PCU9654

8-bit UFm 5 MHz I²C-bus 100 mA 40 V LED driver

Rev. 1 — 2 July 2012 Product data sheet

1. General description

The PCU9654 is a UFm I²C-bus controlled 8-bit LED driver optimized for voltage switch dimming and blinking 100 mA Red/Green/Blue/Amber (RGBA) LEDs. Each LED output has its own 8-bit resolution (256 steps) fixed frequency individual PWM controller that operates at 97 kHz with a duty cycle that is adjustable from 0 % to 99.6 % to allow the LED to be set to a specific brightness value. An additional 8-bit resolution (256 steps) group PWM controller has both a fixed frequency of 190 Hz and an adjustable frequency between 24 Hz to once every 10.73 seconds with a duty cycle that is adjustable from 0 % to 99.6 % that is used to either dim or blink all LEDs with the same value.

Each LED output can be off, on (no PWM control), set at its individual PWM controller value or at both individual and group PWM controller values. The PCU9654 operates with a supply voltage range of 2.3 V to 5.5 V and the 100 mA open-drain outputs allow voltages up to 40 V for LED supply.

The PCU9654 is one of the first LED controller devices in a new Ultra Fast-mode (UFm) family. UFm devices offer higher frequency (up to 5 MHz).

The active LOW Output Enable input pin ($\overline{OE}$) blinks all the LED outputs and can be used to externally PWM the outputs, which is useful when multiple devices need to be dimmed or blinked together without using software control.

Software programmable LED Group and three Sub Call I²C-bus addresses allow all or defined groups of PCU9654 devices to respond to a common I²C-bus address, allowing for example, all red LEDs to be turned on or off at the same time, thus minimizing I²C-bus commands. Six hardware address pins allow up to 64 devices on the same bus.

The Software Reset (SWRST) Call allows the master to perform a reset of the PCU9654 through the I²C-bus, identical to the Power-On Reset (POR) that initializes the registers to their default state causing the outputs to be set HIGH (LED off). This allows an easy and quick way to reconfigure all device registers to the same condition.

2. Features and benefits

- 8 LED drivers. Each output programmable at:
  - Off
  - On
  - Programmable LED brightness
  - Programmable group dimming/blinking mixed with individual LED brightness
- 5 MHz Ultra Fast-mode I²C-bus interface
- 256-step (8-bit) linear programmable brightness per LED output varying from fully off (default) to maximum brightness using a 97 kHz PWM signal
- 256-step group brightness control allows general dimming (using a 190 Hz PWM signal) from fully off to maximum brightness (default)
- 256-step group blinking with frequency programmable from 24 Hz to 10.73 s and duty cycle from 0 % to 99.6 %
- Eight open-drain outputs can sink between 0 mA to 100 mA and are tolerant to a maximum off state voltage of 40 V. No input function.
- Output state change programmable on the Acknowledge (bit 9, this bit is always set to 1 by UFm I²C-bus master) or the STOP Command to update outputs byte-by-byte or all at the same time (default to 'Change on STOP').
- Active LOW Output Enable ($\overline{OE}$) input pin allows for hardware blinking and dimming of the LEDs when LED driver output state is fully ON (LDRx = 01 in LEDOUT0/1 registers)
- Six hardware address pins allow 64 PCU9654 devices to be connected to the same UFm I²C-bus and to be individually programmed
- 4 software programmable UFm I²C-bus addresses (one LED Group Call address and three LED Sub Call addresses) allow groups of devices to be addressed at the same time in any combination (for example, one register used for 'All Call' so that all the PCU9654s on the I²C-bus can be addressed at the same time and the second register used for three different addresses so that $\frac{1}{3}$ of all devices on the bus can be addressed at the same time in a group). Software enable and disable for I²C-bus address.
- Software Reset feature (SWRST Call) allows the device to be reset through the UFm I²C-bus
- 25 MHz internal oscillator requires no external components
- Internal power-on reset
- Noise filter on USDA/USCL inputs
- Glitch free LED outputs on power-up
- Supports hot insertion
- Low standby current
- Operating power supply voltage (V_{DD}) range of 2.3 V to 5.5 V
- 5.5 V tolerant inputs on non-LED pins
- −40 °C to +85 °C operation
- ESD protection exceeds 2000 V HBM per JESD22-A114 and 1000 V CDM per JESD22-C101
- Latch-up testing is done to JEDEC Standard JESD78 which exceeds 100 mA
- Packages offered: TSSOP24

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3. Applications

- RGB or RGBA LED drivers
- LED status information
- LED displays
- LCD backlights
- Keypad backlights for cellular phones or handheld devices

4. Ordering information

Table 1. Ordering information

Type number	Topside mark	Package		
		Name	Description	Version
PCU9654PW	PCU9654	TSSOP24	plastic thin shrink small outline package; 24 leads; body width 4.4 mm	SOT355-1

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5. Block diagram

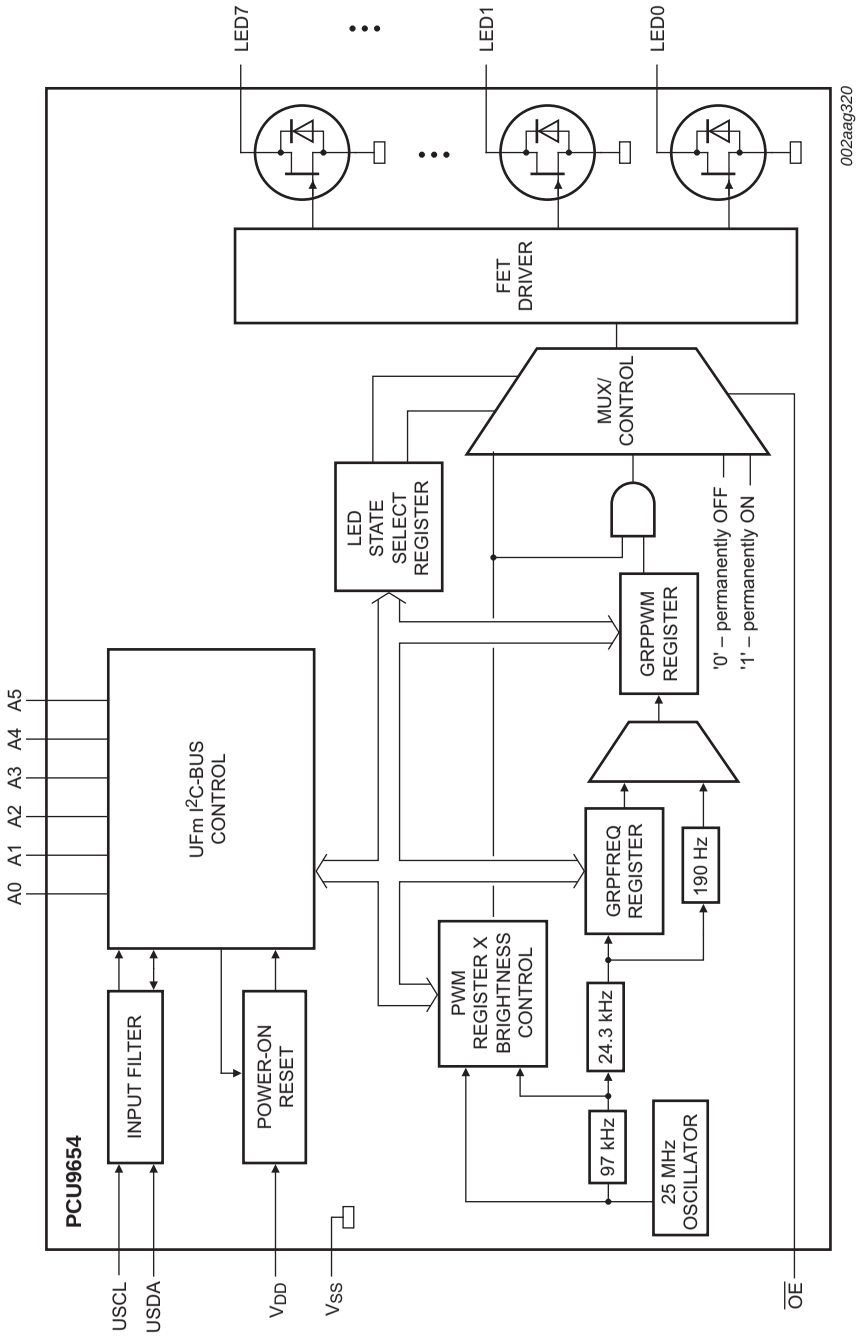


Fig 1. Block diagram of PCU9654

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6. Pinning information

6.1 Pinning

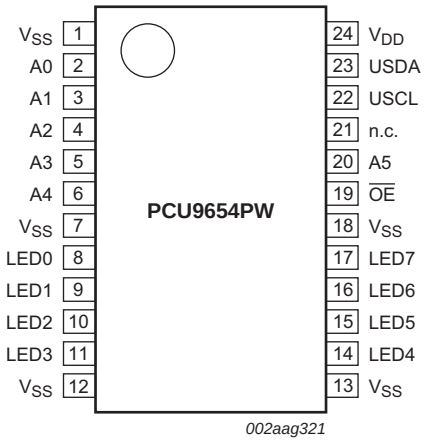


Fig 2. Pin configuration for TSSOP24

6.2 Pin description

Table 2. Pin description

Symbol	Pin	Type	Description
V_{SS}	1, 7, 12, 13, 18	power supply	supply ground
A0	2	I	address input 0
A1	3	I	address input 1
A2	4	I	address input 2
A3	5	I	address input 3
A4	6	I	address input 4
LED0	8	O	LED driver 0
LED1	9	O	LED driver 1
LED2	10	O	LED driver 2
LED3	11	O	LED driver 3
LED4	14	O	LED driver 4
LED5	15	O	LED driver 5
LED6	16	O	LED driver 6
LED7	17	O	LED driver 7
$\overline{OE}$	19	I	active LOW output enable for LEDs
A5	20	I	address input 5
n.c.	21	I	do not connect; reserved input
USCL	22	I	UFm serial clock line
USDA	23	I	UFm serial data line
V_{DD}	24	power supply	supply voltage

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7. Functional description

Refer to Figure 1 “Block diagram of PCU9654”.

7.1 Device addresses

Following a START condition, the bus master must output the address of the slave it is accessing.

There are a maximum of 64 possible programmable addresses using the six hardware address pins. One of these addresses cannot be used as it is reserved for Software Reset (SWRST), leaving a maximum of 63 addresses. Using other reserved addresses can reduce the total number of possible addresses even further.

7.1.1 Regular UFm I²C-bus slave address

The UFm I²C-bus slave address of the PCU9654 is shown in Figure 3. To conserve power, no internal pull-up resistors are incorporated on the hardware selectable address pins and they must be pulled HIGH or LOW.

Remark: Using reserved I²C-bus addresses will interfere with other devices, but only if the devices are on the bus and/or the bus will be open to other I²C-bus systems at some later date. In a closed system where the designer controls the address assignment these addresses can be used since the PCU9654 treats them like any other address. The LED All Call, Software Reset and PCA9564 or PCA9665 slave address (if on the bus) can never be used for individual device addresses.

- PCU9654 LED All Call address (1110 000) and Software Reset (0000 0110) which are active on start-up
- PCA9564 (0000 000) or PCA9665 (1110 000) slave address which is active on start-up
- ‘reserved for future use’ I²C-bus addresses (0000 011, 1111 1XX)
- slave devices that use the 10-bit addressing scheme (1111 0XX)
- slave devices that are designed to respond to the General Call address (0000 000)
- High-speed mode (Hs-mode) master code (0000 1XX)

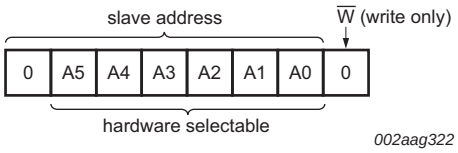


Fig 3. Slave address

The last bit of the address byte defines the operation to be performed. For UFm I²C-bus, there is only write operation in slave device.

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7.1.2 LED All Call UFm I²C-bus address

- Default power-up value (ALLCALLADR register): E0h or 1110 000
- Programmable through I²C-bus (volatile programming)
- At power-up, LED All Call I²C-bus address is enabled.

See Section 7.3.8 “ALLCALLADR, LED All Call UFm I²C-bus address” for more detail.

Remark: The default LED All Call I²C-bus address (E0h or 1110 000) must not be used as a regular I²C-bus slave address since this address is enabled at power-up. All the PCU9654s on the I²C-bus will respond to the address if sent by the I²C-bus master.

7.1.3 LED Sub Call UFm I²C-bus addresses

- 3 different UFm I²C-bus addresses can be used
- Default power-up values:
  - SUBADR1 register: E2h or 1110 001
  - SUBADR2 register: E4h or 1110 010
  - SUBADR3 register: E8h or 1110 100
- Programmable through I²C-bus (volatile programming)
- At power-up, Sub Call I²C-bus addresses are disabled.

See Section 7.3.7 “SUBADR1 to SUBADR3, UFm I²C-bus subaddress 1 to 3” for more detail.

7.1.4 Software Reset UFm I²C-bus address

The address shown in Figure 4 is used when a reset of the PCU9654 needs to be performed by the master. The Software Reset address (SWRST Call) must be used with $\overline{W}$ = logic 0. If $\overline{W}$ = logic 1, the PCU9654 does not recognize the SWRST. See Section 7.6 “Software reset” for more detail.

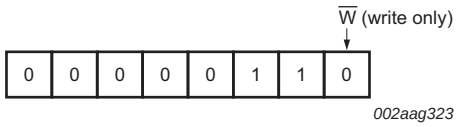


Fig 4. Software Reset address

Remark: The Software Reset UFm I²C-bus address is a reserved address and cannot be used as a regular UFm I²C-bus slave address or as an LED All Call or LED Sub Call address.

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7.2 Control register

Following the successful recognition of the slave address, LED All Call address or LED Sub Call address, the bus master will send a byte to the PCU9654, which will be stored in the Control register.

The lowest 5 bits are used as a pointer to determine which register will be accessed (D[4:0]). The highest 3 bits are used as Auto-Increment Flag (AIF) and Auto-Increment options (AI[1:0]).



reset state = 80h

Remark: The Control register does not apply to the Software Reset I²C-bus address.

Fig 5. Control register

When the Auto-Increment Flag is set (AIF = logic 1), the five low order bits of the Control register are automatically incremented after a write. This allows the user to program the registers sequentially. Four different types of Auto-Increment are possible, depending on AI1 and AI0 values.

Table 3. Auto-Increment options

AIF	AI1	AI0	Function
0	0	0	no Auto-Increment
1	0	0	Auto-Increment for all registers. D[4:0] roll over to 00h after the last register (11h) is accessed.
1	0	1	Auto-Increment for individual brightness registers only. D[4:0] roll over to 02h after the last register (09h) is accessed.
1	1	0	Auto-Increment for global control registers only. D[4:0] roll over to 0Ah' after the last register (0Bh) is accessed.
1	1	1	Auto-Increment for individual and global control registers only. D[4:0] roll over to 02h after the last register (0Bh) is accessed.

Remark: Other combinations not shown in Table 3 (AIF + AI[1:0] = 001b, 010b, and 011b) are reserved and must not be used for proper device operation.

AIF + AI[1:0] = 000b is used when the same register must be accessed several times during a single I²C-bus communication, for example, changes the brightness of a single LED. Data is overwritten each time the register is accessed during a write operation.

AIF + AI[1:0] = 100b is used when all the registers must be sequentially accessed, for example, power-up programming.

AIF + AI[1:0] = 101b is used when the eight LED drivers must be individually programmed with different values during the same I²C-bus communication, for example, changing color setting to another color setting.

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AIF + AI[1:0] = 110b is used when the LED drivers must be globally programmed with different settings during the same I²C-bus communication, for example, global brightness or blinking change.

AIF + AI[1:0] = 111b is used when individual and global changes must be performed during the same I²C-bus communication, for example, changing a color and global brightness at the same time.

Only the 5 least significant bits D[4:0] are affected by the AIF, AI1 and AI0 bits.

When the Control register is written, the register entry point determined by D[4:0] is the first register that will be addressed (write operation), and can be anywhere between 0 0000 and 1 0001 (as defined in Table 4). When AIF = 1, the Auto-Increment flag is set and the rollover value at which the register increment stops and goes to the next one is determined by AI[1:0]. See Table 3 for rollover values. For example, if the Control register = 1110 0100 (E4h), then the register addressing sequence will be (in hex):
04 → … → 0B → 02 → … → 0B → 02 → … → 0B → 02 → … → 0B → 02 → … as long as the master keeps sending data.

7.3 Register definitions

Table 4. Register summary[1]

Register number (hex)	D4	D3	D2	D1	D0	Name	Type	Function
00	0	0	0	0	0	MODE1	write only	Mode register 1
01	0	0	0	0	1	MODE2	write only	Mode register 2
02	0	0	0	1	0	PWM0	write only	brightness control LED0
03	0	0	0	1	1	PWM1	write only	brightness control LED1
04	0	0	1	0	0	PWM2	write only	brightness control LED2
05	0	0	1	0	1	PWM3	write only	brightness control LED3
06	0	0	1	1	0	PWM4	write only	brightness control LED4
07	0	0	1	1	1	PWM5	write only	brightness control LED5
08	0	1	0	0	0	PWM6	write only	brightness control LED6
09	0	1	0	0	1	PWM7	write only	brightness control LED7
0A	0	1	0	1	0	GRPPWM	write only	group duty cycle control
0B	0	1	0	1	1	GRPFREQ	write only	group frequency
0C	0	1	1	0	0	LEDOUT0	write only	LED output state 0
0D	0	1	1	0	1	LEDOUT1	write only	LED output state 1
0E	0	1	1	1	0	SUBADR1	write only	I²C-bus subaddress 1
0F	0	1	1	1	1	SUBADR2	write only	I²C-bus subaddress 2
10	1	0	0	0	0	SUBADR3	write only	I²C-bus subaddress 3
11	1	0	0	0	1	ALLCALLADR	write only	LED All Call I²C-bus address

[1] Only D[4:0] = 0 0000 to 1 0001 are allowed and will be recognized. D[4:0] = 1 0010 to 1 1111 are reserved and will not be recognized.

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7.3.1 Mode register 1, MODE1

Table 5. MODE1 - Mode register 1 (address 00h) bit description

*Legend: * default value.*

Bit	Symbol	Access	Value	Description
7	AIF	not user programmable	0	Register Auto-Increment disabled.
			1*	Register Auto-Increment enabled. **Remark:** set by Control register (Figure 5) in bit 7.
6	AI1	not user programmable	0*	Auto-Increment bit 1 = 0.
			1	Auto-Increment bit 1 = 1. **Remark:** set by Control register (Figure 5) in bit 6.
5	AI0	not user programmable	0*	Auto-Increment bit 0 = 0.
			1	Auto-Increment bit 0 = 1. **Remark:** set by Control register (Figure 5) in bit 5.
4	SLEEP	W	0	Normal mode[1].
			1*	Low power mode. Oscillator off[2].
3	SUB1	W	0*	PCU9654 does not respond to I²C-bus subaddress 1.
			1	PCU9654 responds to I²C-bus subaddress 1.
2	SUB2	W	0*	PCU9654 does not respond to I²C-bus subaddress 2.
			1	PCU9654 responds to I²C-bus subaddress 2.
1	SUB3	W	0*	PCU9654 does not respond to I²C-bus subaddress 3.
			1	PCU9654 responds to I²C-bus subaddress 3.
0	ALLCALL	W	0	PCU9654 does not respond to LED All Call I²C-bus address.
			1*	PCU9654 responds to LED All Call I²C-bus address.

[1] It takes 500 μs max. for the oscillator to be up and running once SLEEP bit has been set to logic 1. Timings on LEDn outputs are not guaranteed if PWMx, GRPPWM or GRPFREQ registers are accessed within the 500 μs window.

[2] No blinking or dimming is possible when the oscillator is off.

7.3.2 Mode register 2, MODE2

Table 6. MODE2 - Mode register 2 (address 01h) bit description

*Legend: * default value.*

Bit	Symbol	Access	Value	Description
7	-	not user programmable	0*	reserved, write must always be a logic 0
6	-	not user programmable	0*	reserved, write must always be a logic 0
5	DMBLNK	W	0*	group control = dimming.
			1	group control = blinking.
4	-	W	0*	reserved; write must always be a logic 0
3	OCH	W	0*	outputs change on STOP command[1]
			1	outputs change on ninth clock cycle (USCL)

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Table 6. MODE2 - Mode register 2 (address 01h) bit description *...continued*

*Legend: * default value.*

Bit	Symbol	Access	Value	Description
2	-	W	1*	reserved; write must always be a logic 1[2]
1	-	W	0*	reserved; write must always be a logic 0[2]
0	-	W	1*	reserved; write must always be a logic 1[2]

[1] Change of the outputs at the STOP command allows synchronizing outputs of more than one PCU9654. Applicable to registers from 02h (PWM0) to 0Dh (LEDOUT1) only.

[2] **Remark:** If you change these bits from their default values, the device will not perform as expected.

7.3.3 PWM0 to PWM7, individual brightness control

Table 7. PWM0 to PWM7 - PWM registers 0 to 7 (address 02h to 09h) bit description

*Legend: * default value.*

Address	Register	Bit	Symbol	Access	Value	Description
02h	PWM0	7:0	IDC0[7:0]	W	0000 0000*	PWM0 Individual Duty Cycle
03h	PWM1	7:0	IDC1[7:0]	W	0000 0000*	PWM1 Individual Duty Cycle
04h	PWM2	7:0	IDC2[7:0]	W	0000 0000*	PWM2 Individual Duty Cycle
05h	PWM3	7:0	IDC3[7:0]	W	0000 0000*	PWM3 Individual Duty Cycle
06h	PWM4	7:0	IDC4[7:0]	W	0000 0000*	PWM4 Individual Duty Cycle
07h	PWM5	7:0	IDC5[7:0]	W	0000 0000*	PWM5 Individual Duty Cycle
08h	PWM6	7:0	IDC6[7:0]	W	0000 0000*	PWM6 Individual Duty Cycle
09h	PWM7	7:0	IDC7[7:0]	W	0000 0000*	PWM7 Individual Duty Cycle

A 97 kHz fixed frequency signal is used for each output. Duty cycle is controlled through 256 linear steps from 00h (0 % duty cycle = LED output off) to FFh (99.6 % duty cycle = LED output at maximum brightness). Applicable to LED outputs programmed with LDRx = 10 or 11 (LEDOUT0 to LEDOUT1 registers).

$$duty\ cycle = \frac{IDCx[7:0]}{256} \quad (1)$$

7.3.4 GRPPWM, group duty cycle control

Table 8. GRPPWM - Group brightness control register (address 0Ah) bit description

*Legend: * default value*

Address	Register	Bit	Symbol	Access	Value	Description
0Ah	GRPPWM	7:0	GDC[7:0]	W	1111 1111*	GRPPWM register

When DMBLNK bit (MODE2 register) is programmed with logic 0, a 190 Hz fixed frequency signal is superimposed with the 97 kHz individual brightness control signal. GRPPWM is then used as a global brightness control allowing the LED outputs to be dimmed with the same value. The value in GRPFREQ is then a ‘Don’t care’.

General brightness for the eight outputs is controlled through 256 linear steps from 00h (0 % duty cycle = LED output off) to FFh (99.6 % duty cycle = maximum brightness). Applicable to LED outputs programmed with LDRx = 11 (LEDOUT0 to LEDOUT1 registers).

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When DMBLNK bit is programmed with logic 1, GRPPWM and GRPFREQ registers define a global blinking pattern, where GRPFREQ contains the blinking period (from 24 Hz to 10.73 s) and GRPPWM the duty cycle (ON/OFF ratio in %).

$$duty\ cycle = \frac{GDC[7:0]}{256} \quad (2)$$

7.3.5 GRPFREQ, group frequency

Table 9. GRPFREQ - Group Frequency register (address 0Bh) bit description

*Legend: * default value.*

Address	Register	Bit	Symbol	Access	Value	Description
0Bh	GRPFREQ	7:0	GFRQ[7:0]	W	0000 0000*	GRPFREQ register

GRPFREQ is used to program the global blinking period when DMBLNK bit (MODE2 register) is equal to 1. Value in this register is a ‘Don’t care’ when DMBLNK = 0. Applicable to LED outputs programmed with LDRx = 11 (LEDOUT0 to LEDOUT1 registers).

Blinking period is controlled through 256 linear steps from 00h (41 ms, frequency 24 Hz) to FFh (10.73 s).

$$global\ blinking\ period = \frac{GFRQ[7:0]+1}{24}(s) \quad (3)$$

7.3.6 LEDOUT0 and LEDOUT1, LED driver output state

Table 10. LEDOUT0 to LEDOUT1 - LED driver output state register (address 0Ch to 0Dh) bit description

*Legend: * default value.*

Address	Register	Bit	Symbol	Access	Value	Description
0Ch	LEDOUT0	7:6	LDR3	W	00*	LED3 output state control
		5:4	LDR2	W	00*	LED2 output state control
		3:2	LDR1	W	00*	LED1 output state control
		1:0	LDR0	W	00*	LED0 output state control
0Dh	LEDOUT1	7:6	LDR7	W	00*	LED7 output state control
		5:4	LDR6	W	00*	LED6 output state control
		3:2	LDR5	W	00*	LED5 output state control
		1:0	LDR4	W	00*	LED4 output state control

LDRx = 00 — LED driver x is off (default power-up state, x = 0 to 7).

LDRx = 01 — LED driver x is fully on (individual brightness and group dimming/blinking not controlled). The $\overline{OE}$ pin can be used as external dimming/blinking control in this state.

LDRx = 10 — LED driver x individual brightness can be controlled through its PWMx register.

LDRx = 11 — LED driver x individual brightness and group dimming/blinking can be controlled through its PWMx registers, the GRPPWM registers and the GRPFREQ register.

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7.3.7 SUBADR1 to SUBADR3, UFm I²C-bus subaddress 1 to 3

Table 11. SUBADR1 to SUBADR3 - I²C-bus subaddress registers 1 to 3 (address 0Eh to 10h) bit description

*Legend: * default value.*

Address	Register	Bit	Symbol	Access	Value	Description
0Eh	SUBADR1	7:1	A1[7:1]	W	1110 001*	I²C-bus subaddress 1
		0	A1[0]	W only	0*	reserved (must write 0)
0Fh	SUBADR2	7:1	A2[7:1]	W	1110 010*	I²C-bus subaddress 2
		0	A2[0]	W only	0*	reserved (must write 0)
10h	SUBADR3	7:1	A3[7:1]	W	1110 100*	I²C-bus subaddress 3
		0	A3[0]	W only	0*	reserved (must write 0)

Subaddresses are programmable through the UFm I²C-bus. Default power-up values are E2h, E4h, E8h, and the device(s) will not respond to these addresses right after power-up (the corresponding SUBx bit in MODE1 register is equal to 0).

Once subaddresses have been programmed to their right values, SUBx bits need to be set to logic 1 in order to have the device respond to these addresses (MODE1 register).

Only the seven MSBs representing the UFm I²C-bus subaddress are valid. The LSB in SUBADRx register is a reserved bit and must write logic 0.

When SUBx is set to logic 1 in MODE1 register, the corresponding UFm I²C-bus subaddress can be used during a UFm I²C-bus write sequence.

7.3.8 ALLCALLADR, LED All Call UFm I²C-bus address

Table 12. ALLCALLADR - LED All Call UFm I²C-bus address register (address 11h) bit description

*Legend: * default value.*

Address	Register	Bit	Symbol	Access	Value	Description
11h	ALLCALLADR	7:1	AC[7:1]	W	1110 000*	ALLCALL I²C-bus address register
		0	AC[0]	W only	0*	reserved (must write 0)

The LED All Call I²C-bus address allows all the PCU9654s on the bus to be programmed at the same time (ALLCALL bit in register MODE1 must be equal to 1 (power-up default state)). This address is programmable through the I²C-bus and can be used during an I²C-bus write sequence. The register address can also be programmed as a Sub Call.

Only the 7 MSBs representing the All Call I²C-bus address are valid. The LSB in ALLCALLADR register is a reserved bit and must write logic 0.

If ALLCALL bit = 0 in the MODE1 register, the device does not respond to the address programmed in register ALLCALLADR.

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7.4 Active LOW output enable input

The active LOW output enable ($\overline{OE}$) pin, allows to enable or disable all the LED outputs at the same time, so user can drive all the LED outputs to OFF state by setting the $\overline{OE}$ pin to HIGH.

- When a LOW level is applied to $\overline{OE}$ pin, all the LED outputs are enabled.
- When a HIGH level is applied to $\overline{OE}$ pin, all the LED outputs are high-impedance.

The $\overline{OE}$ pin can be used as a synchronization signal to switch on/off several PCU9654 devices at the same time. When LED driver output state is set fully ON (LDRx = 01 in LEDOUTx register) in these devices. This requires an external clock reference that provides blinking period and the duty cycle.

The $\overline{OE}$ pin can also be used as an external dimming control signal. The frequency of the external clock must be high enough not to be seen by the human eye, and the duty cycle value determines the brightness of the LEDs.

Remark: Do not use $\overline{OE}$ as an external blinking control signal when internal global blinking is selected (DMBLNK = 1, MODE2 register) since it will result in an undefined blinking pattern. Do not use $\overline{OE}$ as an external dimming control signal when internal global dimming is selected (DMBLNK = 0, MODE2 register) since it will result in an undefined dimming pattern.

Remark: During power-down, slow decay of voltage supplies may keep LEDs illuminated. Consider disabling LED outputs using HIGH level applied to $\overline{OE}$ pin.

7.5 Power-on reset

When power is applied to V_{DD}, an internal power-on reset holds the PCU9654 in a reset condition until V_{DD} has reached V_{POR}. At this point, the reset condition is released and the PCU9654 registers and I²C-bus state machine are initialized to their default states (all zeroes) causing all the channels to be deselected. Thereafter, V_{DD} must be lowered below 0.2 V to reset the device.

7.6 Software reset

The Software Reset Call (SWRST Call) allows all the devices in the UFm I²C-bus to be reset to the power-up state value through a specific formatted I²C-bus command.

The SWRST Call function is defined as the following:

1. A START command is sent by the UFm I²C-bus master.
2. The reserved SWRST I²C-bus address ‘0000 011’ with the $\overline{W}$ bit set to ‘0’ (write) is sent by the I²C-bus master.
3. The PCU9654 device(s) is(are) recognized after seeing the SWRST Call address ‘0000 0110’ (06h) only. If the $\overline{W}$ bit is set to ‘1’, no action is taken in PCU9654.
4. Once the SWRST Call address has been sent, the master sends 2 bytes with two specific values (SWRST data byte 1 and byte 2): Byte 1 = A5h, Byte 2 = 5Ah.

   If more than 2 bytes of data are sent, they will be ignored by the PCU9654.

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5. Once the right 2 bytes (SWRST data byte 1 and byte 2 only) have been sent, the master sends a STOP command to end the SWRST Call: the PCU9654 then resets to the default value (power-up value) and is ready to be addressed again within the specified bus free time (t_{BUF}).

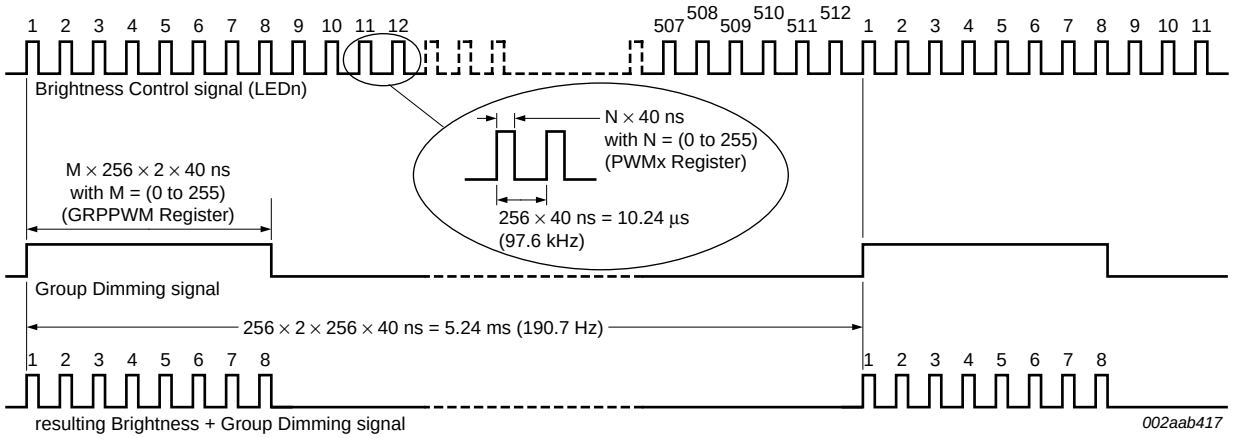
Remark: The reset stage is also the standby state with the internal oscillator turned off. It takes 500 μs for the oscillator to be up and running once the SLEEP bit has been set to a logic 1. PWM registers should not be accessed within the 500 μs window.

7.7 Individual brightness control with group dimming/blinking

A 97 kHz fixed frequency signal with programmable duty cycle (8 bits, 256 steps) is used to control individually the brightness for each LED.

On top of this signal, one of the following signals can be superimposed (this signal can be applied to the 8 LED outputs):

- A lower 190 Hz fixed frequency signal with programmable duty cycle (8 bits, 256 steps) is used to provide a global brightness control.
- A programmable frequency signal from 24 Hz to $^{1}/_{10.73}$ Hz (8 bits, 256 steps) with programmable duty cycle (8 bits, 256 steps) is used to provide a global blinking control.



Minimum pulse width for LEDn Brightness Control is 40 ns.

Minimum pulse width for Group Dimming is 20.48 μs.

When M = 1 (GRPPWM register value), the resulting LEDn Brightness Control + Group Dimming signal will have 2 pulses of the LED Brightness Control signal (pulse width = N × 40 ns, with 'N' defined in PWMx register).

This resulting Brightness + Group Dimming signal above shows a resulting Control signal with M = 4 (8 pulses).

Fig 6. Brightness + Group Dimming signals

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8. Characteristics of the UFm I²C-bus

The PCU9654 LED controller uses the new Ultra Fast-mode (UFm) I²C-bus to communicate with the UFm I²C-bus capable host controller. It uses two lines for communication. They are a serial data line (USDA) and a serial clock line (USCL). The UFm is a unidirectional bus that is capable of higher frequency (up to 5 MHz). The UFm I²C-bus slave devices operate in receive-only mode. That is, only I²C writes to PCU9654 are supported.

8.1 Bit transfer

One data bit is transferred during each clock pulse. The data on the USDA line must remain stable during the HIGH period of the clock pulse as changes in the data line at this time will be interpreted as control signals (see Figure 7).

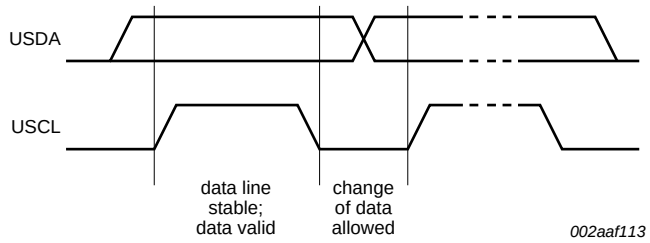


Fig 7. Bit transfer

8.1.1 START and STOP conditions

Both data and clock lines remain HIGH when the bus is not busy. A HIGH-to-LOW transition of the data line while the clock is HIGH is defined as the START condition (S). A LOW-to-HIGH transition of the data line while the clock is HIGH is defined as the STOP condition (P) (see Figure 8).

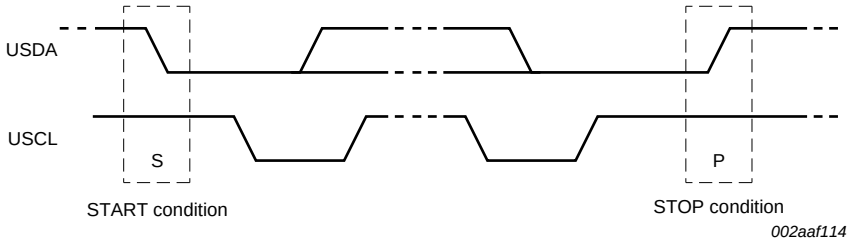


Fig 8. Definition of START and STOP conditions

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8.2 System configuration

A device generating a message is a ‘transmitter’; a device receiving is the ‘receiver’. The device that controls the message is the ‘master’ and the devices which are controlled by the master are the ‘slaves’ (see Figure 9).

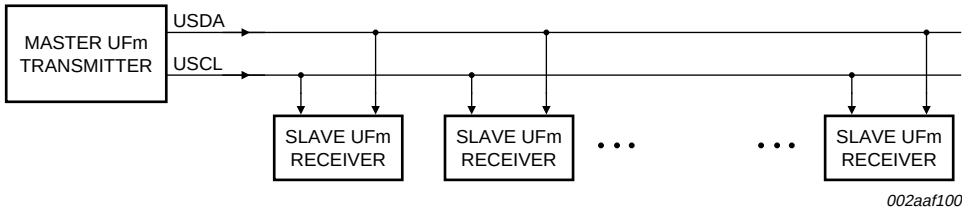


Fig 9. System configuration

8.3 Data transfer

The number of data bytes transferred between the START and the STOP conditions from transmitter to receiver is not limited. Each byte of eight bits is followed by one bit that is always set to 1. The master generates an extra related clock pulse.

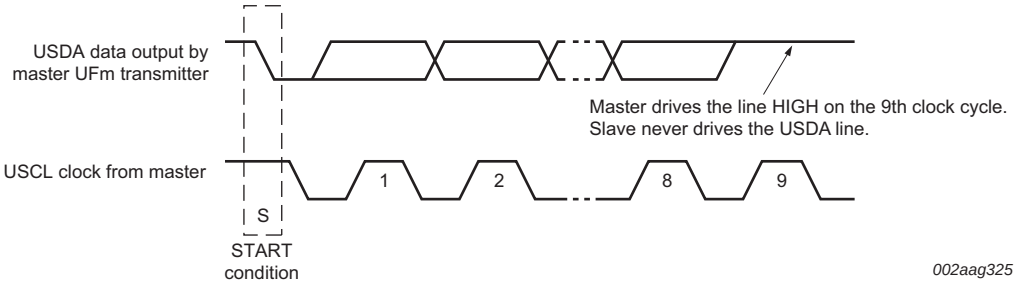
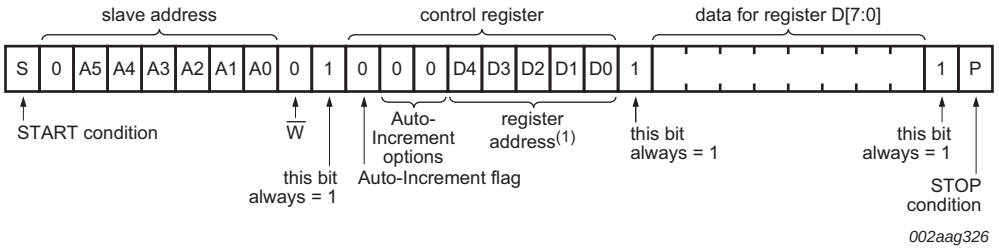


Fig 10. Data transfer

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9. Bus transactions



(1) See Table 4 for register definition.

Fig 11. Write to a specific register

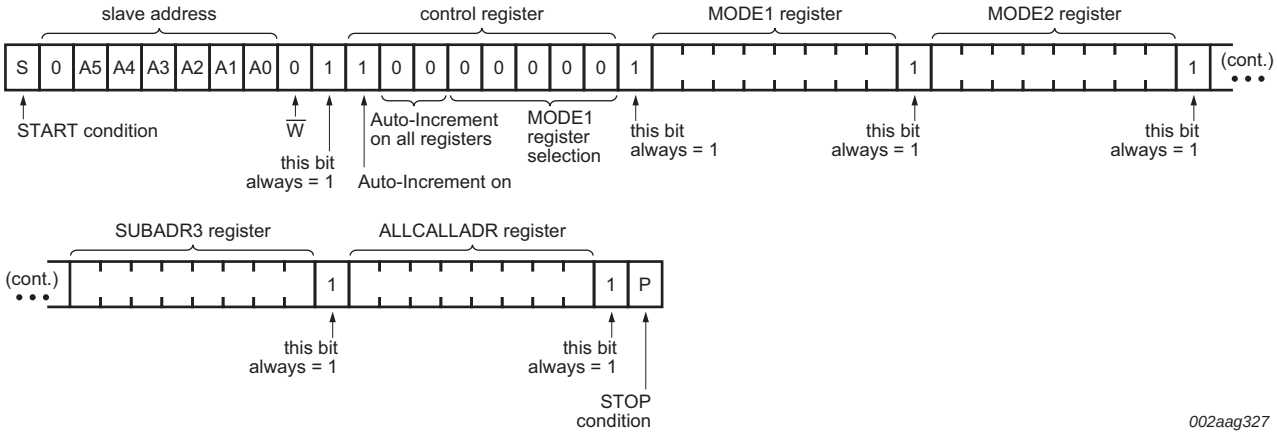


Fig 12. Write to all registers using the Auto-Increment feature

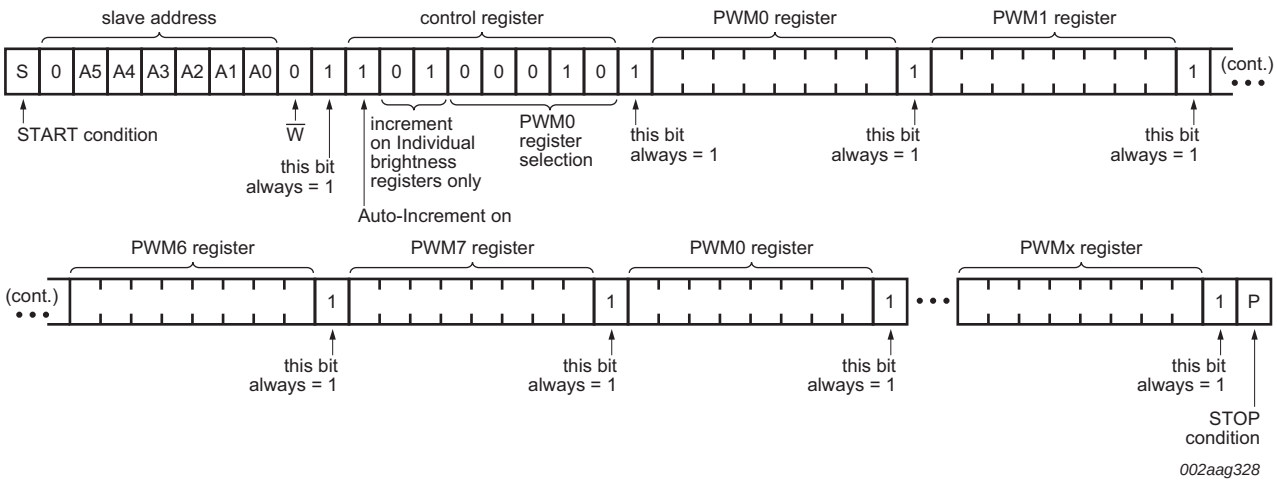
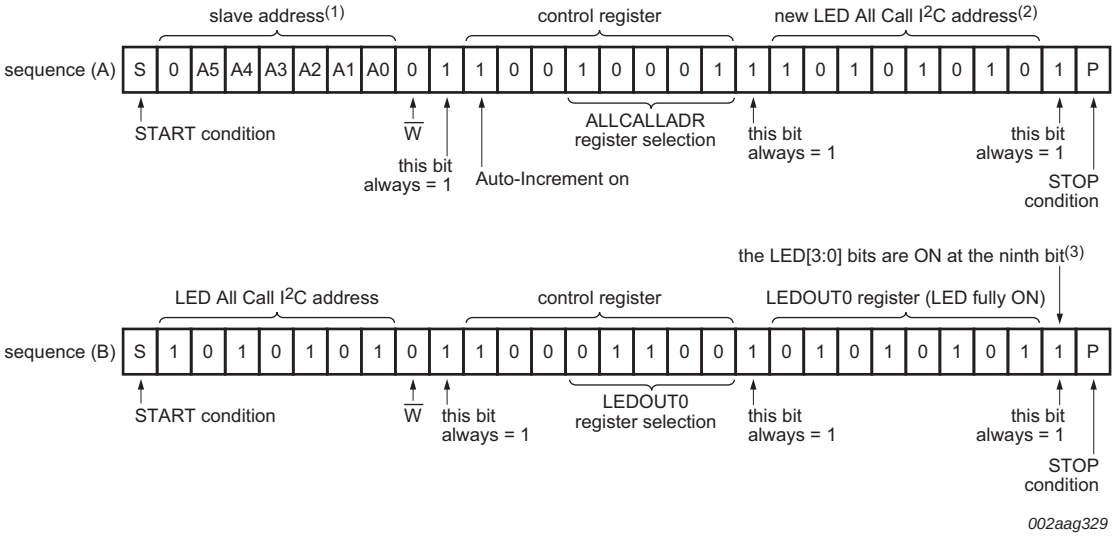


Fig 13. Multiple writes to Individual Brightness registers only using the Auto-Increment feature

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(1) In this example, several PCU9654s are used and the same sequence (A) (above) is sent to each of them.

(2) ALLCALL bit in MODE1 register is equal to 1 for this example.

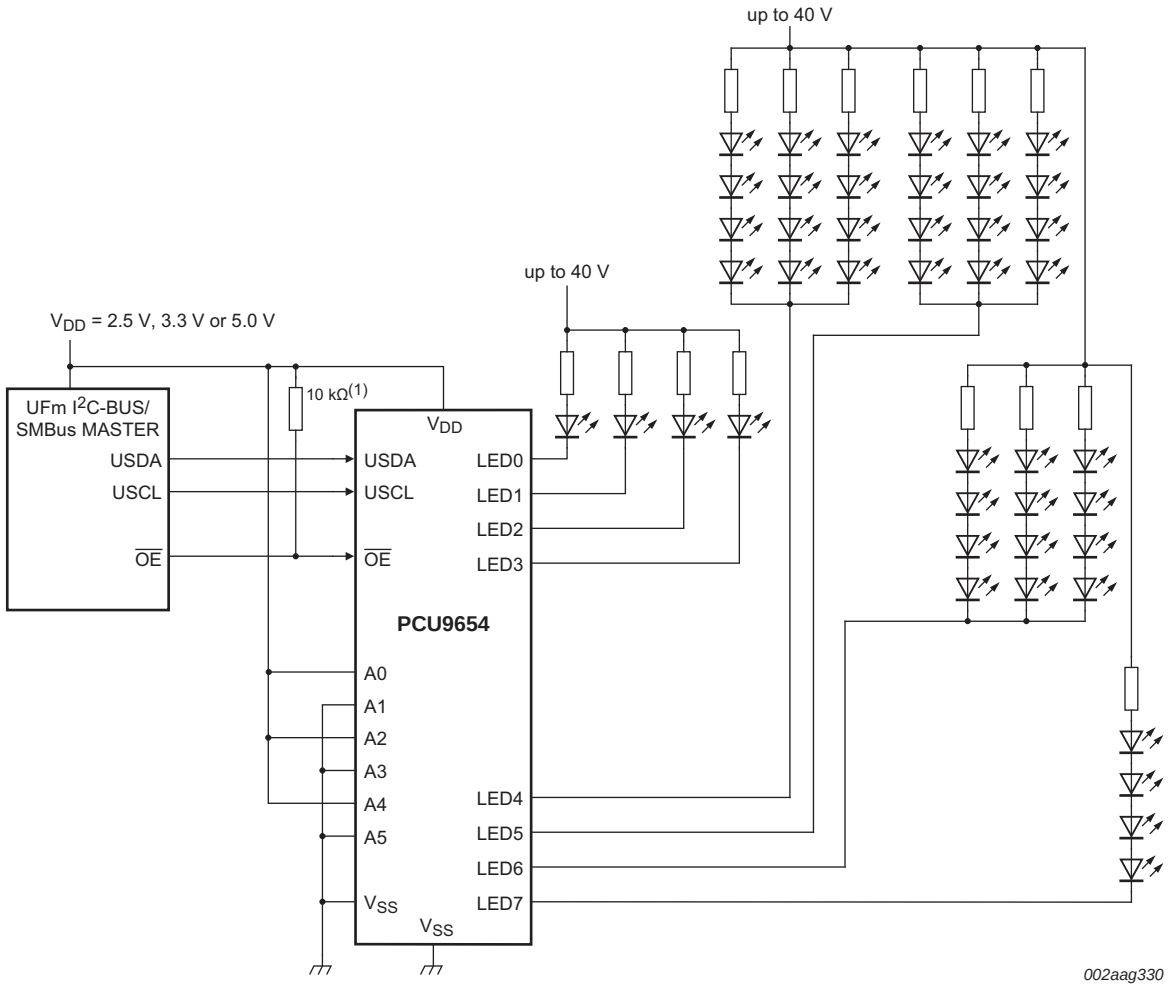
(3) OCH bit in MODE2 register is equal to 1 for this example.

Fig 14. LED All Call UFm I²C-bus address programming and LED All Call sequence example

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10. Application design-in information



(1) $\overline{OE}$ requires pull-up resistor if control signal from the master is open-drain.

I²C-bus address = 0010 101x.

Remark: During power-down, slow decay of voltage supplies may keep LEDs illuminated. Consider disabling LED outputs using HIGH level applied to $\overline{OE}$ pin.

Fig 15. Typical application

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10.1 Junction temperature calculation

A device junction temperature can be calculated when the ambient temperature or the case temperature is known.

When the ambient temperature is known, the junction temperature is calculated using Equation 4 and the ambient temperature, junction to ambient thermal resistance and power dissipation.

$$T_j = T_{amb} + R_{th(j\text{-}a)} \times P_{tot} \quad (4)$$

where:

T_j = junction temperature

T_{amb} = ambient temperature

$R_{th(j\text{-}a)}$ = junction to ambient thermal resistance

P_{tot} = (device) total power dissipation

When the case temperature is known, the junction temperature is calculated using Equation 5 and the case temperature, junction to case thermal resistance and power dissipation.

$$T_j = T_{case} + R_{th(j\text{-}c)} \times P_{tot} \quad (5)$$

where:

T_j = junction temperature

T_{case} = case temperature

$R_{th(j\text{-}c)}$ = junction to case thermal resistance

P_{tot} = (device) total power dissipation

Here are two examples regarding how to calculate the junction temperature using junction to case and junction to ambient thermal resistance. In the first example (Section 10.1.1), given the operating condition and the junction to ambient thermal resistance, the junction temperature of PCU9654PW, in the TSSOP24 package, is calculated for a system operating condition in 50 °C[1] ambient temperature. In the second example (Section 10.1.2), based on a specific customer application requirement where only the case temperature is known, applying the junction to case thermal resistance equation, the junction temperature of the PCU9654, in the TSSOP24 package, is calculated.

1. 50 °C is a typical temperature inside an enclosed system. The designers should feel free, as needed, to perform their own calculation using the examples.

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10.1.1 Example 1: T_j calculation of PCU9654PW, in TSSOP24 package, when T_{amb} is known

$R_{th(j-a)}$ = 108 °C/W

T_{amb} = 50 °C

LED output low voltage (LED V_{OL}) = 0.5 V

LED output current per channel = 80 mA

Number of outputs = 8

$I_{DD(max)}$ = 10 mA

$V_{DD(max)}$ = 5.5 V

1. Find P_{tot} (device total power dissipation):
   - output total power = 80 mA × 8 × 0.5 V = 320 mW
   - chip core power consumption = 10 mA × 5.5 V = 55 mW

   P_{tot} = (320 + 55) mW = **375 mW**
2. Find T_j (junction temperature):

   $T_j = (T_{amb} + R_{th(j-a)} \times P_{tot})$ = (50 °C + 108 °C/W × 375 mW) = **90.5 °C**

10.1.2 Example 2: T_j calculation where only T_{case} is known

This example uses a customer's specific application of the PCU9654, 8-channel LED controller in the TSSOP24 package, where only the case temperature (T_{case}) is known.

$T_j = T_{case} + R_{th(j-c)} \times P_{tot}$, where:

$R_{th(j-c)}$ = 30 °C/W

T_{case} (measured) = 94.6 °C

V_{OL} of LED ~ 0.5 V

$I_{DD(max)}$ = 10 mA

$V_{DD(max)}$ = 5.5 V

LED output voltage LOW = 0.5 V

LED output current per channel = 80 mA

1. Find P_{tot} (device total power dissipation)
   - Output total power = 80 mA × 8 × 0.5 V = **320 mW**
   - chip core power consumption = 10 mA × 5.5 V = 55 mW

   P_{tot} (device total power dissipation) = **375 mW**
2. Find T_j (junction temperature):

   $T_j = T_{case} + R_{th(j-a)} \times P_{tot}$ = 94.6 °C + 30 °C/W × 375 mW = **105.85 °C**

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11. Limiting values

Table 13. Limiting values

In accordance with the Absolute Maximum Rating System (IEC 60134).

Symbol	Parameter	Conditions		Min	Max	Unit
V_{DD}	supply voltage			–0.5	+6.0	V
$V_{I/O}$	voltage on an input/output pin			V_{SS} – 0.5	5.5	V
$V_{drv(LED)}$	LED driver voltage			V_{SS} – 0.5	40	V
$I_{O(LEDn)}$	output current on pin LEDn			-	100	mA
$I_{OL(tot)}$	total LOW-level output current	LED driver outputs; V_{OL} = 0.5 V	[1]	800	-	mA
I_{SS}	ground supply current	per V_{SS} pin		-	800	mA
P_{tot}	total power dissipation	T_{amb} = 25 °C		-	1.8	W
		T_{amb} = 85 °C		-	0.72	W
P/ch	power dissipation per channel	T_{amb} = 25 °C		-	100	mW
		T_{amb} = 85 °C		-	45	mW
T_j	junction temperature		[2]	-	+125	°C
T_{stg}	storage temperature			–65	+150	°C
T_{amb}	ambient temperature	operating		–40	+85	°C

[1] Each bit must be limited to a maximum of 100 mA and the total package limited to 800 mA due to internal busing limits. The pull-up (current limiting) resistor must be of sufficient size (W) and value (Ω) to guarantee that the 100 mA limit is not exceeded on any output.

[2] Refer to Section 10.1 for calculation.

Table 14. TSSOP24 power dissipation and output current capability

Measurement	TSSOP24
T_{amb} = 25 °C	
maximum power dissipation (chip + output drivers)	926 mW
maximum power dissipation (output drivers only)	851 mW
maximum drive current per channel	$< \frac{851\ mW}{8\text{-}bit \times 0.5\ V} = 212.75\ mA$ [1]
T_{amb} = 60 °C	
maximum power dissipation (chip + output drivers)	602 mW
maximum power dissipation (output drivers only)	527 mW
maximum drive current per channel	$< \frac{527\ mW}{8\text{-}bit \times 0.5\ V} = 131.8\ mA$ [1]
T_{amb} = 80 °C	
maximum power dissipation (chip + output drivers)	417 mW
maximum power dissipation (output drivers only)	342 mW
maximum drive current per channel	$< \frac{342\ mW}{8\text{-}bit \times 0.5\ V} = 85.5\ mA$

[1] This value signifies package's ability to handle more than 100 mA per output driver. The device's maximum current rating per output is 100 mA.

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12. Thermal characteristics

Table 15. Thermal characteristics

Symbol	Parameter	Conditions		Typ	Unit
$R_{th(j-a)}$	thermal resistance from junction to ambient	TSSOP24	[1]	108	°C/W
$R_{th(j-c)}$	thermal resistance from junction to case	TSSOP24	[1]	30	°C/W

[1] Calculated in accordance with JESD 51-7.

13. Static characteristics

Table 16. Static characteristics

V_{DD} = 2.3 V to 5.5 V; V_{SS} = 0 V; T_{amb} = −40 °C to +85 °C; unless otherwise specified.

Symbol	Parameter	Conditions		Min	Typ	Max	Unit
Supply							
V_{DD}	supply voltage			2.3	-	5.5	V
I_{DD}	supply current	on pin V_{DD}; operating mode; no load; f_{USCL} = 5 MHz; V_{DD} = 5.5 V		-	5.5	10	mA
I_{stb}	standby current	on pin V_{DD}; no load; f_{USCL} = 0 Hz; I/O = inputs; $V_I = V_{DD}$; V_{DD} = 5.5 V		-	2.1	7	µA
V_{POR}	power-on reset voltage	no load; $V_I = V_{DD}$ or V_{SS}	[1]	-	1.70	2.0	V
UFm I²C-bus inputs USCL and USDA							
V_{IL}	LOW-level input voltage			−0.5	-	$+0.3V_{DD}$	V
V_{IH}	HIGH-level input voltage			$0.7V_{DD}$	-	5.5	V
I_L	leakage current	$V_I = V_{DD}$ or V_{SS}		−1	-	+1	µA
C_i	input capacitance	$V_I = V_{SS}$		-	6	10	pF
LED driver outputs LED[7:0]							
$V_{drv(LED)}$	LED driver voltage			0	-	40	V
I_{OL}	LOW-level output current	V_{OL} = 0.5 V	[2]	100	-	-	mA
I_{LOH}	HIGH-level output leakage current	$V_{drv(LED)}$ = 5 V		-	-	±1	µA
		$V_{drv(LED)}$ = 40 V		-	±1	15	µA
C_o	output capacitance		[3]	-	15	40	pF
OE input							
V_{IL}	LOW-level input voltage			−0.5	-	$+0.3V_{DD}$	V
V_{IH}	HIGH-level input voltage			$0.7V_{DD}$	-	5.5	V
I_{LI}	input leakage current			−1	-	+1	µA
C_i	input capacitance			-	3.7	5	pF
Address inputs A[5:0]							
V_{IL}	LOW-level input voltage			−0.5	-	$+0.3V_{DD}$	V
V_{IH}	HIGH-level input voltage			$0.7V_{DD}$	-	5.5	V
I_{LI}	input leakage current			−1	-	+1	µA
C_i	input capacitance			-	3.7	5	pF

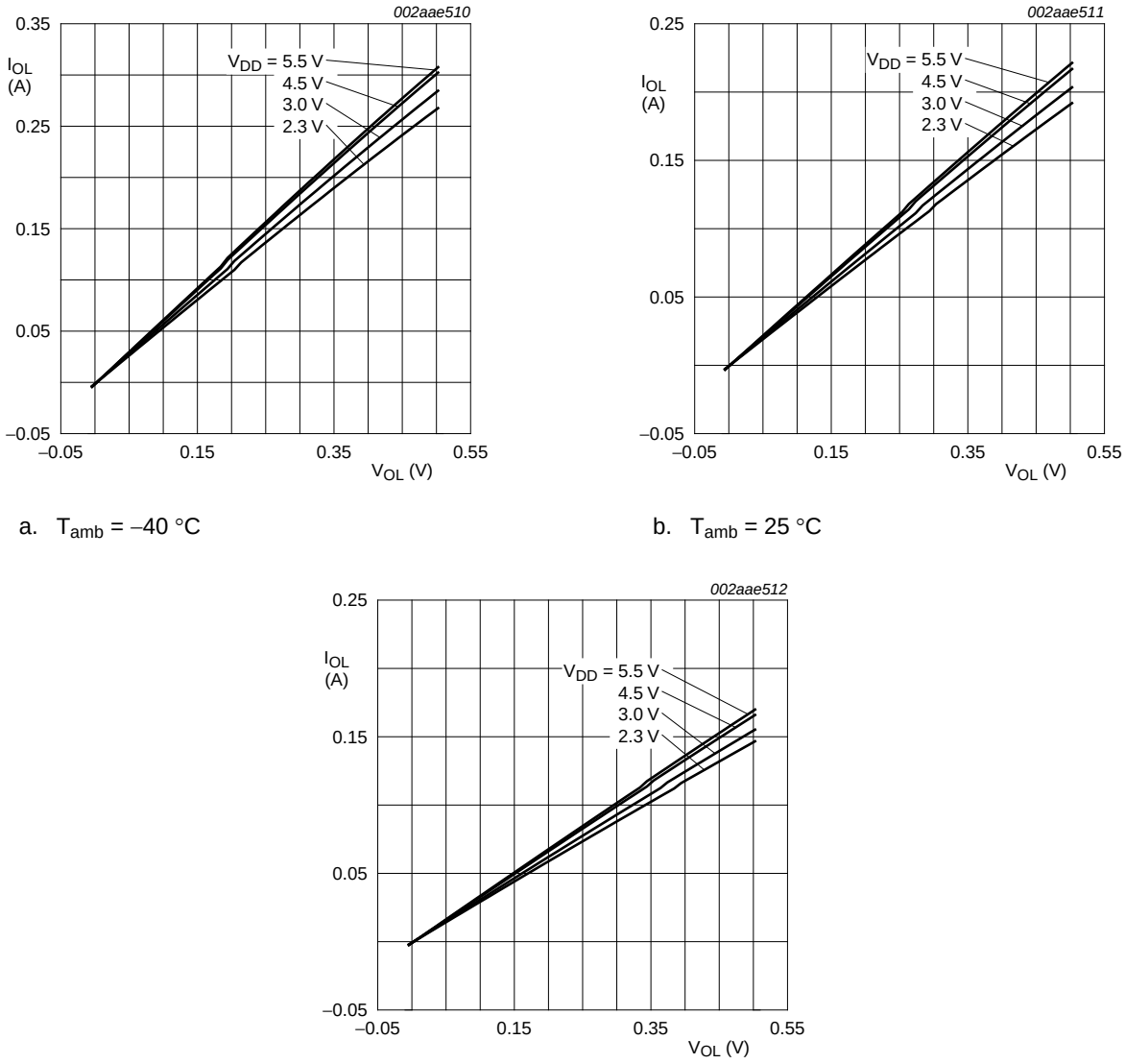
[1] V_{DD} must be lowered to 0.2 V in order to reset part.

[2] Each bit must be limited to a maximum of 100 mA and the total package limited to 800 mA due to internal busing limits.

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[3] Tested with outputs off.



a. T_{amb} = −40 °C

b. T_{amb} = 25 °C

c. T_{amb} = 85 °C

Fig 16. V_{OL} versus I_{OL}

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14. Dynamic characteristics

Table 17. Dynamic characteristics

Symbol	Parameter	Conditions	Min	Typ	Max	Unit
f_{USCL}	USCL clock frequency		-	-	5	MHz
t_{BUF}	bus free time between a STOP and START condition		0.08	-	-	µs
$t_{HD;STA}$	hold time (repeated) START condition		0.05	-	-	µs
$t_{SU;STA}$	set-up time for a repeated START condition		0.05	-	-	µs
$t_{SU;STO}$	set-up time for STOP condition		0.05	-	-	µs
$t_{HD;DAT}$	data hold time		10	-	-	ns
$t_{SU;DAT}$	data set-up time		30	-	-	ns
t_{LOW}	LOW period of the USCL clock		0.05	-	-	µs
t_{HIGH}	HIGH period of the USCL clock		0.05	-	-	µs
t_f	fall time of both USDA and USCL signals		-	-	50	ns
t_r	rise time of both USDA and USCL signals		-	-	50	ns
t_{SP}	pulse width of spikes that must be suppressed by the input filter		-	-	10	ns
Output propagation delay						
t_{PLH}	LOW to HIGH propagation delay	$\overline{OE}$ to LEDn; MODE2[1:0] = 01	-	-	150	ns
t_{PHL}	HIGH to LOW propagation delay	$\overline{OE}$ to LEDn; MODE2[1:0] = 01	-	-	150	ns
Output port timing[1][2]						
$t_{d(USCL-Q)}$	delay time from USCL to data output	USCL to LEDn; MODE2[3] = 1; LEDOUTx = 01; outputs change on ninth clock cycle (USCL)	-	-	450	ns
$t_{d(USDA-Q)}$	delay time from USDA to data output	USDA to LEDn; MODE2[3] = 0; LEDOUTx = 01; outputs change on STOP condition	-	-	450	ns

[1] From LED off to fully on, LED fully on to off, or LED individual brightness control to off.

[2] For LED off state to on with individual brightness control or for changes in the individual brightness control value, there is a synchronization that may take up to 15 µs for the change to take effect.

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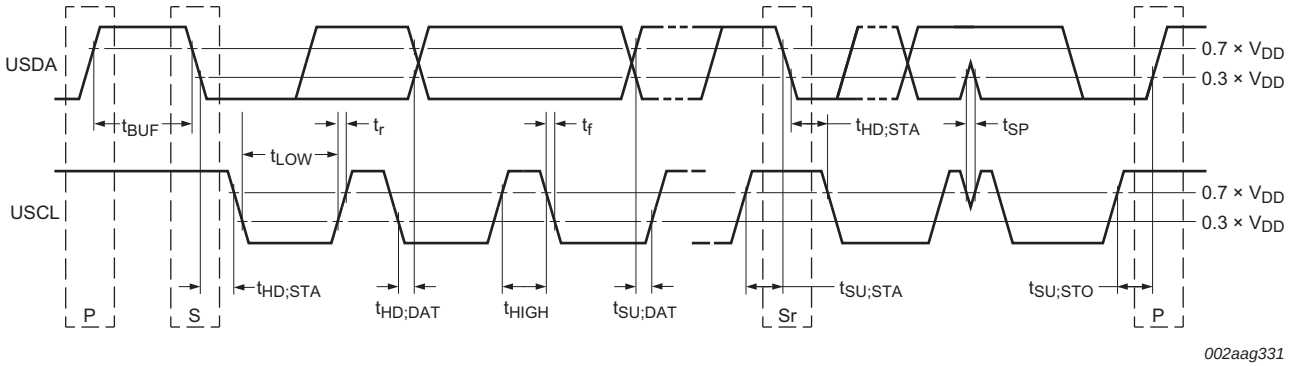
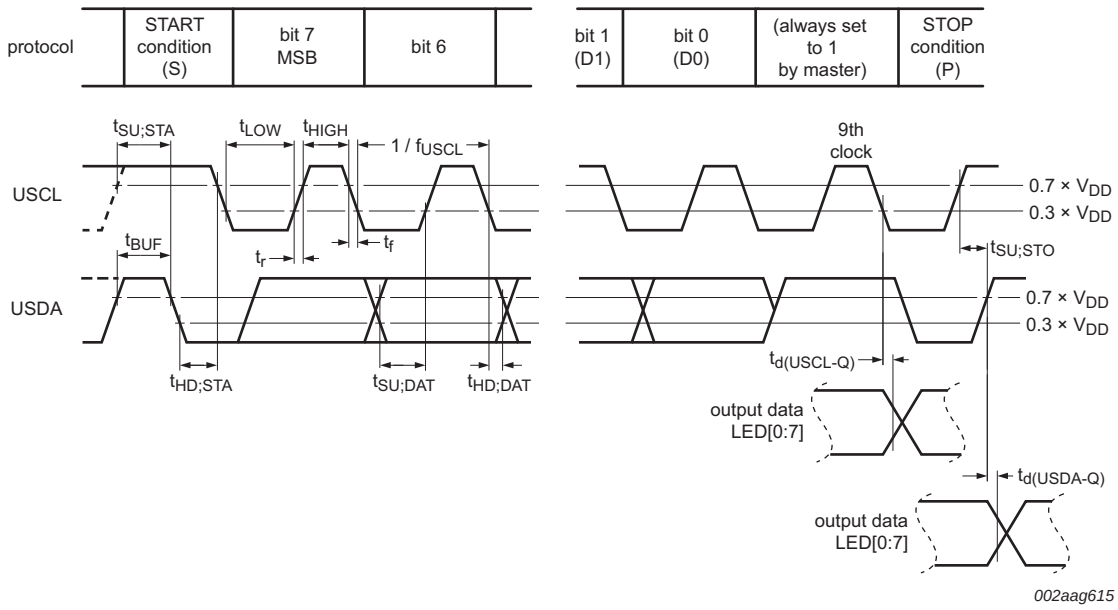


Fig 17. Definition of timing



Rise and fall times refer to V_{IL} and V_{IH}.

Fig 18. UFm I²C-bus timing and output timing diagram

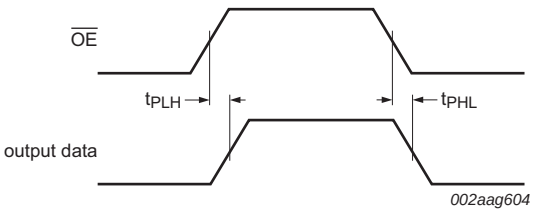
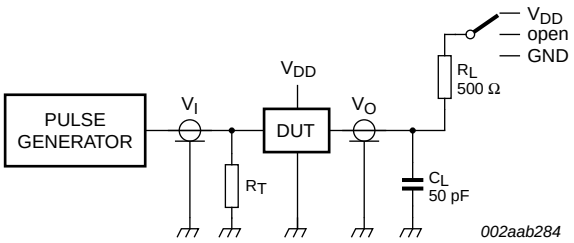


Fig 19. Output propagation delay

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15. Test information



R_L = Load resistor for LEDn.

C_L = Load capacitance includes jig and probe capacitance.

R_T = Termination resistance should be equal to the output impedance Z_o of the pulse generators.

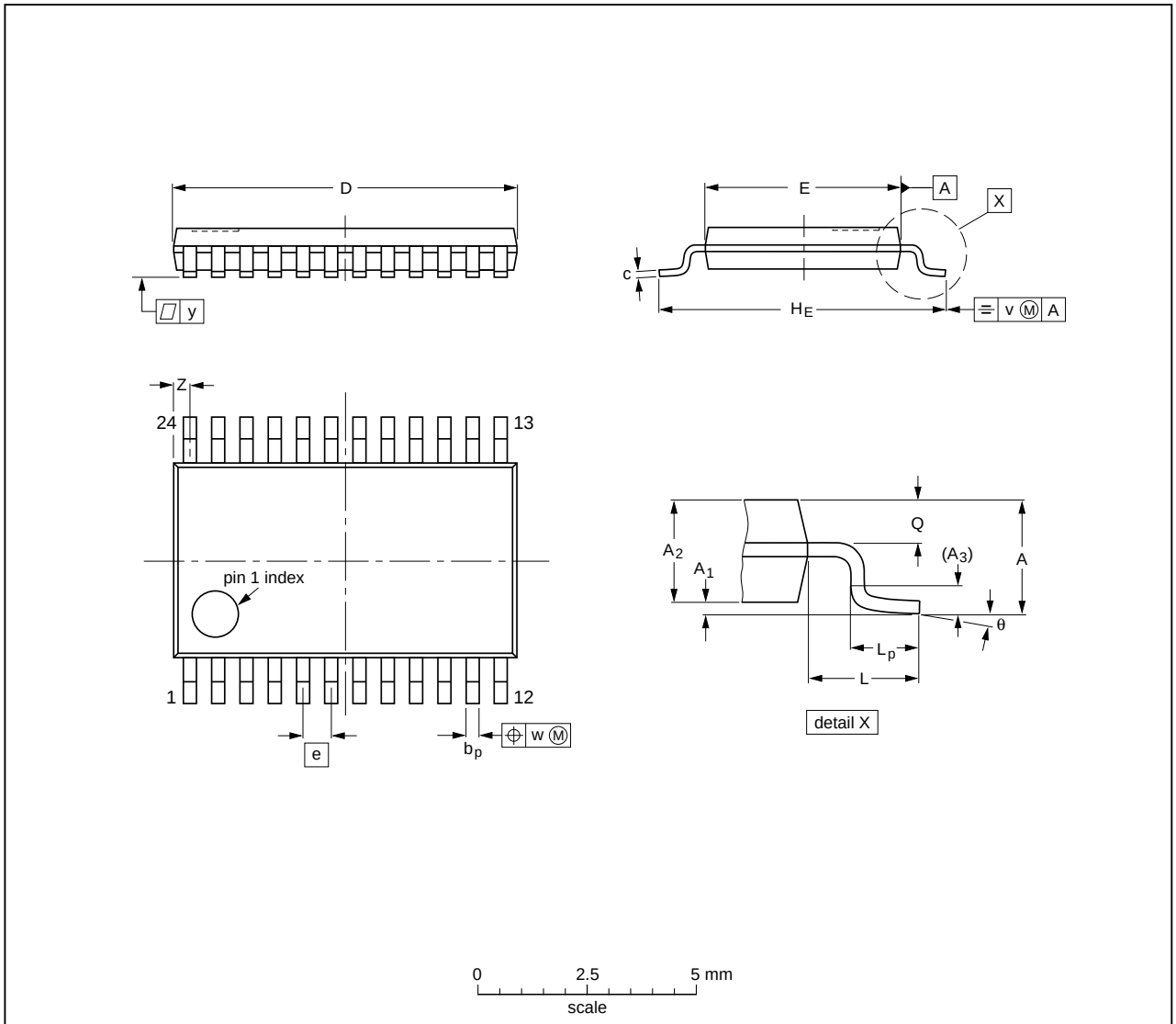
Fig 20. Test circuitry for switching times

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16. Package outline

TSSOP24: plastic thin shrink small outline package; 24 leads; body width 4.4 mm **SOT355-1**



DIMENSIONS (mm are the original dimensions)

UNIT	A max.	A_1	A_2	A_3	b_p	c	$D^{(1)}$	$E^{(2)}$	e	H_E	L	L_p	Q	v	w	y	$Z^{(1)}$	θ
mm	1.1	0.15 0.05	0.95 0.80	0.25	0.30 0.19	0.2 0.1	7.9 7.7	4.5 4.3	0.65	6.6 6.2	1	0.75 0.50	0.4 0.3	0.2	0.13	0.1	0.5 0.2	8^o 0^o

Notes

1. Plastic or metal protrusions of 0.15 mm maximum per side are not included.
2. Plastic interlead protrusions of 0.25 mm maximum per side are not included.

OUTLINE VERSION	REFERENCES				EUROPEAN PROJECTION	ISSUE DATE
	IEC	JEDEC	JEITA			
SOT355-1		MO-153				~~99-12-27~~ 03-02-19

Fig 21. Package outline SOT355-1 (TSSOP24)

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17. Handling information

All input and output pins are protected against ElectroStatic Discharge (ESD) under normal handling. When handling ensure that the appropriate precautions are taken as described in *JESD625-A* or equivalent standards.

18. Soldering of SMD packages

This text provides a very brief insight into a complex technology. A more in-depth account of soldering ICs can be found in Application Note *AN10365 "Surface mount reflow soldering description"*.

18.1 Introduction to soldering

Soldering is one of the most common methods through which packages are attached to Printed Circuit Boards (PCBs), to form electrical circuits. The soldered joint provides both the mechanical and the electrical connection. There is no single soldering method that is ideal for all IC packages. Wave soldering is often preferred when through-hole and Surface Mount Devices (SMDs) are mixed on one printed wiring board; however, it is not suitable for fine pitch SMDs. Reflow soldering is ideal for the small pitches and high densities that come with increased miniaturization.

18.2 Wave and reflow soldering

Wave soldering is a joining technology in which the joints are made by solder coming from a standing wave of liquid solder. The wave soldering process is suitable for the following:

- Through-hole components
- Leaded or leadless SMDs, which are glued to the surface of the printed circuit board

Not all SMDs can be wave soldered. Packages with solder balls, and some leadless packages which have solder lands underneath the body, cannot be wave soldered. Also, leaded SMDs with leads having a pitch smaller than ~0.6 mm cannot be wave soldered, due to an increased probability of bridging.

The reflow soldering process involves applying solder paste to a board, followed by component placement and exposure to a temperature profile. Leaded packages, packages with solder balls, and leadless packages are all reflow solderable.

Key characteristics in both wave and reflow soldering are:

- Board specifications, including the board finish, solder masks and vias
- Package footprints, including solder thieves and orientation
- The moisture sensitivity level of the packages
- Package placement
- Inspection and repair
- Lead-free soldering versus SnPb soldering

18.3 Wave soldering

Key characteristics in wave soldering are:

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- Process issues, such as application of adhesive and flux, clinching of leads, board transport, the solder wave parameters, and the time during which components are exposed to the wave
- Solder bath specifications, including temperature and impurities

18.4 Reflow soldering

Key characteristics in reflow soldering are:

- Lead-free versus SnPb soldering; note that a lead-free reflow process usually leads to higher minimum peak temperatures (see Figure 22) than a SnPb process, thus reducing the process window
- Solder paste printing issues including smearing, release, and adjusting the process window for a mix of large and small components on one board
- Reflow temperature profile; this profile includes preheat, reflow (in which the board is heated to the peak temperature) and cooling down. It is imperative that the peak temperature is high enough for the solder to make reliable solder joints (a solder paste characteristic). In addition, the peak temperature must be low enough that the packages and/or boards are not damaged. The peak temperature of the package depends on package thickness and volume and is classified in accordance with Table 18 and 19

Table 18. SnPb eutectic process (from J-STD-020C)

Package thickness (mm)	Package reflow temperature (°C)	
	Volume (mm³)	
	< 350	≥ 350
< 2.5	235	220
≥ 2.5	220	220

Table 19. Lead-free process (from J-STD-020C)

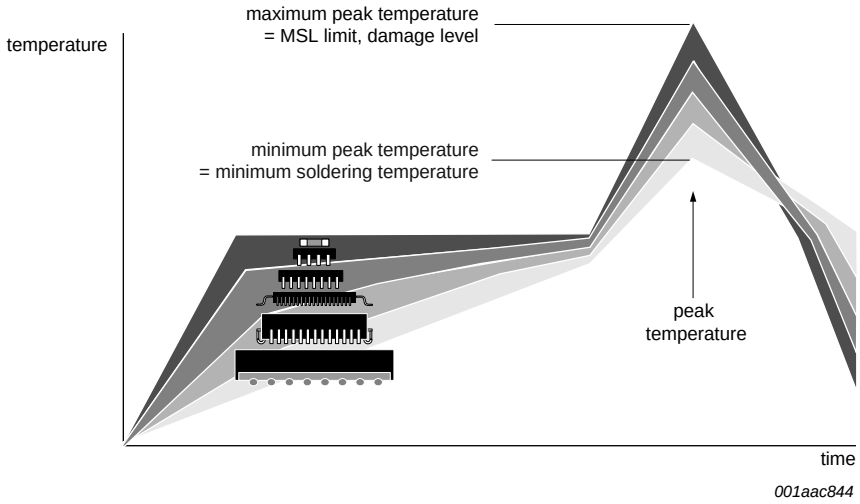
Package thickness (mm)	Package reflow temperature (°C)		
	Volume (mm³)		
	< 350	350 to 2000	> 2000
< 1.6	260	260	260
1.6 to 2.5	260	250	245
> 2.5	250	245	245

Moisture sensitivity precautions, as indicated on the packing, must be respected at all times.

Studies have shown that small packages reach higher temperatures during reflow soldering, see Figure 22.

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MSL: Moisture Sensitivity Level

Fig 22. Temperature profiles for large and small components

For further information on temperature profiles, refer to Application Note *AN10365 "Surface mount reflow soldering description"*.

19. Abbreviations

Table 20. Abbreviations

Acronym	Description
CDM	Charged-Device Model
ESD	ElectroStatic Discharge
FET	Field-Effect Transistor
HBM	Human Body Model
I²C-bus	Inter-Integrated Circuit bus
I/O	Input/Output
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LSB	Least Significant Bit
MSB	Most Significant Bit
NMOS	Negative-channel Metal-Oxide Semiconductor
NPN	bipolar transistor with N-type emitter and collector and a P-type base
PCB	Printed-Circuit Board
PMOS	Positive-channel Metal-Oxide Semiconductor
PNP	bipolar transistor with P-type emitter and collector and an N-type base
PWM	Pulse Width Modulation
RGB	Red/Green/Blue
RGBA	Red/Green/Blue/Amber
SMBus	System Management Bus

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20. Revision history

Table 21. Revision history

Document ID	Release date	Data sheet status	Change notice	Supersedes
PCU9654 v.1	20120702	Product data sheet	-	-

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Document status[1][2]	Product status[3]	Definition
Objective [short] data sheet	Development	This document contains data from the objective specification for product development.
Preliminary [short] data sheet	Qualification	This document contains data from the preliminary specification.
Product [short] data sheet	Production	This document contains the product specification.

[1] Please consult the most recently issued document before initiating or completing a design.

[2] The term 'short data sheet' is explained in section "Definitions".

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