Switching Regulator Series

Types of Capacitors Used for Output Smoothing of Switching Regulators and their Precautions

In recent years, it has become a common practice to recommend multilayer ceramic capacitors for the output smoothing of switching regulators due to the stability of their temperature characteristics and the reduction on the mounting area. On the other hand, they are increasingly being replaced by low-cost, high-capacity aluminum electrolytic capacitors and conductive polymer hybrid aluminum electrolytic capacitors. This application note illustrates the use of various capacitors for output smoothing with simulation results of the output voltage ripple and the gain-phase characteristic of the Open loop transfer function frequency response.

Impedance Characteristics of Capacitors

It should be noted that an ideal capacitor has only a capacitance component, but a real capacitor has both a resistance and an inductance component, and the impedance characteristics determined by these components varies greatly depending on the type and temperature of the capacitor.

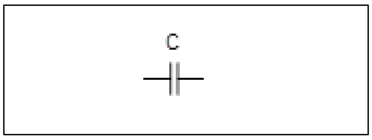

Figure 1. Ideal capacitor

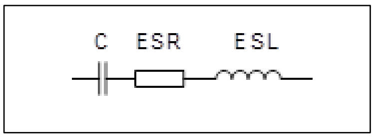

Figure 2. Equivalent circuit of a capacitor considering parasitic components

C: Capacitance
ESR: Equivalent Series Resistance
ESL: Equivalent Series Inductance

The impedance|Z| of the equivalent circuit in Figure 2 can be expressed as follows, with its frequency response as a graph shown in Figure 3.

$$Z = ESR + j2\pi f \times ESL + \frac{1}{j2\pi f \times C}$$

$$|Z| = \sqrt{ESR^2 + \left(2\pi f \times ESL - \frac{1}{2\pi f \times C}\right)^2}$$

In the lower frequency range, the impedance due to capacitance is dominant, and in the higher frequency range, the impedance due to inductance is dominant. The resonant frequency, Fr, is determined by the following equation: at frequencies below Fr, the impedance decreases due to capacitive nature, but at higher frequency bands, it becomes inductive and the impedance increases with increasing frequency.

$$F_r = \frac{1}{2\pi\sqrt{LC}}$$

F_r : Self-resonant frequency

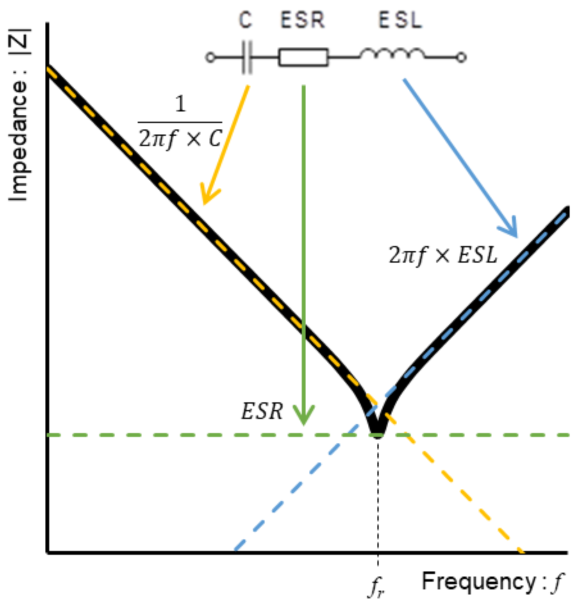

Figure 3. Impedance characteristics of capacitors

For more information on the impedance characteristics of capacitors, please refer to the application note "Impedance Characteristics of Bypass Capacitors".

Impedance Characteristics of Ceramic Capacitors

Figure 4 shows an example of the impedance characteristics of a ceramic capacitor. The temperature characteristic of the product used in this example is X7R, so the change in capacitance is ±15% from -55°C to 125°C. This is relatively small compared to aluminum electrolytic capacitors and conductive polymer hybrid capacitors, which are discussed below.
The ESR also changes very little at the said temperature variation, which is also, very small compared to other products. The ESL is small, around 200 pH, and there is almost no temperature dependence.
As such, it is very stable in terms of impedance characteristics, but it should be noted that the capacitance change due to DC voltage bias is significant, and that it is prone to squeal and also, to cracking due to temperature cycling and shock.

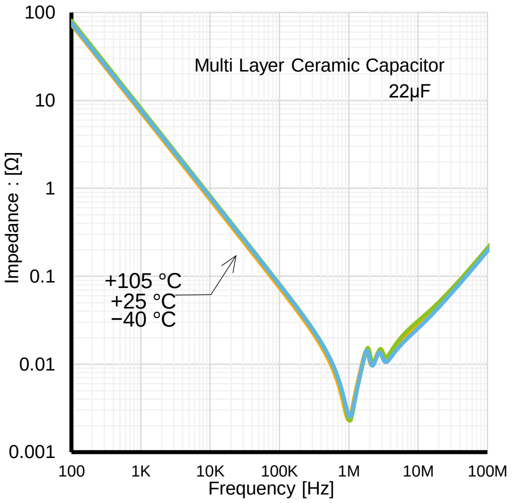

Figure 4. Examples of impedance characteristics of ceramic capacitors

Impedance Characteristics of Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors offer a higher capacitance at a lower cost than ceramic capacitors. However, it is important to note the following characteristics. Figure 5 shows an example of the impedance characteristics of an electrolytic capacitor. At temperatures as low as -40°C, the graph shows a significant increase in impedance. This characteristic is seen as an impedance because aluminum electrolytic capacitors are characterized by a decrease in capacitance and an increase in ESR at low temperatures. If the impedance at 100kHz, near the self-resonant frequency, is taken as the ESR, a change of 1.2Ω @ -40°C is produced, compared to 30mΩ @ 105°C. As will be discussed later, this change will have a significant effect on the output voltage ripple and phase characteristics. The ESL has very little change with temperature, but at 5nH, the value is larger than the ceramic capacitor, which also influences the output voltage ripple.

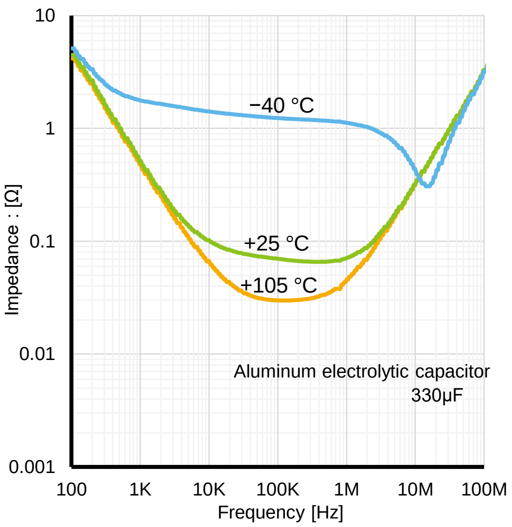

Figure 5. Examples of impedance characteristics of electrolytic capacitors

Impedance Characteristics of Conductive Polymer Hybrid Capacitors

Conductive polymer hybrid capacitors are made by fusing conductive polymer and liquid electrolyte in the electrolyte, resulting in high capacitance and low ESR. It is also generally cheaper than connecting ceramic capacitors in parallel to obtain a capacitance value of several hundred μF. Figure 6 shows an example of the impedance characteristics of a conductive polymer hybrid capacitor. The capacitance changes by about 30% at the same temperature change, and the ESR changes by about 12mΩ to 18mΩ. The ESL varies little with temperature, around 600 pH. The ESR values are close to those of ceramic capacitors, providing a more stable performance than electrolytic capacitors when large capacitance values are required

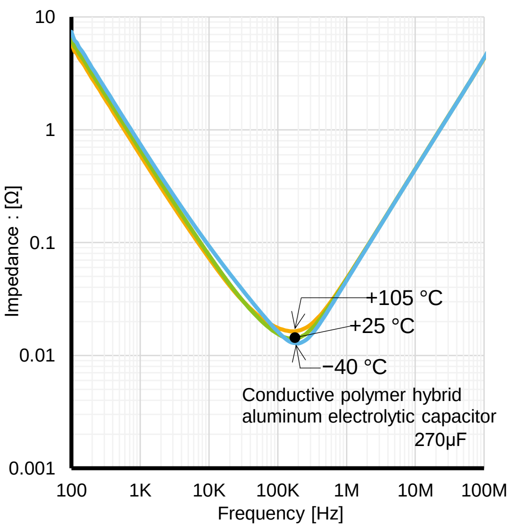

Figure 6. Conductive Polymer Hybrid Capacitors Impedance characteristics

Output Voltage Ripple and Gain-Phase Characteristics of Open Loop Transfer Function Frequency Response When Various Capacitors are Used

Calculate the output voltage ripple and the gain-phase characteristics of the open loop transfer function frequency response of three types of capacitors; ceramic capacitor, aluminum electrolytic capacitor and conductive polymer hybrid capacitor, when they are applied as the output smoothing capacitor of the switching regulator by simulation.

(The simulation is carried out using ROHM Solution Simulator.)

The various settings of the switching regulator and the simulation circuit diagram are shown below.

Setting conditions：

- Switching Regulator IC：BD90640EFJ-C
- Input voltage：12V / Output voltage setting：5.0V / Load current：1.5A / Switching frequency：500kHz
- Output smoothing capacitor：

	Capacitance (-40°C/25°C/105°C)	ESR (-40°C/25°C/105°C)	ESL (-40°C/25°C/105°C)
Ceramic capacitors (2 used in parallel)	22μF/22μF/22μF	1mΩ/1mΩ/1mΩ	200pH/200pH/200pH
Aluminum electrolytic capacitors	311μF/354μF/381μF	1.2Ω/0.07Ω/0.03Ω	5nH/5nH/5nH
Conductive Polymer Hybrid Capacitors	215μF/245μF/268μF	13mΩ/14mΩ/16mΩ	600pH/600pH/600pH

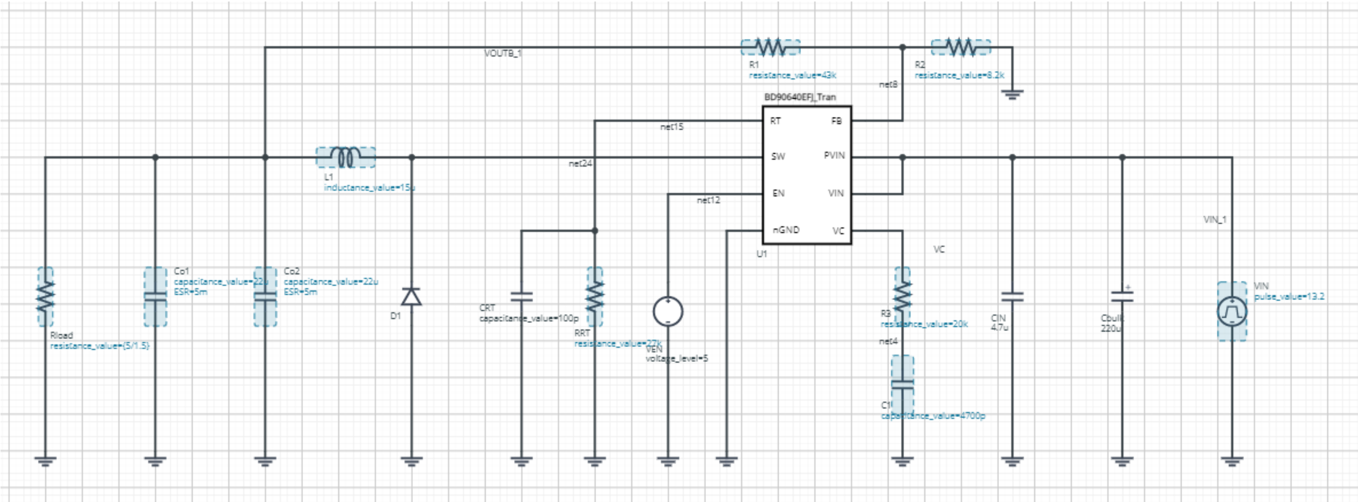

Figure 7. Output voltage ripple simulation circuit diagram

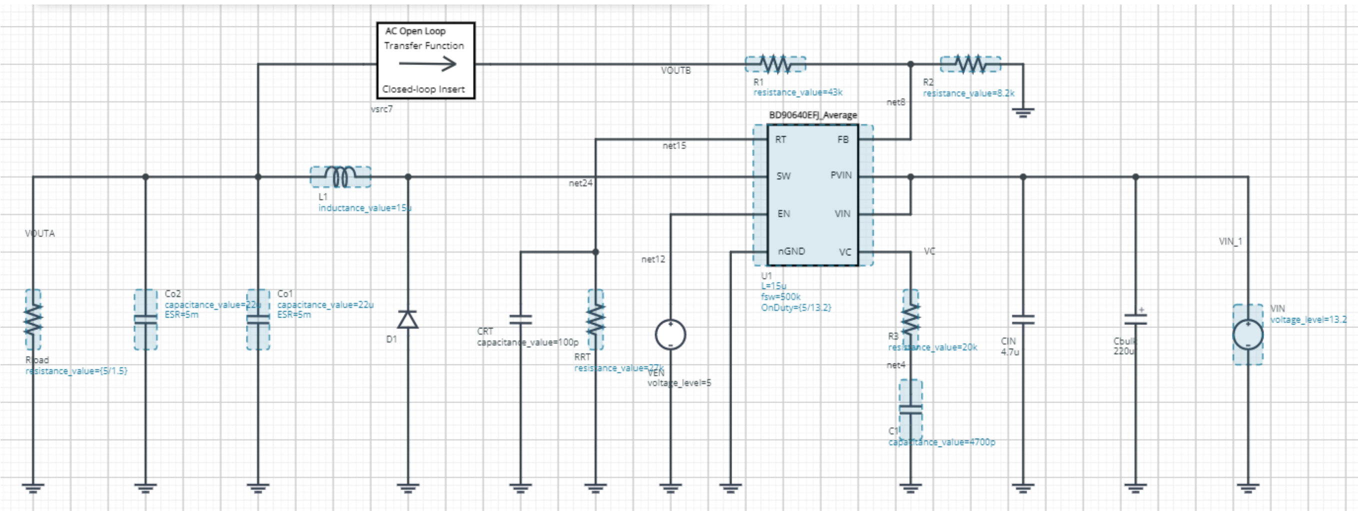

Figure 8. Open loop transfer function frequency response of gain-phase characteristics simulation circuit diagram

Characteristics When Using Ceramic Capacitors

A simulation of the output voltage ripple using a ceramic capacitor with the characteristics shown in Figure 4 is shown in Figure 9. In Figure 9, the impedance |Z| at a switching frequency of 500kHz is dominated by the capacitive component, resulting in a near sinusoidal output voltage ripple waveform. The output voltage ripple is also constant over the whole temperature range, around 2mV, because of the small temperature variation of |Z| in that region.

Figure 10 shows the gain-phase characteristic of the open loop transfer function frequency response, which is also stable over the temperature range, ensuring a Phase margin of 66° over the entire temperature range.

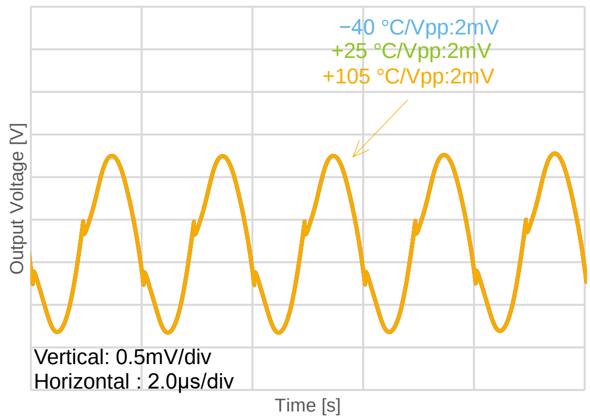

Figure 9. Output voltage ripple when using ceramic capacitors

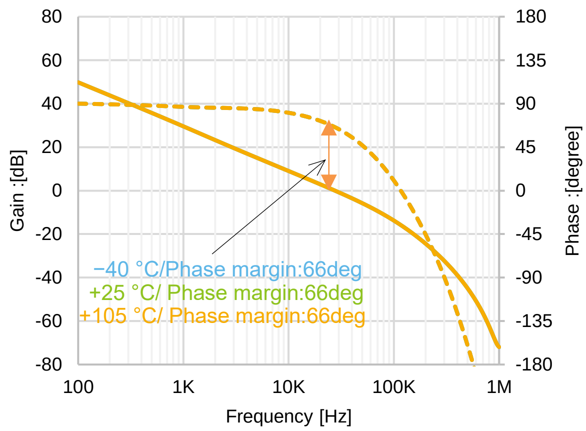

Figure 10. Gain-phase characteristics of the open loop transfer function frequency response when using ceramic capacitors

Characteristics When Using Electrolytic Capacitors

For the electrolytic capacitor with the characteristics shown in Figure 5, the impedance |Z| at a switching frequency of 500kHz is dominated by the resistive component ESR and therefore, the output voltage ripple is also dominated by the resistive component, resulting in a triangular wave shape as shown in Figure 11. At 25°C, the output voltage ripple is around 16mV, but at -40°C, the ripple can be as large as 331mV due to the increased ESR value, which can exceed the voltage specification of the MCU or SoC connected to the back end of the power supply IC.

This change in impedance |Z| also has a significant effect on the gain-phase characteristic of the open loop transfer function frequency response. Only the -40°C characteristic in Figure 12 has a phase margin below 0° and is therefore not stable. This is because the phase advance Fz, which is made up of the capacitance C and ESR of the output capacitor, moves to a lower frequency due to the increase in ESR at the low temperature of -40°C, causing the gain of the gain-phase characteristic of the open loop transfer function frequency response to be lifted at lower frequencies. Therefore, in this case, it is necessary to review the phase compensation circuit to ensure stability over the entire temperature range. General countermeasures include reviewing the phase compensation circuit of the control IC and connecting a ceramic capacitor in parallel with the electrolytic capacitor. At 40°C, stability is not ensured, and the output voltage oscillates, making it impossible to compare the output voltage ripple. For the calculation of the output voltage ripple waveform in Figure 11, the phase compensation circuit has been adjusted to ensure stable operation under all temperature conditions.

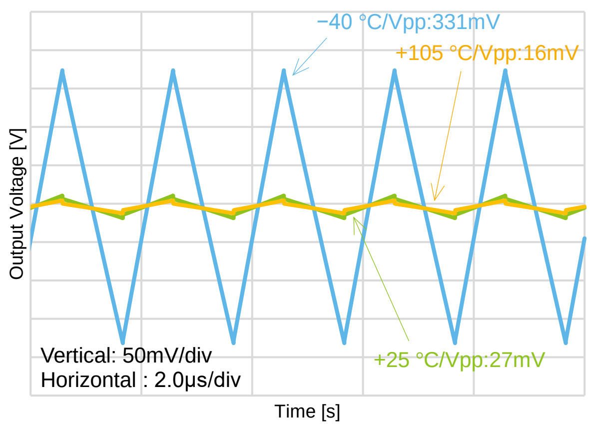

Figure 11. Output voltage ripple when electrolytic capacitors are used (after adjustment of phase compensation circuit)

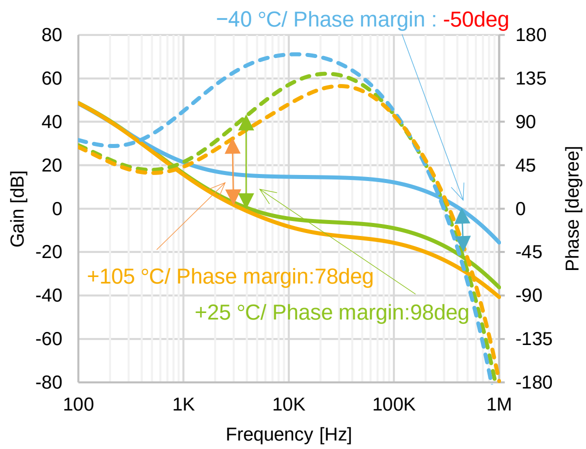

Figure 12. Gain-phase characteristics of open loop transfer function frequency response (when electrolytic capacitor is used)

Characteristics When Using Conductive Polymer Hybrid Capacitors

As shown in Figure 13, the conductive polymer hybrid capacitor, like the electrolytic capacitor, has a dominantly resistive impedance at the switching frequency of 500 kHz, so the output voltage ripple has a triangular shape, but the value is small, up to 7 mV, and has almost no temperature dependence. The gain-phase characteristic of the open loop transfer function frequency response is also stable, similar with semi-rack capacitors.

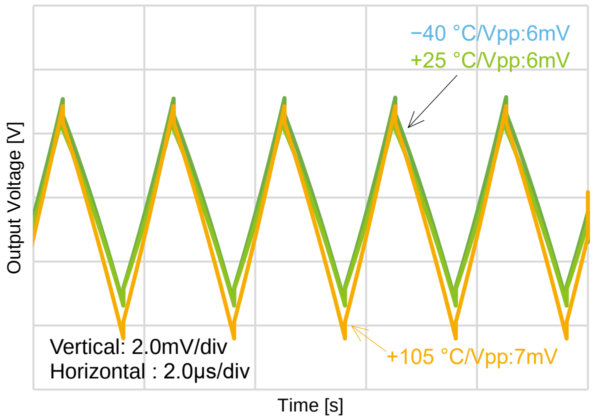

Figure 13. When using conductive polymer hybrid capacitors Output voltage ripple

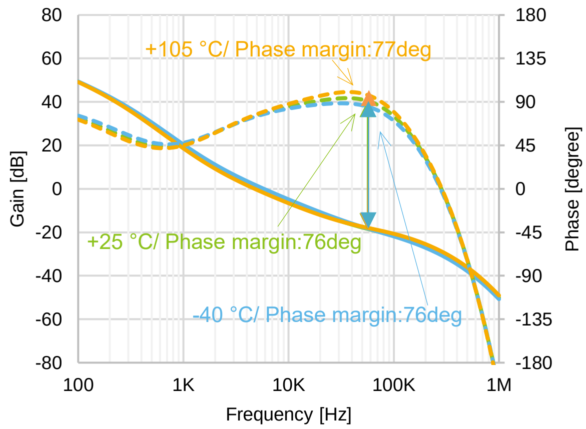

Figure 14. Gain-phase characteristics of open loop transfer function Frequency response (with conductive hybrid capacitor)

Conclusion

- The frequency and temperature characteristics of the impedance of each type of capacitor are different.
- The output voltage ripple and the gain-phase characteristics of the open loop transfer function frequency response are affected by the frequency characteristics and temperature characteristics of the impedance of the output smoothing capacitor used.
- When aluminum electrolytic capacitors are applied, care must be taken because of the large impedance change with temperature.

Notes

1) The information contained herein is subject to change without notice.

2) Before you use our Products, please contact our sales representative and verify the latest specifications :

3) Although ROHM is continuously working to improve product reliability and quality, semiconductors can break down and malfunction due to various factors.
Therefore, in order to prevent personal injury or fire arising from failure, please take safety measures such as complying with the derating characteristics, implementing redundant and fire prevention designs, and utilizing backups and fail-safe procedures. ROHM shall have no responsibility for any damages arising out of the use of our Poducts beyond the rating specified by ROHM.

4) Examples of application circuits, circuit constants and any other information contained herein are provided only to illustrate the standard usage and operations of the Products. The peripheral conditions must be taken into account when designing circuits for mass production.

5) The technical information specified herein is intended only to show the typical functions of and examples of application circuits for the Products. ROHM does not grant you, explicitly or implicitly, any license to use or exercise intellectual property or other rights held by ROHM or any other parties. ROHM shall have no responsibility whatsoever for any dispute arising out of the use of such technical information.

6) The Products specified in this document are not designed to be radiation tolerant.

7) For use of our Products in applications requiring a high degree of reliability (as exemplified below), please contact and consult with a ROHM representative : transportation equipment (i.e. cars, ships, trains), primary communication equipment, traffic lights, fire/crime prevention, safety equipment, medical systems, servers, solar cells, and power transmission systems.

8) Do not use our Products in applications requiring extremely high reliability, such as aerospace equipment, nuclear power control systems, and submarine repeaters.

9) ROHM shall have no responsibility for any damages or injury arising from non-compliance with the recommended usage conditions and specifications contained herein.

10) ROHM has used reasonable care to ensure the accuracy of the information contained in this document. However, ROHM does not warrants that such information is error-free, and ROHM shall have no responsibility for any damages arising from any inaccuracy or misprint of such information.

11) Please use the Products in accordance with any applicable environmental laws and regulations, such as the RoHS Directive. For more details, including RoHS compatibility, please contact a ROHM sales office. ROHM shall have no responsibility for any damages or losses resulting non-compliance with any applicable laws or regulations.

12) When providing our Products and technologies contained in this document to other countries, you must abide by the procedures and provisions stipulated in all applicable export laws and regulations, including without limitation the US Export Administration Regulations and the Foreign Exchange and Foreign Trade Act.

13) This document, in part or in whole, may not be reprinted or reproduced without prior consent of ROHM.

ROHM SEMICONDUCTOR

Thank you for your accessing to ROHM product informations.
More detail product informations and catalogs are available, please contact us.

ROHM Customer Support System

http://www.rohm.com/contact/