Basic Knowledge of LDO

TOREX
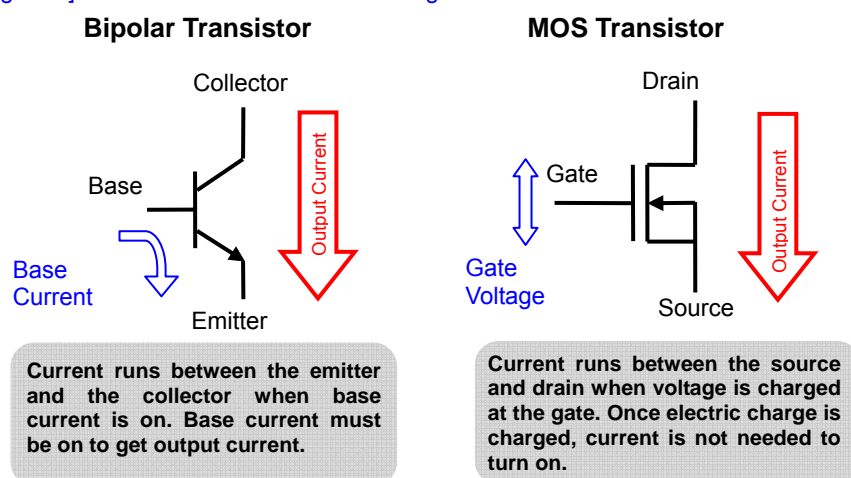
CMOS LINEAR REGULATOR

■ CMOS Linear Regulator Overview

The history of CMOS linear regulators is relatively new. They have developed with battery-powered portable electronics devices. Since CMOS processes have been used in large-scale integrated circuits like LSI and microprocessors, they have been miniaturized constantly. Taking full advantage of the miniaturization technology, CMOS linear regulators have become the power management ICs that are widely used in portable electronics products to realize low profile, low dropout, and low supply current.

● How Are They Different from Bipolar Linear Regulators?

In general, a CMOS linear regulator offers lower supply current compare to a bipolar linear regulator. This is because bipolar process is current-driven, while CMOS process is voltage-driven. [*See Figure 1*]

[Figure 1] Current-Driven Device and Voltage-Driven Device

Bipolar Transistor

Collector

Base

Base Current

Emitter

Output Current

Current runs between the emitter and the collector when base current is on. Base current must be on to get output current.

MOS Transistor

Drain

Gate

Gate Voltage

Source

Output Current

Current runs between the source and drain when voltage is charged at the gate. Once electric charge is charged, current is not needed to turn on.

Linear regulators, which do not require clock operation, are especially suitable to attain low supply current because the operating current of the regulators can be nearly zero in the circuits other than analog operating circuits.

One example of bipolar linear regulators is 78 series, multipurpose 3-pin regulators. Since the input voltage range of the series is as high as 30V ~ 40V and the series can pull more than 1A of current, the series are used in various white goods and industrial equipment. Nevertheless, the series are not low dropout because the series' output structure is NPN Darlington Output. *Table 1* shows some main characteristics of the series.

[Table 1] The Major Characteristics of Multipurpose 78 series Regulators

Product Series	Maximum Output Current	Rated Input Voltage	Operating Current	Dropout Voltage
78xx	1A	35V, 40V	4~8mA	2V@1A
78Mxx	500mA	35V, 40V	6~7mA	2V@350mA
78Nxx	300mA	35V, 40V	5~6mA	1.7V@200mA 2V@300mA
78Lxx	100mA	30V, 35V, 40V	6~6.5mA	1.7V@ 40mA

Still, the number of process needed for bipolar linear regulators is about a half or two thirds of CMOS process, and therefore a bipolar linear regulator is more cost-effective than a CMOS regulator even if its die-size is larger. Thus, a bipolar linear regulator is better suited for large current or high voltage use. On the other hand, CMOS process's miniaturization technologies are well developed and have advantages such as low voltage, low dropout, small size, and low power consumption.

www.torex.co.jp/english

Basic Knowledge of LDO

TOREX

● **Where and How Is CMOS Used?**

CMOS linear regulators are widely used in battery-powered portable electronics devices because of their low dropout and low supply current characteristics. LDO (Low Dropout) regulators enable battery to be used up to the limit, and therefore the regulators are now essential power management ICs for the devices like mobile phones, digital cameras, and laptop PCs to have long battery life. Because LDO regulators feature to pull large current with small input-output voltage differential while minimizing heat losses, they can meet the wide range of current requirements of each device.

Some low supply current types of regulators use lower than 1μA of self-supply current. Because of this feature, those types of regulators can maintain supply current of the electronics devices and wireless applications like mobile phones as low as possible when these devices are in sleep mode. Since these regulators can also provide the benefit of the CMOS miniaturization technology, they offer a great potential to mobile electronics devices that require low profile and high precision.
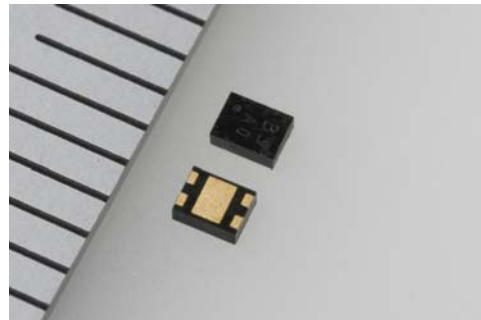
● **Packages**

Standard packages used for CMOS linear regulators are SOT-23 and SOT-89. Recently, ultra small packages like CSP (chip scale package) have also become available. Because the development of the power management ICs is led by the progress of mobile devices, they are typically sealed in surface-mount small packages. *Picture 1* shows the representative packages.
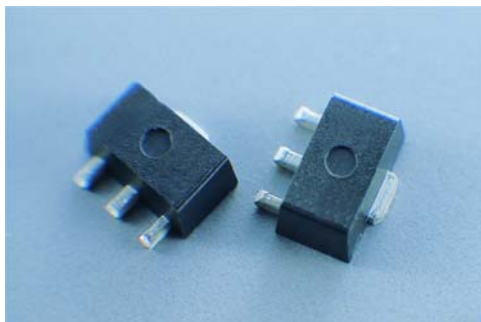
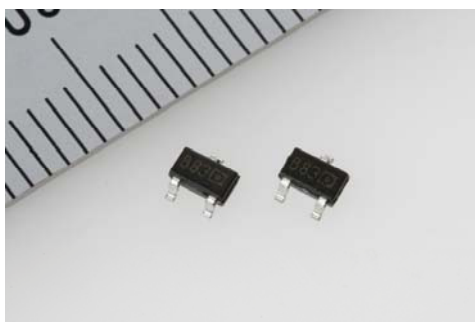[Picture 1] Examples of CMOS Regulator Packages
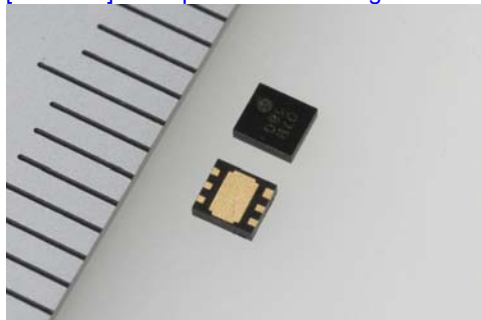
USP-6: Ultra Small Package

USP-4: Ultra Small Package

USP-3: Ultra Small Package

SOT-89: Standard Mini Power Mold Package

SOT-23: Standard Mini Mold Package

www.torex.co.jp/english

Basic Knowledge of LDO
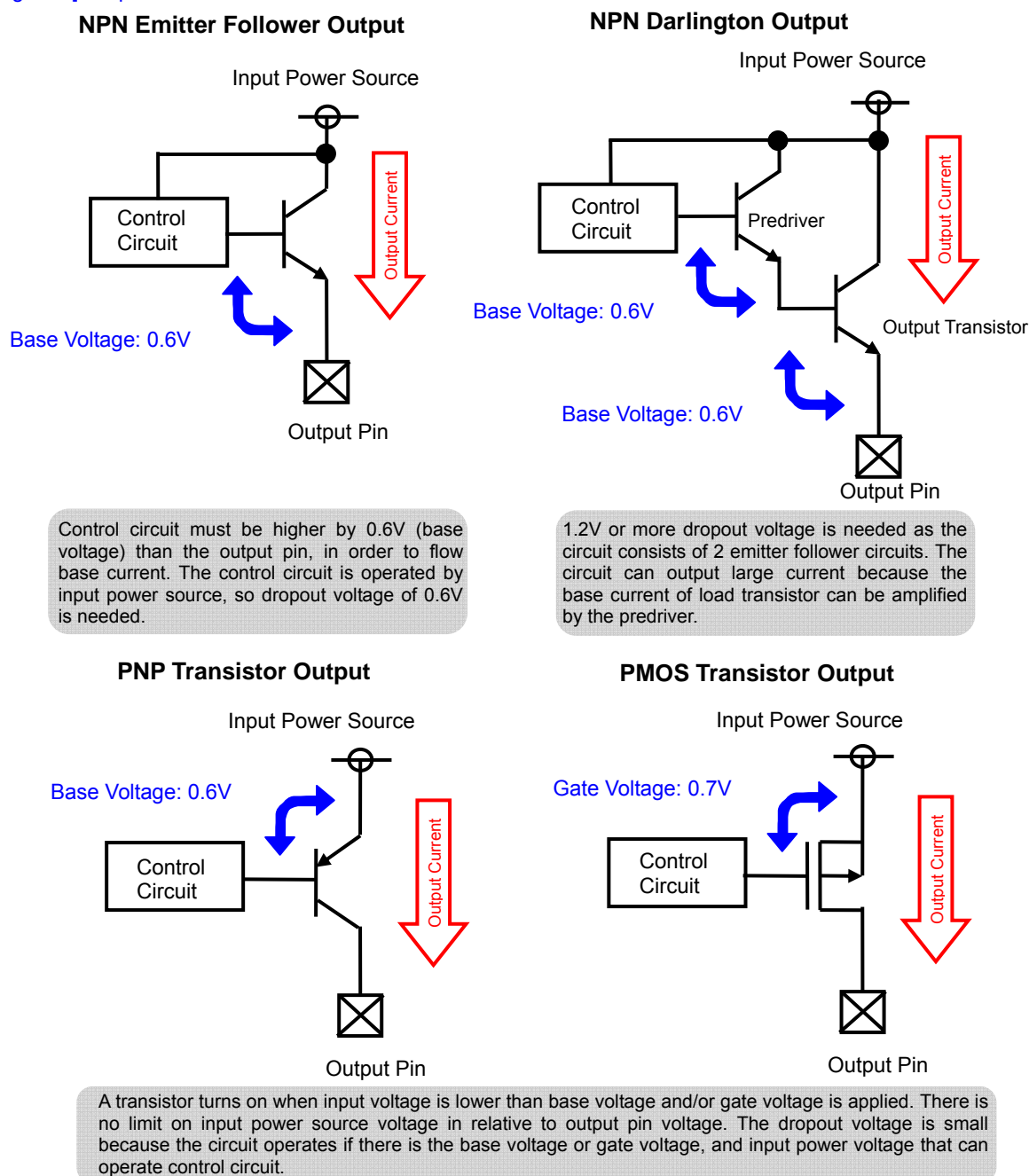
TOREX

- **Features: What Can CMOS Do?**

The premise of linear regulators as the power management ICs is that they are directly connected to a battery or an AC adapter, so you must pay attention to the maximum input voltage. The ICs design rules of CMOS processes vary depending on maximum input voltage, and maximum input voltage and microminiaturization technology are in an inverse relationship; they do not mutually act like "the greater serves for the lesser". If you choose high input voltage, then the ICs size will be bigger and its performance diminishes, and if you choose small sized ICs then you need to be careful about maximum input voltage. There are various CMOS regulators with various maximum input voltages for different applications. You should choose the most appropriate ones by carefully examining the types of power source and desired performances of your device [*See Table 2*].

[Table 2] Product Categories by Operating Voltage (Three-terminal voltage regulators)

Operating Voltage	Product Series	Package				
		USP-3	SOT-23	SOT-89	SOT223	TO252
1.5V ~ 6V	XC6218	○				
1.8V ~ 6V	XC6206		○	○		
2V ~ 10V	XC6201			○		
2V ~ 20V	XC6202		○	○	○	
2V~28V	XC6216			○	○	○

www.torex.co.jp/english

Basic Knowledge of LDO

TOREX

CMOS linear regulators can be categorized as low supply current, large current, high voltage, high-speed, LDO, and so on. There is no strict definition for these categories, but usually "low supply current" are the ones with the supply current of a few μA, "large current" are the ones that can pull 500mA or more, "high voltage" are the ones with the voltage of 15V to 20V or more, and "high-speed" are the ones with the ripple rejection rate of approximately 60dB@1kHz. "LDO" does not have an exact definition either. Originally it referred to the low dropout output of PNP output and P-ch MOSFET output, in comparison to the dropout of NPN emitter follower output and NPN Darlington output of a bipolar linear regulator. *Figure 3* shows the types of output transistors. These days, the value of less than 2Ω@3.3V in on-resistance conversion is becoming one standard of definition.

[Figure 3] Output Driver Models

NPN Emitter Follower Output

Input Power Source

Output Current

Control Circuit

Base Voltage: 0.6V

Output Pin

Control circuit must be higher by 0.6V (base voltage) than the output pin, in order to flow base current. The control circuit is operated by input power source, so dropout voltage of 0.6V is needed.

NPN Darlington Output

Input Power Source

Control Circuit

Predriver

Output Current

Output Transistor

Base Voltage: 0.6V

Base Voltage: 0.6V

Output Pin

1.2V or more dropout voltage is needed as the circuit consists of 2 emitter follower circuits. The circuit can output large current because the base current of load transistor can be amplified by the predriver.

PNP Transistor Output

Input Power Source

Base Voltage: 0.6V

Control Circuit

Output Current

Output Pin

PMOS Transistor Output

Input Power Source

Gate Voltage: 0.7V

Control Circuit

Output Current

Output Pin

A transistor turns on when input voltage is lower than base voltage and/or gate voltage is applied. There is no limit on input power source voltage in relative to output pin voltage. The dropout voltage is small because the circuit operates if there is the base voltage or gate voltage, and input power voltage that can operate control circuit.

Basic Knowledge of LDO

Other than the above types of regulators, there are regulators with an ON/OFF function by Chip Enable pin according to need, composite regulators with 2 or 3 channels, regulators with a build-in voltage detector, and more. Such wide variety is another feature of CMOS. This is attributed to the fact that CMOS process can easily scale up circuits and lower supply current because it can completely shut down specific blocks of ICs when circuits are turned off separately. Figure 2 shows the block diagram of XC6415 series, 2-channel output regulators. This product can turn on and off VR1 and VR2 independently.

[Figure 2] Block Diagram of 2-Channel Regulator (XC6415 Series)

〈XC6415 AAseries〉

Basic Knowledge of LDO
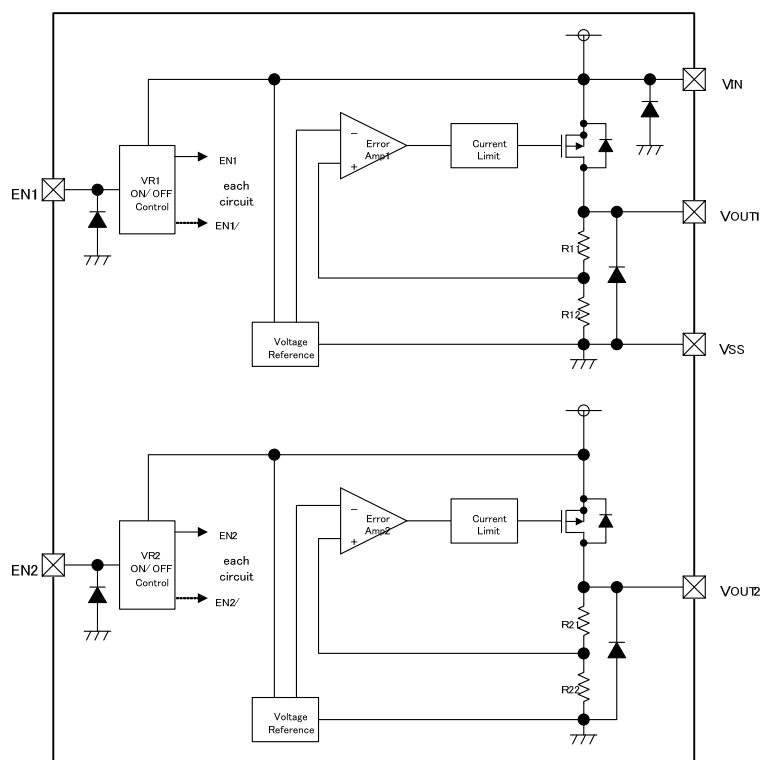
● **Internal Circuit and Basic Structure**

An internal circuit consists of a reference voltage source, an error amplifier, an output voltage preset resistor, and an output P-ch MOSFET transistor. Some circuits also have a constant current limiter, a foldback circuit and a thermal shutdown function for protection purpose. Since it is difficult to build bandgap reference circuits that are used for bipolar processes as a reference voltage source, usually the reference voltage sources used are unique to CMOS process. For this reason, the output voltage temperature characteristics tend to be slightly inferior compare to bipolar linear regulators.

Also, internal phase compensation and circuitries vary depending on the regulator types such as low supply current, high-speed, and low ESR capacitor compatible. For instance, while a low supply current regulator normally uses two amplifiers, a high-speed regulator sometimes contains three amplifiers. *Figure 4* indicates the basic circuitry block diagram of the high-speed regulator.

By adding a buffer amplifier between a preamplifier and an output P-ch MOSFET transistor, the buffer amplifier can drive the load P-ch MOSFET transistor in higher speed despite the large gate capacity. The output voltage can be determined by the values of divided resistors, R1 and R2, and the current limit value is determined by the values of divided resistors, R3 and R4. Each value is precisely set by trimming. Many high-speed type regulators are compatible with low ESR type capacitors, such as ceramic capacitors, because they are mostly used for wireless applications and portable electronics devices and therefore downsizing is necessary.

[Figure 4] Basic Circuitry Block Diagram of High-Speed Type Regulator
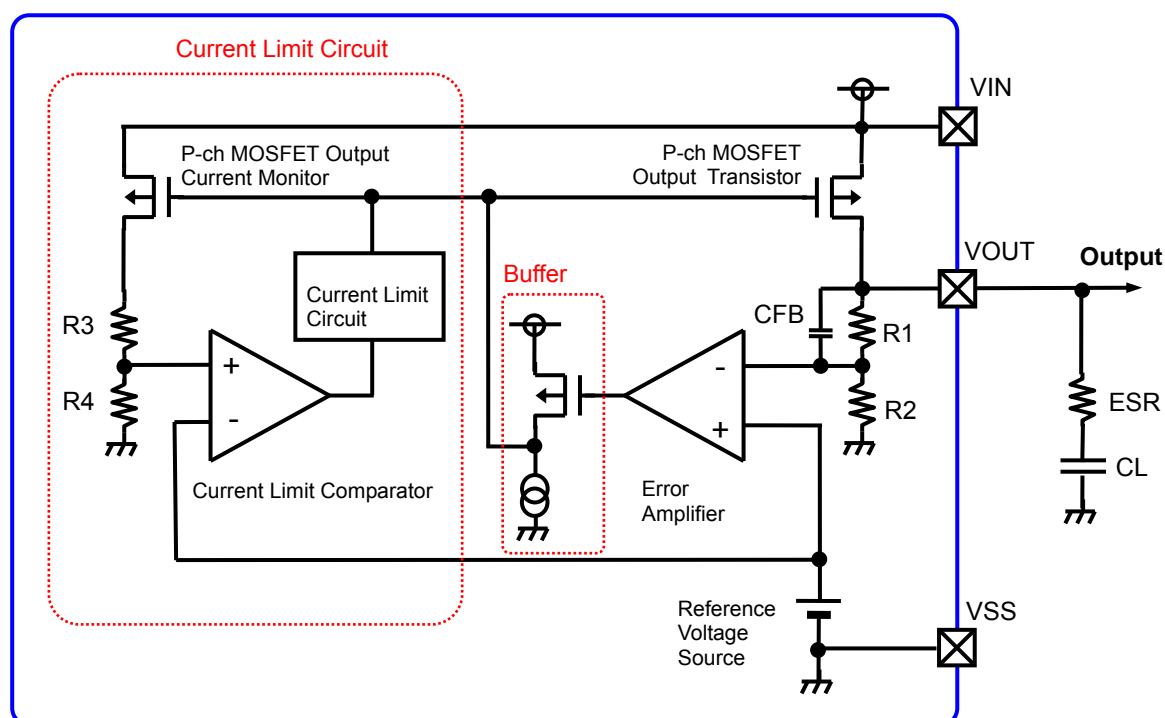
Basic Performance
Basic Electrical Characteristics

Table 3 shows general electrical characteristics of a CMOS regulator.

[Table 3] General Characteristics of CMOS Regulators by Types

Type	Low Supply Current	High Voltage	Large Current	Super High Speed	High speed	Ultra High speed	Unit
	XC6201	XC6216	XC6220	XC6204/05	XC6221	XC6222	
Output Voltage Range	1.3~6	2.0~23	0.8~5	0.9~6	0.8~5	0.8~5	V
Output Voltage Accuracy	±2	±2	±1	±2	±2	±1	%
Output Voltage Temp.Stability	±100	±100	±100	±100	±100	±100	ppm/°C
Max Output Current	200	150	1000	300	200	700	mA
Dropout Voltage@100mA	0.16	1.3	0.02	0.2	0.08	0.04	V
Supply Current	2	5	8(PS mode)	70	25	100	μA
Standby Current	-	0.1	0.01	0.01	0.1	0.01	μA
Line Regulation	0.2	0.3	0.2	0.2	0.2	0.1	%/V
Input Voltage	2~10	2~28	1.6~6	2~10	1.6~6	1.7~6	V
Output Noise	-			30			μVrms
PSRR@1 kHz	30	30	50	70	70	65	dB

Note: The values shown are typical values.

www.torex.co.jp/english

Basic Knowledge of LDO

TOREX

● **Ripple Rejection Rate**

The basic performances of CMOS linear regulators include output voltage accuracy, supply current, line regulation, load regulation, dropout voltage, and output voltage temperature characteristics. Because these parameters are fundamental characteristics of series regulators, there is no major difference between CMOS regulators and bipolar linear regulators.

There are various types of CMOS linear regulators depending on applications, but they can be roughly subdivided into two categories according to their performance; regulators that feature low supply current and high-speed LDO regulators that focus on transient response characteristics. This categorization is based on the differences of the following capability to the changes of input voltage or output current, and therefore this feature is hard to be indicated by conventional DC characteristics. Hence, these days ripple rejection rate is included in the basic characteristics in order to indicate the basic performance of CMOS linear regulators.

The formula of Ripple Rejection Rate is as shown below.

Ripple Rejection Rate
=20*Log (change in output voltage / change in input voltage)

Graph 1 indicates the ripple rejection rate of XC6209 series, high-speed regulators. Also, the actual waveform is shown in *Figure 4*. Using the input voltage with the peak-to-peak voltage of 1V and changing frequency, you can see the changes in the ripple value of output voltage. In *Graph 1*, the ripple rejection rate is -80dB when frequency is 1 kHz. So the output voltage will change approximately 0.1mV as input voltage changes 1V, and therefore we cannot identify major change in the oscilloscope in *Figure 5*. But when frequency is 100 kHz the ripple rejection rate will be 50dB, so the output ripple becomes a few mV and the changes become visible on the oscilloscope.

[Graph 1] Ripple Rejection Rate Characteristics (XC6209B302)
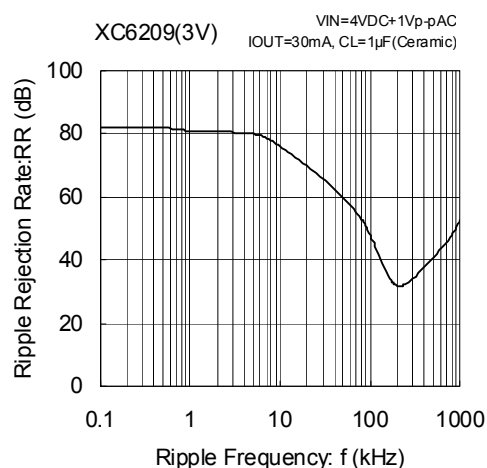
[Figure 5] Ripple Rejection Rate: Actual Input Voltage and Output Voltage Waveform （IOUT=30mA）
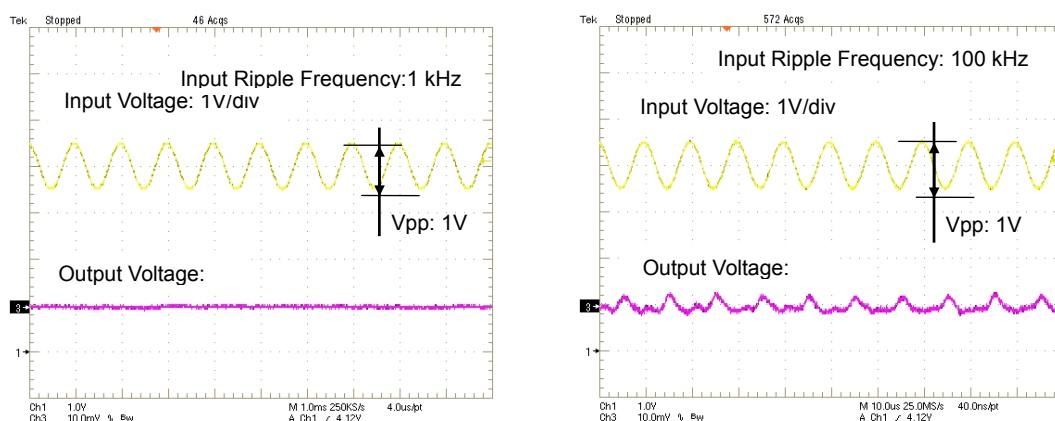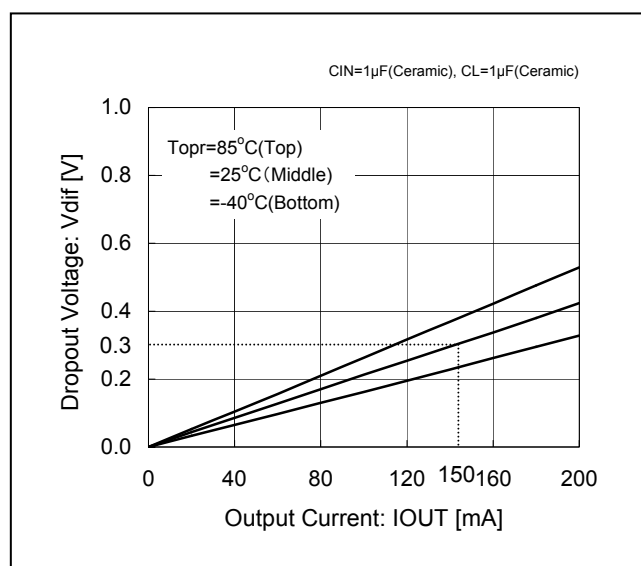
● **Dropout Voltage**

Another basic characteristic of linear regulators is dropout voltage, but most CMOS regulators are low dropout types that have very small dropout voltage. This trait derives from the fact that the regulators have been developed to achieve long-time use of battery life. *Graph 2* shows the relationship between input voltage and output voltage. You can tell that the dropout voltage is remarkably small.

[Graph 2] The Relationship between Input Voltage and Output Voltage (XC6209B302: Output Current=30mA)
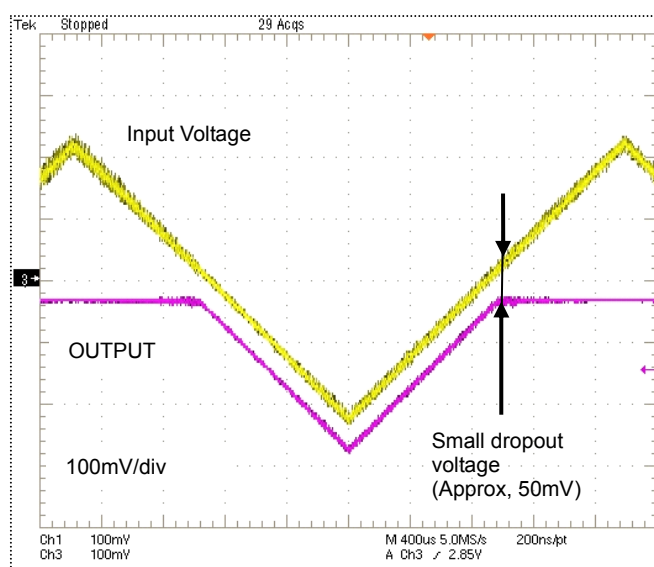
"Input-output dropout voltage" literally means the voltage difference between input and output voltage, but it also suggests the amount of available current. The dropout voltage characteristics of XC6209B302 are shown in *Graph 3* for your reference. For example, if you need the output current of 150mA using a regulator with the output voltage of 3V, then needed dropout voltage is 300mV, and therefore needed input voltage is 3.3V.

[Graph 3] Dropout Voltage vs. Output Current (XC6209B302)

Recent LDO has the improved drivability of a P-ch MOSFET driver, so you are likely able to get output current up to the current limit almost without dropout, if there is certain dropout voltage.

www.torex.co.jp/english

Basic Knowledge of LDO

● **Transient Response Characteristics: Compliance Capability When Input Voltage or Load Current Changes Stepwise**

These days burst mode is commonly used for the digital signal processing of electronics devices, and therefore the change of load current on LSI and memory is getting larger than ever. Hence, transient response characteristics that can be compliant with the changes are now an essential quality of regulators.

Transient response characteristics can be categorized as line-transient response and load transient response, and these characteristics are completely depending on the supply current of a circuit. Let us focus attention on the error amplifier and gate capacitance value of the P-ch MOSFET load switching transistor shown in *Figure 3*, a basic internal circuit block diagram. A CMOS linear regulator contains a large P-ch MOSFET transistor as a load switch, and the response speed is determined almost entirely by the output impedance of the error amplifier to drive the MOSFET transistor and the MOSFET transistor gate capacitance value. The factor that determines the output impedance of the error amplifier is the supply current of a circuit; as supply current increases, the impedance becomes lower and response becomes higher speed.
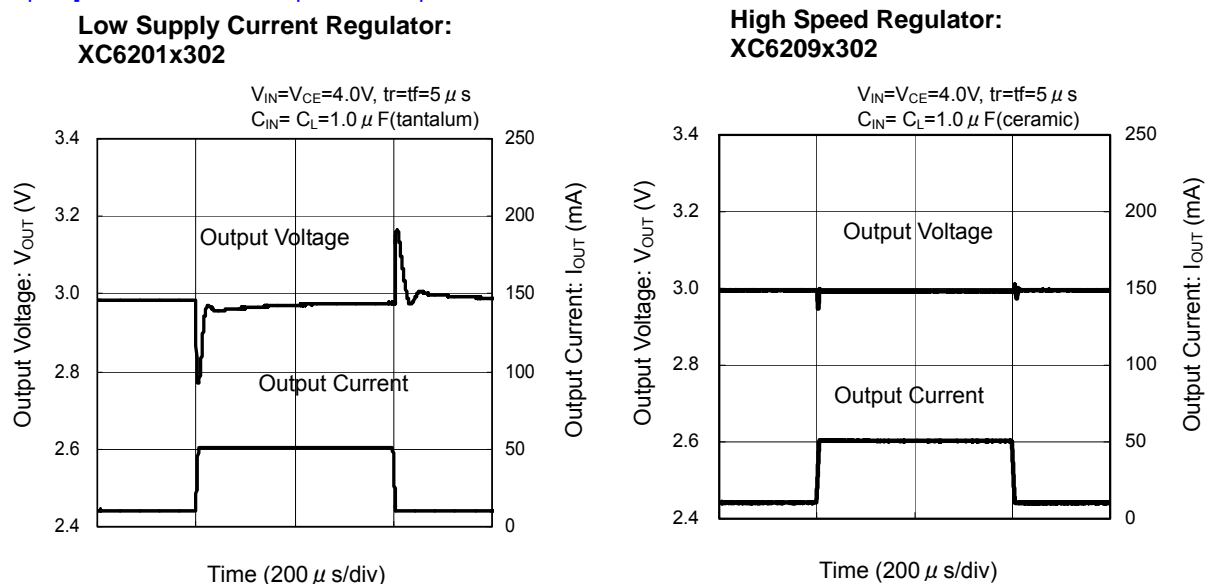
As previously described, the drivability of a high-speed regulator is improved by adding a buffer. Because the buffer functions as an amplifier as well, there will be 3 sets of amplification: a preamplifier error amplifier (40dB), a buffer amplifier (20dB), and a load P-ch MOSFET transistor (20dB). They form a feedback circuit with the open-loop gain of 80dB or more sensitivity and can respond to the change of output voltage in sensitive and high-speed manner. Observing the actual waveform of the load transient response in *Graph 4*, the voltage recovery starts within a few micro seconds after the output voltage changes, which are caused by the change of the load current.

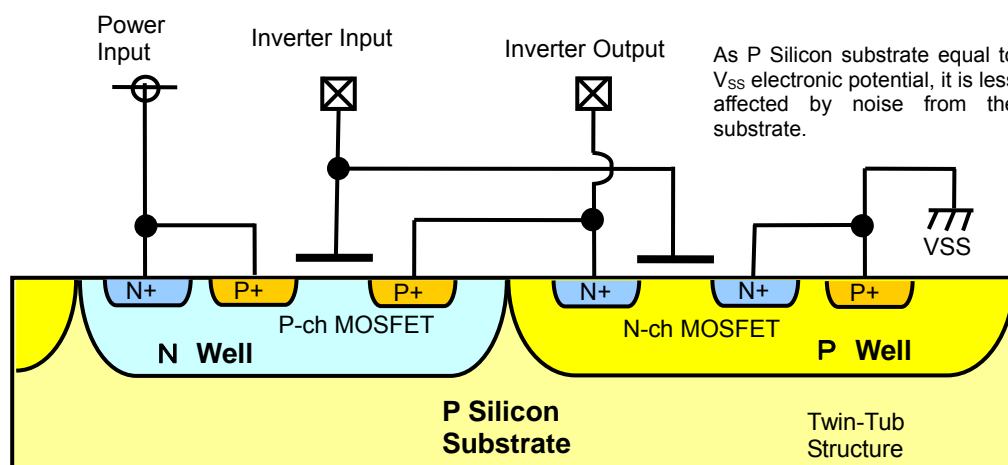[Graph 4] Load Transient Response of High-Speed LDO (XC6209B302)

VIN=VCE=4.0V,tr=tf=5μs
CIN= CL=1.0 μF (ceramic)

Basic Knowledge of LDO

TOREX
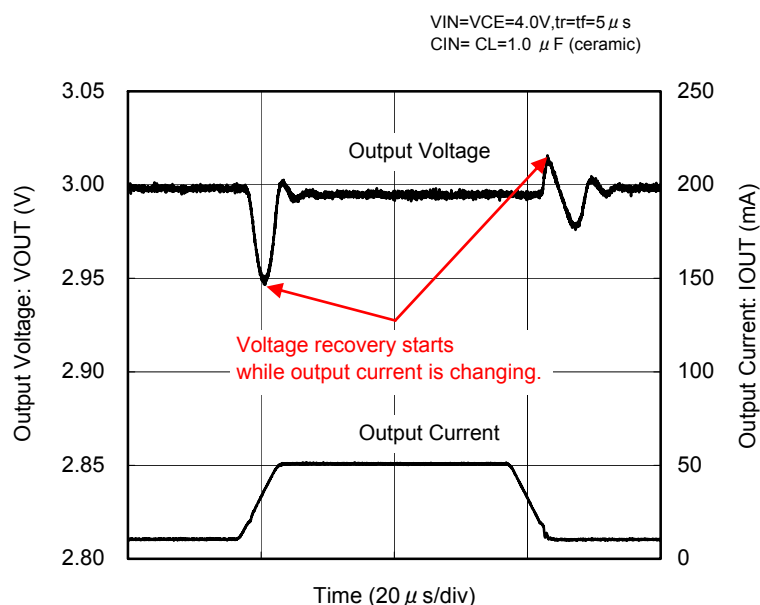
Graph 5 compares the load transient responses between XC6201 series and XC6209 series, a low supply current type and a high-speed type. The size of P-ch MOSFET transistors in both series is just about the same because both ICs are as small as to be assembled in SOT-25 package, but the waveform is apparently different.

[Graph 5] Load Transient Response Comparison

Low Supply Current Regulator:
XC6201x302

$V_{IN}=V_{CE}=4.0V$, tr=tf=5 μs
$C_{IN}=C_L=1.0\mu$F(tantalum)

Output Voltage

Output Current

Time (200 μs/div)

High Speed Regulator:
XC6209x302

$V_{IN}=V_{CE}=4.0V$, tr=tf=5 μs
$C_{IN}=C_L=1.0\mu$F(ceramic)

Output Voltage

Output Current

Time (200 μs/div)

Generally speaking, P-silicon substrate can improve line-transient response time and ripple rejection rate. This is because P- silicon substrate is grounded to the VSS, and therefore circuits on the silicon substrate are less affected by input power source. *Figure 6* shows the inverter circuit on P-silicon substrate. Reference voltage sources inside of ICs are often designed using this characteristic.

[Figure 6] Inverter Formed on P-Silicon Substrate

As P Silicon substrate equal to V_{SS} electronic potential, it is less affected by noise from the substrate.
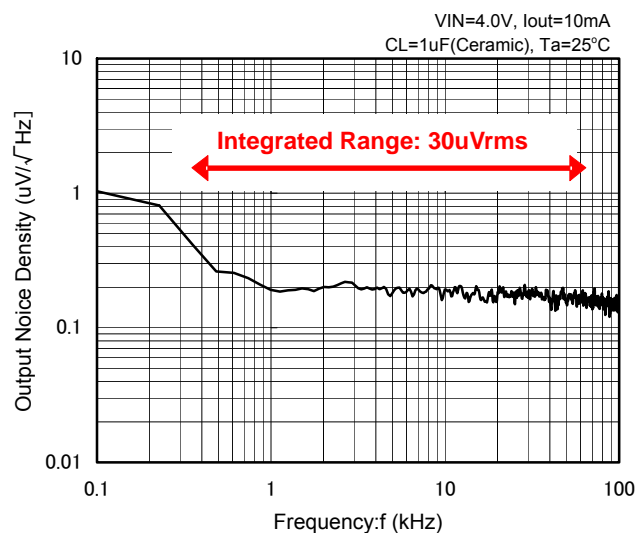
Recent LDO regulators response in extremely high-speed, and have good compliance capability to load transient response. Yet at the same time this high-speed response can make the power line unstable, and it may not only worsen the performance as a high-speed regulator but also can affect output of other linear regulators when there is impedance from connecters and wires at a power line. Wiring on PC board must be designed carefully in order to avoid impedance from the power line.

www.torex.co.jp/english

Basic Knowledge of LDO

● **Output Noise Characteristics**

White noise is one of the output noises, which occurs when thermal noise arising in an output-voltage preset resistor is amplified by an error amplifier. Thermal noise can get larger when impedance is high, so there is ultra high-speed, low noise CMOS regulators of which supply current is 70 μ A.   The noise characteristic of the regulator is shown in *Graph 6*.

[Graph 6] Output Noise Density (XC6204B302)

VIN=4.0V, Iout=10mA
CL=1uF(Ceramic), Ta=25°C

Integrated Range: 30uVrms

Output Noice Density (uV/√Hz)

Frequency:f (kHz)

Basic Knowledge of LDO

TOREX

■ **Protection Function/Power Saving Function**
● **Over current Protection and Heat Protection**

Since linear regulators are power ICs, they normally have some kinds of protection functions. Commonly used protections are current limiter circuits and foldback circuits for overcurrent protection, and thermal shutdown circuits for heat protection.

Graph 7 shows the operational characteristics example of a constant current limiter and a foldback circuit. When output current is going to get higher than 300mA, the constant current limiter operates and the output voltage descends almost vertically in the graph. As the descent continues, the foldback circuit operates and reduces the output current. Eventually the output current is decreased to 10 or 20mA, so the heat loss can be reduced as low as about 100mW in the case input voltage is 4.0V.
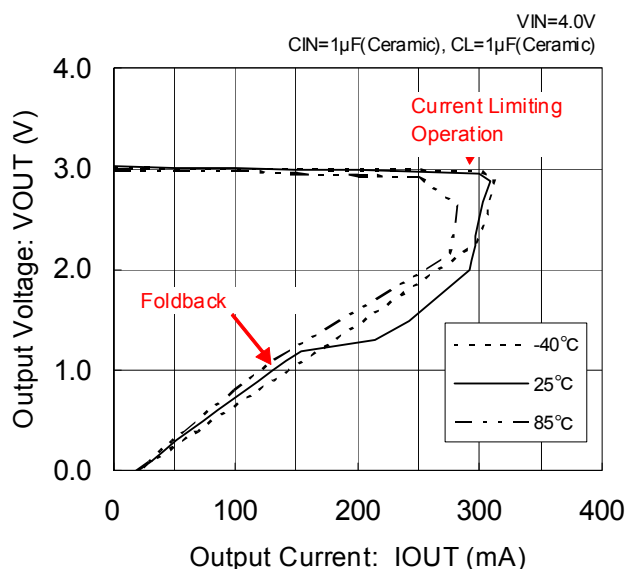

[Graph 7] Current Limit and Foldback Operation (XC6209B302)

● **CE/CL Discharge**

Some of recent CMOS linear regulators can automatically discharge the charge remained in load capacitors, synchronizing the regulators' ON/OFF switch. This power management function is often used to improve the efficiency of the batteries in portable electronic devices. Since each block discharges the charge remained in capacitors at the moment of power off, the time to wait discharging is shortened and thus it is easy to program ON/OFF sequence of each block. *Graph 8* shows an output voltage waveform of the high-speed discharge, XC6221B series when the CE pin is OFF. You can see the remained charge in a load capacitor is discharged in high speed when the CE pin voltage reaches to 0V.

[Graph 8] High Speed Discharge Waveform (XC6221B Series)

XC6221A **With high speed discharge**

XC6221B **Without High speed discharge**

Basic Knowledge of LDO
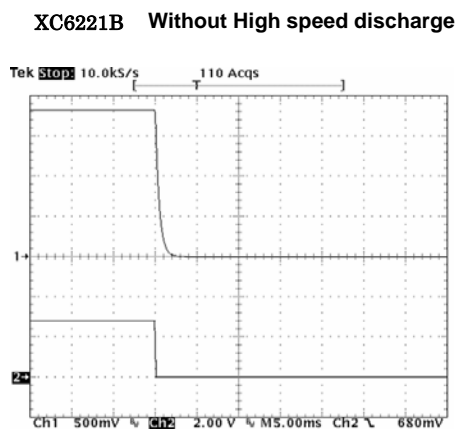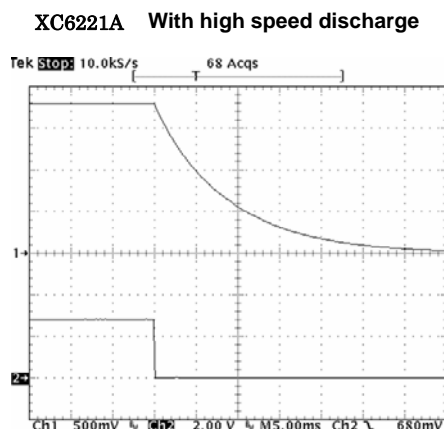
● **G.O(Green Operation)**

XC6217 series are the CMOS linear regulators with Green Operation function that can switch between HS (high-speed mode) and PS (power-save mode) depending on output current. The regulator's internal supply current will automatically be changed to 25μA and will change to high-speed transient response mode when output current goes over 8mA(Max.) and internal supply current will be 4.5μA and becomes low supply current mode when output current goes 0.5mμA(MIN.).   By automatically switching supply current, the series avoids consuming extra current and can ensure both efficiency and high-speed transient response. When the GO pin is high level, the series can be fixed to high-speed transient response, so you can select the operation mode according to need.
Also, the XC6217B series have high-speed discharge function of an output capacitor in addition to the Green Operation function. The function is useful for portable electronics applications that require precise power management, like cellular phones.
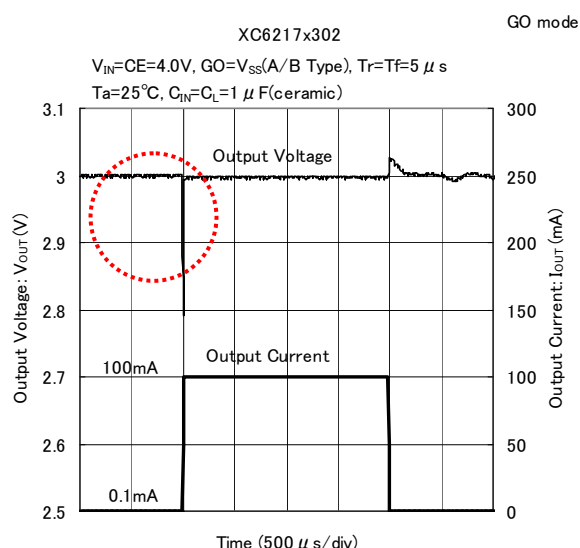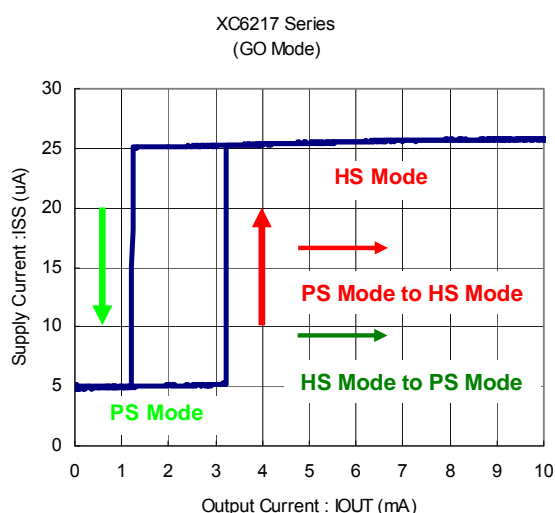
[Figure 7] Operational circuits of XC6217
[Graph 9] Supply current in of Green Operation.
[Graph 10] Example of Load transient response using GO pin

[Figure 7] Operational Circuit of XC6217
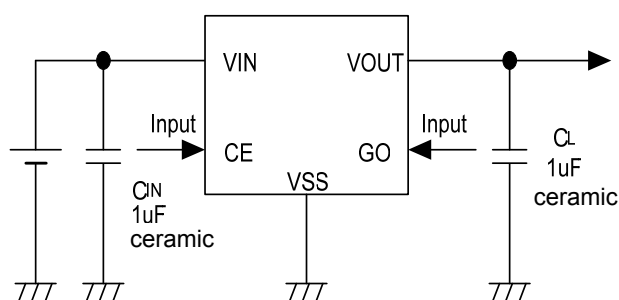
[Graph 9] Supply Current of Green Operation

At the moment of load current change, the Supply current of the ICs become larger and are switched to high speed mode, so transient response is fast. When load current becomes small, supply current will be 5μA after delay time and will be in power save mode.

[Graph 10] Load Transient Response Using GO Pin

XC6217x302   HighSpeed mode

V_{IN}=CE=4.0V, GO=V_{IN}(A/B Type), Tr=Tf=5 μ s

Ta=25°C, C_{IN}=C_L=1 μ F(ceramic)
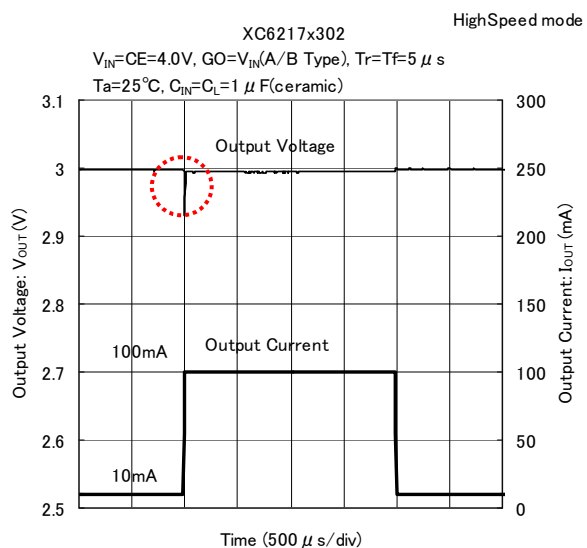
By having GO pin H level before load current change, the ICs can be high speed mode at the moment of the change. This function can make dropout voltage even smaller and is effective when strict output voltage transient response is needed.

www.torex.co.jp/english

■ **Types and Application Examples**

● **Increasing Power Dissipation Capacity by a Package**

The power dissipation of a linear regulator is determined by the relationship among input voltage, output voltage, and output current.

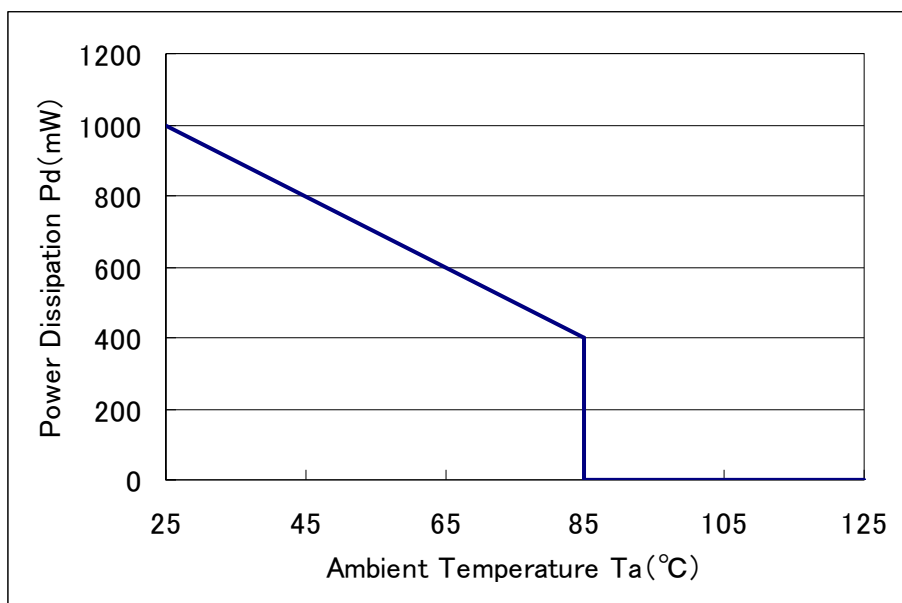Power Dissipation (Pd) = (Input Voltage – Output Voltage) x Output Current

It is important how effectively the package can release heat and prevent from heating in actual devices. USP package is one of the packages that can effectively release heat. On the backside of the package, the metal die which the ICs silicon is on is exposed, and heat is released to the PC board through the die. [*See Photo 2*]

[Photo 2]   Heat Dissipation Pad on the Backside of USP-6C


Bared Metal Surface
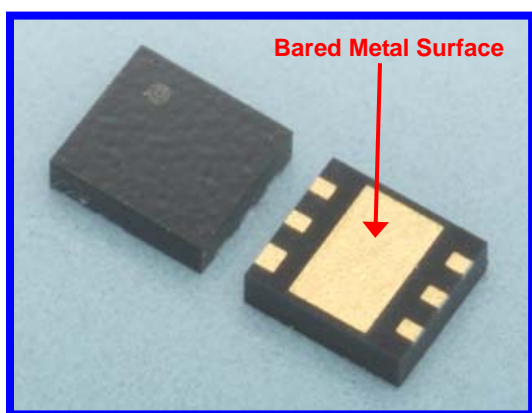
The amount of heat release is determined by the metal area dimension of a PC board. An example of USP-6C power dissipation characteristics is shown in *Graph 11*. If the power dissipation of an USP-6C itself is 120mW, it can be increased to 1W if the IC is mounted on the board shown in *Figure 11*.

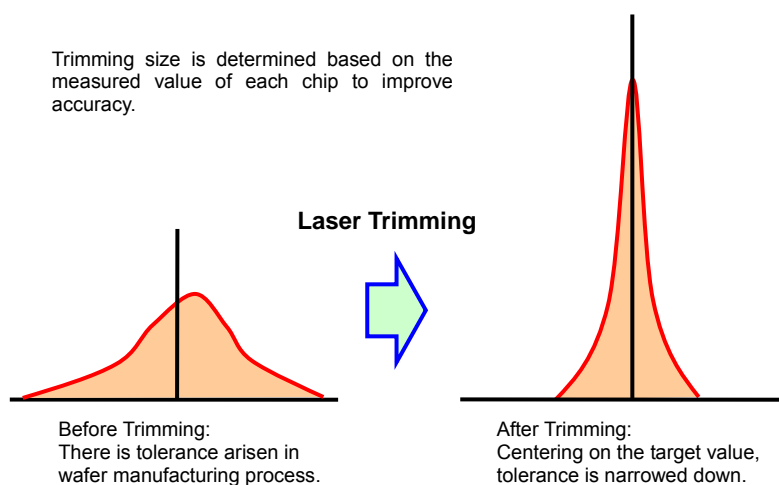[Graph 11] Heat Dissipation Characteristics: USP-6C Package

[Figure 11] PC Board used for the Evaluation of Heat Dissipation
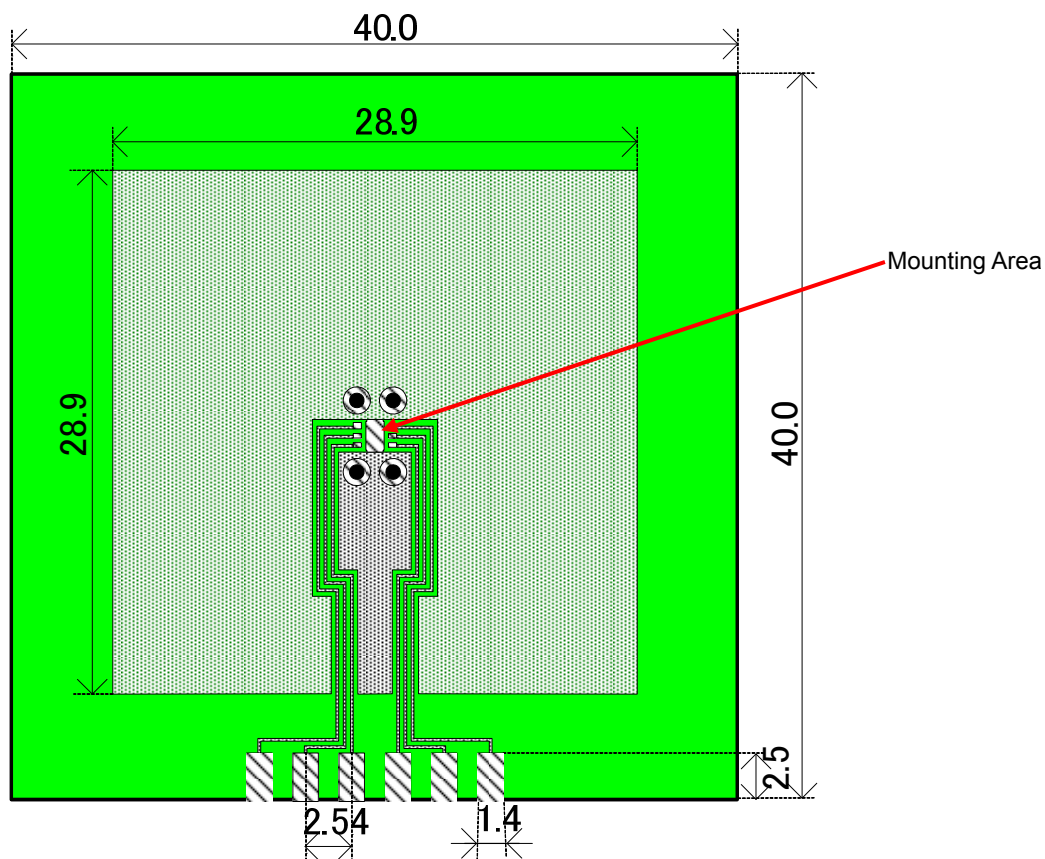
● **Laser Trimming**

The output voltage is fixed in the most of CMOS linear regulators, and is not adjustable by external components such as a resistor [*See Figure 12*].

[Figure 12] The Image of Tolerance Compensation by Lazar Trimming Technology

Trimming size is determined based on the measured value of each chip to improve accuracy.

Laser Trimming

Before Trimming:
There is tolerance arisen in wafer manufacturing process.

After Trimming:
Centering on the target value, tolerance is narrowed down.

www.torex.co.jp/english

Instead, in most cases, the output voltages are set in 0.1 or 0.05V increments precisely by laser-trimming technology. This is because CMOS process cannot generate a stable reference voltage source in its structure like a bandgap reference for bipolar transistors [*See Note 1*]. Voltage is set freely and voltage accuracy is stabilized by trimming off tolerance of the internal reference voltage source and the output voltage preset resistor [*See Figure 12*]. The output voltage accuracy is generally ±2%, and ±1% for high-precision versions. There are also products of which output voltage accuracy within their operating temperature range is strictly defined.

[Note 1] Bandgap Reference
The circuit to obtain stable voltage in certain temperature by using energy bandgaps and resistance of a bipolar transistor, utilizing the antithetic nature of the voltage temperature coefficient relative to the rated temperature.

● **Which Voltage Is Accessible When Small Quantity Is Needed?**
Since most CMOS regulators cannot adjust their output voltage externally, you need to check stock availability before buying it. Popular output voltages such as 5.0V, 3.3V, 3.0V, 2.8V, 1.8V should be more accessible than other.

● **The Trend of Development in Future**
The miniaturization of CMOS process LSI is evolving year by year, and recently even 90nm rule is about to be mass produced. Extreme miniaturization is not always effective for power ICs like linear regulators, as a certain level of input power source voltage is necessary. Still, miniaturization is what CMOS is good at. Utilizing the technology, for instance, a new regulator that can output 1.2V/1A with the input voltage of 1.5V using 0.35μm or 0.5μm should be available in near future. Further improvements of high voltage regulators using various CMOS technologies are also expected. Such positive prediction is possible because CMOS process have a large accumulation of technologies and experiences in the development of LSI and memories. In future, CMOS linear regulators are expected to be used in a wider range of fields including automotives.

~Introduction to XC6601~

■ Examples of Use

The efficiency of a CMOS regulator can be improved by combining with a switching regulator, as described in *Figure 13.*

[Figure 13] Improving Efficiency by Combining with DC/DC Converter
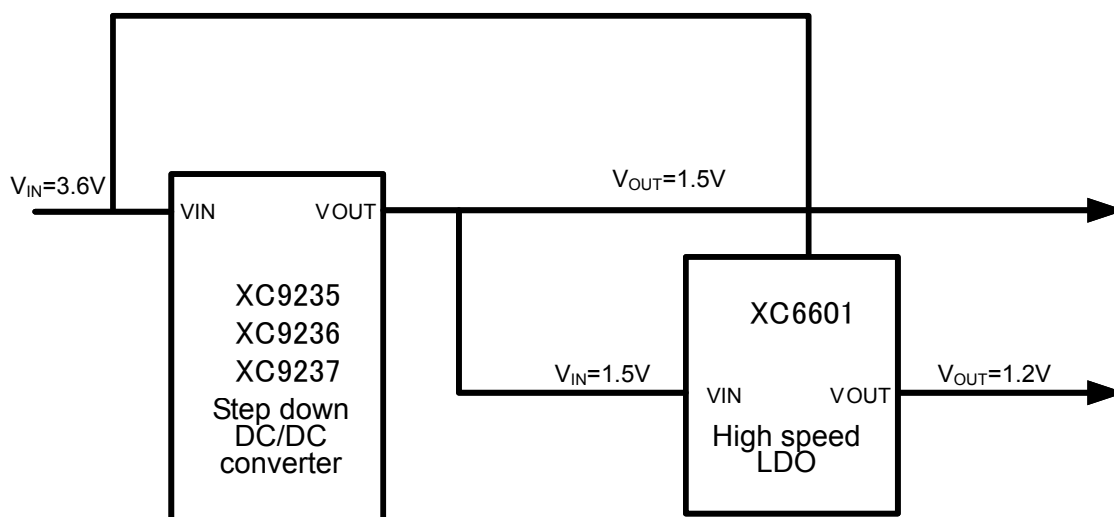
Because recent CMOS linear regulators can operate with extremely low voltage and their dropout voltage is getting smaller [Graph11], the regulator can be used after decreasing voltage efficiently by step-down DC/DC converters. For instance, the regulator can obtain 1.2V output voltage from 3.6V power source with the efficiency of 68%, after stepping down the voltage to 1.5V by DC/DC with efficiency of 85%. If the regulator generates 1.2V of output voltage directly from the power source then the efficiency would be 33%, so it is the improvement of 35%. Also, the regulator functions as a filter and can reduce output ripple. Combining DC/DC converter is especially useful when multiple power sources are needed.

[Graph11] Dropout Voltage Comparing

Dropout Voltage (XC6601/XC6210) VOUT=1.2V

www.torex.co.jp/english