waveform Synthesizer (WFS) and 2-kB on-chip RAM with two waveform generation modes: RAM Playback and RAM Synthesis. These two modes allow haptic waveforms generation with minimal intervention from the host MCU.

The digital front-end gives access to many internal registers, enabling the user to optimize the performance of the device for a specific application. For instance, the voltage on the piezo actuator can be read at any time, allowing the development of advanced sensing algorithms and use a piezo actuator as a force sensor at the input of a system. Finally, the BOS1211 also includes an embedded sensing comparator enabling the controller to detect a pressure applied on a piezo actuator, automatically play a pre-programmed haptic waveform feedback and notify the MCU of an event.

The BOS1211 can use many commercial off-the-shelf (COTS) inductors. The inductor can be chosen to optimize the power, size or performance trade-off for the user application. With a start-up time of less than 500 µs from SLEEP state, the BOS1211 is ideal for low latency haptic feedback.

### 6.2 Features

#### 6.2.1 Digital Front-End Interface

The BOS1211 uses a 35 MHz SPI target interface. This high-speed communication interface enables to share a common communication bus for multi-actuator systems. The digital front-end gives access to internal registers that control the device operation and performance, see section 7.5 for details.

#### 6.2.2 GPO

One general-purpose digital output (GPO) is available and can be used as an interruption to notify the host MCU of various events using [GPO\[2:0\]](#) bits such as haptic detection events or an error. The GPO is a push-pull output between V<sub>DDIO</sub> and GND.

#### 6.2.3 Flexible Haptic Waveform Generation

##### 6.2.3.1 Direct Mode

With [MODE\[1:0\]](#) bits set to 0x0, the haptic waveform samples are played as they are sent from the host MCU to RAM using [REFERENCE](#) register. The rate at which the RAM data is read to generate the haptic waveform is set by [PLAY\[2:0\]](#) bits. See section 6.5 for details.

### 6.2.3.2 FIFO Mode

A 1024-sample FIFO is available for waveform playback with [MODE\[1:0\]](#) bits set to 0x1. The FIFO entries are appended every time waveform samples are written in the [REFERENCE](#) register. Digital samples are represented as 12-bit unsigned values. If [OE](#) bit is set to 0x1, the FIFO entries are read automatically out of the FIFO at a rate set by [PLAY\[2:0\]](#) bits. See section 6.6 for more details.

### 6.2.3.3 RAM Playback Mode

RAM Playback mode is selected with [MODE\[1:0\]](#) bits set to 0x2. In RAM Playback mode, the on-chip RAM of 2 kB is used to store haptic waveforms as waveform amplitude samples in 12-bit unsigned format with minimum interventions from the MCU. The waveform is sampled at a rate set by [PLAY\[2:0\]](#) bits. See section 6.7 for details.

### 6.2.3.4 RAM Synthesis Mode

RAM Synthesis mode is selected with [MODE\[1:0\]](#) bits set to 0x3. In RAM Synthesis mode, the BOS1211 uses the Waveform Synthesizer (WFS) to generate waveforms using parameters stored in the 2 kB RAM. RAM Synthesis mode allows generating sinusoidal waveforms of various amplitudes and frequencies without having to send every sample of the waveform to RAM as is the case with RAM Playback mode. This allows complex waveforms to be produced with minimal data communication. See section 6.8 for details.

### 6.2.4 SLEEP state

When no haptic waveform is being requested ([OE](#) bit set to 0x0), the BOS1211 can enter in one of the two low-power modes: IDLE or SLEEP state. [DS](#) bit sets the device power mode when no haptic waveform is requested. By default, the power mode is IDLE ([DS](#) bit set to 0x0). SLEEP state is selected when [DS](#) bit is set to 0x1. In SLEEP, the BOS1211 is in its lowest power state and all registers are set back to their default values as well as the RAM data is reset. The BOS1211 goes out of SLEEP state on pin  $\overline{CS}$  falling edge.

### 6.2.5 Low Latency Startup

The BOS1211 features a fast start-up time. From IDLE or SLEEP state, the device takes approximately 500  $\mu$ s to start playing the waveform when the auto-calibration piezo zeroing is set to 500  $\mu$ s ([SHORT\[1:0\]](#) bits set to 0x0). That makes the BOS1211 a very small contributor to system latency.

### 6.2.6 Piezo Actuator Sensing

The digital front-end gives access to internal registers [0xA](#) and [0x12](#) that allow the use of piezo actuators as a force sensor.

The BOS1211 features an embedded sensing comparator that can be configured to detect a sensing event. The sensing comparator can adapt to a specific application by setting its voltage threshold ([STHRESH\[8:0\]](#) bits), hold time ([REP\[2:0\]](#)) and crossing direction ([SIGN](#) bit).

It is also possible to automatically trigger an programmed waveform when a sensing event is detected by the sensing comparator. GPO output pin can be configured using [GPO\[2:0\]](#) bits to inform the MCU that a sensing event occurred or that the triggered waveform has finished playing. Setting [BC\[4:0\]](#) bits to 0x12 will output sensing voltage data, which can be read at any time and is useful for MCU-based customized sensing algorithms. See section 6.9 for details.

### 6.2.7 Device Reset

The BOS1211 device has software-based reset functionality. When [RST](#) bit is set, all registers are set to their default value and the BOS1211 goes to IDLE state. [RST](#) bit self-clears once the reset is complete.

The following sequence must be done to safely reset the device while playing a waveform in FIFO or Direct mode:

1. Set [CONFIG.OE](#) bit must be set to 0x0.
2. Wait for the device to be in IDLE by polling [IC\\_STATUS.STATE\[1:0\]](#) bits.
3. Reset the device by setting [RST](#) bit to 0x1.

### 6.2.8 Actuator Synchronization

Multiple BOS1211 devices can play haptic waveforms simultaneously using the SYNC pin. This feature allows synchronizing a waveform across several devices with a phase delay of less than 2  $\mu$ s between them.

Synchronization is achieved by connecting the SYNC pin of all devices together. A 10 k $\Omega$  pull-up resistor is needed between SYNC pin node and V<sub>DDIO</sub>. Synchronization is performed as the wave is played with a signal on the SYNC pin having a frequency that depends on the sampling rate defined by [PLAY\[2:0\]](#) bits.

The following sequence presents an example allowing synchronizing two BOS1211 devices:

1. On both devices perform the following configuration:
  - a. In the [CONFIG](#) register:
    - i. Set [CONFIG.OE](#) bit to 0x0 to disable the haptic waveform generation.
    - ii. Set [CONFIG.PLAY\[2:0\]](#) bits to the desired sampling rate.
    - iii. Set [CONFIG.SYNC](#) bit to 0x1 to enable device synchronization.
  - b. Set [RAM.MODE\[1:0\]](#) bits to 0x2 or 0x3 to select RAM Playback or RAM Synthesis mode.
  - c. Properly configure the waveform depending on the mode selected (see section 6.7 or 6.8).
2. Set [CONFIG.OE](#) bit to 0x1 on device 1.
3. Set [CONFIG.OE](#) bit to 0x1 on device 2 and waveform will start playing on both devices.

### 6.2.9 Adjustable Current Limit

The maximum current of the BOS1211 power converter must be limited to avoid damage to the inductor. Current flowing in the inductor is determined by the BOS1211 by measuring the voltage drop across R<sub>sense</sub> placed between pins VIN/RP and RM. The current limit of the power converter is adjusted by selecting the proper R<sub>sense</sub> value (see section 7.4.3 for more detail).

The current limit of Q<sub>1</sub> and Q<sub>2</sub> NMOS transistors should be selected based on the following:

- Ensure that the current is lower than the saturation limit of the inductor L<sub>1</sub>.
- Ensure that the current is high enough to allow sufficient energy transfer to and from the piezo actuator.

The circuit should be tested under worst-case conditions to ensure that the BOS1211 will meet the bandwidth requirement of the application (see section 7.4.5 for more detail).

### 6.2.10 Energy Recovery

The BOS1211 implements bidirectional power transfer: input ( $V_{IN}$ ) to OUTPUT, and OUTPUT to input ( $V_{IN}$ ), which makes the device power efficient. Such architecture enables the recovery of the energy accumulated on the capacitive load and transfers it back to the input ( $C_{VIN}$ ). The internal controller determines the direction of the power flow during waveform playback.

### 6.2.11 Adjustable Internal Clock

The internal BOS1211 clock oscillator frequency is trimmed during fabrication using hardware fuses. When initialized, the BOS1211 retrieves the hardware fuse values and push them to the TRIM block to adjust the oscillator frequency based on the fuse values (Figure 21). The [TRIM](#) register allows modifying the TRIM value to adjust oscillator frequency.

This feature can be used to match the external system clock frequency with the BOS1211 internal clock frequency, which is used to determine the FIFO read-out rate. This might be needed to minimize waveforms distortion if the user writes waveform data at a constant rate to the FIFO, without managing space available in it. To successfully adjust internal clock frequency, [OE](#) bit must be set to 0x0.

The internal oscillator can be adjusted with the following sequence:

1. Set [OE](#) bit to 0x0.
2. Set [TRIM.TRIMRW\[1:0\]](#) bits to either one of the following values:
  - a. Set to 0x1 to latch the hardware fuses and push their value into the TRIM block and the [TRIM](#) register, or
  - b. Set to 0x2 to retrieve the oscillator trim value contained in the TRIM block and push it to the [TRIM](#) register.
3. Wait for 1 ms.
4. Read [TRIM.TRIM OSC\[6:0\]](#) bits to get the internal oscillator trim value specific to the device.
5. In one transaction, set the [TRIM](#) register with the following fields:
  - a. [TRIM.TRIM OSC\[6:0\]](#) bits set to the desired value.
  - b. [TRIM.TRIMRW\[1:0\]](#) bits set to 0x3 to write [TRIM OSC\[6:0\]](#) value to TRIM block.

The same procedure can be used to adjust the internal 1.8 V regulator voltage using [TRIM REG\[2:0\]](#) bit instead of [TRIM OSC\[6:0\]](#).

### 6.2.12 Fault Behavior

This section lists the various faults detected by the device. Note that the faults detected by the device may be caused by the following:

- Device operating outside of its safe operating conditions.
- Wrong component value (e.g.,  $R_{sense}$ ,  $C_{HV}$  or  $L_1$ ).
- Noise induced by improper printed circuit board layout.

If one of the following faults is detected, the device will safely ramp down the OUTPUT node voltage to  $V_{IN}$  and raise an error flag with a specific error code.

#### 6.2.12.1 Overvoltage

If an overvoltage condition at the HV pin is detected during waveform generation, [OVV](#) bit is set, and the OUTPUT node voltage will safely ramp down to  $V_{DD}$ . A software reset ([RST](#) bit set to 0x1) is required to clear the fault and resume normal operation.

### 6.2.12.2 Output Short Circuit

The BOS1211 has an output short circuit protection to prevent excessive current to flow because of a short-circuit load. In case the short circuit condition is detected during waveform generation, [SC](#) bit is set and BOS1211 is put in IDLE state. A software reset ([RST](#) bit set to 0x1) is required to clear the fault and resume normal operation.

### 6.2.12.3 Overtemperature

The BOS1211 has an internal temperature sensor that puts the device in IDLE state in case the die temperature exceeds 145 °C. In this condition, [OVT](#) bit is set and will clear automatically once conditions are safe for a restart.

The BOS1211 device is unlikely to reach 145 °C even during continuous operation at maximum load in the  $T_A$  operating range because of its low power dissipation.

### 6.2.12.4 Brownout

The BOS1211 has internal brownout protections. If  $V_{REG}$  goes below 1 V, the device issues a reset signal, and all registers are set back to their default value. When  $V_{REG}$  goes back to a normal operating voltage, the BOS1211 goes to the IDLE state.

### 6.2.12.5 Under Voltage/Over Voltage Lockout

The controller also monitors the  $V_{IN}$  and  $V_{DD}$  supplies to ensure the minimum conditions are met to operate. The controller won't start a waveform if the voltage is below or above specified limits. Table 9 presents those limits.

If an under/overvoltage condition at  $V_{IN}$  is detected during waveform generation, the following events occur:

- [UVLO12/OVLO12](#) bit is set to 0x1.
- [STATE\[1:0\]](#) bits are set to 0x3 (ERROR state).

If an undervoltage condition at  $V_{DD}$  is detected, the following events occur:

- [UVLO5](#) bit is set to 0x1.
- [STATE\[1:0\]](#) bits are set to 0x3 (ERROR state).

The BOS1211 will go to IDLE state ([STATE\[1:0\]](#) bits to 0x0) with the following conditions:

- $V_{IN}$  and  $V_{DD}$  go back to a normal operating voltage.
- [OE](#) bit is reset to 0x0.

Table 9: Under voltage / over voltage lockout limits

| Supply   | UVLO limit | OVLO limit | Unit |
|----------|------------|------------|------|
| $V_{IN}$ | 8.8        | 19.9       | V    |
| $V_{DD}$ | 4.4        | N/A        | V    |

### 6.2.12.6 Current Detection Status Fault

For proper operation, the BOS1211 monitors the current using  $R_{sense}$  resistor connected to  $V_{IN}/RP$  and  $RM$  pins. If no current is detected during waveform generation, the following event occurs:

- [IC STATUS.IDAC](#) fault bit is set.
- [IC STATUS.STATE\[1:0\]](#) bits are changed to 0x3 (ERROR state).

Typically, [IDAC](#) bit is set when  $R_{sense}$  or  $L_1$  is disconnected.

The BOS1211 will go to IDLE state ([STATE\[10\]](#) bits to 0x0) with the following conditions:

- $V_{IN}$  and  $V_{DD}$  go back to a normal operating voltage.
- [OE](#) bit is reset to 0x0.

### 6.3 Automatic Output Shutdown

[TOUT](#) bit allows programming a 4 ms timeout delay after which the device will automatically go to SLEEP if it didn't receive a proper communication on its digital interface.

### 6.4 SPI Interface

A target SPI port enables communication with the BOS1211. SPI is a 4-wire synchronous serial interface that uses two control lines and two data lines: Chip Select ( $\overline{CS}$ ), Serial Clock (SCLK), Serial Data Output (SDO) and Serial Data Input (SDI). These signals are in the  $V_{DDIO}$  voltage domain.

The SPI interface supports 16 bits per transfer. Transfer is done in full duplex: data is output on SDO at the same time data is sent on SDI.

SPI transmission starts when  $\overline{CS}$  line goes low and ends when  $\overline{CS}$  line goes high. Each SPI target device requires its own  $\overline{CS}$  line from the controller. The Figure 14 shows the correct configuration for the SPI Controller. Because different manufacturers have different definitions of SPI modes, the user should rely on Figure 14 to select the appropriate SPI mode for its MCU.

The SPI communication bus features the following:

1. Each transmission is 16 bits.
2. MSB is sent first.
3. Data is latched on the rising edge of SCLK.
4. Input Data should be transitioned on the falling edge of SCLK.
5. Data rates up to 35 Mbps are supported.
6. Single and burst read/write transmissions are supported. For burst data transmission,  $\overline{CS}$  line can be maintained low.

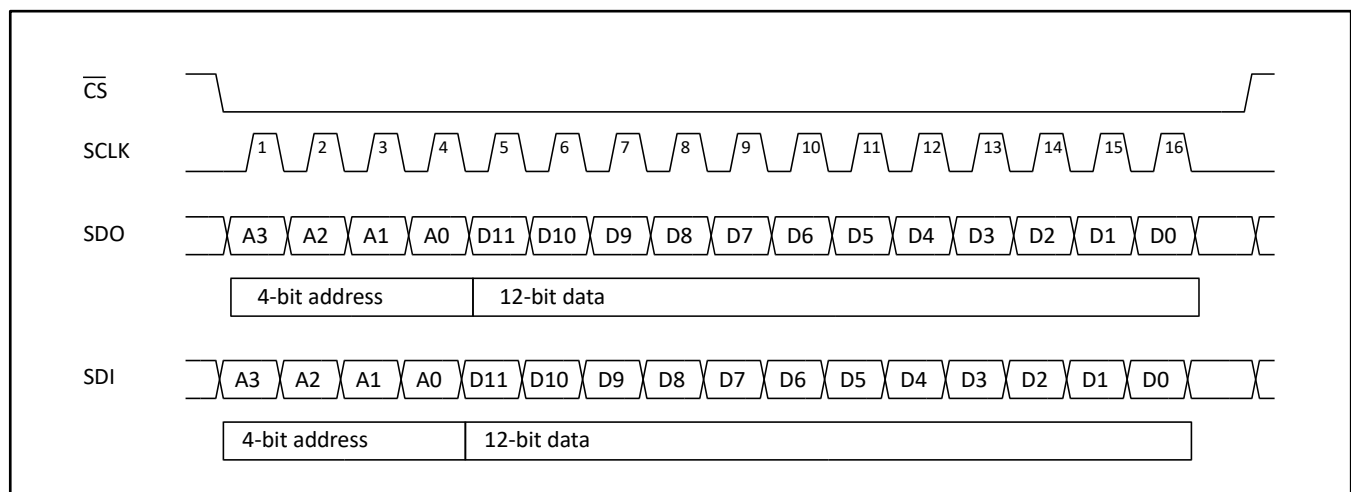


Figure 14: SPI typical specification



## 6.5 Direct Mode

In Direct mode ([MODE\[1:0\]](#) bits set to 0x0), the haptic waveform samples are played as they are sent from the host MCU to the [REFERENCE](#) register. The rate at which the data is read to generate the haptic waveform is set by [PLAY\[2:0\]](#) bits.

Data management and synchronization can be facilitated by setting [GPO \[2:0\]](#) bits to 0x7 to allow the GPO to generate an interruption pulse that notifies the MCU when the device is ready to receive the next sample.

When [MODE\[1:0\]](#) bits is set to 0x0 to use Direct mode, RAM is not used and its content previously written using RAM Playback mode (section 6.7) or RAM Synthesis mode (section 6.8) is preserved.

Note that waveforms should begin and end with 0 V amplitude.

### 6.5.1 Typical Operation Sequence

The following sequence use Direct mode to play haptic waveforms:

1. Set [RAM.MODE\[1:0\]](#) bits to 0x0 to select Direct mode.
2. In the CONFIG register:
  - a. Set [CONFIG.OE](#) to 0x1.
  - b. Set [CONFIG.PLAY\[2:0\]](#) to the desired sampling rate.
3. Set [SPI.GPO\[2:0\]](#) bits to 0x7 to allow the GPO pin to generate an interruption to notify the MCU when the device is ready to receive the next sample.
4. Write the 12-bit waveform data into the [REFERENCE](#) register.
5. Monitor the GPO pin and wait until the device is ready to receive the next sample.
6. Repeat step 4 and 5 until the desired waveform is completed.

## 6.6 FIFO Mode

In FIFO mode ([MODE\[1:0\]](#) bits set to 0x1), the waveform playback is set in a 1024-sample FIFO. The FIFO entries are appended every time waveform data is written in the [REFERENCE](#) register. Digital samples are represented as 12-bit unsigned values. The waveform is played when [OE](#) bit is set to 0x1 at a rate set by [PLAY \[2:0\]](#) bits. For waveform playback streaming, the user should ensure the FIFO never becomes empty. If the FIFO becomes empty, [EMPTY](#) bit is set and the FIFO maintains the last valid data, keeping the waveform in a steady state. [FULL](#) bit is set when the FIFO is full and cannot accept more data.

Burst data transfers can be used to minimize the communication interface usage (see section 6.4). In this use case, packets of 16-bit words can sequentially be written in the FIFO at a maximum speed of 35 Mbps. [FIFO\\_SPACE \[9:0\]](#) field can be read prior writing burst data to validate the space available.

Waveforms should begin and end with 0 V amplitude. If [OE](#) bit is set to 0x0 during waveform playback, the voltage across the piezo actuator will be ramped down to 0 V and the remaining data in the FIFO will be preserved.

The device uses RAM to implement FIFO. Using FIFO mode overwrites any waveform data previously programmed using RAM Playback mode (section 6.7) or RAM Synthesis mode (section 6.8).



Note the following:

- For waveform playback streaming, the FIFO data write rate must match the readout rate of the waveform playback set by [PLAY\[2:0\]](#) bits to always keep valid data inside the FIFO. The [EMPTY](#) bit is set to 0x1 when the FIFO becomes empty, causing the FIFO to hold the last valid data and keep the output waveform in a steady state.
- Waveforms should begin and end with 0 V amplitude.
- In case OE bit is set to 0x0 during waveform playback, the output will ramp down automatically to 0 V and the remaining FIFO entries will be kept and played the next time OE bit is set to 0x1 again.

### 6.6.1 Typical Operation Sequence

The following sequence use FIFO mode to play haptic waveforms:

1. Set [RAM.MODE\[1:0\]](#) bits to 0x1 to select FIFO mode.
2. In the [CONFIG](#) register:
  - a. Set [CONFIG.OE](#) bit to 0x1 to enable the haptic waveform generation.
  - b. Set [CONFIG.PLAY\[2:0\]](#) bits to the desired sampling rate.
3. Read [FIFO STATUS](#) register to determine how much space is available in the FIFO for new data.
4. Write as much 12-bit waveform data as possible according to the available space in the FIFO into the [REFERENCE](#) register.
5. Read [FULL](#) bit to determine if the FIFO can accept more data.
  - a. If more data can be accepted, repeat steps 3, 4 and 5 until the desired waveform is completed.
  - b. If the FIFO is FULL repeat step 5.

### 6.6.2 FIFO Example

In section 6.6.1, the FIFO is filled after setting [OE](#) bit to 0x1. Table 10 is an example where the waveform data is written in the FIFO before setting [OE](#) bit to 0x1.

Table 10: FIFO mode example

| Code                          | Description   |
|-------------------------------|---|
| Configure for FIFO mode:      |   |
| 0x8001                        | Select FIFO mode to <a href="#">RAM</a> register.                           |
| Write Data to FIFO:           |   |
| 0x0000                        | Write waveform sample data to <a href="#">REFERENCE</a> register.           |
| 0x0066                        |   |
| 0x00CC                        |   |
| 0x0132                        |   |
| 0x0198                        |   |
| 0x01FE                        |   |
| 0x0264                        |   |
| 0x02CA                        |   |
| 0x0330                        |   |
| 0x0393                        |   |
| 0x0330                        |   |
| 0x02CA                        |   |
| 0x0264                        |   |
| 0x01FE                        |   |
| 0x0198                        |   |
| 0x0132                        |   |
| 0x00CC                        |   |
| 0x0066                        |   |
| 0x0000                        |   |
| Configure the Waveform Start: |   |
| 0x5017                        | Set <a href="#">CONFIG.OE</a> bit to 0x1 to start haptic waveform playback. |

## 6.7 RAM Playback

In RAM Playback mode ([MODE](#) bits set to 0x2), the waveform to be played is defined by storing all the amplitude samples in sequence in RAM. The waveform is played when [OE](#) bit is set to 0x1.

The samples are written to RAM using the [BURST RAM WRITE](#) WFS command. More than one waveform can be stored in RAM. The 2 kB memory can store up to 1024 samples. Each sample defines a 16-bit data word containing the 12-bit waveform amplitude in the 12 LSBs of that word and using the same format as the [REFERENCE](#) register. The start and end RAM address must be stored in the [RAM PLAYBACK](#) command, which indicates the RAM address of the samples to be fetched when the playback is initiated. When playback starts, the data is read out sequentially at the sample rate set by [PLAY \[2:0\]](#) bits. An interpolation is done between user samples to generate the output waveform when [PLAY \[2:0\]](#) bits are 0x1 to 0x7.

The start and end RAM addresses must be written again using the [RAM PLAYBACK](#) command each time a waveform already programmed in RAM needs to be played again (see section 6.7.1).

Note that waveforms should begin and end with 0 V amplitude.

### 6.7.1 Typical Operation Sequence

The following sequence shows how to use RAM Playback mode to play haptic waveforms:

1. In the [RAM](#) register:
  - a. Set [RAM.MODE\[1:0\]](#) to 0x2 to select RAM playback mode.
  - b. Set [RAM.RAMSEL](#) to 0x1 so that subsequent SPI communication is sent to the WFS command interpreter.
2. Program RAM using [BURST RAM WRITE](#) command. See section 6.7.2 for an example. To keep access to the WFS command interpreter, make sure the SPI transactions are sent within 4  $\mu$ s of each other to continue writing in RAM.
3. Write the start and end RAM address using [RAM PLAYBACK](#) WFS command.
4. Wait for more than 4  $\mu$ s to access to the main register map.
5. Set [BC\[4:0\]](#) to 0xC to output [IC STATUS](#) register content on SDO pin.
6. In the [CONFIG](#) register:
  - a. Set [CONFIG.OE](#) bit to 0x1 to start haptic waveform playback.
  - b. Set [CONFIG.PLAY\[2:0\]](#) bits to the desired sampling rate.
7. Poll [EMPTY](#) bit on SDO communication port until it is set to 0x1 and waveform is completed.
8. Set [CONFIG.OE](#) bit to 0x0 to deactivate haptic waveform playback.

To start playback with sensing detection, the sensing parameters can be configured between step 4. and 5. See section 6.9 for sensing configuration details.

### 6.7.2 RAM Playback Example

An example of waveform playback is presented in Table 11 where a waveform of 9 samples is played. Table 12 is an example where a waveform already programmed in RAM is played.

Table 11: Example of playing a haptic waveform using RAM Playback mode

| Code  | Description  |
|---|--|
| Configure RAM playback:                                       |  |
| 0x8006  | Select RAM Playback mode and request access to the WFS command interpreter. The following SPI transactions must be sent less than 4 $\mu$ s from each other to keep using WFS command interpreter. |
| 0x0014  | Use <a href="#">BURST RAM WRITE</a> WFS command.   |
| 0x0000  | Set RAM start RAM address to 0x0000.   |
| 0x000A  | Set Data count (10 samples to be written starting at address 0x0000).  |
| 0x0000  | Sample Data at RAM address 0x0000.   |
| 0x0066  | Sample Data at RAM address 0x0001.   |
| 0x00CC  | Sample Data at RAM address 0x0002.   |
| 0x0132  | Sample Data at RAM address 0x0003.   |
| 0x0198  | Sample Data at RAM address 0x0004.   |
| 0x0198  | Sample Data at RAM address 0x0005.   |
| 0x0132  | Sample Data at RAM address 0x0006.   |
| 0x00CC  | Sample Data at RAM address 0x0007.   |
| 0x0066  | Sample Data at RAM address 0x0008.   |
| 0x0000  | Sample Data at RAM address 0x0009.   |
| 0x0013  | Use <a href="#">RAM Playback</a> WFS command.  |
| 0x0000  | Set RAM Playback start address to 0x0000.  |
| 0x0009  | Set RAM Playback end address to 0x0008.  |
| Wait for more than 4 $\mu$ s to access to the main registers. |  |
| Start and stop waveform playback:                             |  |
| 0x9628  | Set <a href="#">BC[4:0]</a> to 0xC to output <a href="#">IC STATUS</a> register content on SDO pin.  |
| 0x5017  | Set <a href="#">OE</a> bit to 0x1 to start haptic waveform playback.   |
| 0x0000  | Poll <a href="#">EMPTY</a> bit on SDO communication port until it is set to 0x1 and waveform is completed.   |
| 0x5007  | Set <a href="#">OE</a> bit to 0x0 to deactivate haptic waveform playback.  |

Table 12: Example of playing a haptic waveform already programmed in RAM using RAM Playback mode

| Code  | Description  |
|---|--|
| Set start and end RAM addresses:                              |  |
| 0x8006  | Select RAM Playback mode and request access to the WFS command interpreter. The following SPI transactions must be sent less than 4 $\mu$ s from each other to keep using WFS command interpreter. |
| 0x0013  | Use <a href="#">RAM Playback</a> WFS command.  |
| 0x0000  | Set RAM Playback start address to 0x0000.  |
| 0x0009  | Set RAM Playback end address to 0x0008.  |
| Wait for more than 4 $\mu$ s to access to the main registers. |  |
| Start and stop waveform playback:                             |  |
| 0x9628  | Set <a href="#">BC[4:0]</a> to 0xC to output <a href="#">IC STATUS</a> register content on SDO pin.  |
| 0x5017  | Set <a href="#">OE</a> bit to 0x1 to start haptic waveform playback and <a href="#">PLAY[2:0]</a> to set sample rate to 8 ksp/s.   |
| 0x0000  | Poll <a href="#">EMPTY</a> bit on SDO communication port until it is set to 0x1 and waveform is completed.   |
| 0x5007  | Set <a href="#">OE</a> bit to 0x0 to deactivate haptic waveform playback.  |

## 6.8 RAM Synthesis Mode

In RAM Synthesis mode ([MODE](#) bits set to 0x3), RAM stores sine wave parameters to generate simple and complex waveforms using the following:

- 1) SLICES, written in RAM using the [RAM SYNTHESIS WRITE](#) command. Each SLICE contains a group of parameters used to produce a sine wave of defined amplitude, frequency, and number of cycles. It may also be ramped up and down (as shown in Figure 17). See section 6.8.1.1 for more details.
- 2) WAVES, written in RAM using the [RAM SYNTHESIS WRITE](#) WFS command. A WAVE defines a series of SLICES to be played successively. All SLICES of a WAVE must be written in order and contiguously in RAM. See section 6.8.1.2. for more details.
- 3) SEQUENCES, written using the [SEQUENCER](#) WFS command. The [SEQUENCER](#) command is used to store up to 15 WAVE addresses in RAM (called WAVEFORM\_IDs). The WAVES may all be played sequentially, or in any contiguous subsets, down to a single WAVEFORM\_ID. See section 6.8.1.3 for more details.

The [SEQUENCE START/STOP](#) WFS command defines the start and end WAVEFORM\_IDs from the WAVEFORM\_IDs list stored using the [SEQUENCER](#) command.

The start and end WAVEFORM\_IDs must be written again using the [SEQUENCE START/STOP](#) WFS command each time a waveform already programmed in RAM needs to be played again (see section 6.8.3).

### 6.8.1 RAM Programming

WAVE and SLICE data are stored in RAM. RAM is divided in two sections as shown in Figure 15. The first section stores the WAVE blocks, and the second section stores the SLICES.

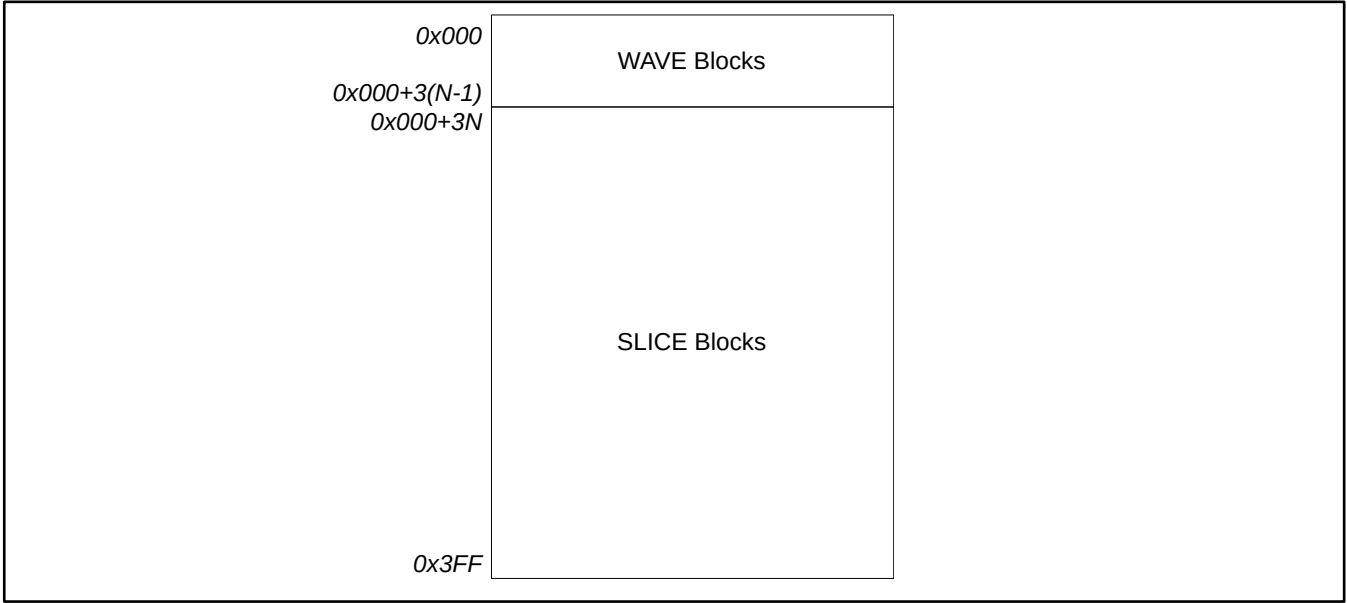


Figure 15: Example of  $N$  WAVE blocks followed with SLICES organized in RAM ( $1024 \times 16\text{-Bit}$ )

6.8.1.1 SLICE Blocks

SLICE blocks in RAM contains the parameters used to synthesize sine waveforms. Each SLICE block contains three words grouping five parameters as described in Figure 16 and Table 13. The Figure 17 illustrates how SLICE parameters shape a SLICE waveform. Many SLICES may be successively played to form complex waveforms.

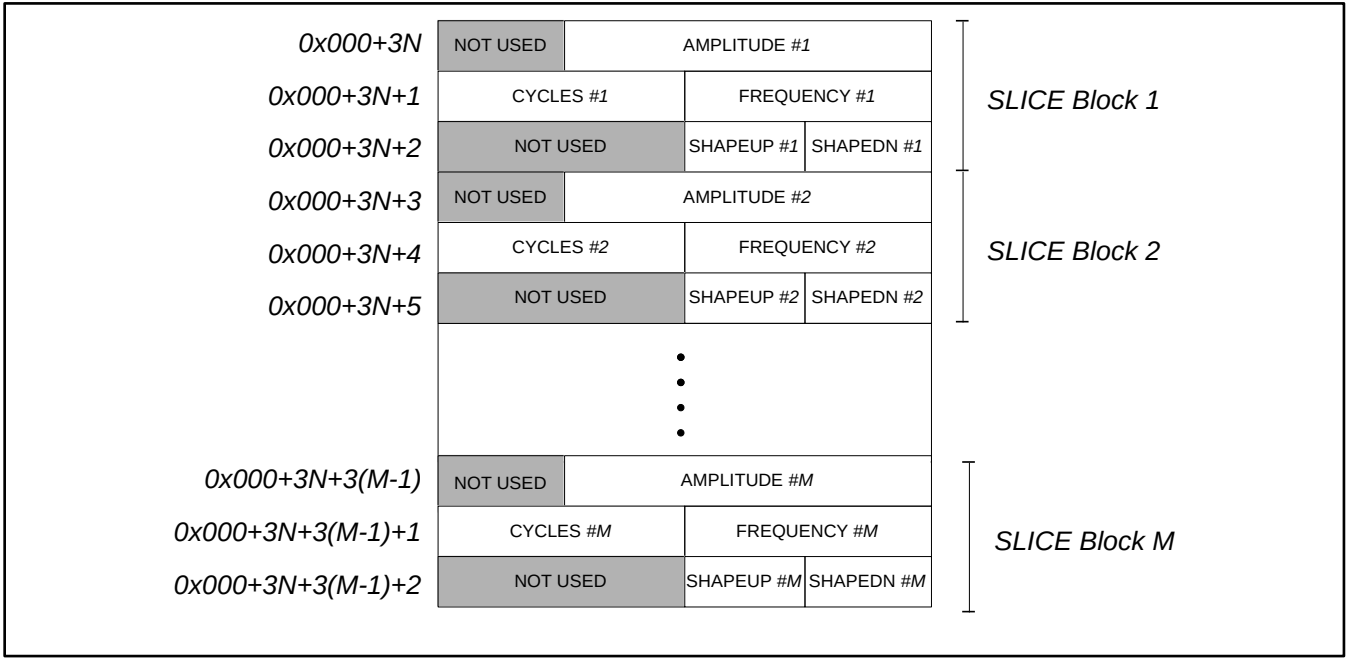


Figure 16:  $M$  SLICE blocks in RAM preceded by  $N$  WAVE blocs

Table 13: Sine wave SLICE parameters

| 15             | 14       | 13        | 12  | 11              | 10 | 9 | 8 | 7              | 6 | 5 | 4 | 3            | 2 | 1 | 0 |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
|----------------|----------|-----------|---|-----------------|----|---|---|----------------|---|---|---|--------------|---|---|---|------|----------|------|-------|------|-------|------|-------|------|--------|------|--------|------|--------|------|--------|------|--------|------|--------|------|--------|------|---------|------|---------|------|---------|------|---------|------|---------|
| NOT USED: 0x0  |          |           |   | AMPLITUDE[11:0] |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| CYCLES[7:0]    |          |           |   |                 |    |   |   | FREQUENCY[7:0] |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| NOT USED: 0x00 |          |           |   |                 |    |   |   | SHAPEUP[3:0]   |   |   |   | SHAPEDN[3:0] |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| WORD           | BITS     | NAME      | DESCRIPTION   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 1              | 11:0     | AMPLITUDE | <p>Sets the output waveform peak voltage amplitude (<math>V_{OUT-pk}</math>) as follows:</p> $AMPLITUDE[11:0] = \frac{4095 \times V_{OUT-pk}}{120}$ <p>This AMPLITUDE value calculation is valid only for RAM Synthesis mode (<a href="#">MODE[1:0]</a> bits set to 0x3).</p>   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 2              | 15:8     | CYCLES    | CYCLES refers to the number of times a full sine wave period will be repeated, excluding the ramp-up and ramp-down duration set by <a href="#">SHAPEUP[3:0]</a> and <a href="#">SHAPEDN[3:0]</a> .  |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 2              | 7:0      | FREQUENCY | <p>The waveform synthesizer has a frequency resolution of 3.9 Hz.</p> <p>The synthesized sine wave frequency will be:</p> $\text{Synthesized sine wave frequency (Hz)} = 3.9 \times FREQUENCY$  |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 3              | 7:4      | SHAPEUP   | <p>SHAPEUP [3:0] sets the time to ramp up from 0 V to <math>V_{OUT-PK}</math>.</p> <p>SHAPEDN[3:0] sets the time required to ramp down from <math>V_{OUT-pk}</math> to 0 V.</p> <p>SHAPEUP and SHAPEDN duration must be greater than the waveform period and are added to the SLICE waveform duration. The SLICE waveform duration in <i>ms</i> (<math>t_{SLICE}</math>) is calculated as follows:</p> $t_{SLICE} = SHAPEUP + \frac{CYCLES[7:0]}{3.9 \times FREQUENCY} + SHAPEDN$ <table><tr><td>0x0:</td><td>No shape</td></tr><tr><td>0x1:</td><td>32 ms</td></tr><tr><td>0x2:</td><td>64 ms</td></tr><tr><td>0x3:</td><td>96 ms</td></tr><tr><td>0x4:</td><td>128 ms</td></tr><tr><td>0x5:</td><td>160 ms</td></tr><tr><td>0x6:</td><td>192 ms</td></tr><tr><td>0x7:</td><td>224 ms</td></tr><tr><td>0x8:</td><td>256 ms</td></tr><tr><td>0x9:</td><td>512 ms</td></tr><tr><td>0xA:</td><td>768 ms</td></tr><tr><td>0xB:</td><td>1024 ms</td></tr><tr><td>0xC:</td><td>1280 ms</td></tr><tr><td>0xD:</td><td>1536 ms</td></tr><tr><td>0xE:</td><td>1792 ms</td></tr><tr><td>0xF:</td><td>2048 ms</td></tr></table> |                 |    |   |   |                |   |   |   |              |   |   |   | 0x0: | No shape | 0x1: | 32 ms | 0x2: | 64 ms | 0x3: | 96 ms | 0x4: | 128 ms | 0x5: | 160 ms | 0x6: | 192 ms | 0x7: | 224 ms | 0x8: | 256 ms | 0x9: | 512 ms | 0xA: | 768 ms | 0xB: | 1024 ms | 0xC: | 1280 ms | 0xD: | 1536 ms | 0xE: | 1792 ms | 0xF: | 2048 ms |
| 0x0:           | No shape |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x1:           | 32 ms    |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x2:           | 64 ms    |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x3:           | 96 ms    |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x4:           | 128 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x5:           | 160 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x6:           | 192 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x7:           | 224 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x8:           | 256 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0x9:           | 512 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0xA:           | 768 ms   |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0xB:           | 1024 ms  |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0xC:           | 1280 ms  |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0xD:           | 1536 ms  |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0xE:           | 1792 ms  |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 0xF:           | 2048 ms  |           |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |
| 3              | 3:0      | SHAPEDN   |   |                 |    |   |   |                |   |   |   |              |   |   |   |      |          |      |       |      |       |      |       |      |        |      |        |      |        |      |        |      |        |      |        |      |        |      |         |      |         |      |         |      |         |      |         |

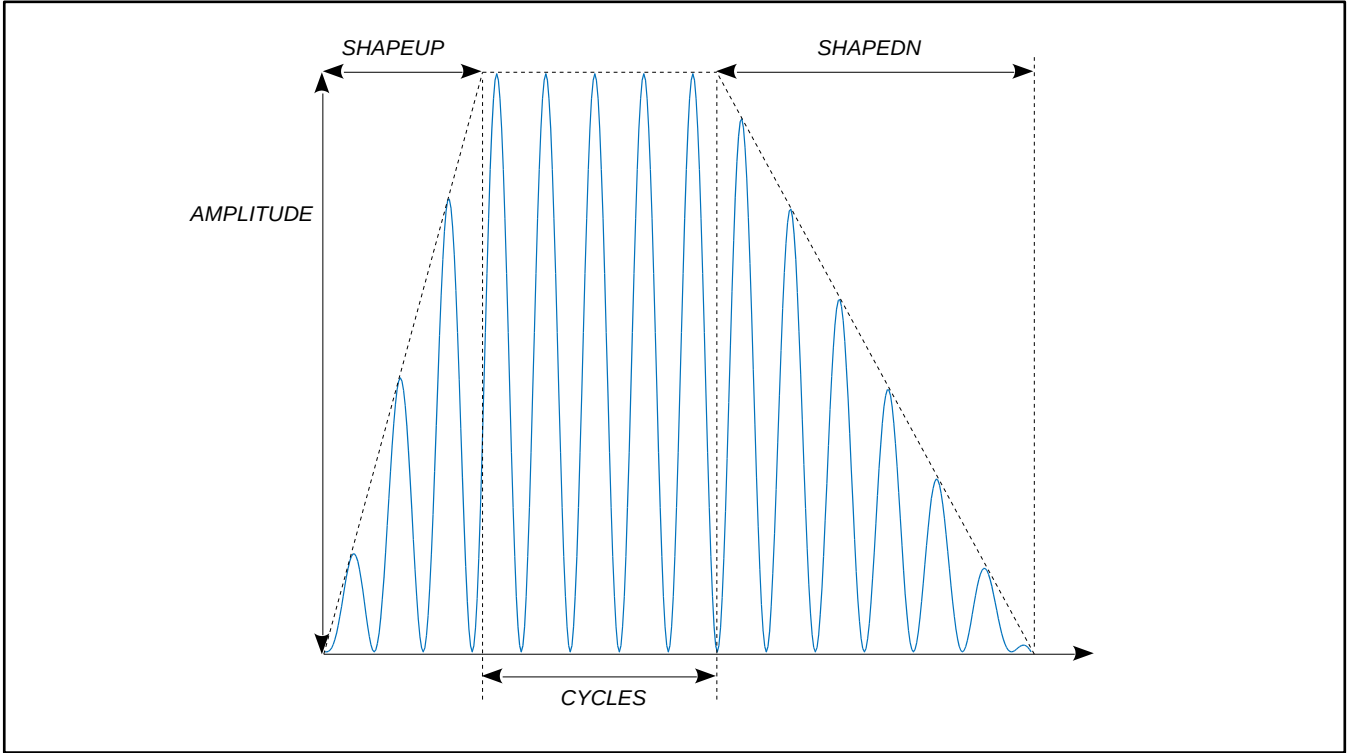


Figure 17: Sine wave SLICE parameters illustration

**6.8.1.2 WAVE Blocks**

As shown in Table 14 and Figure 18, each WAVE block in RAM contains three words:

- 1. The SLICE START ADDRESS [9:0]
- 2. The SLICE END ADDRESS [9:0]
- 3. The WAVE CYCLE COUNT [15:0]

SLICES to be played sequentially must be placed contiguously in RAM.

Table 14: Wave block description

|                        |      |    |                     |    |  |                          |   |   |   |   |   |   |   |   |   |
|------------------------|------|----|---------------------|----|--|--------------------------|---|---|---|---|---|---|---|---|---|
| 15                     | 14   | 13 | 12                  | 11 | 10   | 9                        | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| NOT USED: 0x00         |      |    |                     |    |  | SLICE START ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| NOT USED: 0x00         |      |    |                     |    |  | SLICE END ADDRESS[9:0]   |   |   |   |   |   |   |   |   |   |
| WAVE CYCLE COUNT[15:0] |      |    |                     |    |  |                          |   |   |   |   |   |   |   |   |   |
| WORD                   | BITS |    | NAME                |    | DESCRIPTION  |                          |   |   |   |   |   |   |   |   |   |
| 1                      | 9:0  |    | SLICE START ADDRESS |    | Defines RAM address of the first SLICE block (location of its first word).   |                          |   |   |   |   |   |   |   |   |   |
| 2                      | 9:0  |    | SLICE END ADDRESS   |    | Defines RAM address of the last SLICE block (location of its last word).   |                          |   |   |   |   |   |   |   |   |   |
| 3                      | 15:0 |    | WAVE CYCLE COUNT    |    | Sets the number of times the WAVE block is repeated. If the CYCLE COUNT is set to zero, it will be considered as a request to play the WAVE only once. |                          |   |   |   |   |   |   |   |   |   |



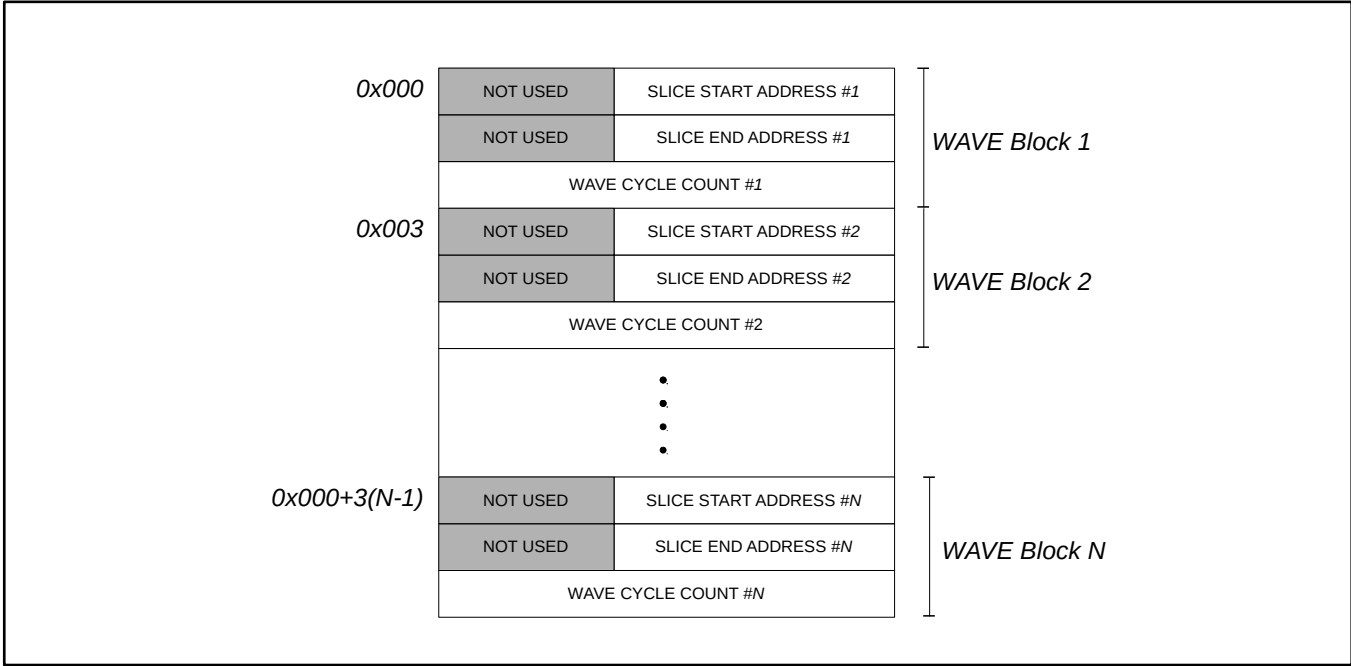


Figure 18: WAVE blocks in RAM

6.8.1.3 Sequencer

The sequencer stores up to 15 WAVEFORM\_IDs to be played sequentially. WAVEFORM\_ID 0 to 14 are stored into the SEQUENCER using the [SEQUENCER](#) WFS command. Each WAVEFORM\_ID contains the address in memory of a WAVE block to play. All 15 WAVEFORM\_IDs must be written sequentially. WAVEFORM\_IDs not used may be filled with any address.

Various sets of waveform sequences can be played. The start and end WAVEFORM\_IDs to play are defined using the [SEQUENCE START/STOP](#) command. The largest sequence to play covers the 15 WAVEFORM\_IDs from WAVEFORM\_IDs 0 up to WAVEFORM\_IDs 14. The smallest sequence is when the start address is equal to the end address and thus only one WAVEFORM\_ID will be played. The Figure 19 shows an example where the waveform starts at WAVEFORM\_ID 3 and ends when WAVEFORM\_ID 6 has finished playing.

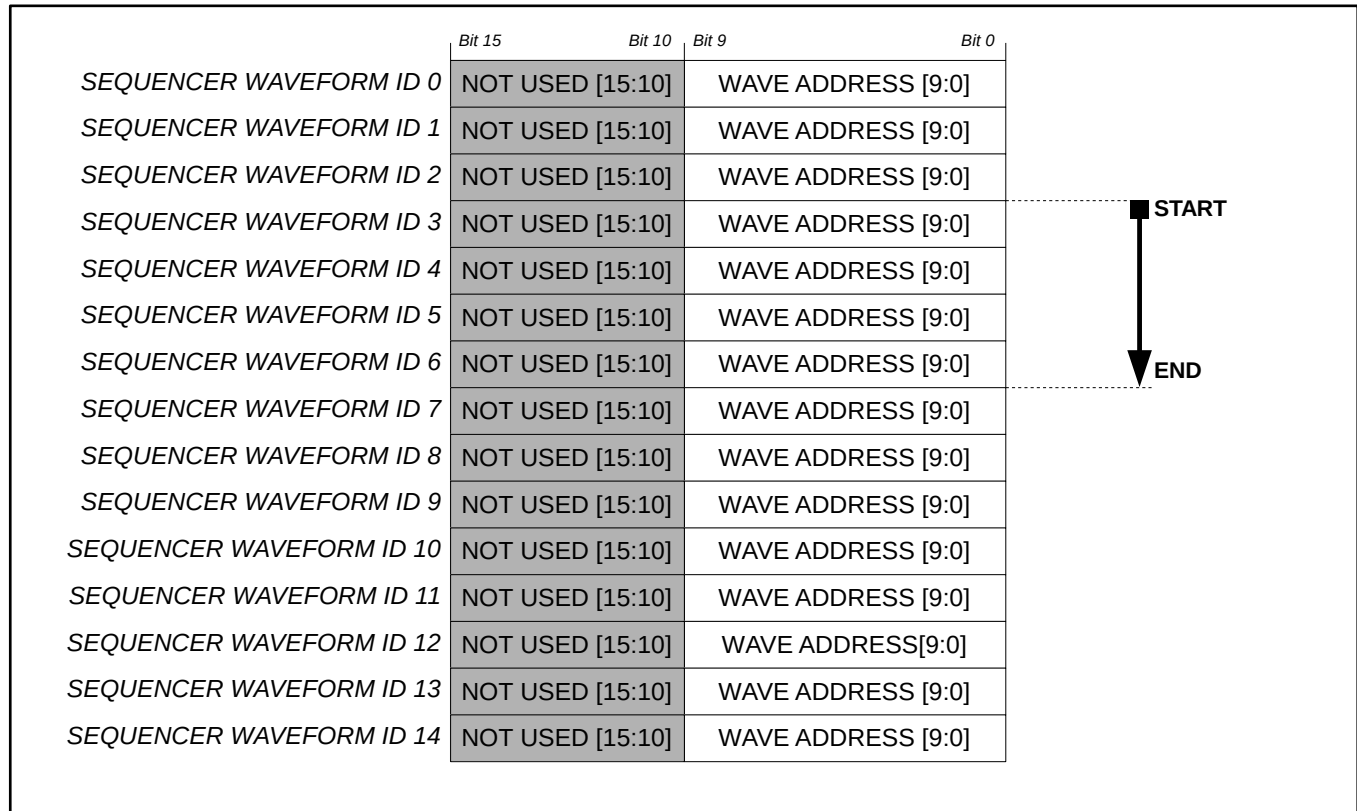


Figure 19: Sequencer example where waveform start at WAVEFORM\_ID 3 and ends at 6

### 6.8.2 Typical Operation Sequence

- In the [RAM](#) register:
  - Set [RAM.MODE\[1:0\]](#) bits to 0x3 to select RAM synthesis mode.
  - Set [RAM.RAMSEL](#) bit to 0x1 so that subsequent SPI communication is sent to the WFS command interpreter.
- Write the WAVE blocks and SLICE blocks in the memory using [RAM SYNTHESIS WRITE](#) WFS command. Multiple write sequences are needed to program the WAVE(s) and SLICES(s). [BURST RAM WRITE](#) WFS command can also be used to write WAVE and SLICE blocks. To keep access to the WFS command interpreter, make sure the commands are sent within 4  $\mu$ s of each other to continue writing in RAM.
- Write the WAVEFORM\_IDs using the [SEQUENCER](#) WFS command with the WAVE blocks RAM address.
- Write start and end SEQUENCER\_Wx that will be played into the [SEQUENCE START/STOP](#) WFS command.
- Wait for more than 4  $\mu$ s to access to the main register map.
- Set [BC\[4:0\]](#) to 0xC to output [IC STATUS](#) register content on SDO pin.
- Set [CONFIG.OE](#) bit to 0x1 to enable the haptic waveform generation.
- Poll [EMPTY](#) bit on SDO communication port until it is set to 0x1 and waveform is completed.
- Set [CONFIG.OE](#) bit to 0x0 to deactivate haptic waveform playback.

To start playback with sensing detection, the sensing parameters can be configured between step 4. and 5. See section 6.9 for sensing configuration details.

### 6.8.3 RAM Synthesis Mode Example

Table 15 and Figure 20 present a waveform playback example using RAM Synthesis mode with 3 SLICES and 2 WAVES. Table 17 is an example where a waveform already programmed in RAM is played.

Table 15: Example of playing a haptic waveform using RAM Synthesis mode

| Code                       | Description   |
|----------------------------|---|
| Select RAM Synthesis mode: |   |
| 0x8007                     | Select RAM Synthesis and request access to the WFS command interpreter. The following SPI transactions must be sent less than 4 µs from each other to keep using WFS command interpreter. |
| Program WAVE #1 in RAM:    |   |
| 0x0001                     | Use <a href="#">RAM SYNTHESIS WRITE</a> WFS command.  |
| 0x0000                     | Set the RAM address, where the WAVE #1 will be programmed, to 0x0000.   |
| 0x0100                     | WAVE #1 Data: Set <a href="#">SLICE START ADDRESS</a> to 0x0100 (RAM start address of SLICE #1).  |
| 0x0102                     | WAVE #1 Data: Set <a href="#">SLICE END ADDRESS</a> to 0x0102 (RAM end address of SLICE #1).  |
| 0x0001                     | WAVE #1 Data: Set <a href="#">WAVE CYCLE COUNT</a> to 1.  |
| Program SLICE #1 in RAM:   |   |
| 0x0001                     | Use <a href="#">RAM SYNTHESIS WRITE</a> WFS command.  |
| 0x0100                     | Set the RAM address, where the SLICE #1 will be programmed, to 0x0100.  |
| 0x0800                     | SLICE #1 Data: Set <a href="#">AMPLITUDE</a> to 60 V .  |
| 0x031A                     | SLICE #1 Data: Set <a href="#">CYCLES</a> to 3 and <a href="#">FREQUENCY</a> to 101.4 Hz.   |
| 0x0020                     | SLICE #1 Data: Set <a href="#">SHAPEUP[3:0]</a> to 64 ms and <a href="#">SHAPEDN[3:0]</a> to 0 ms.  |
| Program WAVE #2 in RAM:    |   |
| 0x0001                     | Use <a href="#">RAM SYNTHESIS WRITE</a> WFS command.  |
| 0x0003                     | Set the RAM address, where the WAVE #2 will be programmed, to 0x0003.   |
| 0x0200                     | WAVE #2 Data: Set <a href="#">SLICE START ADDRESS</a> to 0x0200 (RAM start address of SLICE #2).  |
| 0x0205                     | WAVE #2 Data: Set <a href="#">SLICE END ADDRESS</a> to 0x0205 (RAM end address of SLICE #3).  |
| 0x0003                     | WAVE #2 Data: Set <a href="#">WAVE CYCLE COUNT</a> to 3.  |
| Program SLICE #2 in RAM:   |   |
| 0x0001                     | Use <a href="#">RAM SYNTHESIS WRITE</a> WFS command.  |
| 0x0200                     | Set the RAM address, where the SLICE #2 will be programmed, to 0x0200.  |
| 0x0AAA                     | SLICE #2 Data: Set <a href="#">AMPLITUDE</a> to 80 V.   |
| 0x020D                     | SLICE #2 Data: Set <a href="#">CYCLES</a> to 2 and <a href="#">FREQUENCY</a> to 50.7 Hz.  |
| 0x0000                     | SLICE #2 Data: Set <a href="#">SHAPEUP[3:0]</a> to 0 ms and <a href="#">SHAPEDN[3:0]</a> to 0 ms.   |
| Program SLICE #3 in RAM:   |   |
| 0x0001                     | Use <a href="#">RAM SYNTHESIS WRITE</a> WFS command.  |
| 0x0203                     | Set the RAM address, where the SLICE #3 will be programmed, to 0x0203.  |
| 0x0555                     | SLICE #3 Data: Set <a href="#">AMPLITUDE</a> to 40 V.   |
| 0x0427                     | SLICE #3 Data: Set <a href="#">CYCLES</a> to 4 and <a href="#">FREQUENCY</a> to 152.1 Hz.   |
| 0x0000                     | SLICE #3 Data: Set <a href="#">SHAPEUP[3:0]</a> to 0 ms and <a href="#">SHAPEDN[3:0]</a> 0 ms.  |

| Code  | Description  |
|---|--|
| Program sequencer entries:                                    |  |
| 0x0002  | Use <a href="#">SEQUENCE</a> WFS command.  |
| 0x0000  | WAVEFORM_ID 0 value: WAVE #1 block address.  |
| 0x0003  | WAVEFORM_ID 1 value: WAVE #2 block address.  |
| 0x0000  | WAVEFORM_ID 2 value: not used.   |
| 0x0000  | WAVEFORM_ID 3 value: not used.   |
| 0x0000  | WAVEFORM_ID 4 value: not used.   |
| 0x0000  | WAVEFORM_ID 5 value: not used.   |
| 0x0000  | WAVEFORM_ID 6 value: not used.   |
| 0x0000  | WAVEFORM_ID 7 value: not used.   |
| 0x0000  | WAVEFORM_ID 8 value: not used.   |
| 0x0000  | WAVEFORM_ID 9 value: not used.   |
| 0x0000  | WAVEFORM_ID 10 value: not used.  |
| 0x0000  | WAVEFORM_ID 11 value: not used.  |
| 0x0000  | WAVEFORM_ID 12 value: not used.  |
| 0x0000  | WAVEFORM_ID 13 value: not used.  |
| 0x0000  | WAVEFORM_ID 14 value: not used.  |
| Set start and end sequencer:                                  |  |
| 0x0012  | Use <a href="#">SEQUENCE START/STOP</a> WFS command.   |
| 0x1000  | Set start to WAVEFORM_ID 0 and end to WAVEFORM_ID 2.   |
| Wait for more than 4 $\mu$ s to access to the main registers. |  |
| Start and stop waveform playback:                             |  |
| 0x9628  | Set <a href="#">BC[4:0]</a> to 0xC to output <a href="#">IC_STATUS</a> register content on SDO pin.        |
| 0x5010  | Set <a href="#">CONFIG.OE</a> to 0x1 to start waveform playback.   |
| 0x0000  | Poll <a href="#">EMPTY</a> bit on SDO communication port until it is set to 0x1 and waveform is completed. |
| 0x5000  | Set <a href="#">OE</a> bit to 0x0 to deactivate haptic waveform playback.                                  |

Table 16: Example of playing a haptic waveform already programmed in RAM using RAM Synthesis mode

| Code  | Description  |
|---|--|
| Set start and end sequencer:                                  |  |
| 0x8007  | Select RAM Synthesis and request access to the WFS command interpreter. The following SPI transactions must be sent less than 4 $\mu$ s from each other to keep using WFS command interpreter. |
| 0x0012  | Use <a href="#">SEQUENCE START/STOP</a> WFS command.   |
| 0x1000  | Set start to WAVEFORM_ID 0 and end to WAVEFORM_ID 2.   |
| Wait for more than 4 $\mu$ s to access to the main registers. |  |
| Start and stop waveform playback:                             |  |
| 0x9628  | Set <a href="#">BC[4:0]</a> to 0xC to output <a href="#">IC_STATUS</a> register content on SDO pin.  |
| 0x5010  | Set <a href="#">OE</a> bit to 0x1 to start haptic waveform playback and <a href="#">PLAY[2:0]</a> to 8 ksp.  |
| 0x0000  | Poll <a href="#">EMPTY</a> bit on SDO communication port until it is set to 0x1 and waveform is completed.   |
| 0x5000  | Set <a href="#">OE</a> bit to 0x0 to deactivate haptic waveform playback.  |

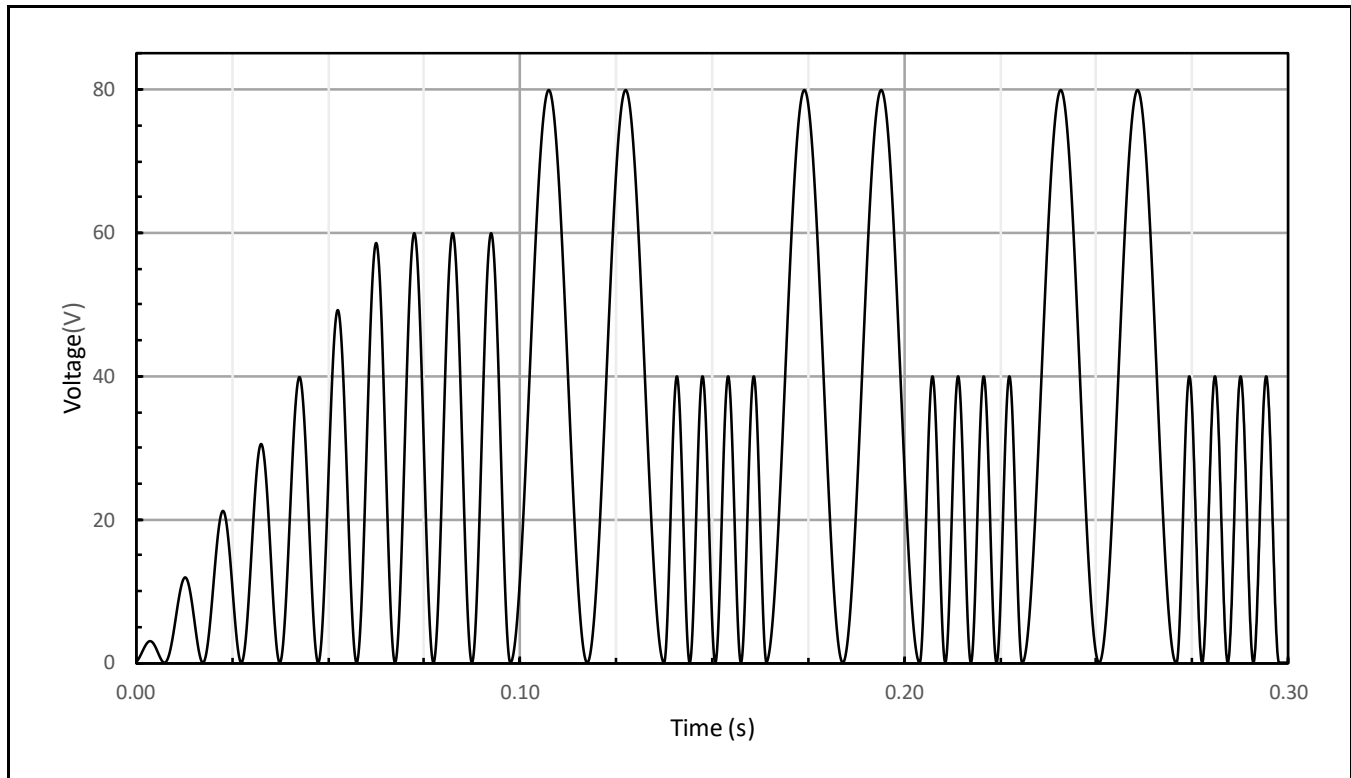


Figure 20: RAM Synthesis waveform example

## 6.9 Piezo Actuator Sensing

The digital front-end gives access to internal registers [0xA](#) and [0x12](#) to use the piezo actuator as a force sensor. An embedded comparator can be used to detect when a voltage threshold has been crossed. A waveform may be automatically played with minimum intervention from the MCU. It is also possible to access to the sensed voltage for a custom detection.

The following control bits activate the sensing operation:

- [CONFIG.SENSE](#) bit deactivate  $Q_1$  &  $Q_2$  to sense the actuator voltage on pin HV without forcing a voltage on the OUTPUT node. This bit allows the piezo actuator voltage to vary freely as the user physically interacts with it.
- [CONFIG.OE](#) bit enables voltage sensing of the HV pin, which is required for the sensing to operate.

Note the following:

- To stop the sensing feature, it is recommended to reset the device using [RST](#) bit to reset registers and RAM.
- No haptic waveform should be playing while setting [CONFIG.SENSE](#) bit to 0x1. Wait until the [IC\\_STATUS.EMPTY](#) bit is 0x1 before setting [CONFIG.SENSE](#) bit to 0x1.
- When sensing is activated, no haptic waveform can be output.

### 6.9.1 Embedded Sensing Comparator

The embedded sensing parameters are the following:

- [ONCOMP](#) bit enables the embedded comparator performing the automatic sensing. It must be set to 0x1 to enable the sensing. Once an event has been detected once, [ONCOMP](#) bit must be reset to 0x0 then set again to 0x1 to allow the comparator to detect a second event.
- [REP\[2:0\]](#) bits set the hold time, which is the time the voltage must be above or below the threshold for the detection to be successful.
- [STHRESH\[8:0\]](#) bits set the differential voltage threshold that must be reached for the detection to succeed.
- [SIGN](#) bit defines if voltage feedback value should be above or below the threshold to trigger an event from the sense comparator.

### 6.9.2 GPO Used as Interrupt

The GPO output pin can be used to convey information and implement interrupts for the system with the following configurations:

- Setting [GPO\[2:0\]](#) to 0x1 (SENSE\_TRIGGER) will indicate when the embedded sensing ([ONCOMP](#) bit set to 0x1) is successful.
- Setting [GPO\[2:0\]](#) to 0x2 (waveform done) will indicate when the waveform playback following a sensing detection event has completed ([ONCOMP](#) and [AUTO](#) bits set to 0x1).

### 6.9.3 Automatic Haptic Playback

With the Automatic Haptic Playback, the BOS1211 can detect force applied on a piezo actuator by measuring voltage across its terminal and then automatically play a pre-programmed waveform using RAM Playback (section 6.7) or RAM Synthesis (section 6.8) modes with minimum intervention from the MCU.

The Automatic Haptic Playback is enabled by setting [AUTO](#) bit to 0x1. Pin GPO can notify the MCU that both the sensing event and waveform are completed (see section 6.9.2). Once a detection occurs, the automatic playback can be enabled again doing the following:

1. The next waveform should be armed (see section 6.9.3.2 for detail).
2. The sensing comparator should be restarted by first resetting [ONCOMP](#) bit to 0x0, and then setting it back to 0x1.

### 6.9.3.1 Sequence Example for Button Press Sensing with Automatic Playback

A typical communication sequence to configure automatic haptic playback activated by a button press event is as follows:

1. Program waveform using RAM Playback (section 6.7) or RAM Synthesis (section 6.8) modes.
2. Set [SPI.GPO\[2:0\]](#) bits to 0x2 to be notified of a detection event and that waveform completed on the GPO output pin.
3. Write 0xAA07 in the [SENSING](#) register to set the following:
  - a. [SENSING.REP\[2:0\]](#) bits to 0x5 to set 4096  $\mu$ s hold time.
  - b. [SENSING.STHRESH\[8:0\]](#) bits to 0x7 to set 900 mV threshold.
4. Write 0x5B17 in the [CONFIG](#) register to set the following:
  - a. [CONFIG.SIGN](#) bit to 0x0 to trigger on a voltage above the threshold (detect an increasing voltage).
  - b. [CONFIG.AUTO](#) bit to 0x1 to play a pre-programmed RAM Playback or RAM Synthesis waveform automatically on a successful detection.
  - c. Set [CONFIG.ONCOMP](#) bit to 0x1 to enable the embedded sensing comparator.
  - d. Set [CONFIG.SENSE](#) bit to 0x1 to enable piezo actuator sensing.
  - e. Set [CONFIG.OE](#) bit to 0x1 to start sensing.

### 6.9.3.2 Sequence Example for Button Release Sensing with Automatic Playback

Once a detection occurred, sensing can be configured again for automatic haptic playback activated by a button release event using the following typical communication sequence:

1. Set [CONFIG.ONCOMP](#) bit to 0x0 to reset the sensing comparator.
2. Arm the next waveform depending on the playback mode:
  - a. RAM Playback: write the start and end addresses in the [RAM PLAYBACK](#) WFS command (see section 6.7).
  - b. RAM Synthesis: write the start and end WAVEFORM\_IDs in the [SEQUENCE START/STOP](#) WFS command (see section 6.8).
3. Write 0xABFE in the [SENSING](#) register to set the following:
  - a. [SENSING.REP\[2:0\]](#) bits to 0x5 to set 4096  $\mu$ s hold time.
  - b. [SENSING.STHRESH\[8:0\]](#) bits to 0x1FE to set -260 mV threshold.
4. Write 0x5F17 in the [CONFIG](#) register to set the following:
  - a. [CONFIG.SIGN](#) bit to 0x1 to trigger on voltage below the threshold (detect a decreasing voltage).
  - b. [CONFIG.AUTO](#) bit to 0x1 to play a pre-programmed RAM Playback or RAM Synthesis waveform automatically on a successful detection.
  - c. [CONFIG.ONCOMP](#) bit to 0x1 to enable the sensing comparator.
  - d. [CONFIG.SENSE](#) bit to 0x1 to enable piezo actuator sensing.
  - e. [CONFIG.OE](#) bit to 0x1 to start sensing.

### 6.9.4 Reading the Sensed Voltage

The sensed voltage can be read at any time by setting the SDO output using `SPI.BC = 0x12`. It is seldom read when the embedded sensing feature is used, but it can be read to implement more complex sensing algorithm running in a MCU such as slope detection or voltage profile pattern recognition.

The sensed voltage is continually updated and pushed to the [SENSE\\_VALUE\[8:0\]](#) field so the last voltage sensed can be read at any time. The [RS](#) bit allow to reset the voltage across the piezo actuator as well as the [SENSE\\_VALUE\[8:0\]](#) bits. Such a reset might be needed if [SENSE\\_VALUE\[8:0\]](#) is non-zero while the user is not interacting with the actuator.

The following control bits are used to read the sensed voltage:

- [SENSE](#) bit in broadcast register [0x12](#) indicates if the sensing mode is running.
- [SENSE\\_FLAG](#) bit in broadcast register [0x12](#) indicates if the sensing conditions are met based on [CONFIG.SIGN](#), [SENSING.STHRESH\[8:0\]](#) and [SENSING.REP\[2:0\]](#) bits.
- [SENSE\\_VALUE\[8:0\]](#) bits is the 9-bit signed sensed voltage.
- [RS](#) bit resets the sensing interface without disabling it. This resets the sensing value ([SENSE\\_VALUE\[8:0\]](#)). The bit self-clears.
- [SHORT\[1:0\]](#) bits determine the time to short the piezo actuator. This occurs periodically while the sensed voltage is negative. The accumulated voltage is output in the sensing value ([SENSE\\_VALUE\[8:0\]](#) of the broadcast register [0x12](#)). [SHORT\[1:0\]](#) bits are typically set to their default value but may be changed depending on the actuator used and the application conditions.

#### 6.9.4.1 Polling Sequence Example

A typical communication sequence to poll [SENSE\\_VALUE\[8:0\]](#) is as follows:

1. Write 0x5217 in the [CONFIG](#) register to set the following:
  - a. [CONFIG.ONCOMP](#) bit to 0x0 to prevent it from triggering a sensing event.
  - b. [CONFIG.SENSE](#) bit to 0x1 to enable piezo actuator sensing.
  - c. [CONFIG.OE](#) bit to 0x1 to start sensing.
2. Set [SPI.BC\[4:0\]](#) bits to [0x12](#) to broadcast the [SENSE\\_VALUE\[8:0\]](#) on SDO.
3. Write a dummy 0xF000 to SPI interface, read a word and extract [SENSE\\_VALUE\[8:0\]](#) bits to monitor the voltage across the piezo (see section 6.11.17 for more detail on how to use the SDO Broadcast).
4. Repeat the step 3) as needed.



## 6.10 WFS Command Interpreter

The 1024×16 RAM is programmed using the WFS command interpreter through the [REFERENCE](#) register. The WFS commands are also used to store RAM Playback (section 6.7) and RAM Synthesis (section 6.8) configuration data. To access the WFS Command Interpreter, the [RAMSEL](#) bit must first be set to 0x1. WFS commands are summarized in Table 17 and detailed in section 6.10.1.

Table 17: WFS command list summary

| COMMAND                             | WORD | 15                                | 14 | 13 | 12 | 11 | 10                  | 9   | 8                                  | 7            | 6 | 5 | 4 | 3 | 2 | 1 | 0 |  |
|-------------------------------------|------|-----------------------------------|----|----|----|----|---------------------|-----|------------------------------------|--------------|---|---|---|---|---|---|---|--|
| <a href="#">RAM SYNTHESIS WRITE</a> | 0    | COMMAND[15:0] = 0x0001            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 1    | RSVD                              |    |    |    |    |                     | W/R |                                    | ADDRESS[9:0] |   |   |   |   |   |   |   |  |
|                                     | 2    | DATA1[15:0]                       |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 3    | DATA2[15:0]                       |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 4    | DATA3[15:0]                       |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
| <a href="#">SEQUENCER</a>           | 0    | COMMAND[15:0] = 0x0002            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 1    |                                   |    |    |    |    |                     |     | WAVEFORM ID 0 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 2    |                                   |    |    |    |    |                     |     | WAVEFORM ID 1 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 3    |                                   |    |    |    |    |                     |     | WAVEFORM ID 2 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 4    |                                   |    |    |    |    |                     |     | WAVEFORM ID 3 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 5    |                                   |    |    |    |    |                     |     | WAVEFORM ID 4 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 6    |                                   |    |    |    |    |                     |     | WAVEFORM ID 5 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 7    |                                   |    |    |    |    |                     |     | WAVEFORM ID 6 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 8    |                                   |    |    |    |    |                     |     | WAVEFORM ID 7 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 9    |                                   |    |    |    |    |                     |     | WAVEFORM ID 8 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 10   |                                   |    |    |    |    |                     |     | WAVEFORM ID 9 - WAVE_ADDRESS[9:0]  |              |   |   |   |   |   |   |   |  |
|                                     | 11   |                                   |    |    |    |    |                     |     | WAVEFORM ID 10 - WAVE_ADDRESS[9:0] |              |   |   |   |   |   |   |   |  |
|                                     | 12   |                                   |    |    |    |    |                     |     | WAVEFORM ID 11 - WAVE_ADDRESS[9:0] |              |   |   |   |   |   |   |   |  |
|                                     | 13   |                                   |    |    |    |    |                     |     | WAVEFORM ID 12 - WAVE_ADDRESS[9:0] |              |   |   |   |   |   |   |   |  |
|                                     | 14   |                                   |    |    |    |    |                     |     | WAVEFORM ID 13 - WAVE_ADDRESS[9:0] |              |   |   |   |   |   |   |   |  |
|                                     | 15   |                                   |    |    |    |    |                     |     | WAVEFORM ID 14 - WAVE_ADDRESS[9:0] |              |   |   |   |   |   |   |   |  |
| <a href="#">SEQUENCE START/STOP</a> | 0    | COMMAND[15:0] = 0x0012            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 1    | SEQUENCE END[3:0]                 |    |    |    |    | SEQUENCE START[3:0] |     |                                    |              |   |   |   |   |   |   |   |  |
| <a href="#">RAM PLAYBACK</a>        | 0    | COMMAND[15:0] = 0x0013            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 1    |                                   |    |    |    |    |                     |     | RAM PLAYBACK ADDRESS START[9:0]    |              |   |   |   |   |   |   |   |  |
|                                     | 2    |                                   |    |    |    |    |                     |     | RAM PLAYBACK ADDRESS END[9:0]      |              |   |   |   |   |   |   |   |  |
| <a href="#">BURST RAM WRITE</a>     | 0    | COMMAND[15:0] = 0x0014            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 1    |                                   |    |    |    |    |                     |     | BURST START ADDRESS[9:0]           |              |   |   |   |   |   |   |   |  |
|                                     | 2    |                                   |    |    |    |    |                     |     | BURST DATA COUNT[9:0]              |              |   |   |   |   |   |   |   |  |
|                                     | 3    | DATA[15:0]                        |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | ...  | ...                               |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
|                                     | 2+n  | DATAn (n = BURST DATA COUNT[9:0]) |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
| <a href="#">FULL RAM READ</a>       | 0    | COMMAND[15:0] = 0x0015            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |
| <a href="#">FULL RAM READ BREAK</a> | 0    | COMMAND[15:0] = 0xFF15            |    |    |    |    |                     |     |                                    |              |   |   |   |   |   |   |   |  |

### 6.10.1 0x0001 RAM SYNTHESIS WRITE

Table 18: RAM SYNTHESIS WRITE command details

ADDRESS: 0x0001 RAM SYNTHESIS WRITE

Word

15

14

13

12

11

10

9

8

7

6

5

4

3

2

1

0

0

1

2

3

4

COMMAND[15:0] = 0x0001

Not used: 0x0

W/R

ADDRESS[9:0]

DATA1[15:0]

DATA2[15:0]

DATA3[15:0]

WORD, BITS

NAME

DESCRIPTION

Word 1, Bit [10]

W/R

0: RAM Write Enable  
1: RAM Read Enable ([SPI.BC\[4:0\]](#) bits must be set to 0x1C)

Word 1, Bits [9:0]

ADDRESS

Starting RAM address for reading or writing to RAM.

Word 2, Bits [15:0]

DATA1

Data written to RAM at address ADDRESS[9:0].  
The word is required if W/R bit is set to 0x0 to enable RAM write.

Word 3, Bits [15:0]

DATA2

Data written to RAM at address ADDRESS[9:0]+1.  
The word is required if W/R bit is set to 0x0 to enable RAM write.

Word 4, Bits [15:0]

DATA3

Data written to RAM at address ADDRESS[9:0]+2.  
The word is required if W/R bit is set to 0x0 to enable RAM write.

The RAM SYNTHESIS WRITE register is used to program a WAVE or SLICE block to RAM or read a RAM location. See sections 6.8.1.1 and 6.8.1.2 for details on the content of WAVE and SLICE blocks.

Table 15 presents an example on how to write a WAVE and SLICE blocks in RAM.

Table 19 presents an example on how to read a RAM location using RAM SYNTHESIS WRITE command.

Table 19: RAM read sequence example using RAM SYNTHESIS WRITE command

| Code   | Description   |
|--------|---|
| 0x9E28 | Set <a href="#">SPI.BC[4:0]</a> bits to 0x1C and <a href="#">TE</a> bit to 0x1.                         |
| 0x8007 | Select RAM Synthesis and request access to the WFS command.   |
| 0x0001 | WFS command: set to RAM SYNTHESIS WRITE.  |
| 0x0000 | Set RAM address for data reading to 0x0000 and wait for more than 4 µs to access to the main registers. |
| 0x0000 | Read 2 bytes corresponding to the content of RAM at address 0x0000.                                     |

## 6.10.2 0x0002 SEQUENCER

Table 20: SEQUENCER command details

| ADDRESS: 0x0002 SEQUENCER   |                        |              |    |    |    |   |                                    |   |   |   |   |   |   |   |   |   |
|---|------------------------|--------------|----|----|----|---|------------------------------------|---|---|---|---|---|---|---|---|---|
| Word  | 15                     | 14           | 13 | 12 | 11 | 10  | 9                                  | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0   | COMMAND[15:0] = 0x0002 |              |    |    |    |   |                                    |   |   |   |   |   |   |   |   |   |
| 1   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 0 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 2   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 1 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 3   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 2 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 4   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 3 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 5   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 4 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 6   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 5 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 7   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 6 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 8   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 7 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 9   | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 8 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 10  | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 9 - WAVE_ADDRESS[9:0]  |   |   |   |   |   |   |   |   |   |
| 11  | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 10 - WAVE_ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| 12  | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 11 - WAVE_ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| 13  | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 12 - WAVE_ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| 14  | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 13 - WAVE_ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| 15  | Not used: 0x0          |              |    |    |    |   | WAVEFORM ID 14 - WAVE_ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| BIT   |                        | NAME         |    |    |    | DESCRIPTION   |                                    |   |   |   |   |   |   |   |   |   |
| Word 1 to 15, Bits [9:0]  |                        | WAVE_ADDRESS |    |    |    | Address of a WAVE block in RAM. The SEQUENCER can store up to 15 different WAVE ADDRESS, named WAVEFORM_ID 0 to WAVEFORM_ID 14. |                                    |   |   |   |   |   |   |   |   |   |
| The SEQUENCER is composed of 15 WAVEFORM_ID numbered 0x0 to 0xE (WAVEFORM_ID 0 to WAVEFORM_ID 14). Each WAVEFORM_ID contains a RAM address of a WAVE block. |                        |              |    |    |    |   |                                    |   |   |   |   |   |   |   |   |   |
| Table 15 presents an example on how to use SEQUENCE command.  |                        |              |    |    |    |   |                                    |   |   |   |   |   |   |   |   |   |
| Note that all 15 WAVEFORM_ID must be written. The WAVEFORM_ID registers that are not used may be assigned to any value.                                     |                        |              |    |    |    |   |                                    |   |   |   |   |   |   |   |   |   |

### 6.10.3 0x0012 SEQUENCE START/STOP

Table 21: SEQUENCE START/STOP command details

| ADDRESS: 0x0012 SEQUENCE START/STOP  |                        |                |    |    |                     |  |   |   |               |   |   |   |   |   |   |   |
|--|------------------------|----------------|----|----|---------------------|--|---|---|---------------|---|---|---|---|---|---|---|
| Word   | 15                     | 14             | 13 | 12 | 11                  | 10   | 9 | 8 | 7             | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0  | COMMAND[15:0] = 0x0012 |                |    |    |                     |  |   |   |               |   |   |   |   |   |   |   |
| 1  | SEQUENCE END[3:0]      |                |    |    | SEQUENCE START[3:0] |  |   |   | Not used: 0x0 |   |   |   |   |   |   |   |
| BIT  |                        | NAME           |    |    | TYPE                | DESCRIPTION  |   |   |               |   |   |   |   |   |   |   |
| Word 1,<br>Bits [15:12]  |                        | SEQUENCE END   |    |    | W                   | Set the SEQUENCER end WAVEFORM_ID number (numbered 0x0 to 0xE, see <a href="#">SEQUENCER</a> register) pointing to the last WAVE block to play.    |   |   |               |   |   |   |   |   |   |   |
| Word 1,<br>Bits [11:8]   |                        | SEQUENCE START |    |    | W                   | Set the SEQUENCER start WAVEFORM_ID number (numbered 0x0 to 0xE, see <a href="#">SEQUENCER</a> register) pointing to the first WAVE block to play. |   |   |               |   |   |   |   |   |   |   |
| The SEQUENCER will play all WAVE blocks starting from SEQUENCE START[3:0] up to SEQUENCE_END[3:0].   |                        |                |    |    |                     |  |   |   |               |   |   |   |   |   |   |   |
| Using SEQUENCE START/STOP command indicates that the waveform specified from SEQUENCE START to SEQUENCE END is armed and ready to be played. |                        |                |    |    |                     |  |   |   |               |   |   |   |   |   |   |   |
| Table 15 presents an example on how to use SEQUENCE START/STOP command.  |                        |                |    |    |                     |  |   |   |               |   |   |   |   |   |   |   |

### 6.10.4 0x0013 RAM PLAYBACK

Table 22: RAM PLAYBACK command details

| ADDRESS: 0x0013 RAM PLAYBACK  |                        |                            |    |    |    |      |                                 |   |   |   |   |   |   |   |   |   |
|---|------------------------|----------------------------|----|----|----|------|---------------------------------|---|---|---|---|---|---|---|---|---|
| Word  | 15                     | 14                         | 13 | 12 | 11 | 10   | 9                               | 8   | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0   | COMMAND[15:0] = 0x0013 |                            |    |    |    |      |                                 |   |   |   |   |   |   |   |   |   |
| 1   | Not used: 0x0          |                            |    |    |    |      | RAM PLAYBACK ADDRESS START[9:0] |   |   |   |   |   |   |   |   |   |
| 2   | Not used: 0x0          |                            |    |    |    |      | RAM PLAYBACK ADDRESS END[9:0]   |   |   |   |   |   |   |   |   |   |
| BIT   |                        | NAME                       |    |    |    | TYPE |                                 | DESCRIPTION   |   |   |   |   |   |   |   |   |
| Word 1,<br>Bits [9:0]   |                        | RAM PLAYBACK ADDRESS START |    |    |    | W    |                                 | Defines the starting address for fetching RAM Playback samples. |   |   |   |   |   |   |   |   |
| Word 2,<br>Bits [9:0]   |                        | RAM PLAYBACK ADDRESS END   |    |    |    | W    |                                 | Defines the address of the last sample read during playback.    |   |   |   |   |   |   |   |   |
| The start and end addresses of the RAM PLAYBACK register indicate the location in RAM of the samples to be fetched when RAM Playback is initiated. The samples in RAM can be set using BURST RAM WRITE register with the same format as the <a href="#">REFERENCE</a> register. |                        |                            |    |    |    |      |                                 |   |   |   |   |   |   |   |   |   |
| Using RAM PLAYBACK command indicates that the waveform specified RAM PLAYBACK ADDRESS START[9:0] and RAM PLAYBACK ADDRESS END[9:0] is ready to be played.   |                        |                            |    |    |    |      |                                 |   |   |   |   |   |   |   |   |   |
| Table 11 presents an example on how to use RAM PLAYBACK command.  |                        |                            |    |    |    |      |                                 |   |   |   |   |   |   |   |   |   |

### 6.10.5 0x0014 BURST RAM WRITE

Table 23: BURST RAM WRITE command details

| ADDRESS: 0x0014 BURST RAM WRITE   |                        |               |    |      |    |  |                    |   |   |   |   |   |   |   |   |   |
|---|------------------------|---------------|----|------|----|--|--------------------|---|---|---|---|---|---|---|---|---|
| Word  | 15                     | 14            | 13 | 12   | 11 | 10   | 9                  | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0   | COMMAND[15:0] = 0x0014 |               |    |      |    |  |                    |   |   |   |   |   |   |   |   |   |
| 1   | Not used: 0x0          |               |    |      |    |  | START ADDRESS[9:0] |   |   |   |   |   |   |   |   |   |
| 2   | Not used: 0x0          |               |    |      |    |  | DATA COUNT[9:0]    |   |   |   |   |   |   |   |   |   |
| 3   | DATA[15:0]             |               |    |      |    |  |                    |   |   |   |   |   |   |   |   |   |
| BIT   |                        | NAME          |    | TYPE |    | DESCRIPTION  |                    |   |   |   |   |   |   |   |   |   |
| Word 1,<br>Bits [9:0]   |                        | START ADDRESS |    | W    |    | RAM address from where to start writing.   |                    |   |   |   |   |   |   |   |   |   |
| Word 2,<br>Bits [9:0]   |                        | DATA COUNT    |    | W    |    | The number of data words to be written on RAM with the following constraints:<br>DATA COUNT value of 0 will be considered as 1024 (all RAM locations).<br>DATA COUNT ≤ (1024 – START ADDRESS[9:0]) |                    |   |   |   |   |   |   |   |   |   |
| Word 3,<br>Bits [15:0]  |                        | DATA          |    | W    |    | Data to be written in RAM. DATA[15:0].<br>The RAM write address is incremented automatically between each written word.  |                    |   |   |   |   |   |   |   |   |   |
| BURST RAM WRITE is used to write multiple words to RAM. Words can be any data for RAM Playback mode (see section 6.7) or RAM Synthesis such as WAVE and SLICE blocks (see section 6.8). |                        |               |    |      |    |  |                    |   |   |   |   |   |   |   |   |   |
| Table 11 presents an example on how to use BURST RAM WRITE command.   |                        |               |    |      |    |  |                    |   |   |   |   |   |   |   |   |   |

### 6.10.6 0x0015 FULL RAM READ

Table 24: FULL RAM READ command

| COMMAND: 0x0015 FULL RAM READ   |                        |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|---|------------------------|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
| Word  | 15                     | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0   | COMMAND[15:0] = 0x0015 |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
| <p>Prior using FULL RAM READ command, <a href="#">SPI.BC[4:0]</a> bits must be set to 0x1C. Once 0x0015 is set, the full RAM content can be read on the communication interface, starting at the RAM address = 0x000, with the address self-incrementing after each read until one of the following conditions occurs:</p> <ul style="list-style-type: none"><li>• All 1024 addresses have been read</li><li>• <a href="#">FULL RAM READ BREAK</a> command is sent</li><li>• 4 μs timeout occurs between each read.</li></ul> <p>The communication sequence to use the FULL RAM READ command includes the following:</p> <ol style="list-style-type: none"><li>1. Write 0x8006 to set <a href="#">RAM.RAMSEL</a> to 0x1 and <a href="#">RAM.MODE</a> to 0x10 to select RAM PLAYBACK mode.</li><li>2. Write 0x9E28 to set <a href="#">SPI.BC[4:0]</a> bits to 0x1C and output the RAM content on SDO pin.</li><li>3. Write 0x0015 on SPI communication bus to use the FULL RAM READ command.</li><li>4. Wait at least 500 ns and less than 4 μs.</li><li>5. Make a single dummy write using 0x0000 on SPI communication.</li><li>6. Wait a minimum of 500 ns</li><li>7. Make one dummy write using 0x000 and read one word on SPO pin.</li><li>8. Repeat steps 4) and 5) until the last RAM address.</li></ol> |                        |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

6.10.7 0xFF15 FULL RAM READ BREAK

Table 25: FULL RAM READ BREAK command

|                                     |   |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|-------------------------------------|---|----|----|----|----|----|---|---|---|---|---|---|---|---|---|---|
| COMMAND: 0xFF15 FULL RAM READ BREAK |   |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
| Word                                | 15  | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| 0                                   | COMMAND[15:0] = 0xFF15  |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |
|                                     | The FULL RAM READ BREAK command 0xFF15 is used to stop the RAM content reading loop started with the FULL RAM READ command. |    |    |    |    |    |   |   |   |   |   |   |   |   |   |   |

## 6.11 Main Register Map

Table 26 lists the main register map used to configure the BOS1211 and Table 27 lists registers accessible for reading with [SPI.BC\[4:0\]](#) register. Access to the WFS command interpreter requires [RAMSEL](#) bit set to 0x1.

Table 26: Main register map

| ADDRESS<br>[15:12]  | NAME        | DEFAULT<br>VALUE | R/W <sup>3</sup> | 11              | 10 | 9        | 8             | 7               | 6               | 5           | 4            | 3        | 2            | 1    | 0                 |     |               |          |        |    |    |           |      |  |       |  |
|---------------------|-------------|------------------|------------------|-----------------|----|----------|---------------|-----------------|-----------------|-------------|--------------|----------|--------------|------|-------------------|-----|---------------|----------|--------|----|----|-----------|------|--|-------|--|
| <a href="#">0x0</a> | REFERENCE   | 0x000            | RW               | REFERENCE[11:0] |    |          |               |                 |                 |             |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x1</a> | ION_BL      | 0x11C            | RW               | FSWMAX[1:0]     |    |          | SB[1:0]       |                 | I_ON_SCALE[7:0] |             |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x2</a> | DEADTIME    | 0x46A            | RW               | DHS[6:0]        |    |          |               |                 |                 |             |              | DLS[4:0] |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x3</a> | KP          | 0x080            | RW               | SQ              |    | KP[10:0] |               |                 |                 |             |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x4</a> | KPA_KI      | 0x310            | RW               | KIBASE[3:0]     |    |          |               |                 | KPA[7:0]        |             |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x5</a> | CONFIG      | 0x000            | RW               | ONCOMP          |    | SIGN     |               | SENSE           |                 | AUTO        |              | SYNC     |              | LOCK |                   | RST |               | OE       |        | DS |    | PLAY[2:0] |      |  |       |  |
| <a href="#">0x6</a> | PARCAP      | 0x00A            | RW               | SHS[1:0]        |    |          | SLS[1:0]      |                 |                 | PARCAP[7:0] |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x7</a> | SUP_RISE    | 0x5CF            | RW               | TOUT            |    | VIN[4:0] |               |                 |                 |             |              |          | TI_RISE[5:0] |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0x8</a> | RAM         | 0x001            | RW               | RSVD            |    |          |               |                 |                 |             |              |          |              |      | RAM_SEL           |     | MODE[1:0]     |          |        |    |    |           |      |  |       |  |
| <a href="#">0x9</a> | SPI         | 0x7A8            | RW               | BC[4:0]         |    |          |               |                 |                 |             | SHORT[1:0]   |          |              | RS   |                   | TE  |               | GPO[2:0] |        |    |    |           |      |  |       |  |
| <a href="#">0xA</a> | SENSING     | 0x000            | RW               | REP[2:0]        |    |          |               |                 | STHRESH[8:0]    |             |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0xB</a> | THRESHOLD   | 0x048            | RW               | VTHRESH[8:0]    |    |          |               |                 |                 |             |              |          |              |      | THRESH_ERROR[2:0] |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0xC</a> | IC_STATUS   | 0x001            | RW               | STATE[1:0]      |    |          | OVV           |                 | OVT             |             | MXPWR        |          | IDAC         |      | UVLO5             |     | UVLO12        |          | OVLO12 |    | SC |           | FULL |  | EMPTY |  |
| <a href="#">0xD</a> | FIFO_STATUS | 0x400            | RW               | ERROR           |    | EMPTY    |               | FIFO_SPACE[9:0] |                 |             |              |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |
| <a href="#">0xE</a> | TRIM        | 0x000            | RW               | TRIMRW[1:0]     |    |          | TRIM_OSC[6:0] |                 |                 |             |              |          |              |      |                   |     | TRIM_REG[2:0] |          |        |    |    |           |      |  |       |  |
| <a href="#">0xF</a> | CHIP_ID     | 0x034            | RW               | RSVD            |    |          |               |                 |                 |             | CHIP ID[5:0] |          |              |      |                   |     |               |          |        |    |    |           |      |  |       |  |

Table 27: Extra broadcast register map

| ADDRESS IN<br><a href="#">SPI.BC [4:0]</a> | NAME         | R/W <sup>1</sup> | 15                 | 14 | 13 | 12 | 11  | 10    | 9              | 8          | 7 | 6                | 5 | 4 | 3 | 2 | 1 | 0 |
|--|--------------|------------------|--------------------|----|----|----|---|-------|----------------|------------|---|------------------|---|---|---|---|---|---|
| 0x0 to <a href="#">0xF</a>                 |              | RO               | BC[3:0]            |    |    |    | Content of main register with address BC[3:0] |       |                |            |   |                  |   |   |   |   |   |   |
| <a href="#">0x10</a>                       | VFEEDBACK    | RO               | RSVD               |    |    |    | STATE[1:0]                                    |       | VFEEDBACK[9:0] |            |   |                  |   |   |   |   |   |   |
| <a href="#">0x11</a>                       | OFFSET       | RO               | RSVD               |    |    |    |   |       | OFFSET [9:0]   |            |   |                  |   |   |   |   |   |   |
| <a href="#">0x12</a>                       | SENSE_STATUS | RO               | RSVD               |    |    |    |   | SENSE |                | SENSE_FLAG |   | SENSE_VALUE[8:0] |   |   |   |   |   |   |
| <a href="#">0x1C</a>                       | RAM_DATA     | RO               | RAM_DATA_RAW[15:0] |    |    |    |   |       |                |            |   |                  |   |   |   |   |   |   |

<sup>3</sup> RO are read-only registers.  
RW are read/write registers.



### 6.11.1 0x0 REFERENCE

Table 28: REFERENCE register details

| ADDRESS: 0x0    |           | REFERENCE |      |  |   | DEFAULT:0x000 |   |   |   |   |   |
|-----------------|-----------|-----------|------|--|---|---------------|---|---|---|---|---|
| 11              | 10        | 9         | 8    | 7  | 6 | 5             | 4 | 3 | 2 | 1 | 0 |
| REFERENCE[11:0] |           |           |      |  |   |               |   |   |   |   |   |
| Bits            | Name      | Default   | Type | Description  |   |               |   |   |   |   |   |
| 11:0            | REFERENCE | 0x00      | R/W  | <p>In Direct or FIFO mode (<a href="#">MODE[1:0]</a> bits set to 0x0 or 0x1), REFERENCE[11:0] defines the OUTPUT node amplitude in 12-bit unsigned format.</p> <p>The relation between REFERENCE[11:0] and output amplitude (OUTPUT) in volt is determined by:</p> $REFERENCE[11:0] = OUTPUT \times 30.74$ <p>REFERENCE[11:0] should not exceed 3689 to keep the voltage sensed on HV pin <math>\leq 120</math> V.</p> <p>In RAM PLAYBACK or RAM SYNTHESIS mode (<a href="#">MODE[1:0]</a> bits set to 0x2 or 0x3), REFERENCE[11:0] defines the WFS commands (see section 6.10 for details).</p> |   |               |   |   |   |   |   |

### 6.11.2 0x1 ION\_BL

Table 29: ION\_BL register details

| ADDRESS: 0x1 |          | ION_BL  |      |   |   | DEFAULT:0x11C |   |   |   |   |   |
|--------------|----------|---------|------|---|---|---------------|---|---|---|---|---|
| 11           | 10       | 9       | 8    | 7   | 6 | 5             | 4 | 3 | 2 | 1 | 0 |
| FSWMAX[1:0]  |          | SB[1:0] |      | IONSCALE[7:0]   |   |               |   |   |   |   |   |
| Bits         | Name     | Default | Type | Description   |   |               |   |   |   |   |   |
| 11:10        | FSWMAX   | 0x0     | R/W  | <p>Boost converter maximum switching frequency.</p> <p>0x0: 1 MHz<br/>0x1: 833 kHz<br/>0x2: 666 kHz<br/>0x3: 500 kHz</p>  |   |               |   |   |   |   |   |
| 9:8          | SB       | 0x1     | R/W  | <p>Boost converter blanking time.</p> <p>0x0: 70 ns<br/>0x1: 88 ns<br/>0x2: 106 ns<br/>0x3: 124 ns</p> <p>Default value should work for all applications.</p>                             |   |               |   |   |   |   |   |
| 7:0          | IONSCALE | 0x1C    | R/W  | <p>Minimum current required to turn on high-side switch (Q2).</p> <p>IONSCALE[7:0] must be determined by:</p> $IONSCALE[7:0] = \text{round}\left(\frac{R_{sense}}{150 \times L_1}\right)$ |   |               |   |   |   |   |   |

### 6.11.3 0x2 DEADTIME

Table 30: DEADTIME register details

| ADDRESS: 0x2 |      |         |      | DEADTIME   |   |   |          | DEFAULT:0x46A |   |   |   |
|--------------|------|---------|------|--|---|---|----------|---------------|---|---|---|
| 11           | 10   | 9       | 8    | 7  | 6 | 5 | 4        | 3             | 2 | 1 | 0 |
| DHS[6:0]     |      |         |      |  |   |   | DLS[4:0] |               |   |   |   |
| Bits         | Name | Default | Type | Description  |   |   |          |               |   |   |   |
| 11:5         | DHS  | 0x23    | R/W  | <p>Defines <math>t_{Q1-Q2}</math>, which is the minimum time between low-side switch (<math>Q_1</math>) turns off and high-side switch (<math>Q_2</math>) turns on. <math>t_{Q1-Q2}</math> is determined by:</p> $t_{Q1-Q2} = DHS \times 1.1 \text{ ns}$ <p>DHS [6:0] is determined by:</p> $DHS[6:0] = \frac{2\pi \sqrt{L_1 \times (C_{oss-Q1} + C_{oss-Q2} + C_{par})}}{4 \times 1.1 \times 10^{-9}}$ <p>Where <math>C_{oss-Q1}</math> and <math>C_{oss-Q2}</math> are the output capacitance of the power transistors <math>Q_1</math> and <math>Q_2</math> and <math>C_{par}</math> is the parasitic capacitance seen on pin SW which includes the parasitic capacitance of inductor (<math>L_1</math>) and PCB layout. DHS[6:0] can be optimized for specific applications.</p> |   |   |          |               |   |   |   |
| 4:0          | DLS  | 0x0A    | R/W  | <p>Defines the minimum time between high-side switch (<math>Q_2</math>) turn off and low-side switch (<math>Q_1</math>) turn on (<math>t_{Q2-Q1}</math>). The relation between <math>t_{Q2-Q1}</math> in second and DHS[4:0] is determined by:</p> $DLS[4:0] = \frac{t_{Q2-Q1}}{4.4 \times 10^{-9}}$ <p>Default value provides a delay of 46 ns minimum and should work for most applications but DLS[4:0] can be optimized for specific applications.</p>   |   |   |          |               |   |   |   |

### 6.11.4 0x3 KP

Table 31: KP register details

| ADDRESS: 0x3 |          | KP      |      |   |   |   |   | DEFAULT:0x080 |   |   |   |
|--------------|----------|---------|------|---|---|---|---|---------------|---|---|---|
| 11           | 10       | 9       | 8    | 7   | 6 | 5 | 4 | 3             | 2 | 1 | 0 |
| SQ           | KP[10:0] |         |      |   |   |   |   |               |   |   |   |
| Bits         | Name     | Default | Type | Description   |   |   |   |               |   |   |   |
| 11           | SQ       | 0x0     | R/W  | <p>Allows the user to safely send discontinuous waveforms with arbitrary sample rate. As soon as a sample is received, the OUTPUT node voltage will start to move toward the new value.</p> <p>1: Square waves (not recommended for typical applications)<br/>0: Continuous waveforms</p> |   |   |   |               |   |   |   |
| 10:0         | KP       | 0x080   | R/W  | <p>Sets the physical value (<math>k_{Physical}</math>) of the integrated PI controller proportional gain. <math>K_{pPhysical}</math> in A/V is determined by:</p> $Kp_{physical} = \frac{KP[10:0] \times 2^{-14}}{R_{sense}}$   |   |   |   |               |   |   |   |

### 6.11.5 0x4 KP

Table 32: KPA\_KI register details

| ADDRESS: 0x4 |        |   |         | KPA_KI   |  |   |   | DEFAULT:0x310 |   |   |   |
|--------------|--------|---|---------|----------|--|---|---|---------------|---|---|---|
| 11           | 10     | 9 | 8       | 7        | 6  | 5 | 4 | 3             | 2 | 1 | 0 |
| KIBASE[3:0]  |        |   |         | KPA[7:0] |  |   |   |               |   |   |   |
| BITS         | NAME   |   | DEFAULT | TYPE     | DESCRIPTION  |   |   |               |   |   |   |
| 11:8         | KIBASE |   | 0x3     | R/W      | Determines the pole location ( $f_{pole}$ ) of the integrated PI controller. The pole location ( $f_{pole}$ ) in kHz is determined by:<br>$f_{pole} = \frac{1024}{2^{KIBASE}}$ |   |   |               |   |   |   |
| 7:0          | KPA    |   | 0x10    | R/W      | Determines the proportional gain (KPC) used in the integrated PI controller. KPC is calculated by:<br>$KPC = KP[10:0] + KPA[7:0] \times REFERENCE[11:0]$                       |   |   |               |   |   |   |

### 6.11.6 0x5 CONFIG

Table 33: CONFIG register details

| ADDRESS: 0x5 |        |       |         | CONFIG |  | DEFAULT:0x000 |    |    |           |   |   |
|--------------|--------|-------|---------|--------|--|---------------|----|----|-----------|---|---|
| 11           | 10     | 9     | 8       | 7      | 6  | 5             | 4  | 3  | 2         | 1 | 0 |
| ONCOMP       | SIGN   | SENSE | AUTO    | SYNC   | LOCK   | RST           | OE | DS | PLAY[2:0] |   |   |
| BITS         | NAME   |       | DEFAULT | TYPE   | DESCRIPTION  |               |    |    |           |   |   |
| 11           | ONCOMP |       | 0x0     | R/W    | Enables sensing comparator used use to trigger sensing detection event.<br>ONCOMP bit needs to be reset to 0x0 to clear <a href="#">SENSE_FLAG</a> bit after a detection.<br><br>0x1: Comparator active<br>0x0: Comparator inactive  |               |    |    |           |   |   |
| 10           | SIGN   |       | 0x0     | R/W    | Defines if <a href="#">SENSE_VALUE[8:0]</a> should be above or below the threshold set by <a href="#">STHRESH[8:0]</a> bits to trigger a sensing detection event.<br><br>0x1: Below<br>0x0: Above  |               |    |    |           |   |   |
| 9            | SENSE  |       | 0x0     | R/W    | Disables Q <sub>1</sub> and Q <sub>2</sub> to set OUTPUT node to high impedance, enables piezo sensing and push voltage detected on piezo in <a href="#">SENSE_VALUE[8:0]</a> field.<br><a href="#">ONCOMP</a> , <a href="#">SIGN</a> , <a href="#">AUTO</a> , <a href="#">REP</a> and <a href="#">STHRESH[8:0]</a> fields have no effect if SENSE is set to 0x0.<br><br>A successful sensing detection clears SENSE bit if <a href="#">AUTO</a> bit is set to 0x1.<br>The waveform must be finished playing before enabling SENSE bit.<br><br>0x1: Enable<br>0x0: Disable |               |    |    |           |   |   |

| ADDRESS: 0x5 |      | CONFIG |         | DEFAULT:0x000 |  |     |    |    |           |   |   |
|--------------|------|--------|---------|---------------|--|-----|----|----|-----------|---|---|
| 11           | 10   | 9      | 8       | 7             | 6  | 5   | 4  | 3  | 2         | 1 | 0 |
| ONCOMP       | SIGN | SENSE  | AUTO    | SYNC          | LOCK   | RST | OE | DS | PLAY[2:0] |   |   |
| BITS         | NAME |        | DEFAULT | TYPE          | DESCRIPTION  |     |    |    |           |   |   |
| 8            | AUTO |        | 0x0     | R/W           | Enables a waveform programmed using RAM Playback or RAM Synthesis to be played automatically when the sensing comparator detect a signal meeting the conditions defined by <a href="#">STHRESH[8:0]</a> and <a href="#">SIGN</a> fields.<br><br>Auto bit self-clears when the output waveform has finished playing.<br>0x0: Disable<br>0x1: Enable |     |    |    |           |   |   |
| 7            | SYNC |        | 0x0     | R/W           | Activate multi-chip synchronization.<br>0x0: Disable<br>0x1: Enable  |     |    |    |           |   |   |
| 6            | LOCK |        | 0x0     | R/W           | Enable write protections on all registers except <a href="#">CONFIG</a> and <a href="#">REFERENCE</a> registers when <a href="#">OE</a> bit is set to 0x1.<br>0x0: Disable register write protection<br>0x1: Enable register write protection  |     |    |    |           |   |   |
| 5            | RST  |        | 0x0     | R/W           | Software reset. The controller resets internal registers to default values and goes to the IDLE state. RST self-clears once the reset is completed.<br>0x0: Normal operation<br>0x1: RESET   |     |    |    |           |   |   |
| 4            | OE   |        | 0x0     | RW            | Activate haptic waveform playback or piezo actuator sensing.<br>0x0: Disable<br>0x1: Enable  |     |    |    |           |   |   |
| 3            | DS   |        | 0x0     | RW            | Power mode when <a href="#">OE</a> is set to 0x0. In SLEEP, registers and RAM data are reset.<br>0x0: IDLE<br>0x1: SLEEP   |     |    |    |           |   |   |
| 2:0          | PLAY |        | 0x0     | RW            | Sets the waveform playback sampling rate when using Direct, FIFO or RAM Playback mode.<br>0x0: 1024 ksps<br>0x1: 512 ksps<br>0x2: 256 ksps<br>0x3: 128 ksps<br>0x4: 64 ksps<br>0x5: 32 ksps<br>0x6: 16 ksps<br>0x7: 8 ksps   |     |    |    |           |   |   |

### 6.11.7 0x6 PARCAP

Table 34: PARCAP register details

| ADDRESS: 0x6 |         |          |      | PARCAP   |   | DEFAULT:0x00A |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
|--------------|---------|----------|------|--|---|---------------|---|---|---|---|---|--|--------|------|-------|--------|--------|-------|--------|--------|-------|--------|--------|-------|---------|--------|
| 11           | 10      | 9        | 8    | 7  | 6 | 5             | 4 | 3 | 2 | 1 | 0 |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| SHS[1:0]     |         | SLS[1:0] |      | PARCAP[7:0]  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| Bits         | Name    | Default  | Type | Description  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 11:10        | SHS     | 0x0      | R/W  | <div>Sets high-side gate driver strength based on transistor Q<sub>2</sub> used (see section 7.4.5). Default value should work with C<sub>ISS</sub> of Q<sub>2</sub> of ≤ 2 nF.</div> <div>An increase in SHS reduces the rise and fall time of the GDHS signal, at the cost of increasing EMI and noise.</div> <table><tr><td></td><td>Source</td><td>Sink</td></tr><tr><td>0x0 :</td><td>250 mA</td><td>170 mA</td></tr><tr><td>0x1 :</td><td>500 mA</td><td>340 mA</td></tr><tr><td>0x2 :</td><td>825 mA</td><td>550 mA</td></tr><tr><td>0x3 :</td><td>1100 mA</td><td>800 mA</td></tr></table> |   |               |   |   |   |   |   |  | Source | Sink | 0x0 : | 250 mA | 170 mA | 0x1 : | 500 mA | 340 mA | 0x2 : | 825 mA | 550 mA | 0x3 : | 1100 mA | 800 mA |
|              | Source  | Sink     |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x0 :        | 250 mA  | 170 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x1 :        | 500 mA  | 340 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x2 :        | 825 mA  | 550 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x3 :        | 1100 mA | 800 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 9:8          | SLS     | 0x0      | R/W  | <div>Sets low-side gate driver strength based on transistor Q<sub>1</sub> used (see section 7.4.5). Default value should work with C<sub>ISS</sub> of Q<sub>1</sub> of ≤ 2 nF.</div> <div>An increase in SLS reduces the rise and fall time of the GDLS signal, at the cost of increasing EMI and noise.</div> <table><tr><td></td><td>Source</td><td>Sink</td></tr><tr><td>0x0:</td><td>250 mA</td><td>200 mA</td></tr><tr><td>0x1:</td><td>500 mA</td><td>380 mA</td></tr><tr><td>0x2:</td><td>850 mA</td><td>620 mA</td></tr><tr><td>0x3:</td><td>1200 mA</td><td>850 mA</td></tr></table>      |   |               |   |   |   |   |   |  | Source | Sink | 0x0:  | 250 mA | 200 mA | 0x1:  | 500 mA | 380 mA | 0x2:  | 850 mA | 620 mA | 0x3:  | 1200 mA | 850 mA |
|              | Source  | Sink     |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x0:         | 250 mA  | 200 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x1:         | 500 mA  | 380 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x2:         | 850 mA  | 620 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 0x3:         | 1200 mA | 850 mA   |      |  |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |
| 7:0          | PARCAP  | 0x0A     | R/W  | <div>Internal parameter determined by:</div> <div><math display="block">PARCAP[7:0] = \sqrt{\frac{C_{oss-Q1} + C_{oss-Q2} + C_{par}}{L}} \times R_{sense} \times 2^{16}</math></div> <div>Where C<sub>oss-Q1</sub> and C<sub>oss-Q2</sub> are the output capacitance of Q<sub>1</sub> and Q<sub>2</sub> transistors and C<sub>par</sub> is the parasitic capacitance seen on pin SW which depends on inductor (L<sub>1</sub>) and PCB layout.</div> <div>Typically, the optimal setting for a system is 20% to 50% higher than the calculated value.</div>   |   |               |   |   |   |   |   |  |        |      |       |        |        |       |        |        |       |        |        |       |         |        |

### 6.11.8 0x7 SUP\_RISE

Table 35: SUP\_RISE register details

| ADDRESS: 0x7 |          |         |      | SUP_RISE   |   | DEFAULT:0x5CF |   |   |   |   |   |
|--------------|----------|---------|------|--|---|---------------|---|---|---|---|---|
| 11           | 10       | 9       | 8    | 7  | 6 | 5             | 4 | 3 | 2 | 1 | 0 |
| TOUT         | VIN[4:0] |         |      |  |   | TI_RISE[5:0]  |   |   |   |   |   |
| Bits         | Name     | Default | Type | Description  |   |               |   |   |   |   |   |
| 11           | TOUT     | 0x0     | R/W  | Timeout in Direct mode and FIFO mode. If TOUT is set to 0x1, <a href="#">EMPTY</a> bit is set to 0x1 and no new data has been received for more than 4 ms, the device automatically goes to SLEEP state. RAM and registers are reset, except PLAY[2:0] bits are set to 0x7.<br><br>0x0: Timeout disabled<br>0x1: Timeout enabled |   |               |   |   |   |   |   |
| 10:6         | VIN      | 0x17    | R/W  | Digital representation of the supply voltage V <sub>IN</sub> . VIN[4:0] is determined by the following:<br><br>$VIN [4:0] = \frac{V_{IN}}{0.52}$<br><br>Where, V <sub>IN</sub> is the supply voltage in volt and 0x11 ≤ VIN[4:0] ≤ 0x1F.   |   |               |   |   |   |   |   |
| 5:0          | TI_RISE  | 0x0F    | R/W  | Proportional gain for the offset, which is determined by:<br><br>$TI\_RISE[5:0] = \frac{R_{sense}}{428.9 \times L_1}$  |   |               |   |   |   |   |   |

### 6.11.9 0x8 RAM

Table 36: RAM register details

| ADDRESS: 0x8 |            |         | RAM  |  | DEFAULT:0x001 |   |   |   |        |           |   |
|--------------|------------|---------|------|--|---------------|---|---|---|--------|-----------|---|
| 11           | 10         | 9       | 8    | 7  | 6             | 5 | 4 | 3 | 2      | 1         | 0 |
| RSVD         |            |         |      |  |               |   |   |   | RAMSEL | MODE[1:0] |   |
| Bits         | Name       | Default | Type | Description  |               |   |   |   |        |           |   |
| 2            | RAMSEL     | 0x0     | R/W  | <p>Defines whether SPI communication is transmitted to the WFS command interpreter or to the main register map bank.</p> <p>RAMSEL bit self-clears 4 us after last SPI communication and when the CS pin is back to logic 1. If the CS pin remains at a logic 0, RAMSEL bit doesn't self-clears.</p> <p>0x0: Communication is transmitted to the main register map bank.<br/>0x1: Communication is transmitted to the WFS command interpreter.</p> |               |   |   |   |        |           |   |
| 1:0          | MODE [1:0] | 0x1     | R/W  | <p>Define waveform playback mode. This register can only be modified if <a href="#">OE</a> bit is set to 0x0.</p> <p>0x0: Direct mode<br/>0x1: FIFO mode<br/>0x2: RAM Playback<br/>0x3: RAM Synthesis</p>  |               |   |   |   |        |           |   |

### 6.11.10 0x9 SPI

Table 37: SPI register details

| ADDRESS: 0x9 |    |       |   |         | SPI        |  |   |    |    |          |   | DEFAULT:0x7A8 |  |  |  |  |  |  |
|--------------|----|-------|---|---------|------------|--|---|----|----|----------|---|---------------|--|--|--|--|--|--|
| 11           | 10 | 9     | 8 | 7       | 6          | 5  | 4 | 3  | 2  | 1        | 0 |               |  |  |  |  |  |  |
| BC[4:0]      |    |       |   |         | SHORT[1:0] |  |   | RS | TE | GPO[2:0] |   |               |  |  |  |  |  |  |
| BITS         |    | NAME  |   | DEFAULT | TYPE       | DESCRIPTION  |   |    |    |          |   |               |  |  |  |  |  |  |
| 11:7         |    | BC    |   | 0x0F    | R/W        | Address of internal register whose content is output on SPI port (SDO pin). See section 6.11.17 for details.   |   |    |    |          |   |               |  |  |  |  |  |  |
| 6:5          |    | SHORT |   | 0x1     | R/W        | Defined the length of time the piezo is periodically shorted during sensing (section 6.9).<br>SHORT bit also defines the duration of the piezo zeroing during auto-calibration when <a href="#">OE</a> bit is set to 0x1.<br>0x0: 500 μs<br>0x1: 1000 μs<br>0x2: 1500 μs<br>0x3: 2000 μs   |   |    |    |          |   |               |  |  |  |  |  |  |
| 4            |    | RS    |   | 0x0     | R/W        | Resets <a href="#">SENSE_VALUE[8:0]</a> fields. RS bit self-clears.<br>0x0: No effect<br>0x1: Reset sensing interface  |   |    |    |          |   |               |  |  |  |  |  |  |
| 3            |    | TE    |   | 0x1     | R/W        | Transmit Enable.<br>0x0: SDO pin is disabled and forced to 0 V during a transmission<br>0x1: The device can transmit data on the SDO pin   |   |    |    |          |   |               |  |  |  |  |  |  |
| 2:0          |    | GPO   |   | 0x0     | R/W        | Determines the output signal on GPO pin.<br><br>0x0: nternal reset. When the device is ready to receive the first communication after power-up, the output will be set to a logic 1. Note that during power-up, the GPO pin will go briefly to 1 during internal calibration and the device will then automatically go to SLEEP state.<br>0x1: Sense Trigger:<br>Indicates if <a href="#">SENSE_VALUE[8:0]</a> met the threshold detection conditions. Same as the state of <a href="#">SENSE_FLAG</a> bit.<br>0: Signal on the piezo doesn't meet the threshold set<br>1: Signal on piezo meets the threshold set ( <a href="#">STHRESH[8:0]</a> )<br><br>0x2: Waveform done and FIFO empty:<br>Same as the <a href="#">EMPTY</a> bit state.<br>0: Data available to play<br>1: No more data to play<br><br>0x3: Error. (Any type of faults):<br>0: No error detected<br>1: An error was detected<br><br>0x4: MXPWR:<br>0: Amount of power is acceptable<br>1: Maximum power, the waveform is likely distorted<br><br>0x7: NEXT_DATA. Use in Direct mode ( <a href="#">MODE[1:0]</a> = 0x0)<br>0: No data required from MCU<br>1: Next data required from MCU |   |    |    |          |   |               |  |  |  |  |  |  |

### 6.11.11 0xA SENSING

Table 38: SENSING register details

| ADDRESS: 0xA |         | SENSING |              |      |   | DEFAULT:0x000 |   |   |   |   |   |
|--------------|---------|---------|--------------|------|---|---------------|---|---|---|---|---|
| 11           | 10      | 9       | 8            | 7    | 6   | 5             | 4 | 3 | 2 | 1 | 0 |
| REP[2:0]     |         |         | STHRESH[8:0] |      |   |               |   |   |   |   |   |
| Bits         | Name    |         | Default      | Type | Description   |               |   |   |   |   |   |
| 11:9         | REP     |         | 0x0          | R/W  | Length of time during which the sensed voltage must be $\geq$ <a href="#">STHRESH[8:0]</a> or $\leq$ <a href="#">STHRESH[8:0]</a> , depending on the <a href="#">SIGN</a> bit.<br><br>0x0: 1 $\mu$ s<br>0x1: 15 $\mu$ s<br>0x2: 500 $\mu$ s<br>0x3: 1000 $\mu$ s<br>0x4: 2000 $\mu$ s<br>0x5: 4000 $\mu$ s<br>0x6: 8000 $\mu$ s<br>0x7: 16000 $\mu$ s   |               |   |   |   |   |   |
| 8:0          | STHRESH |         | 0x0          | R/W  | Differential voltage reference in signed decimal value of the sensing comparator, which is required to detect a sensing event and notify the user.<br><br>STHRESH[8:0] must be different than 0x0 otherwise no comparison is made.<br><br>The relation between the threshold voltage amplitude ( $V_{th}$ ) in volts and STHRESH[8:0] is determined by:<br><br>$STHRESH [8:0] = V_{th} \times 7.68$ |               |   |   |   |   |   |

### 6.11.12 0xB THRESH

Table 39: THRESH register details

| ADDRESS: 0xB |         | THRESH  |      | DEFAULT:0x048   |   |   |                   |   |   |   |   |
|--------------|---------|---------|------|---|---|---|-------------------|---|---|---|---|
| 11           | 10      | 9       | 8    | 7   | 6 | 5 | 4                 | 3 | 2 | 1 | 0 |
| VTHRESH[6:0] |         |         |      |   |   |   | THRESH_ERROR[4:0] |   |   |   |   |
| BITS         | NAME    | DEFAULT | TYPE | DESCRIPTION   |   |   |                   |   |   |   |   |
| 11:5         | VTHRESH | 0x10    | R/W  | <p>Determine the threshold voltage (<math>V_{th}</math>), below which the error between the output voltage and the setpoint must be to trigger a transition boost-to-buck. The boost-to-buck transition occurs after a delay determined by <a href="#">THRESH_ERROR[4:0]</a>. VTHRESH[6:0] is determined by:</p> $VTHRESH [6:0] = -V_{th} \times 30.7$ <p>This register may need to be optimized depending on the actuator characteristics and the presence of an output filter. A small VTHRESH[6:0] value results in rapid boost-to-buck transitions and can lead to discontinuities at the top of the output waveform. A high value results in a delay before the boost-to-buck transition and can lead to flattening at the top of the output waveform.</p> |   |   |                   |   |   |   |   |



| ADDRESS: 0xB |              | THRESH |         | DEFAULT:0x048 |   |   |                   |   |   |   |   |
|--------------|--------------|--------|---------|---------------|---|---|-------------------|---|---|---|---|
| 11           | 10           | 9      | 8       | 7             | 6   | 5 | 4                 | 3 | 2 | 1 | 0 |
| VTHRESH[6:0] |              |        |         |               |   |   | THRESH_ERROR[4:0] |   |   |   |   |
| BITS         | NAME         |        | DEFAULT | TYPE          | DESCRIPTION   |   |                   |   |   |   |   |
| 4:0          | THRESH_ERROR |        | 0x08    | R/W           | <p>Represents the amount of time the error between the output voltage and the setpoint must be less than the threshold voltage set by <a href="#">VTHRESH[6:0]</a> to trigger a boost-to-buck transition.</p> <p>This register may need to be optimized depending on the actuator characteristics and the presence of an output filter. A small THRESH_ERROR[4:0] value results in rapid boost-to-buck transitions and can lead to discontinuities at the top of the output waveform. A high value results in a delay before the boost-to-buck transition and can lead to flattening at the top of the output waveform.</p> |   |                   |   |   |   |   |

### 6.11.13 0xC IC\_STATUS

Table 40: IC\_STATUS register details

| ADDRESS: 0xC |       | IC_STATUS (read-only) |         |       |  | DEFAULT:0x001 |        |        |    |      |       |
|--------------|-------|-----------------------|---------|-------|--|---------------|--------|--------|----|------|-------|
| 11           | 10    | 9                     | 8       | 7     | 6  | 5             | 4      | 3      | 2  | 1    | 0     |
| STATE[1:0]   |       | OVV                   | OVT     | MXPWR | IDAC   | UVLO5         | UVLO12 | OVLO12 | SC | FULL | EMPTY |
| Bits         | Name  |                       | Default | Type  | Description  |               |        |        |    |      |       |
| 11:10        | STATE |                       | 0x0     | R     | <p>STATE of the controller.</p> <p>0x0: IDLE<br/>0x1: CALIBRATION<br/>0x2: RUN<br/>0x3: ERROR</p>  |               |        |        |    |      |       |
| 9            | OVV   |                       | 0x0     | R     | <p>Over voltage bit.</p> <p>0x0: Pin HV voltage is OK<br/>0x1: Pin HV voltage exceeded the maximum voltage allowed</p>   |               |        |        |    |      |       |
| 8            | OVT   |                       | 0x0     | R     | <p>Overtemperature status bit.</p> <p>0x0: IC temperature is OK<br/>0x1: Overtemperature detected on the IC</p>  |               |        |        |    |      |       |
| 7            | MXPWR |                       | 0x0     | R     | <p>Device is processing maximum amount of power.</p> <p>0x0: Amount of power is acceptable<br/>0x1: Maximum power, distortion likely</p>                                       |               |        |        |    |      |       |
| 6            | IDAC  |                       | 0x0     | R     | <p>IDAC status bit.</p> <p>0x0: No problem with current detection<br/>0x1: Problem with current detection</p>  |               |        |        |    |      |       |
| 5            | UVLO5 |                       | 0x0     | R     | <p>UVLO 5 V status bit. Voltage at VDD pin is too low for proper operation of haptic feedback.</p> <p>0x0: V<sub>DD</sub> is OK<br/>0x1: V<sub>DD</sub> voltage &lt; 4.4 V</p> |               |        |        |    |      |       |

| ADDRESS: 0xC |        | IC_STATUS (read-only) |         |       |   | DEFAULT:0x001 |        |        |    |      |       |
|--------------|--------|-----------------------|---------|-------|---|---------------|--------|--------|----|------|-------|
| 11           | 10     | 9                     | 8       | 7     | 6   | 5             | 4      | 3      | 2  | 1    | 0     |
| STATE[1:0]   |        | OVV                   | OVT     | MXPWR | IDAC  | UVLO5         | UVLO12 | OVLO12 | SC | FULL | EMPTY |
| Bits         | Name   |                       | Default | Type  | Description   |               |        |        |    |      |       |
| 4            | UVLO12 |                       | 0x0     | R     | UVLO 12 V status bit. Voltage at VIN/RP pin is too low for proper operation of haptic feedback.<br><br>0x0: V <sub>IN</sub> voltage is OK<br>0x1: V <sub>IN</sub> voltage < 8.8 V   |               |        |        |    |      |       |
| 3            | OVLO12 |                       | 0x0     | R     | OVLO 12 V status bit. Voltage at VIN/RP pin is too high for proper operation of haptic feedback.<br><br>0x0: V <sub>IN</sub> voltage is OK<br>0x1: V <sub>IN</sub> voltage >19.9 V  |               |        |        |    |      |       |
| 2            | SC     |                       | 0x0     | R     | Short circuit status bit.<br><br>0x0: IC is OK<br>0x1: Short circuit detected between OUTPUT and V <sub>IN</sub>  |               |        |        |    |      |       |
| 1            | FULL   |                       | 0x0     | R     | The FIFO is full.<br><br>0x0: Not Full<br>0x1: Full   |               |        |        |    |      |       |
| 0            | EMPTY  |                       | 0x1     | R     | Waveform playback multi-function status bit. Its function depends on <a href="#">Mode[1:0]</a> bits.<br><br>In Direct mode ( <a href="#">Mode[1:0]</a> bits set to 0x0), EMPTY indicates when new data is needed:<br>0x0: No sample required<br>0x1: Next sample required<br><br>In FIFO mode ( <a href="#">Mode[1:0]</a> bits set to 0x1), EMPTY indicates when FIFO is empty:<br>0x0: FIFO is not empty<br>0x1: FIFO is empty<br><br>In RAM Synthesis or RAM Playback modes ( <a href="#">Mode[1:0]</a> bits set to 0x2 or 0x3), EMPTY indicates when the haptic waveform has finished playing:<br>0x0: Waveform is not completed<br>0x1: Waveform is completed |               |        |        |    |      |       |

#### 6.11.14 0xD FIFO\_STATUS

Table 41: FIFO\_STATUS register details

| ADDRESS: 0xD |       | FIFO_STATUS (read-only) |         |      |   | DEFAULT:0x400 |   |   |   |   |   |
|--------------|-------|-------------------------|---------|------|---|---------------|---|---|---|---|---|
| 11           | 10    | 9                       | 8       | 7    | 6   | 5             | 4 | 3 | 2 | 1 | 0 |
| ERROR        | EMPTY | FIFO_SPACE[9:0]         |         |      |   |               |   |   |   |   |   |
| Bits         | Name  |                         | Default | Type | Description   |               |   |   |   |   |   |
| 11           | ERROR |                         | 0x0     | R    | Indicates that an error occurred (any type of faults).<br>0x0: No error<br>0x1: An error has occurred |               |   |   |   |   |   |

| ADDRESS: 0xD |            | FIFO_STATUS (read-only) |      |  |   |   | DEFAULT:0x400 |   |   |   |   |
|--------------|------------|-------------------------|------|--|---|---|---------------|---|---|---|---|
| 11           | 10         | 9                       | 8    | 7  | 6 | 5 | 4             | 3 | 2 | 1 | 0 |
| ERROR        | EMPTY      | FIFO_SPACE[9:0]         |      |  |   |   |               |   |   |   |   |
| Bits         | Name       | Default                 | Type | Description  |   |   |               |   |   |   |   |
| 10           | EMPTY      | 0x1                     | R    | <p>Waveform playback multi-function status bit. Its function depends on <a href="#">Mode[1:0]</a> bits.</p> <p>In Direct mode (<a href="#">Mode[1:0]</a> bits set to 0x0), EMPTY indicates when new data is needed:</p> <ul style="list-style-type: none"> <li>0x0: No sample required</li> <li>0x1: Next sample required</li> </ul> <p>In FIFO mode (<a href="#">Mode[1:0]</a> bits set to 0x1), EMPTY indicates when FIFO is empty:</p> <ul style="list-style-type: none"> <li>0x0: FIFO is not empty</li> <li>0x1: FIFO is empty</li> </ul> <p>In RAM Synthesis or RAM Playback modes (<a href="#">Mode[1:0]</a> bits set to 0x2 or 0x3), EMPTY indicates when the haptic waveform has finished playing:</p> <ul style="list-style-type: none"> <li>0x0: Waveform is not completed</li> <li>0x1: Waveform is completed</li> </ul> |   |   |               |   |   |   |   |
| 9:0          | FIFO_SPACE | 0x000                   | R    | <p>Space available in the FIFO for new data.</p> <p>A value of 0x000 with <a href="#">EMPTY</a> bit equal to 0x1 indicates that all the FIFO locations are available.</p> <p>A value of 0x000 with <a href="#">EMPTY</a> bit equals to 0x0 indicates that none of the FIFO locations are available, and the FIFO is full.</p>  |   |   |               |   |   |   |   |

### 6.11.15 0xE TRIM

Table 42: TRIM register details

| ADDRESS: 0xE |    |               |         | TRIM |      | DEFAULT:0x000  |   |   |               |   |   |  |
|--------------|----|---------------|---------|------|------|--|---|---|---------------|---|---|--|
| 11           | 10 | 9             | 8       | 7    | 6    | 5  | 4 | 3 | 2             | 1 | 0 |  |
| TRIMRW[1:0]  |    | TRIM_OSC[6:0] |         |      |      |  |   |   | TRIM_REG[2:0] |   |   |  |
| BITS         |    | NAME          | DEFAULT |      | TYPE | DESCRIPTION  |   |   |               |   |   |  |
| 11:10        |    | TRIMRW        | 0x0     |      | R/W  | <p>Trim control bits for adjusting the internal clock oscillator frequency (TRIM_OSC[6:0]) and 1.8 V internal regulator voltage (TRIM_REG[2:0]), see Figure 21. Hardware fuses values vary from chip-to-chip. More detail is available in section 6.2.11.</p> <p>TRIMRW[1:0] bits are automatically reset to 0x0 after each operation.</p> <p>0x0: Default behaviour where Hardware fuses are latched to the Trim Block at power-up</p> <p>0x1: Resets the Trim Block with the Hardware Fuses and then transfers Trim Block data to <a href="#">TRIM_OSC[6:0]</a> and <a href="#">TRIM_REG[2:0]</a> for reading (wait for 1 ms before reading)</p> <p>0x2: Transfers Trim Block data to <a href="#">TRIM_OSC[6:0]</a> and <a href="#">TRIM_REG[2:0]</a> for reading (wait for 1 ms before reading)</p> <p>0x3: Writes <a href="#">TRIM_OSC[6:0]</a> and <a href="#">TRIM_REG[2:0]</a> to Trim Block and transfers back Trim Block data to <a href="#">TRIM_OSC[6:0]</a> and <a href="#">TRIM_REG[2:0]</a> for reading (wait for 1 ms before reading)</p> |   |   |               |   |   |  |
| 9:3          |    | TRIM_OSC      | 0x00    |      | R/W  | <p>Oscillator trimming bits in two’s complement.</p> <p>The step size is approximately 120 kHz.</p> <p>Maximum frequency at 0x3F.</p> <p>Minimum frequency at 0x40.</p> <p>Excessive change in oscillator frequency may induce circuit malfunction. This is an advanced feature.</p>   |   |   |               |   |   |  |
| 2:0          |    | TRIM_REG      | 0x0     |      | R/W  | <p>1.8 V Regulator trimming bits in two’s complement.</p> <p>The step size is approximately 22 mV.</p> <p>Maximum voltage at 0x3.</p> <p>Minimum voltage at 0x4.</p> <p>Changing this parameter is not recommended as it affects waveform amplitude.</p>   |   |   |               |   |   |  |

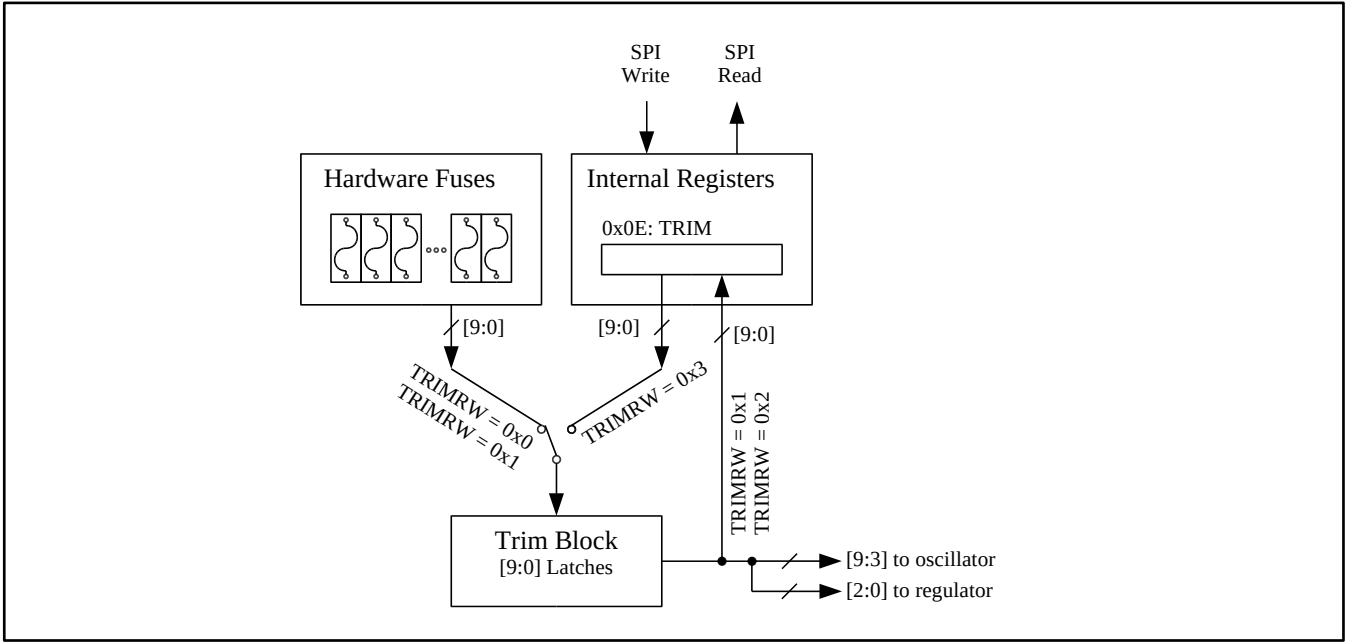


Figure 21: Trim control block diagram

6.11.16 0xF CHIP\_ID

Table 43: CHIP\_ID register details

| ADDRESS: 0xF |    | CHIP_ID |   |         |   | DEFAULT:0x034 |   |   |   |   |   |
|--------------|----|---------|---|---------|---|---------------|---|---|---|---|---|
| 11           | 10 | 9       | 8 | 7       | 6 | 5             | 4 | 3   | 2 | 1 | 0 |
| RSVD         |    |         |   |         |   | CHIP_ID[5:0]  |   |   |   |   |   |
| BITS         |    | NAME    |   | DEFAULT |   | TYPE          |   | DESCRIPTION   |   |   |   |
| 5:0          |    | CHIP_ID |   | 0x34    |   | R             |   | The field indicates the product revision of the device, as follows:<br>0x34: Rev. D |   |   |   |

6.11.17 SDO Broadcast Details

The internal register whose content is returned to the full-duplex SPI port (SDO pin) is selected by [BC\[4:0\]](#) bits. Note that the SPI transaction to read register content on the SDO pin must be performed at least 400 ns after the [BC\[4:0\]](#) bits are written.

The main register content can be broadcast by setting [BC\[4:0\]](#) bits from 0x00 to 0x0F and the returned 16-bit content is detailed in Table 44.

Extra broadcast registers are also available by setting [BC\[4:0\]](#) bits to 0x10, 0x11, 0x12 and 0x1C, and the returned 16-bit content is detailed in Table 45 to Table 48.

Table 44: BC [4:0] = 0x00 to 0x0F: details of the 16-bit data returned on the SPI port (SDO pin)

| BC [4:0] = 0x00 to 0x0F |    |    |    |  |    |   |   |   |   |   |   |   |   |   |   |
|-------------------------|----|----|----|--|----|---|---|---|---|---|---|---|---|---|---|
| 15                      | 14 | 13 | 12 | 11                                       | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| BC[3:0]                 |    |    |    | Content of register with address BC[3:0] |    |   |   |   |   |   |   |   |   |   |   |

Table 45: BC [4:0] = 0x10: details of the 16-bit data returned on the SPI port (SDO pin)

| BC [4:0] = 0x10 |    |    |           |            |    |                |  |   |   |   |   |   |   |   |   |
|-----------------|----|----|-----------|------------|----|----------------|--|---|---|---|---|---|---|---|---|
| 15              | 14 | 13 | 12        | 11         | 10 | 9              | 8  | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| RSVD            |    |    |           | STATE[1:0] |    | VFEEDBACK[9:0] |  |   |   |   |   |   |   |   |   |
| BITS            |    |    | NAME      |            |    |                | DESCRIPTION  |   |   |   |   |   |   |   |   |
| 11:10           |    |    | STATE     |            |    |                | STATE of the controller.<br>0x0: IDLE<br>0x1: CALIBRATION<br>0x2: RUN<br>0x3: ERROR  |   |   |   |   |   |   |   |   |
| 9:0             |    |    | VFEEDBACK |            |    |                | 10-bit unsigned value representing the voltage measured on HV pin (V <sub>HV</sub> ). The relation between V <sub>HV</sub> in volt and VFEEDBACK[9:0] is determined by:<br><br>$VFEEDBACK[9:0] = V_{HV} \times 7.68$ |   |   |   |   |   |   |   |   |

Table 46: BC [4:0] = 0x11: details of the 16-bit data returned on the SPI port (SDO pin)

| BC [4:0] = 0x11 |    |        |    |    |    |  |   |   |   |   |   |   |   |   |   |
|-----------------|----|--------|----|----|----|--|---|---|---|---|---|---|---|---|---|
| 15              | 14 | 13     | 12 | 11 | 10 | 9  | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| RSVD            |    |        |    |    |    | OFFSET[9:0]  |   |   |   |   |   |   |   |   |   |
| BITS            |    | NAME   |    |    |    | DESCRIPTION  |   |   |   |   |   |   |   |   |   |
| 9:0             |    | OFFSET |    |    |    | 10-bit unsigned value representing an internal offset voltage when the voltage across the piezo is 0 V. This value is updated every time <a href="#">OE</a> bit is set to 0x1. The OFFSET[9:0] value varies from chip to chip. |   |   |   |   |   |   |   |   |   |

Table 47: BC [4:0] = 0x12: details of the 16-bit data returned on the SPI port (SDO pin)

| BC [4:0] = 0x12 |    |                  |    |    |  |            |                  |   |   |   |   |   |   |   |   |
|-----------------|----|------------------|----|----|--|------------|------------------|---|---|---|---|---|---|---|---|
| 15              | 14 | 13               | 12 | 11 | 10   | 9          | 8                | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| RSVD            |    |                  |    |    | SENSE  | SENSE_FLAG | SENSE_VALUE[8:0] |   |   |   |   |   |   |   |   |
| BITS            |    | NAME             |    |    | DESCRIPTION  |            |                  |   |   |   |   |   |   |   |   |
| 10              |    | SENSE            |    |    | Indicate when the BOS1211 sensing is activated and <a href="#">SENSE</a> bit is set to 0x1. If value is 0x0, then SENSE_FLAG and SENSE_VALUE bits should be ignored.<br><br>0x0: Not Sensing<br>0x1: Sensing                 |            |                  |   |   |   |   |   |   |   |   |
| 9               |    | SENSE_FLAG       |    |    | Indicates if <a href="#">SENSE_VALUE[8:0]</a> met the threshold detection conditions. <a href="#">ONCOMP</a> bit must be reset to 0x0 to reset SENSE_FLAG.<br><br>0x1: signal above/below threshold<br>0x0: Nothing detected |            |                  |   |   |   |   |   |   |   |   |
| 8:0             |    | SENSE_VALUE[8:0] |    |    | Signed representation of the piezo sensed voltage ( <i>Amplitude</i> ) in volt.  |            |                  |   |   |   |   |   |   |   |   |

Table 48: BC [4:0] = 0x1C: details of the 16-bit data returned on the SPI port (SDO pin)

| BC [4:0] = 0x1C    |    |              |    |  |    |   |   |   |   |   |   |   |   |   |   |
|--------------------|----|--------------|----|--|----|---|---|---|---|---|---|---|---|---|---|
| 15                 | 14 | 13           | 12 | 11   | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
| RAM_DATA_RAW[15:0] |    |              |    |  |    |   |   |   |   |   |   |   |   |   |   |
| BITS               |    | NAME         |    | DESCRIPTION  |    |   |   |   |   |   |   |   |   |   |   |
| 15:0               |    | RAM_DATA_RAW |    | Read the data present in RAM. To be used in conjunction with RAM SYNTHESIS WRITE and FULL_RAM_READ WFS command (see section 6.10). |    |   |   |   |   |   |   |   |   |   |   |





## 7.2 External Components

Table 49: Recommended external components for a 4  $\mu\text{F}$  / 120 V load

| COMPONENT          | DESCRIPTION  | TYPICAL VALUE       |
|--------------------|--|---------------------|
| C <sub>VIN</sub>   | Input capacitor located close to L <sub>1</sub> <sup>(1)</sup> | 22 $\mu\text{F}$    |
| C <sub>VIN2</sub>  | Input capacitor located close to OUT <sup>(2)</sup>            | 330 nF              |
| C <sub>VDD</sub>   | V <sub>DD</sub> decoupling capacitor                           | 100 nF              |
| C <sub>VDDIO</sub> | V <sub>DDIO</sub> decoupling capacitor                         | 100 nF              |
| C <sub>REG</sub>   | Internal regulator decoupling capacitor                        | 100 nF              |
| C <sub>VDD9</sub>  | Internal V <sub>DD9</sub> capacitor                            | 100 nF              |
| C <sub>VDDH</sub>  | VDDH capacitor   | 4.7 nF              |
| C <sub>HV</sub>    | Boost capacitor  | 5% of load          |
| C <sub>OUT</sub>   | OUTPUT capacitor <sup>(3)</sup>                                | 220 nF              |
| C <sub>RP</sub>    | RP bypass capacitor (optional)                                 | 4.7 nF              |
| C <sub>RM</sub>    | RM bypass capacitor (optional)                                 | 4.7 nF              |
| R <sub>sense</sub> | Current sense resistor   | 39 m $\Omega$ , 1 W |
| R <sub>SYNC</sub>  | SYNC pull-up resistor  | 10 k $\Omega$       |
| R <sub>LS</sub>    | Q <sub>1</sub> gate series resistance                          | 20 $\Omega$         |
| R <sub>HS</sub>    | Q <sub>2</sub> gate series resistance                          | 20 $\Omega$         |
| L <sub>1</sub>     | Boost inductor   | 10 $\mu\text{H}$    |
| Q <sub>1</sub>     | Low side NMOS switch   | See section 7.4.5   |
| Q <sub>2</sub>     | High side NMOS switch  |                     |

(1) C<sub>VIN</sub> is the capacitor required to be located close to L<sub>1</sub>. Another capacitor may be required. See section 7.4.4 for the total capacitance to put on V<sub>IN</sub> node.

(2) A second capacitor C<sub>VIN3</sub> (typically 3.9 nF) & C<sub>VIN4</sub> (typically 100 nF) can optionally be placed in parallel to improve EMC performances.

(3) A second capacitor C<sub>OUT2</sub> (typically 3.9 nF) can optionally be placed in parallel to minimize high frequency noise.

## 7.3 Initialization

### 7.3.1 Power-Up Sequence

With an active MCU connected to its digital interface, the BOS1211 can be powered on with the following sequence:

1. Apply power to the BOS1211 device. Note that the  $V_{DD}$  ramp-up rate should be at least 3V/ms,  $V_{IN}$  can be applied before or at the same time as  $V_{DD}$ , and  $V_{DDIO}$  can be applied at any time.
2. Wait 3 ms for the BOS1211 to start-up with the sequence presented in Figure 23, with the following steps:
  - a.  $V_{DD}$  Power-up
  - b. Device initialization
  - c. Device going to SLEEP
3. Wake-up from SLEEP forcing a pulse low on  $\overline{CS}$  pin or performing a dummy SPI write.
4. Wait 50  $\mu$ s for the device to wake-up and enter the IDLE state.
5. Program the desired main registers according to your application.
6. The device is ready for waveform playback.

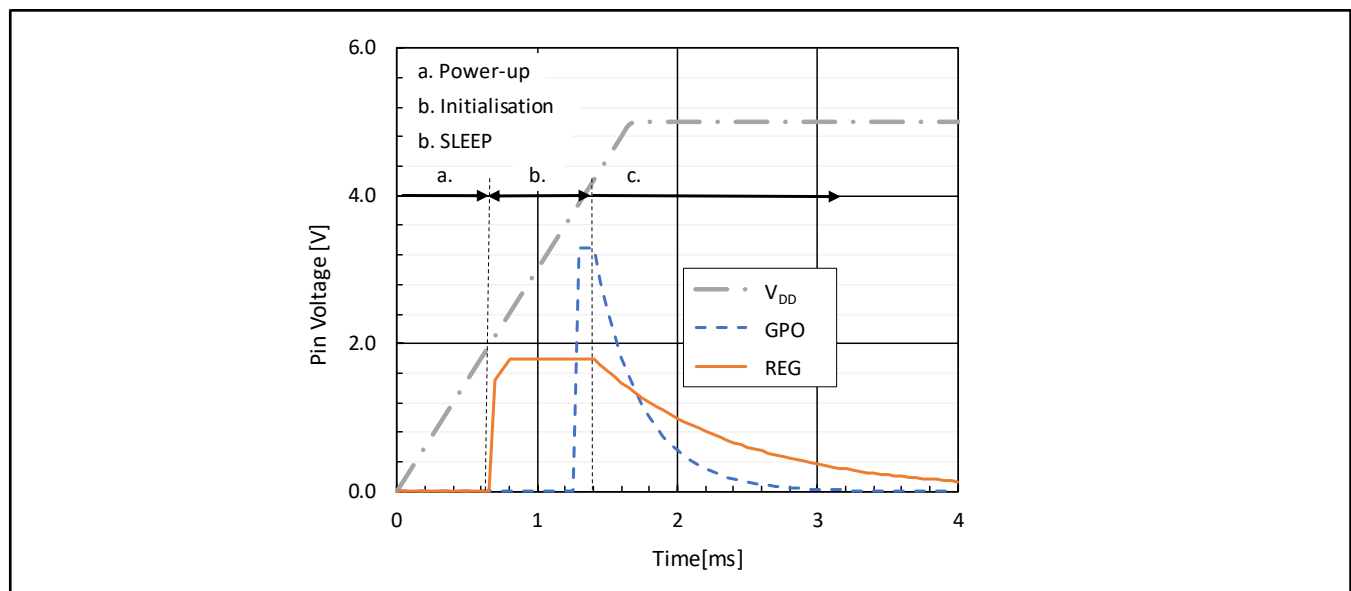


Figure 23: Typical  $V_{DD}$ , GPO & REG pin voltage during device initialization

### 7.3.2 Start-Up Sequence

Once the BOS1211 is powered up, it can wake-up from SLEEP state with the following start-up sequences:

- From SLEEP state, users must perform steps 3 to 7 of section 7.3.1.
- From IDLE state, the device is ready for waveform playback.

## 7.4 Design Methodology: selection of components

### 7.4.1 Load Selection

The BOS1211 is designed to drive a load of up to 4  $\mu\text{F}$  at 120 V and 300 Hz. Larger load capacitances ( $C_{\text{Load}}$ ) can be driven if the waveform frequency and/or the waveform amplitude is reduced or if discrete components are scaled appropriately.

Load capacitance defines the required value of component  $C_{\text{HV}}$  using the following equation:

$$C_{\text{HV}} = 5\% C_{\text{Load}} \quad (1)$$

The capacitor should have a voltage rating at least equivalent to the maximum amplitude of the waveform. For instance, for a 120 V waveform, a capacitor with a minimum voltage rating of 120 V is required.

### 7.4.2 Inductor Selection

A 10  $\mu\text{H}$   $L_1$  inductor is recommended but many COTS inductor may be used depending on the application. The peak current required in your design will set the minimum saturation current acceptable for your inductor.

You can use the following procedure to find the  $L_1$  minimum saturation current required:

1. Set the haptic waveform maximum frequency ( $f_{\text{sig}}$ ). e.g., 300 Hz.
2. Set the maximum amplitude of the waveform ( $V_{\text{pk}}$ ). e.g., 120 V
3. Set the minimum supply voltage ( $V_{\text{IN}}$ ) value during operation, e.g., 12 V
4. Calculate the maximum power transfer point with the following equations:

$$V_{\text{OUT}} = \frac{V_{\text{pk}}}{2} (1 + \sin(30)) + V_{\text{IN}} \quad (2)$$

$$\overline{I_{\text{OUT}}} = \pi f_{\text{sig}} C_{\text{Load}} V_{\text{pk}} \cos(30) \quad (3)$$

5. Calculate the average input current ( $\overline{I_{\text{IN}}}$ ) in amps with the following equation:

$$\overline{I_{\text{IN}}} = 1.5 \times \frac{V_{\text{out}} \times \overline{I_{\text{out}}}}{V_{\text{IN}}} \quad (4)$$

6. Calculate the inductor peak current ( $I_{\text{pk}}$ ) in amps using the following equation:

$$I_{\text{pk}} = 1.5 \times \overline{I_{\text{IN}}} \quad (5)$$

For an optimal design, the inductor with the smallest DCR value possible should be used with saturation current higher than  $I_{\text{pk}}$ .

### 7.4.3 Current Limit Selection ( $R_{\text{sense}}$ )

The current limit of the power converter is set by  $R_{\text{sense}}$ . The value of  $R_{\text{sense}}$  must be selected to enable a current range appropriate for the  $I_{\text{pk}}$  value calculated for the inductor (see section 7.4.2). Refer to Table 50 and equation (6) to estimate  $R_{\text{sense}}$  value. Make sure that the saturation current of the inductor

selected is higher than the current limit. The current limit that will flow passing through  $R_{sense}$  in amps is determined by the following equation:

$$\text{Current Limit} = \frac{0.256}{R_{sense}} \quad (6)$$

Table 50: Inductor peak current limit, min/max values

| $R_{sense}$ [ $\Omega$ ] | CURRENT LIMIT [A] | COMMENT                   |
|--------------------------|-------------------|---------------------------|
| 1.0                      | 0.256             | Maximum $R_{sense}$ value |
| 0.068                    | 3.8               |                           |
| 0.03                     | 8.5               | Minimum $R_{sense}$ value |

#### 7.4.4 Input Capacitor ( $C_{VIN}$ )

An input capacitor ( $C_{VIN}$ ) must be placed next to the inductor because of the current requirement of the power converter. A low-ESR capacitor of at least 10  $\mu\text{F}$  is recommended.

The energy recovered from the load in reverse mode accumulates on  $C_{VIN}$  and causes the input voltage to increase. The voltage increase must not make the total voltage on  $C_{VIN}$  exceed the 19.9 V limit ( $V_{IN\_max}$ ). Equation (7) helps find the minimum capacitance value for your specific design. The capacitance maybe distributed across the power distribution network on  $V_{IN}$ .

$$C_{VIN} = \frac{C_{load} \times V_{pk}^2}{V_{IN\_max}^2 - V_{Supply12V\_max}^2} \quad (7)$$

Where  $V_{Supply12V\_max}$  is the maximum voltage expected on the 12 V supply for the application and  $V_{IN\_max} = 19.9$  V is the maximum tolerable voltage at VIN/RP pin without triggering a [OVLO12](#) fault. When selecting the capacitor, make sure its effective capacitance is closed to the calculated value in your operating conditions.

#### 7.4.5 External Transistors ( $Q_1$ & $Q_2$ )

The external NMOS transistors must be chosen with the following criteria:

1. Peak drain current greater than  $I_{pk}$  when  $V_{GS}$  is greater than 6 V.
2. Lowest drain-source resistance ( $R_{DS(on)}$ ) possible.
3. The Gate capacitance ( $C_{ISS}$ ) should be  $\leq 2$  nF to have a fast enough rise time of the gate driver output.
4. Drain-source breakdown voltage ( $BV_{DSS}$ ) greater than  $V_{pk} + V_{INMAX}$ .
5. Lowest gate to drain ( $C_{RSS}$ ) capacitance possible.

#### 7.4.6 VDDH Capacitor ( $C_{VDDH}$ )

The  $C_{VDDH}$  capacitance depends on gate capacitance of  $Q_2$  ( $C_{ISS-Q2}$ ) and must be selected as follows:

$$7 \times C_{ISS-Q2} \leq C_{VDDH} \leq 20 \times C_{ISS-Q2} \quad (8)$$

#### 7.4.7 Validating Component Choice

The [MXPWR](#) bit can be monitored to validate that the components choice is performing well in a specific design. A [MXPWR](#) bit going to 0x1 means that the peak current calculated is too low and the circuit needs to be modified.

Also note that a higher  $L_1$  inductor DCR and  $Q_1/Q_2$  NMOS  $R_{DS(on)}$  reduce the BOS1211 efficiency and lead to a higher  $I_{pk}$  requirement.

Designing a circuit to drive a wide range of piezo OUTPUT voltage may require larger components to accommodate the higher  $I_{pk}$  at low voltage. One can consider using a lower haptic waveform amplitude or frequency at lower  $V_{IN}$  to reduce the size and cost of the solution.

## 7.5 Design Methodology: Programming

Many operational settings are adjustable through the digital front end. Users should program the following parameters according to its specific design.

### 7.5.1 Waveform Playback

- Set FIFO readout speed: [CONFIG.PLAY\[2:0\]](#)

### 7.5.2 Power Converter

- Set the maximum switching frequency of the power converter: [ION BL.FSWMAX\[1:0\]](#)
- Set SLS and SHS parameters according to the selected MOS transistors: [PARCAP.SLS\[1:0\]](#), [PARCAP.SHS\[1:0\]](#)

### 7.5.3 Loop Controller

The BOS1211 implements a proportional-integral (PI) control loop feedback. Users can optimize the following parameters if required:

- Set proportional gain using [KP.KP\[10:0\]](#)
- Set proportional gain term related to waveform amplitude with [KPA KI.KPA\[7:0\]](#)
- Set integral term [KPA KI.KIBASE\[3:0\]](#)

Table 51 shows the recommended value for a 4  $\mu$ F load operating at up to 120 V and 300 Hz with a  $L_1 = 10 \mu$ H and  $R_{sense} = 39m\Omega$ .

Table 51: Loop controller parameters

| PARAMETER | RECOMMENDED VALUE    | COMMENT   |
|-----------|----------------------|---|
| KP        | 0x80 (default value) | Reduce value for smaller loads                        |
| KPA       | 0x10 (default value) | Reduce value for smaller loads                        |
| KIBASE    | 0x3 (default value)  | Increase value to 3 or 4 when using a larger inductor |

### 7.5.4 Power Efficiency

The power consumption of the BOS1211 and haptic waveform integrity can be optimized by configuring the internal controller and the switching timing of the power MOSFETs. To do so, adjust the following registers based on the selected inductor (L), current sense limit ( $R_{sense}$ ) and power transistors ( $Q_1$  and  $Q_2$ ):

- Set proportional gain using [KP.KP\[10:0\]](#)
- Adjust power switch deadtime using [DEADTIME.DHS\[6:0\]](#) and [DEADTIME.DLS\[4:0\]](#)
- Adjust low-side and high-side gate drivers strength using [PARCAP.SLS\[1:0\]](#) and [PARCAP.SHS\[1:0\]](#)
- Adjust minimum current required to turn on HS using [ION.BL.IONSCALE\[7:0\]](#)
- Adjust [PARCAP.PARCAP\[7:0\]](#) based on capacitance seen on pin SW
- Adjust proportional gain for the offset using [SUP\\_RISE.TI\\_RISE\[5:0\]](#)
- Set the nominal supply voltage ( $V_{IN}$ ) of the design using [SUP\\_RISE.VIN\[4:0\]](#)

## 8 Layout

A 4-layer PCB layout example is presented in Figure 24. The recommended layers are as following:

- Top layer - Components, main routing and  $V_{IN}$ .
- Layer 2 - Full ground plane, avoid interruptions/slot as much as possible.
- Layer 3 - Power plane split between  $V_{DD}$ ,  $V_{DDIO}$  and GND.
- Bottom layer - Routing.

Layout considerations:

1. Keep  $V_{IN}$  node on the Top layer, using a minimum trace length (avoid the use of a power plane).
2. Keep SW node area as small as possible, the use of a copper region is recommended to increase current capability.
3. Place and route components  $Q_1$ ,  $C_{VIN1}$  to  $C_{VIN4}$ ,  $C_{OUT1}$  and  $C_{OUT2}$  with the following considerations:
  - a. Place components close to each other to minimize area of the high di/dt current loop and reduce high voltage ringing & spikes.
  - b. Force the high current path on the OUT and VIN nodes to flow through the decoupling capacitors  $C_{VINx}$  and  $C_{OUTx}$  in increasing order of values; the lower value capacitors should be closer to the high di/dt current loop.
  - c. Create a GND island on the Top layer connecting to all these components, fill with vias to layer 2 ground plane. This GND island must not be tied to the top layer ground polygon/plane (if applicable).
4. Place  $C_{HV}$  between  $C_{OUT1}$  and  $C_{VIN2}$ .
5. Route Vin/RP & RM sensing lines parallel to each other.
6. Route SW & GDHS lines going to  $Q_2$  in parallel to each other and keep lines length as short as possible (bottom layer).
7. Route VIN-FB & OUT sensing lines parallel to each other and keep lines length as short as possible (bottom layer).

## EMI recommendations:

8. Use RHS and RLS resistors of  $20\ \Omega$  on GDHS and GDLS signals.
9. Use a Common mode choke at the input of  $V_{IN}$  and/or at the output if needed.

## Notes on important components:

- The layout example is sized for a piezo TDK Powerhap™ actuator with a capacitance in the range of 3 to 4  $\mu\text{F}$ .  $L_1$  inductor and  $C_{HV}$  capacitor footprints can be reduced with reduced capacitive load.
- Components packages
  - ✓  $Q_1$  and  $Q_2$  transistors are surface mount  $3.3 \times 3.3\ \text{mm}$  package.
  - ✓  $C_{OUTX}$  and  $C_{VIN2}$  to  $C_{VIN3}$  capacitors are 0805 (2012).
  - ✓  $C_{VIN1}$  and  $CHV$  capacitors are 1210 (3125).
  - ✓  $R_{Sense}$  resistor is 1206 (3216).

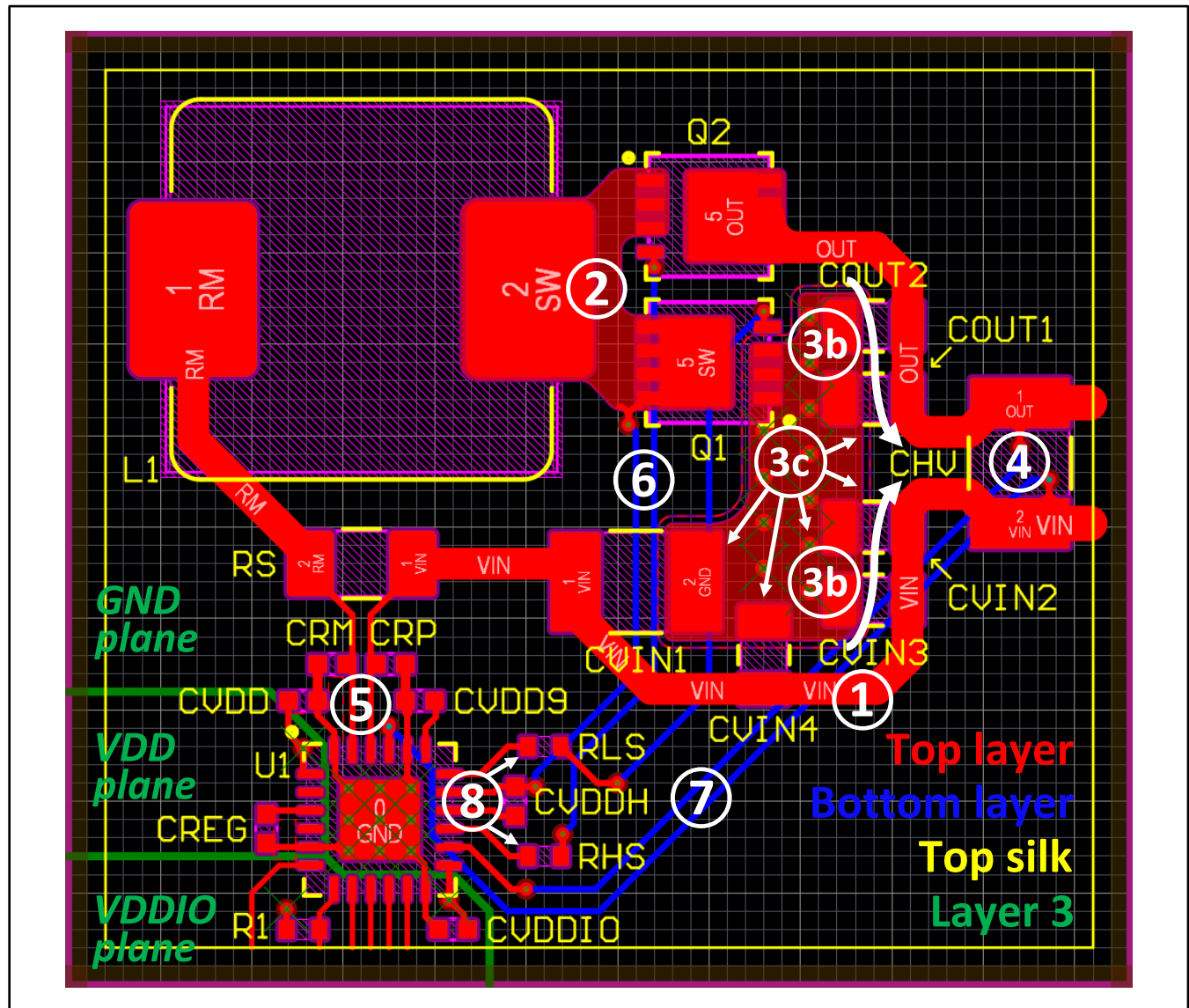


Figure 24: Recommended PCB Layout

## 9 Mechanical - BOS1211AQ (QFN)

### 9.1 Package Description

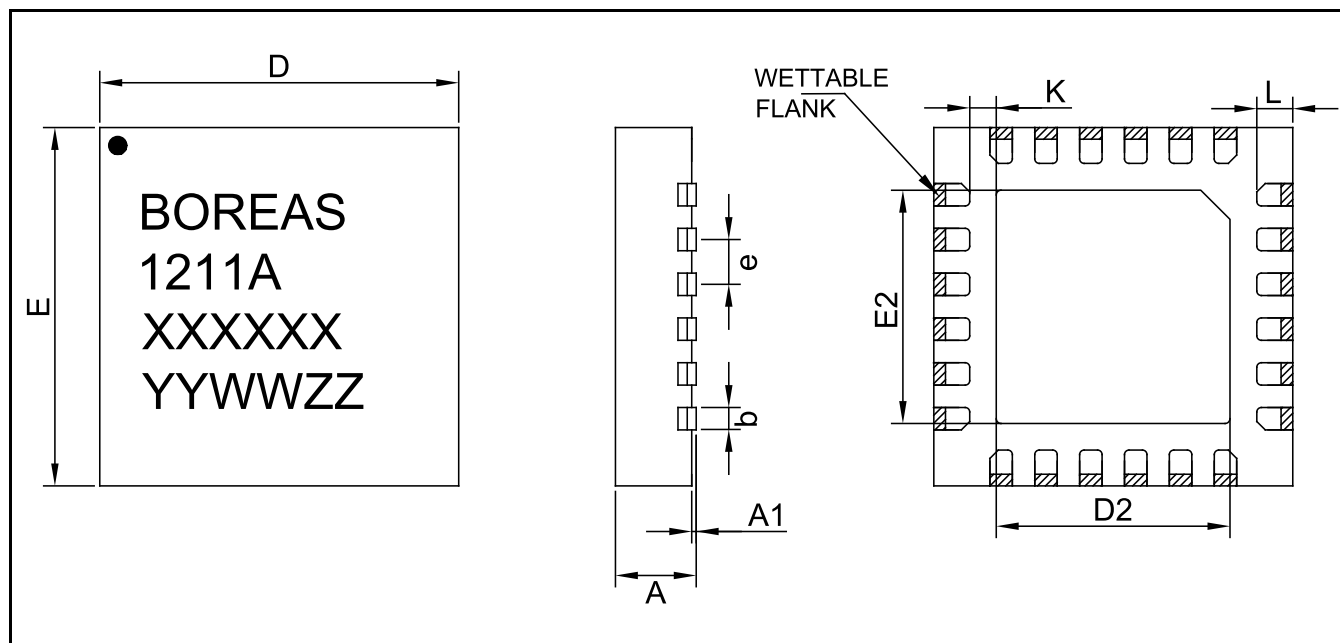


Figure 25: QFN 24L 4.0mm x 4.0mm package outline drawing

Table 52: QFN 24L 4.0mm x 4.00mm package dimensions

| SYMBOL | MILLIMETERS |       |      |
|--------|-------------|-------|------|
|        | MIN         | NOM   | MAX  |
| A      | 0.80        | 0.85  | 0.90 |
| A1     | 0.00        | 0.025 | 0.05 |
| b      | 0.20        | 0.25  | 0.30 |
| D      | 4.00 BSC    |       |      |
| D2     | 2.45        | 2.50  | 2.55 |
| E      | 4.00 BSC    |       |      |
| E2     | 2.45        | 2.50  | 2.55 |
| e      | 0.50 BSC    |       |      |
| K      | 0.17        | -     | -    |
| L      | 0.45        | 0.50  | 0.55 |

#BSC: Basic Spacing between Center

##Reference: JEDEC MO-220-WGGD

Four lines are branded on the package:

- (1) Company Name: BOREAS
- (2) Device Marking: 1211A
- (3) Wafer Batch Number: XXXXXX
- (4) Assembly Date Code: YY (Year), WW, (Week) and ZZ (Assembly House)



## 9.2 Package Soldering Footprint

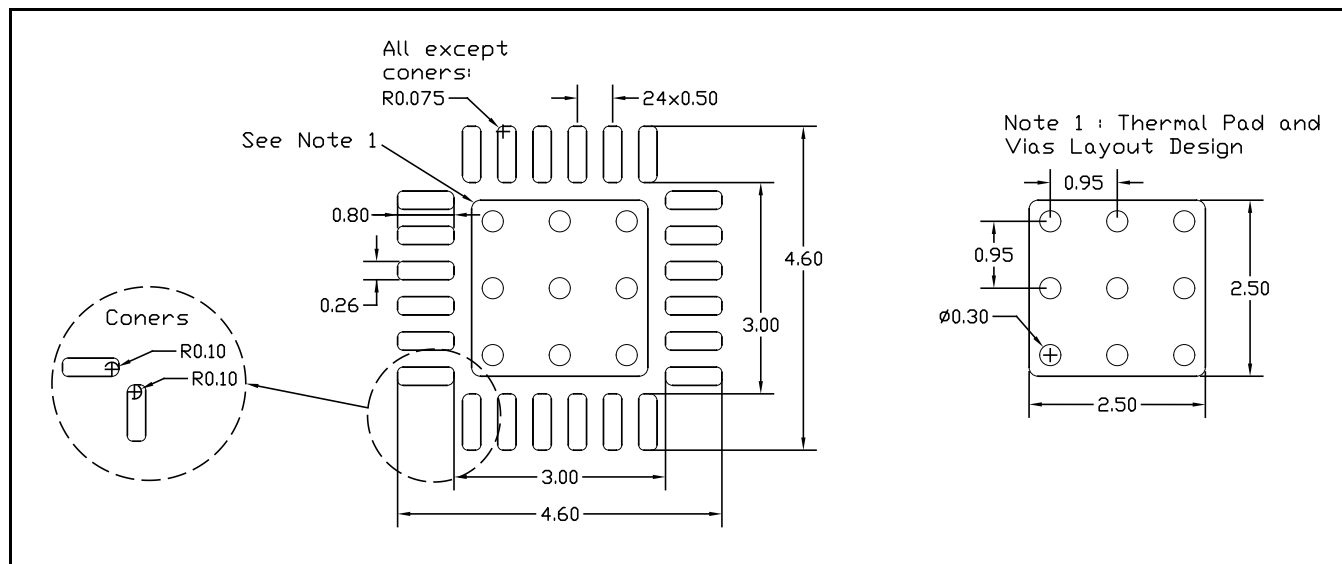


Figure 26: QFN 24L 4.0mm x 4.0mm soldering footprint (NOT TO SCALE)

## 9.3 QFN Reflow

The QFN package soldering reflow profile should be determined based on the recommended reflow profile made by the manufacturer of the solder paste used. Also, it is important to take into considerations that the circuit board dimensions, other board components and the reflow soldering oven may affect the reflow profile.

Finally, please note that the quality of the solder paste plays an important role in board assembly and allows for a reliable and repeatable assembly process.

9.4 Tape and Reel Specification

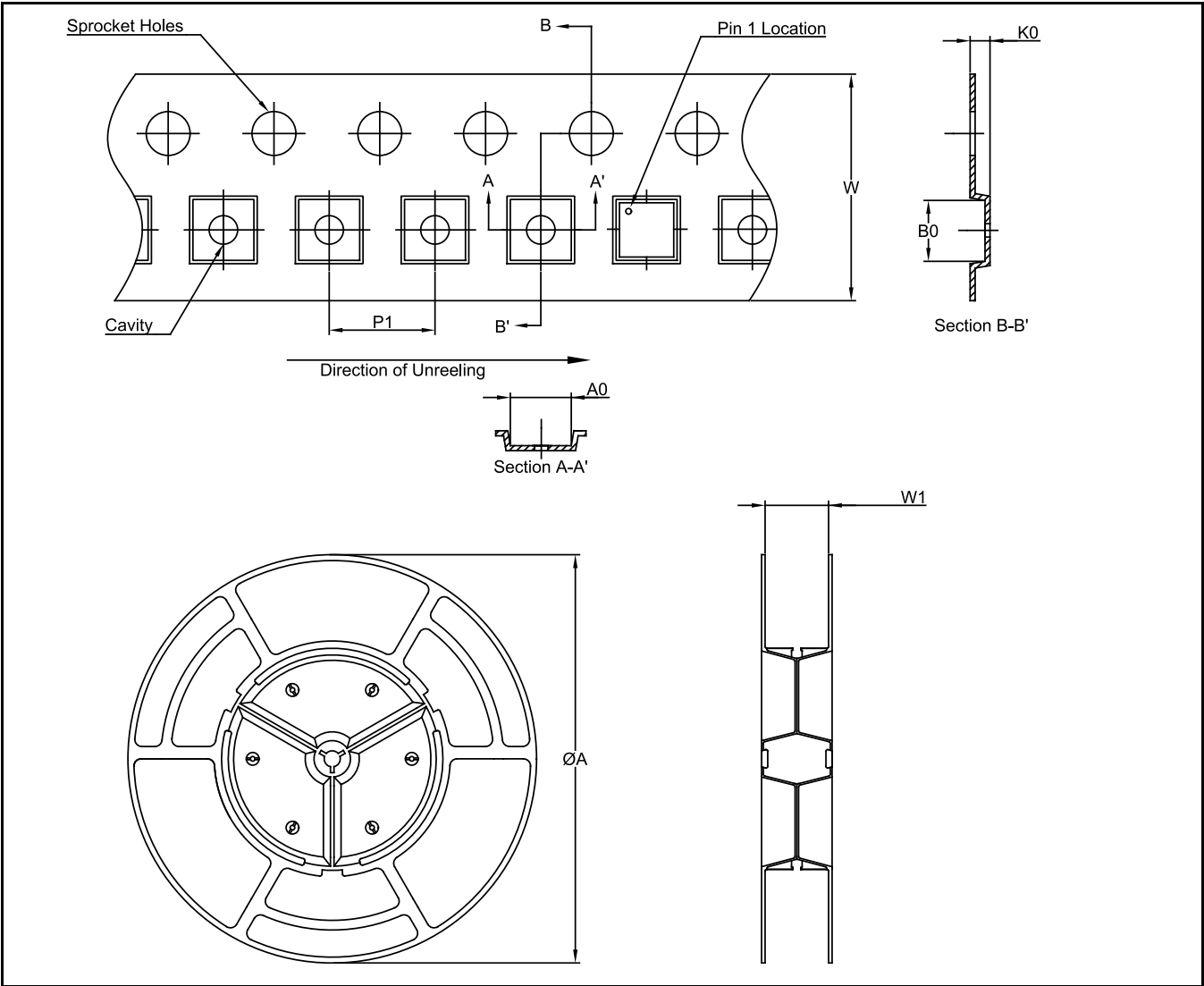


Figure 27: Embossed carrier tape and reel outline (NOT TO SCALE)

Table 53 Tape and reel dimensions

| PART NUMBER | PACKAGE TYPE | A0<br>(mm) | B0<br>(mm) | K0<br>(mm) | P1<br>(mm) | W    | ØA<br>(mm) | W1<br>(mm) |
|-------------|--------------|------------|------------|------------|------------|------|------------|------------|
| BOS1211AQ   | QFN          | 4.40       | 4.40       | 1.80       | 8.00       | 16.0 | 330.0      | 13.9       |

## 10 Ordering Information

Table 54: Ordering information

|   | ORDERING PART<br>NUMBER<br>(1) | PACKAGE<br>(2)        | PACKING<br>FORMAT | QUANTITY<br>(3) | MSL<br>PEAK TEMP. (4)     | DEVICE<br>MARKING |
|---|--------------------------------|-----------------------|-------------------|-----------------|---------------------------|-------------------|
| 1 | BOS1211AQR                     | QFN 24L 4.0mm x 4.0mm | Tape & Reel (R)   | 2500 / Reel     | Level 3<br>260 °C/168 Hrs | 1211A             |

### NOTE

- (1) Ordering Part Number where last letter indicates packing format.
- (2) All parts are RoHS compliant.
- (3) Contact [sales@boreas.ca](mailto:sales@boreas.ca) to order.
- (4) MSL is the Moisture Sensitivity Levels, IPC/JEDEC J-STD-020.

## 11 Document History

| ISSUE | DATE         | DOCUMENT NUMBER | CHANGES   |
|-------|--------------|-----------------|---|
| 5     | March 2024   | BT002DDS01.01   | <p>Product Datasheet.</p> <p>Updated section 5.3 &amp; 5.4.</p> <p>Added typical performance characteristics (section 5.6).</p> <p>Clarified examples of section 6.5, 6.6, 6.7, 6.8 &amp; 6.9.</p> <p>Added notes to sensing feature (section 6.9).</p> <p>Added CHIP_ID field details (section 6.11.16).</p> <p>Updated power-up sequence (section 7.3.1).</p> <p>Updated layout recommendation (section 8).</p> <p>Updated POD and soldering footprint (section 9.1 &amp; 9.2).</p> |
| 4     | January 2022 | BT002CDS01.02   | <p>Preliminary Datasheet.</p> <p>Improved WFS commands explanation (section 6.9).</p> <p>VDDIO operating conditions widened (section 5.3).</p> <p>Added Tape and Reel information (section 9.4).</p>  |

## 12 Notice and Warning

### Warning High Voltage



For safety, this integrated circuit must be used by qualified and skilled personnel familiar with all applicable safety standards.

### ESD Caution



This integrated circuit is ESD (Electrostatic Discharge) sensitive. Therefore, proper ESD precautions and procedures are recommended for handling and installation to avoid damage.

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