

Photovoltaic-Output Photocoupler and MOSFET as Replacement for Mechanical Relay

Design Guide

RD048-DGUIDE-01

TOSHIBA ELECTRONIC DEVICES & STORAGE CORPORATION

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1. Introduction

Mechanical relays have commonly been used for the switch of electric circuits in a wide range of equipment because of: 1) high isolation and withstand voltage, 2) high immunity to surge transients, and 3) availability of extensive contact configuration options. There are two switching modes for relays. One mode is called hot switching in which a relay opens and closes while applying voltage between input and output terminals. The other is called cold switching in which a relay opens and closes when there is no voltage between input and output terminals. Despite the above-mentioned advantages, hot switching of a mechanical relay causes 1) contact wear because of the electric current that flows to a load upon the closing of the contact and 2) contact arcing upon the opening of the contact. The wear and arcing of the contact can eventually lead to contact failure and reduce the contact life.

High relay reliability is required for industrial equipment whereas reducing the frequency of maintenance is important for HVAC (heating, ventilation, and air conditioning) and security systems. Mechanical relays for these applications are being replaced by semiconductor relays that compare favorably with mechanical relays in terms of operating stability and service life. Table 1.1 summarizes the advantages and disadvantages of mechanical and semiconductor relays. Semiconductor relays are principally characterized by 1) long life, 2) high reliability (no contact failure), and 3) silent operation.

Table 1.1 Advantages and disadvantages of mechanical and semiconductor relays

	Advantages	Disadvantages
Mechanical relays	<ul style="list-style-type: none"> • High isolation and withstand voltage • High immunity to surge transients • Available in various contact configurations • Little on-resistance 	<ul style="list-style-type: none"> • Subject to contact failure • Subject to chattering and bouncing • Generates a mechanical sound • Causes contact arcing • Limited service life (on the order of 10^5 to 10^7 open/close cycles)
Semiconductor relays	<ul style="list-style-type: none"> • Long life • Low power consumption • Capable of switching a small signal • No contact failure (high contact reliability) • High vibration and shock resistance 	<ul style="list-style-type: none"> • Subject to permanent damage in the event of exposure to conditions exceeding electric ratings • Electrical characteristics dependent on temperature • On-resistance (high power loss)

Semiconductor relays incorporate a photocoupler to provide electrical isolation between the input (primary) and output (secondary) sides. There are two types of photocouplers used for this purpose: 1) photorelays in which a photodiode array is followed by output-stage MOSFETs and 2) photovoltaic-output photocouplers designed to drive the gate of an external MOSFET with an internal photodiode array. Figure 1.1 compares the configurations of a photorelay and a photovoltaic-output photocoupler.

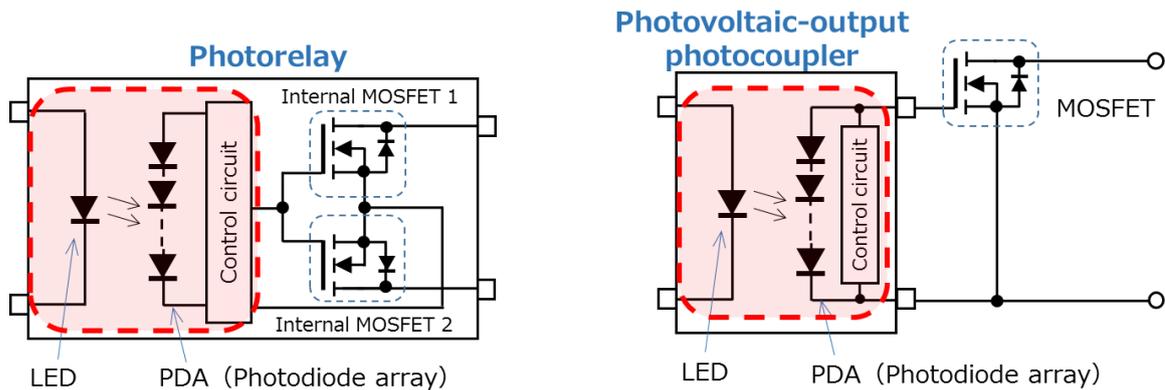


Figure 1.1 Comparison of the photorelay and photovoltaic-output photocoupler configurations

A photorelay can be viewed as a relay that integrates a photovoltaic-output photocoupler (surrounded by a red box) and MOSFETs in a single package, as shown in Figure 1.1. In the photorelay, two MOSFETs are connected in a common-source configuration at the output stage. Therefore, a photorelay requires much less board space than a combination of a photovoltaic-output photocoupler and an external MOSFET. However, photorelays in a small surface-mount package are available with an on-state current of only up to a few amperes because there is a restriction on the maximum chip size, depending on the size and shape of the package used. Nonetheless, for applications that switch both AC and DC currents, photorelays compare favorably with photovoltaic-output photocouplers in terms of design workload and board space. Despite a space disadvantage, the combination of a photovoltaic-output photocoupler and a MOSFET provides greater design flexibility than a photorelay, depending on the required on-state current.

In cases where relays are incorporated inside a system to provide basic insulation and control a power line from the user interface, reinforced insulation is necessary. Toshiba product portfolio includes photorelays and photovoltaic-output photocouplers with reinforced insulation (with an isolation voltage of 3.75kV) that satisfy insulation requirements for a wide range of applications.

Types of photovoltaic-output photocouplers

For the gate drive of a MOSFET, it is necessary not only to store electric charge in the gate but also to remove it from the gate. Two types of photovoltaic-output photocouplers are available: those with and without a discharge circuit for the removal of electric charge. Table 1.2 shows their characteristics. Photovoltaic-output photocouplers without a discharge circuit require an external discharge resistor connected in parallel with the output stage. In contrast, those with a discharge circuit do not need an external discharge resistor. Both types have advantages and disadvantages. We recommend using photovoltaic-output photocouplers with a discharge circuit if you need to simplify the relay circuit configuration. Instead of a discharge resistor, the TLP3906 incorporates a function that enables a discharge clamp circuit at turn-off. The TLP3906 provides an output without degrading the photodiode array capability when the LED turns on and quickly discharges the gate when it turns off. It simplifies system design and provides excellent performance. The TLP3906 can be used as a semiconductor relay on a system board in combination with a desired MOSFET according to the required specification.

Table 1.2 Types and characteristics of photovoltaic-output photocouplers

Type	Advantages	Disadvantages
Without a discharge circuit (TLP3905) 	<ul style="list-style-type: none"> Fast turn-off when a small discharge resistor is used 	<ul style="list-style-type: none"> Slow turn-on because of leakage when a small discharge resistor is used Requires board space for an external resistor Lower electromotive force because of a discharge resistor
With a discharge circuit (TLP3906) 	<ul style="list-style-type: none"> Does not require board space for an external discharge resistor Higher electromotive force 	<ul style="list-style-type: none"> Increase in turn-on time when a discharge resistor is added

In this design guide, the TLP3906 photovoltaic-output photocoupler is used because: 1) it provides the shortest typical turn-off time (t_{OFF}) of 0.3ms among our current product lineup and 2) it saves board space and simplifies system design as it does not require an external resistor. The application circuit shown herein uses the TLP3906 and a MOSFET in combination as a replacement for a mechanical relay under conditions close to DC switching conditions.

For details of the TLP3906, see its datasheet.

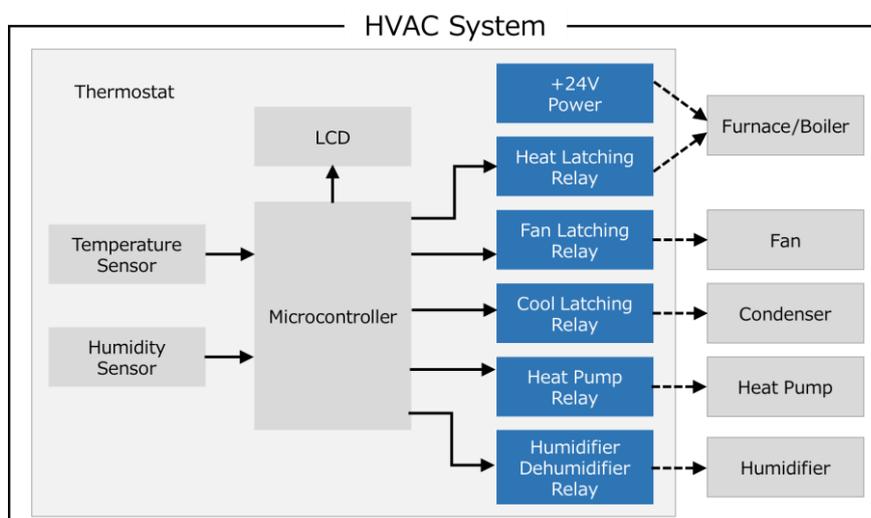
To download the datasheet for the TLP3906→

[Click Here](#)

Target applications:

- HVAC (heating, ventilation, and air conditioning) systems
- Security systems
- Factory automation control systems
- Measuring instruments

Relay usage example in an HVAC system



2. Application circuit example and bill of materials

2.1. Application circuit example

Figure 2.1 shows an example of an application circuit using a combination of a photovoltaic-output photocoupler and a MOSFET as a replacement for a mechanical relay.

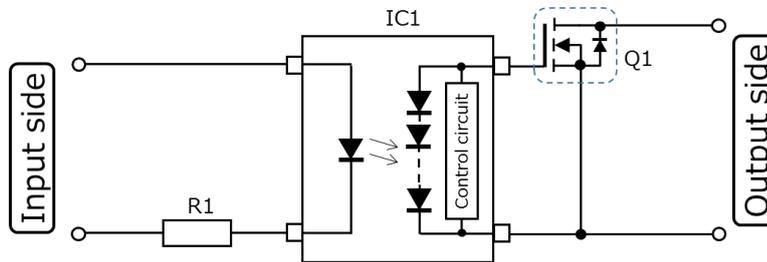


Figure 2.1 Example of an application circuit using a photovoltaic-output photocoupler and a MOSFET in combination

2.2. Bill of materials

Table 2.1 Bill of materials

No.	Ref.	Qty	Value	Part Number	Manufacturer	Description	Packaging	Typical Dimensions mm (inch)
1	IC1	1	—	TLP3906	Toshiba	Photovoltaic-output photocoupler	SO6	3.7×7.0
2	Q1	1	—	TPH1R306PL	Toshiba	MOSFET	SOP Advance	5.0×6.0
3	R1	1	200Ω	—	—	0.1W, ±5%	1608	1.6 x 0.8 (0603)

3. Application example

This section provides an example of an application circuit as a replacement for a mechanical relay that operates under conditions close to DC switching conditions.

3.1. Circuit example

This circuit uses the TLP3906 photovoltaic-output photocoupler with a discharge circuit that does not require an external discharge resistor. The assumption is that this circuit operates at an ambient temperature (T_a) of up to 85°C. First, let's calculate the output open-circuit voltage (V_{OC}) of the TLP3906 at a T_a of 85°C necessary to drive an external MOSFET. The V_{OC} of the TLP3906 decreases as T_a increases as shown in Figure 3.1. At a T_a of 25°C, the TLP3906 has a minimum V_{OC} of 7V. Translate the V_{OC} - T_a line (A) so that it is tangent to an intersection point of V_{OC} =7V and T_a =25°C as indicated by line B (red dashed line). Read the V_{OC} value on line B at T_a =85°C. In this example, V_{OC} is 5V at T_a =85°C.

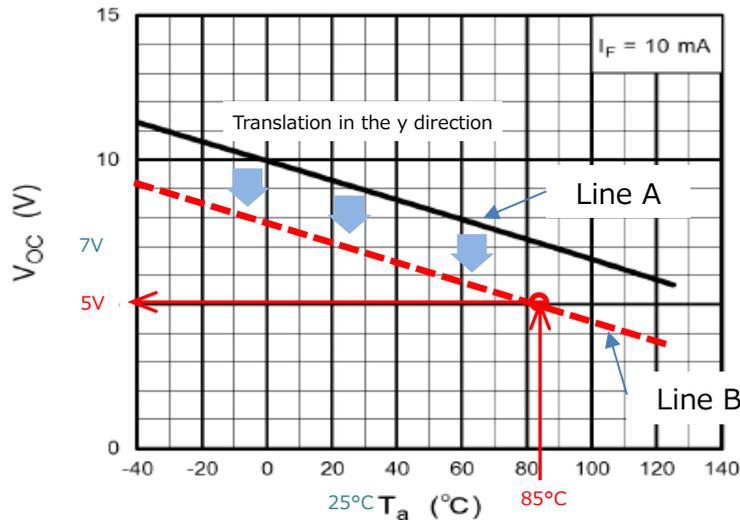


Figure 3.1 $V_{OC}-T_a$ characteristics of the TLP3906

Next, let's select a MOSFET to be driven by the photovoltaic-output photocoupler.

The drain-source voltage (V_{DSS}) rating is important for the selection of a MOSFET because application of a voltage exceeding V_{DSS} might result in the destruction of the MOSFET. It is necessary to choose a MOSFET with a V_{DSS} sufficiently higher than the voltage at which it will actually be used. However, a MOSFET with high V_{DSS} tends to have large drain-source on-resistance, $R_{DS(ON)}$. A downside of using such a MOSFET is an increase in conduction loss. Here, let's suppose that we use a MOSFET at $V_{DS}=24V$ and therefore need a MOSFET with a breakdown voltage of 60V.

See the test conditions of $R_{DS(ON)}$ for the recommended gate voltage of the MOSFET. Because $V_{OC}=5V$, select a MOSFET showing $V_{GS}=4.5V$ as a test condition of $R_{DS(ON)}$. Toshiba provides several MOSFETs that satisfy this condition. The application circuit uses the TPH1R306PL with low gate resistance (r_g) so as to reduce power loss, considering a safe operating area (SOA) described later.

The operating waveforms of a circuit composed of the TLP3906 and TPH1R306PL should be verified. Figure 3.2 shows a test circuit for this verification.

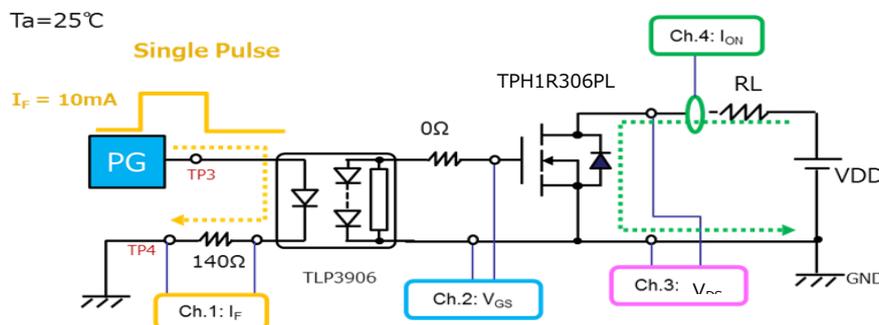


Figure 3.2 Example of a test circuit

3.2. Operating waveforms

Figure 3.3 shows examples of the operating waveforms of the circuit of Figure 3.2.

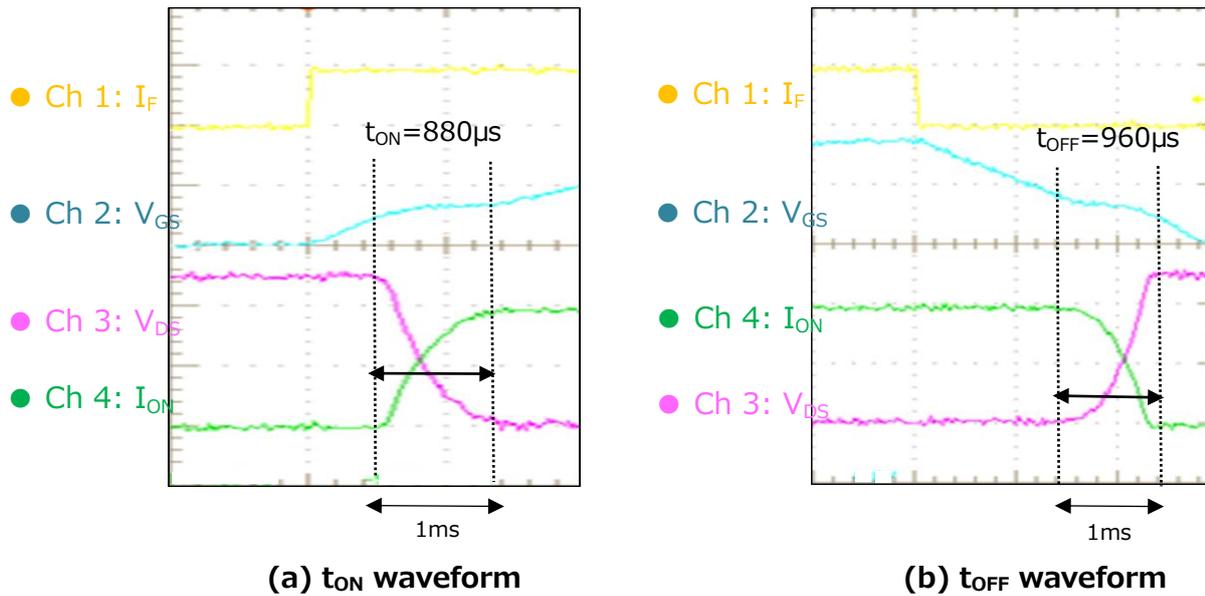


Figure 3.3 Examples of operating waveforms

A triangle is formed by the overlap of the I_{ON} and V_{DS} waveforms, with the apex being their intersection. This triangle represents the switching loss ($P_{W(sw)}$) of a MOSFET. In order to accurately transform a waveform into a rectangular shape, it is necessary to perform integral approximation. Alternatively, $P_{W(sw)}$ can be approximated as shown in Figure 3.4.

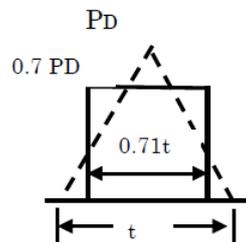


Figure 3.4 Waveform approximation

3.3. MOSFET channel temperature and safe operating area

To ensure that the channel temperature of the MOSFET does not exceed the rated temperature, it should be estimated using the test circuit shown in Figure 3.2 and its operating waveforms shown in Figure 3.3.

The test conditions of the circuit of Figure 3.2 are as follows:

Ambient temperature: $T_a=25^\circ\text{C}$, LED forward current: $I_F=10\text{mA}$, $V_{DD}=24\text{V}$, $I_{DS(on)}=3.5\text{mA}$ (maximum), $R_L=2.4\Omega$ ($I_{ON}\approx 5\text{A}$)

Figure 3.5 shows an example of a transient thermal resistance curve of this MOSFET when it is mounted on an evaluation board. The MOSFET channel temperature is calculated from this curve.

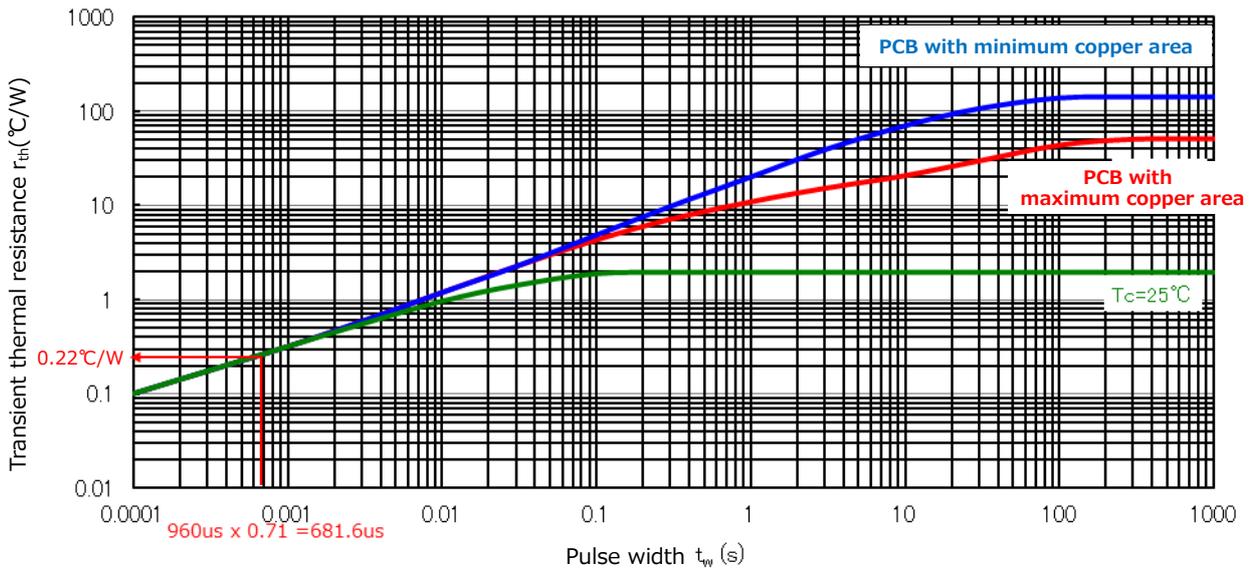


Figure 3.5 Example of a transient thermal resistance curve of the MOSFET when mounted on an evaluation board

The assumption is that the maximum ambient temperature (T_a) is 85°C.

The MOSFET channel temperature (T_{ch}) is the sum of the ambient temperature (T_a), a rise in channel temperature caused by a steady flow of current I_D (I_{ON}), $\Delta T_{ch(bias)}$, and a rise in temperature caused by the switching loss of the MOSFET, $\Delta T_{ch(SW)}$.

$$T_{ch} = T_a + \Delta T_{ch(bias)} + \Delta T_{ch(SW)}$$

where,

$$\Delta T_{ch(bias)} = P_{D(bias)} \times R_{th(ch-a)(bias)} = (I_{ON}^2 \times R_{DS(on)}) \times R_{th(ch-a)(bias)}$$

$$\Delta T_{ch(SW)} = (P_{D(SW-ON)} \times R_{th(ch-a)(SW-ON)}) + (P_{D(SW-OFF)} \times R_{th(ch-a)(SW-OFF)})$$

Temperature rise in the steady state

From Figure 3.5, the steady-state thermal resistance, $R_{th(ch-a)(bias)}$, is 50°C/W. Hence, a power loss and a temperature rise in the steady state can be approximated as follows:

$$\begin{aligned} \Delta T_{ch(bias)} &= (I_{ON}^2 \times R_{DS(on)}) \times R_{th(ch-a)(bias)} \\ &= 5A \times 5A \times 3.5m\Omega \times 50^\circ C/W = 0.0875W \times 50^\circ C/W \approx 4.5^\circ C \end{aligned}$$

Temperature rise caused by switching

First, let's calculate switching loss from Figure 3.3, Figure 3.4, and Figure 3.5.

Figure 3.3 shows that the turn-on pulse width (t_{ON}) is $880\mu\text{s}$. The area of this triangle is approximated as being equal to that of a rectangular pulse with a width of $625\mu\text{s}$ ($880\mu\text{s} \times 0.71$). Therefore, the transient thermal resistance during the period of t_{ON} , $R_{th(ch-a)(SW-ON)}$, can be read as 0.21°C/W from Figure 3.5.

Likewise, the transient thermal resistance during the period of t_{OFF} can be approximated as a thermal resistance caused by a rectangular pulse with a width of $682\mu\text{s}$ ($960\mu\text{s} \times 0.71$), which is read as 0.22°C/W from Figure 3.5.

$P_{D(SW-ON)}$ and $P_{D(SW-OFF)}$ become the maximum when $I_{ON}=2.5\text{A}$ and $V_{DS}=12\text{V}$. Therefore, from Figure 3.4,

$$P_{D(SW=ON)} = P_{D(SW=OFF)} = 2.5\text{A} \times 12\text{V} \times 0.7 = 21\text{W}$$

Hence,

$$\begin{aligned} \Delta T_{ch(SW)} &= (P_{D(SW-ON)} \times R_{th(ch-a)(SW-ON)}) + (P_{D(SW-OFF)} \times R_{th(ch-a)(SW-OFF)}) \\ &= (21\text{W} \times 0.21^\circ\text{C/W}) + (21\text{W} \times 0.22^\circ\text{C/W}) = 4.41^\circ\text{C} + 4.62^\circ\text{C} \approx 9.0^\circ\text{C} \end{aligned}$$

As a result of the foregoing, the MOSFET channel temperature at a T_a of 85°C is approximated as:

$$T_{ch} = T_a + \Delta T_{ch(bias)} + \Delta T_{ch(SW)} = 85^\circ\text{C} + 4.5^\circ\text{C} + 9.0^\circ\text{C} = 98.5^\circ\text{C}$$

Therefore, the channel temperature (T_{ch}) of the TPH1R306PL does not exceed its maximum rated channel temperature of 175°C .

Figure 3.6 shows the safe operating area (SOA) of the TPH1R306PL. The red line in Figure 3.6 represents the SOA when $T_{ch}=100^\circ\text{C}$ and the pulse width (T_w) = 1ms . The red circle indicates the point at which the switching loss becomes the maximum ($I_D=2.5\text{A}$ and $V_{DS}=12\text{V}$). It is therefore confirmed that this point is within the SOA.

An application note discussing the MOSFET SOA derating is also available. Also see this application note.

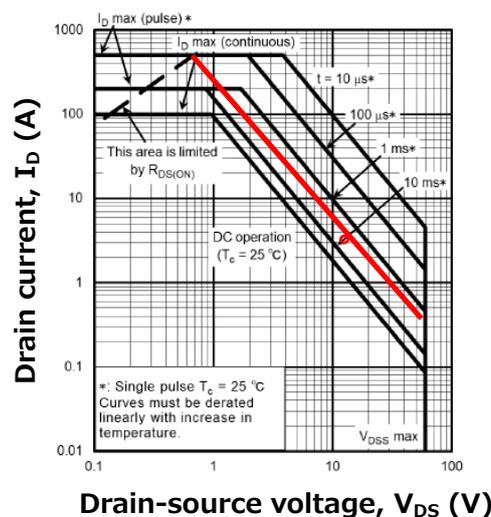


Figure 3.6 Safe operating area (SOA) of the TPH1R306PL

4. Overview of the devices used

4.1. TLP3906

4.1.1. Overview

The TLP3906 is a photocoupler in the SO6 package that consists of a photodiode array optically coupled with an infrared light-emitting diode (LED). The series-connected photodiodes are suitable for the gate drive of a MOSFET. The TLP3906 incorporates a control circuit on the output side, eliminating the need for an external discharge resistor, and therefore helps improve switching speed.

- Open-circuit voltage: 7V (min)
- Short-circuit current: 12 μ A (min)
- Isolation voltage: 3750Vrms (min)
- Safety standards

UL-approved: UL1577, File No. E67349

cUL-approved: CSA Component Acceptance Service No. 5A File No. E67349

VDE-approved: EN60747-5-5, EN60065, EN60950-1 (Note 1)

Note 1: When VDE-approved parts are needed, please designate the Option (V4).

4.1.2. External view and pin assignment

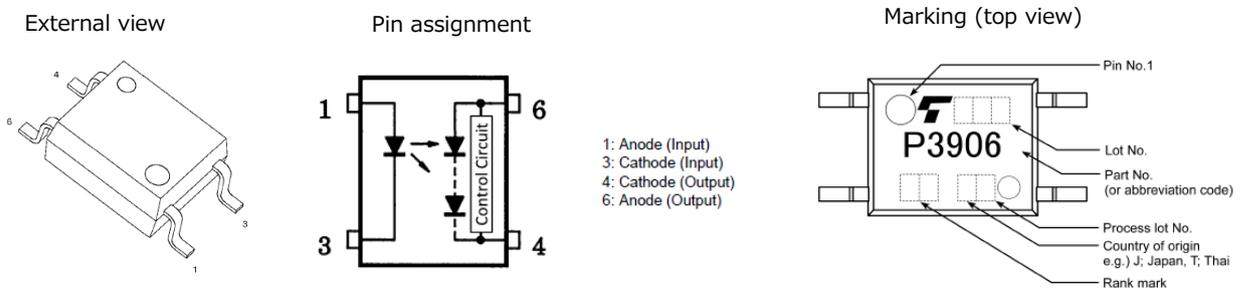


Figure 4.1 External view and marking of the TLP3906

4.1.3. Mechanical parameters

Table 4.1 Mechanical parameters of the TLP3906

Characteristics	Min	Unit
Creepage distance	5.0	mm
Clearance distance	5.0	
Distance through insulation	0.4	

4.2. TPH1R306PL

4.2.1. Overview

The TPH1R306PL is an N-channel silicon MOSFET in the SOP Advance package fabricated using Toshiba's U-MOSIX-H MOSFET process. Because of low on-resistance and low leakage current, the TPH1R306PL is suitable for a wide range of applications, including DC-DC converters, switching regulators, and motor drivers.

- Fast switching speed
- Low input gate charge: $Q_{SW} = 22\text{nC}$ (typ.)
- Low output charge: $Q_{OSS} = 77.5\text{nC}$ (typ.)
- Low on-resistance: $R_{DS(ON)} = 1.0\text{m}\Omega$ (typ. at $V_{GS} = 10\text{V}$)
- Low leakage current: $I_{DSS} = 10\mu\text{A}$ (max. at $V_{DS}=60\text{V}$)
- Easy-to-use enhanced-mode MOSFET: $V_{th} = 1.5$ to 2.5V ($V_{DS} = 10\text{V}$, $I_D = 1.0\text{mA}$)

4.2.2. External view and pin assignment

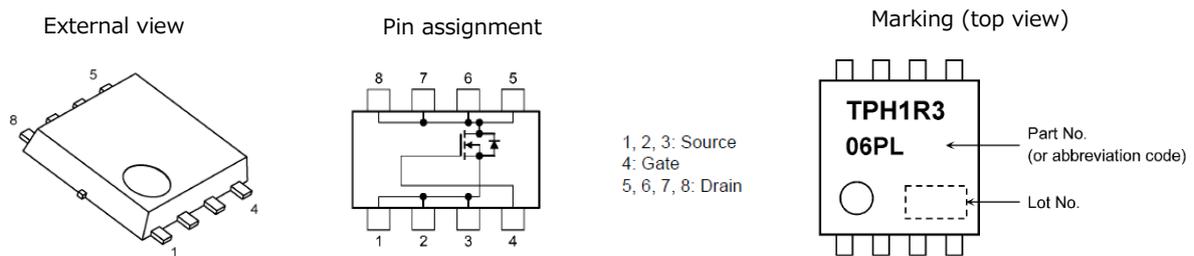


Figure 4.2 External view and marking of the TPH1R306PL

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