Analog Engineer's Circuit

Smart DAC circuit for appliance light fade-in fade-out

Smart DAC *Valavala Likhit Teja, Akhilesh Kesavanunnithan*

Design Objective

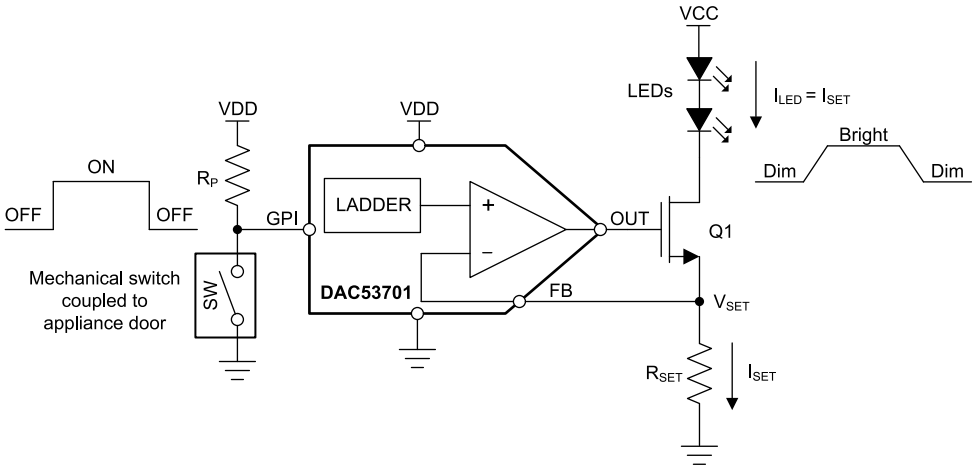
Key Input Parameter	Key Output Signal	Recommended Device
GPI trigger, Values programmed in MARGIN_HIGH and MARGIN_LOW registers	DAC output transitioning from MARGIN_LOW to MARGIN_HIGH value at a programmed slew rate, current output to adjust the brightness of LED	DAC53701, DAC43701

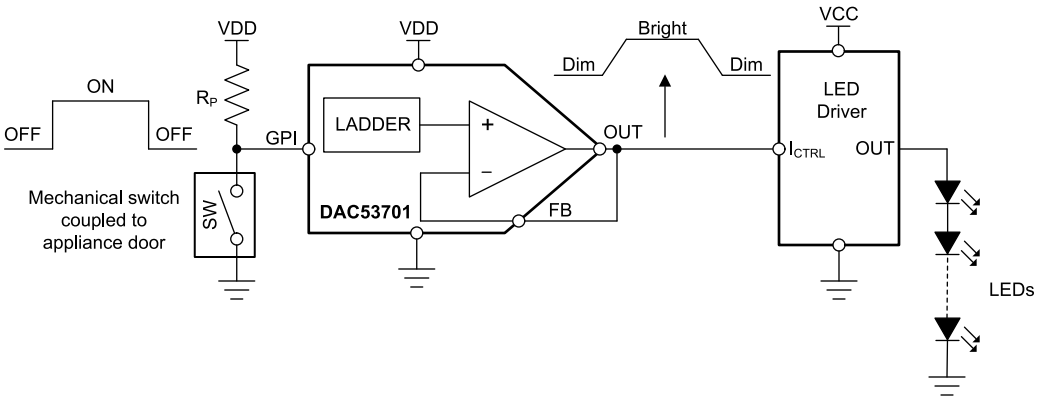
Objective: *Programmable LED biasing*.

Design Description

This circuit design describes a key application of the DACx3701 – programmable LED biasing for appliance fade-in and fade-out applications. Appliances such as toaster ovens, microwave ovens, refrigerators and clothes dryers implement door lights for monitoring the status of the function of the appliance. These door lights dim and brighten for a certain time frame when the door closes and opens, respectively. Appliance manufacturers prefer to provide a smooth-dimming transition for a better user experience. However, a microcontroller is required for such an operation, and implementing a separate microcontroller and associated software is an overhead for a heavily-commoditized appliance market. For this reason, only the high-end appliances have such features. The DACx3701 provides an easy-to-implement, low-cost way to control the slew of such lighting without the need for software.

The following images show a *simplified circuit diagram of light fade-in fade-out using MOSFET based control* and an *external LED driver*. For high-power LEDs, *external LED drivers* with headroom control are preferred over MOSFET-based LED control, see *AN-1656 Design Challenges of Switching LED Drivers*. As the following figures show, a sample use case can involve a mechanical switch coupled to the appliance door. When the door is closed, the switch is ON by default thus keeping the GPI, the general purpose input pin of the DACx3701 low. As soon as the door is opened, the switch is turned OFF, thus pulling the GPI high.





The GPI functionality is configured to margin a high-low function. Thus, a rising edge on the GPI pin takes the DAC output to the value programmed in the MARGIN-HIGH register at a slew-rate defined by the values programmed in the SLEW_RATE and CODE_STEP bits of the GENERAL_CONFIG register. The feedback loop, closed by the MOSFET ensures that V_{SET} is equal to the DAC output (Here, DAC output means the output of the DAC ladder, not the output pin). This configuration provides a benefit of accounting for the V_{GS} drop of the MOSFET. The LED current is given by V_{SET}/R_{SET} and is thus regulated by the DAC. Similarly when the appliance door is closed, the switch is now turned ON, thus pulling the GPI pin low. This high-to-low trigger on the GPI pin drives the DAC output to the value programmed in MARGIN-LOW register. This way, the LED brightening and dimming can be regulated at a specified rate using the DACx3701.

This design explains how to program the respective DAC registers to set the required LED current and to control the rate at which the LEDs become brighter or dimmer. Also included with this article is pseudocode to get started with the application. The error in LED current is also estimated based on various factors such as load resistor tolerance, DAC feedback impedance and drift in value of a particular DAC code. The power dissipation through MOSFET has been calculated to help the user choose an appropriate part based on their application.

Design Requirements and Detailed Design Procedure

The design procedure is laid out with the following requirements and components in mind

- Slew time approximately 1.5s
- Bright LED current = 20mA
- Dim LED current = 10mA
- MOSFET CSD16342Q5A
- DAC53701 (the DAC43701 is an 8-bit device while the DAC53701 is a 10-bit device. This example uses the latter)

Choose a small V_{SET} so that the power dissipation across R_{SET} is minimum. While there is an option to use the DACx3701 with either an external or an internal reference, it is important to note that the DACx3701 has a single supply voltage which will also serve as a reference in the external mode. In a practical scenario, it is unlikely that a user would have a precision reference available for VDD. With the standard power supplies, the noise and accuracy of an external reference will not be at par with the internal reference of the DACx3701. It is therefore recommended to use the internal reference of the DACx3701 to have an accurate I_{SET}.

A V_{SET} of 1V is chosen for the bright condition. The internal reference of the device is 1.212V with optional gain settings of 1.5×, 2×, 3×, or 4×. Using the 1.5× gain setting, the DAC53701 will have an output span of $1.212V \times 1.5 = 1.818V$ (the internal reference of the DAC is trimmed to 1.212V (typical) at room temperature). This results in $R_{SET}$of $1V/20mA = 50\Omega$

The output buffer of the DAC is connected in a force-sense configuration to the MOSFET as previously shown. This configuration compensates the gate-source voltage drop caused by temperature, drain current, and aging of the MOSFET. Considering a typical gate-source voltage of 1.2V and a power supply headroom of 200mV, the VDD for the DAC must be a minimum of (1V + 1.2V + 200mV) = 2.4V. Use a standard 3.3-V or 5-V power supply for the DAC. A bipolar junction transistor (BJT) provides a much smaller base-emitter voltage drop, but a MOSFET has better matching between the drain and source currents. It is recommended to choose BJT over the MOSFET when less than 2.4-V supply voltage is available for the DAC. The fact that the power supply of the DAC should be kept at or below 5.5V imposes a constraint on the V_{GS} across the MOSFET for higher values of V_{SET}. The V_{GS} of the MOSFET will change with temperature and with I_{SET} as well. A higher I_{SET} requires a higher V_{GS} but a high V_{SET} may clip the V_{GS} and subsequently the MOSFET current due to the supply limitations of the DAC. This presents a stronger case to use a lower V_{SET}.

Configure the MARGIN-HIGH register value to the code equivalent of 1V; that is $({}^{1V}/_{1.818V}) \times 1024 = 563d$ or 0x233. The MARGIN-LOW value should be the equivalent of the dim LED current that is 10mA, which corresponds to a DAC voltage of $(10mA \times 50\Omega) = 500mV$. The code for MARGIN-LOW is $({}^{500mV}/_{1.818V}) \times 1024 = 282d$ or 0x11A.

Error Calculation and Thermal Management

The last term in the equation comes from the error in V_{REF} . It is important to note that all the terms involved in the calculation must have the same units. While gain error and offset error are specified in %FSR (full scale error), INL is specified in LSB. With these units, the following equation is represented as:

$$\text{Error}_{\text{CODE}} = V_{REF} \times \frac{\text{Gain\_Error(\%FSR)}}{100} \times \frac{(\text{CODE} - \text{Offset\_Code})}{\text{Full\_Code}} + V_{REF} \times \frac{\text{Offset\_Error(\%FSR)}}{100} + \text{Real\_Gain} \times \text{INL} + \frac{(V_{REF} - V_{REF\_IDEAL})}{2^{\text{DAC\_resolution}}} \times \text{CODE}$$

The real gain is found from the Gain_Error based on the following formula:

$$\text{Real\_Gain} = V_{REF} \times \left(\frac{\text{Gain\_Error(\%FSR)}}{100} \times \frac{1}{\text{Full\_Code}} + \frac{1}{2^{\text{DAC\_resolution}}} \right)$$

For DAC53701, which is a 10-bit DAC, the full-code is 1023d and offset error is measured at 8d while for DAC43701, the full-code is 255d and the offset error is measured at 2d. In the external reference, the error in V_{REF} emerges from the error in VDD while in the internal reference the error in V_{REF} emerges from the internal reference of the DAC which is trimmed to have a value of 1.212V at room temperature (25°C). The trim resolution of this internal reference is around 5mV, so there can be an error of ±2.5mV.

Based on the gain setting in the internal mode, V_{REF} is given by:

$$V_{REF} = \text{DAC}_{\text{internal\_reference}} \times \text{GAIN}$$

Gain settings of 1.5×, 2×, 3×, and 4× are provided and thus the error in V_{REF} is given by:

$$\Delta V_{REF} = \Delta \text{DAC}_{\text{internal\_reference}} \times \text{GAIN}$$

Similarly, these errors also drift with temperature and based on the gain error drift (%FSR/°C), offset error drift (%FSR/°C) and the drift in reference (ppm/°C) across temperature, one can find out the gain error, offset error and V_{REF} at a higher (or lower) temperature and use them in the previous equations to calculate the error at a different temperature.

$$\text{Gain\_Error}_{T_2}(\text{\%FSR}) = \text{Gain\_Error}_{T_1}(\text{\%FSR}) + \text{Gain\_Error\_Drift}\left(\text{\%FSR}/\text{C}\right) \times (T_2 - T_1)$$

$$\text{Offset\_Error}_{T_2}(\text{\%FSR}) = \text{Offset\_Error}_{T_1}(\text{\%FSR}) + \text{Offset\_Error\_Drift}\left(\text{\%FSR}/\text{C}\right) \times (T_2 - T_1)$$

The drift in the internal reference of the DAC is specified in ppm/°C (parts per million per deg. C) and its maximum value is 65 ppm/°C. Thus, the V_{REF} at a higher (or lower) temperature is given by the following equation:

$$V_{REF\_T2} = V_{REF\_T_{ambient}} \times \frac{\text{DAC}_{\text{internal\_reference\_drift}}\left(\text{ppm}/\text{C}\right)}{1e6} \times (T_2 - T_1) + V_{REF\_T1}$$

The ambient temperature is 25°C. To calculate the worst-case errors in second equation, take the maximum or minimum values of all the parameters involved to estimate the maximum or minimum error, respectively. The following table shows the minimum and maximum values of gain error, offset error, gain error drift and offset error drift for the internal mode of reference with a gain of 1.5×. The INL drift across temperature can be considered negligible in comparison to the other terms.

Offset error drift (MIN) (%FSR/C)	–2.23E-04		**Gain error drift (MIN) (%FSR/C)**	–1.50E-04
Offset error drift (MAX) (%FSR/C)	2.99E-04		**Gain error drift (MAX) (%FSR/C)**	–6.77E-05
Offset Error Min (%FSR)	–0.2571		**Gain Error Min (%FSR)**	–0.133
Offset Error Max (%FSR)	0.2698		**Gain Error Max (%FSR)**	0.09735

Also V_{REF} maximum can be estimated as the ideal V_{REF} of the following equation:

$$1.212V \times 1.5V = 1.818V + 0.0025V(\text{error in the internal reference of DAC}) \times 1.5\text{V}(\text{gain setting})$$

Similarly, V_{REF} minimum can be derived by 1.818V – 0.0025V × 1.5 = 1.81425V. Putting these maximum and minimum values and considering the maximum and minimum INL as +1 and –1 LSB respectively, using the second equation yields:

$ERROR_{CODE\_MAX}$ = 0.009719784V and V_{SET_MAX} = 1.009264706V

$ERROR_{CODE\_MIN}$ = –0.009804654V and V_{SET_MIN} = 0.989740268V

Similarly, by taking the drift values from the previous table and by considering a V_{RFE} drift of ±65ppm/°C, the following maximum and minimum errors are obtained (T1 = Tambient = 25°C) $Error_{CODE\_MAX\_WITH\_DRIFT}$ = 0.016760781V

$ERROR_{CODE\_MIN\_WITH\_DRIFT}$ = –0.01678633V

It is important to note that these errors have been calculated by adding all the maximum (or minimum) values of different errors in the same direction. In reality, this may not always be the case and some errors may diminish the effect of each other. Thus, the previous calculated errors are more pessimistic.

The feedback impedance (looking in impedance at the V_{FB} node) as well the load resistor tolerance of R_{SET} also has an impact on I_{SET}. The total impedance (R_{tot}) at the DAC feedback node will thus be a parallel combination of R_{SET} and R_{VFB} given by following equation:

$$R_{tot} = \frac{(R_{SET} \times R_{VFB})}{(R_{SET} + R_{VFB})}$$

While R_{SET} has a tolerance of its own, R_{VFB} also varies from 160kΩ to 240kΩ for the internal reference gain of 1.5×. If we have an R_{SET} with 5% tolerance, the worst-case maximum and minimum values of R_{tot} will be:

R_{TOT_MAX} = 52.4885Ω

R_{TOT_MIN} = 47.4859Ω

With the V_{SET_MAX}, V_{SET_MIN}, R_{TOT_MAX}, R_{TOT_MIN} values, we can calculate the worst-case LED currents as follows:

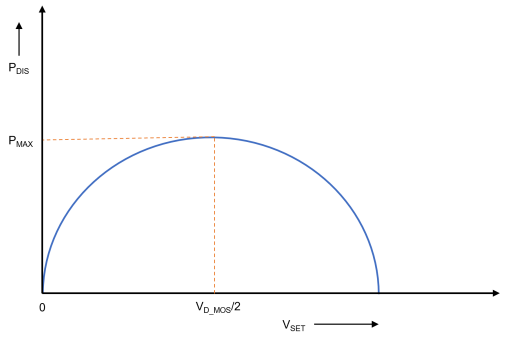
$$I_{LED\_MAX} = \frac{V_{SET\_MAX}}{R_{TOT\_MIN}}$$

$$I_{LED\_MIN} = \frac{V_{SET\_MIN}}{R_{TOT\_MAX}}$$

From the previous two equations we get the worst-case I_{LED_MIN} and I_{LED_MAX} as 18.8563mA and 21.254mA, respectively. The total power dissipated across the MOSFET is given by:

$$P_{dis} = (V_{D\_MOS} - V_{SET}) \times I_{SET} = (V_{D\_MOS} - V_{SET}) \times \left(\frac{V_{SET}}{R_{TOT}}\right)$$

Where V_{D_MOS} is the drain voltage of the MOSFET. In this application, V_{D_MOS} will be VCC – VF where V_F is the voltage drop across the diodes. V_F depends on the I_{SET} flowing through them. The relationship between P_{dis} and V_{SET} is evident in the following figure showing MOSFET power dissipation and voltage set value.



If the V_{SET} for LED bright current condition is chosen to be greater than $V_{D\_MOS/2}$, the power dissipation will be more when the LED dims down, that is, when the appliance door is closed. This is not a desirable condition so it is better to have V_{SET} below $V_{D\_MOS/2}$, that is, (VCC – VF)/2.

It is also important to note that V_{CC} cannot be significantly reduced to reduce the power dissipation as there is also a V_F drop across the diodes to account for, and based on variation across I_{SET}, there should be a sufficient margin to cater to changes in V_F. In addition, reducing the V_{CC} reduces the V_{DS} of the MOSFET, and a drastic decrease in V_{DS} demands a higher V_{GS} to support the same I_{SET} which may cause certain headroom issues as mentioned in the previous sections.

The CSD16342Q5A MOSFET chosen for this example has a maximum junction-to-ambient thermal resistance, $R_{\theta JA}$ of 50W/°C. With V_{SET} of 1V, V_{CC} of 5V and a typical V_F of 2V (single LED in the chain), P_{DIS} =

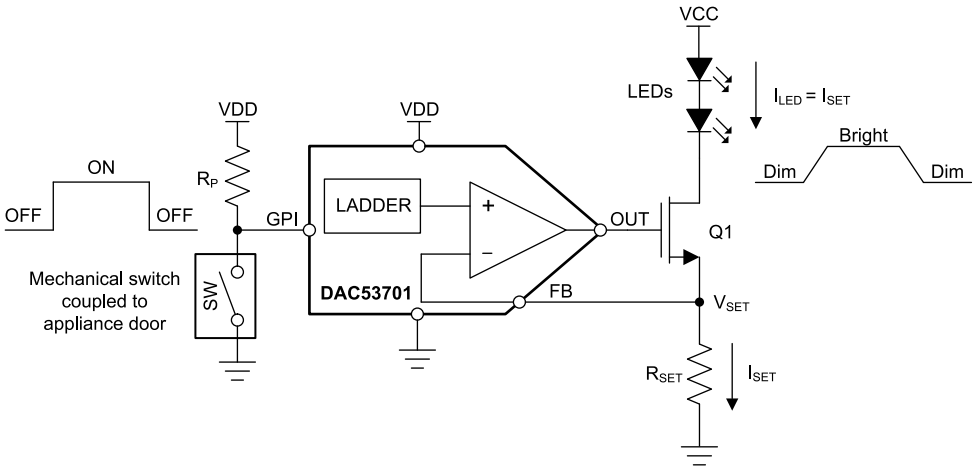
$$(5 - 2 - 1) \times 0.02 \; = \; 40\text{mW}$$

This would mean a rise of $(0.04 \times 50) = 2^{o}C$ above the ambient temperature which is not much. However, care needs to be taken while dealing with higher currents.

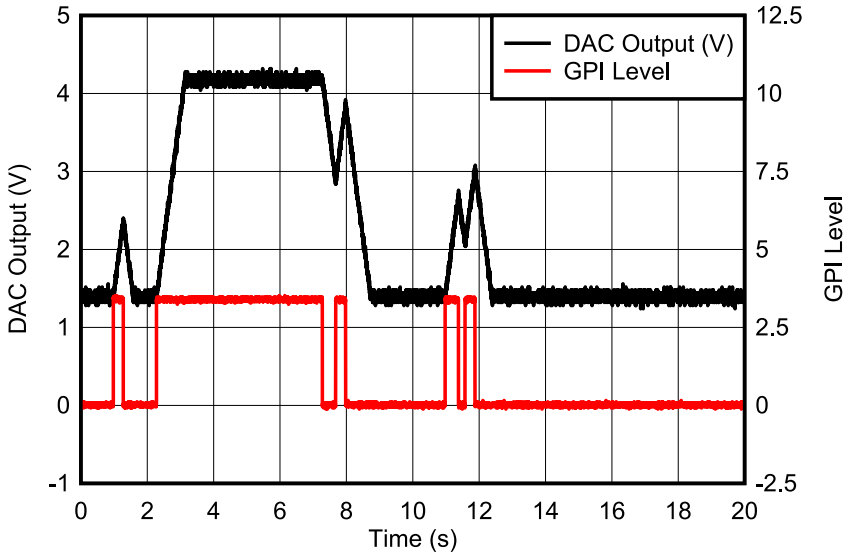
For instance, a bright current of 200mA would give a P_{DIS} of 400mW implying a rise of 200°C above the ambient temperature. If the ambient temperature is close to the maximum operating temperature of the MOSFET, a 200°C rise may damage it.

Test Setup and Measurements

The test setup for appliance LED Fade-in Fade-out with GPI pin follows:



To control the system without the use of software, map the GPI pin to margin high-low operation as listed in the *GPI Configuration* table of the *DACx3701 10-Bit and 8-Bit, Voltage-Output Smart DACs With Nonvolatile Memory and PMBus™ Compatible I2C Interface With GPI Control* data sheet. The rising edge of the GPI triggers the MARGIN-HIGH output voltage, supplying 20mA of current to the LED, and the falling edge triggers the MARGIN-LOW voltage, supplying 10-mA LED current. When the DAC output is in the slewing condition, any change in the GPI state changes the direction of the slew dynamically after the ongoing SLEW_RATE time, as shown in the following figure.



Register Settings

The table lists the register configuration of the TPL1401 for appliance LED fade-in fade-out.

Register Address	Register Name	Setting	Description
0xD1	GENERAL_CONFIG	0x0164	[15:14] 0b00: Selects the type of waveform to be generated by the continuous waveform generator (CWG)
			[13] 0b0: Write 0b0 to lock device. Unlock by writing 0b0101 to DEVICE_UNLOCK_CODE field in the PROTECT register
			[11:9] 0b000: Selects the code step used for programmable slew rate control
			[8:5] 0b1011: Selects the code step used for programmable slew rate control
			[4:3] 0b00: Powers up the device output
			[2] 0b1: Disables the internal reference
			[1:0] 0b00: Selects the gain to be applied to the internal reference
			[12] 0b0: Write 0b0 to enable PMBus mode
0xD2	CONFIG2	0x1000	[15:14] 0b00: Configures the device I2C address
			[13:11] 0b010: Configures the GPI pin as Margin-High, Low trigger
			[9] 0b0: Write 0b1 to generate a medium priority medical alarm
			[8] 0b0: Write 0b1 to generate a medium priority medical alarm
			[7:6] 0b00: Always write 0b00
			[5:4] 0b00: Selects the interburst time for medical alarms
			[3:2] 0b00: Selects the pulse off time for medical alarms
			[1:0] 0b00: Selects the pulse on time for medical alarms
			[10] 0b0: Write 0b1 to generate a high priority medical alarm
0xD3	TRIGGER	0x0408	[15:12] 0b0000: Write 0b0101 to unlock the device
			[11] 0b0: Don't care
			[10] 0b1: Write 0b1 to enable the GPI pin
			[9] 0b0: Write 0b1 to load all registers with factory reset values
			[8] 0b0: Write 0b1 to enable continuous waveform generation mode
			[7] 0b0: Write 1 to initiate PMBus MARGIN_HIGH command
			[6] 0b0: Write 1 to initiate PMBus MARGIN_LOW command
			[4] 0b1: Write 0b1 to store applicable register settings to the NVM
			[3:0] 0b0000: Write 0b1000 to reset registers with existing NVM settings or default settings
			[5] 0b0: Write 0b1 to reload applicable registers with existing NVM settings
0x25	DAC_MARGIN_HIGH	0x08CC	[15:12] 0b0000: Don't care
			[11:2] 0x8CC: 10-bit data updates the MARGIN_HIGH code
			[1:0] 0b00: Don't care
0x26	DAC_MARGIN_LOW	0x0468	[15:12] 0b0000: Don't care
			[11:2] 0x468: 10-bit data updates the MARGIN_LOW code
			[1:0] 0b00: Don't care

Pseudocode Examples

The following pseudocode helps to get started with LED Fade-in Fade-out applications.

```
//SYNTAX: WRITE <REGISTER NAME (Hex code)>, <MSB DATA>, <LSB DATA>
//Write MARGIN-HIGH code (12-bit aligned) for bright LED light
//For a 1.818-V output range, the 10-bit hex code for 1 V is 0x0233.
//With 12-bit alignment, it becomes 0x08CC
WRITE DAC_MARGIN_HIGH(0x25), 0x08, 0xCC
//Write MARGIN-LOW code (12-bit aligned) for dim LED light
//For a 1.818-V output range, the 10-bit hex code for 0.5 V is 0x011A.
//With 12-bit alignment, it becomes 0x0468
WRITE DAC_MARGIN_LOW(0x26), 0x04, 0x68
//Map GPI to margin high-low function
WRITE CONFIG2(0xD2), 0x10, 0x00
//Enable GPI
WRITE TRIGGER(0xD3), 0x04, 0x08
//Configure internal reference with 1.5x output span, and slew time and power-up the device //
CODE_STEP: 1 LSB, SLEW_RATE: 4915.2 us
WRITE GENERAL_CONFIG(0xD1), 0x01, 0x64
//Program the EEPROM
WRITE TRIGGER(0xD3), 0x04, 0x18
```

Design Featured Devices

Device	Key Features	Link
DAC53701	10-bit buffered voltage-output smart digital-to-analog converter	ti.com/product/DAC53701
DAC53701-Q1	Automotive 10-bit buffered voltage-output smart digital-to-analog converter	ti.com/product/DAC53701-Q1
DAC43701	8-bit buffered voltage-output smart digital-to-analog converter	ti.com/product/DAC43701
DAC43701-Q1	Automotive 8-bit buffered voltage-output smart digital-to-analog converter	ti.com/product/DAC43701-Q1

Find other possible devices using the Parametric search tool.

Design References

See *Analog Engineer's Circuit Cookbooks* for TI's comprehensive circuit library.

Download the companion Excel Calculator for Smart DAC LED Fade-in Fade-out.

Additional Resources

- Texas Instruments, DAC53701 Evaluation Module
- Texas Instruments, *DAC53701EVM User's Guide*
- Texas Instruments, Precision Labs - DACs

For direct support from TI Engineers use the E2E community:

e2e.ti.com

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale (https:www.ti.com/legal/termsofsale.html) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265