



Basic Knowledge of Discrete Semiconductor Device

Chapter V

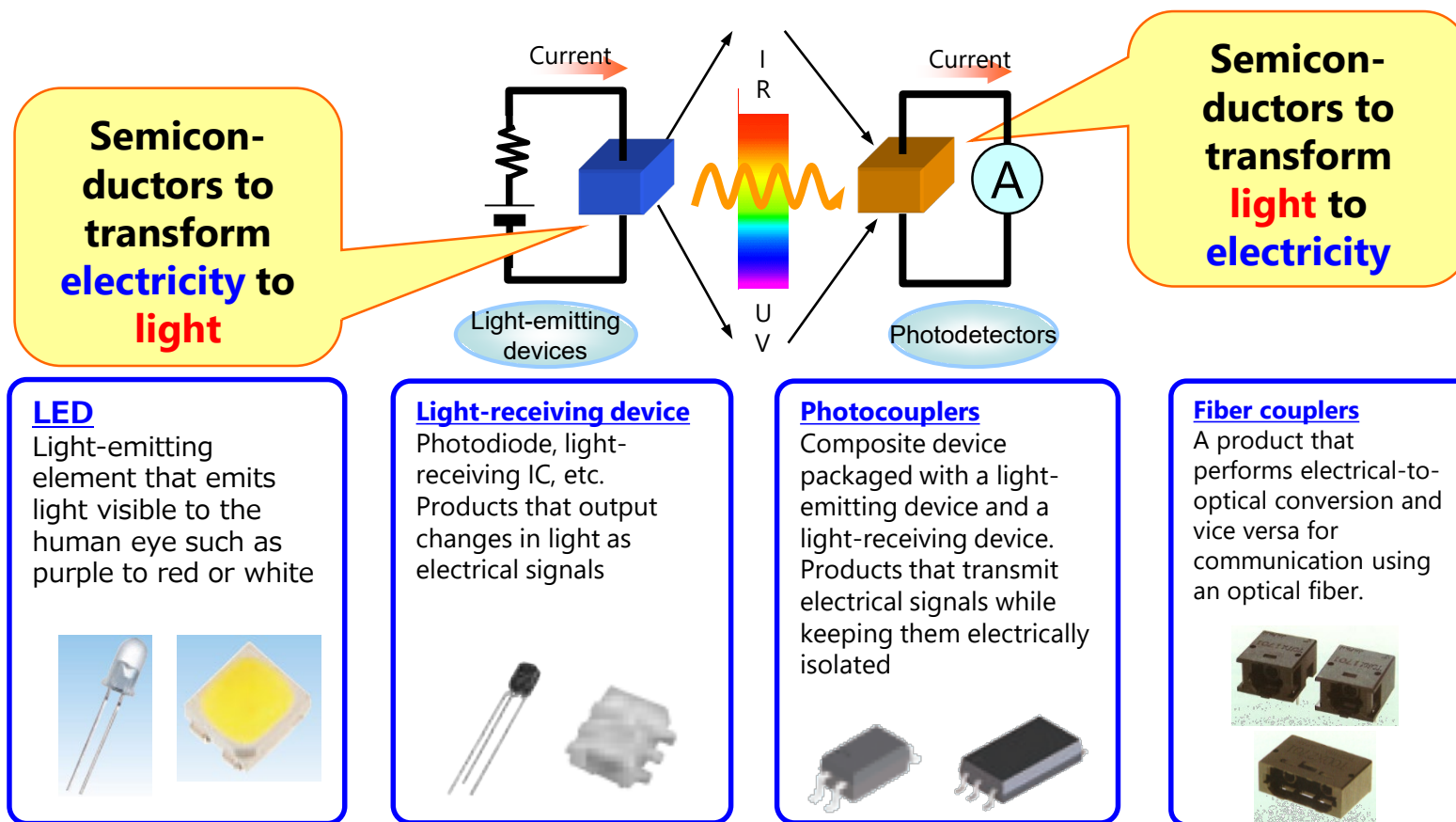
Optical Semiconductors
Isolators/Solid State Relays

February 2022
Toshiba Electronic Devices & Storage Corporation

Types of Optical Semiconductors

The types of optical semiconductors are as follows:

1. Light-emitting device ··· visible-light LED, infrared LED, ultraviolet LED, laser diode
2. Light-receiving device ··· photosensor, solar cell, CMOS sensor
3. Composite device (combination of light-emitting element and light-receiving element alignment) ··· photocoupler, fiber coupler

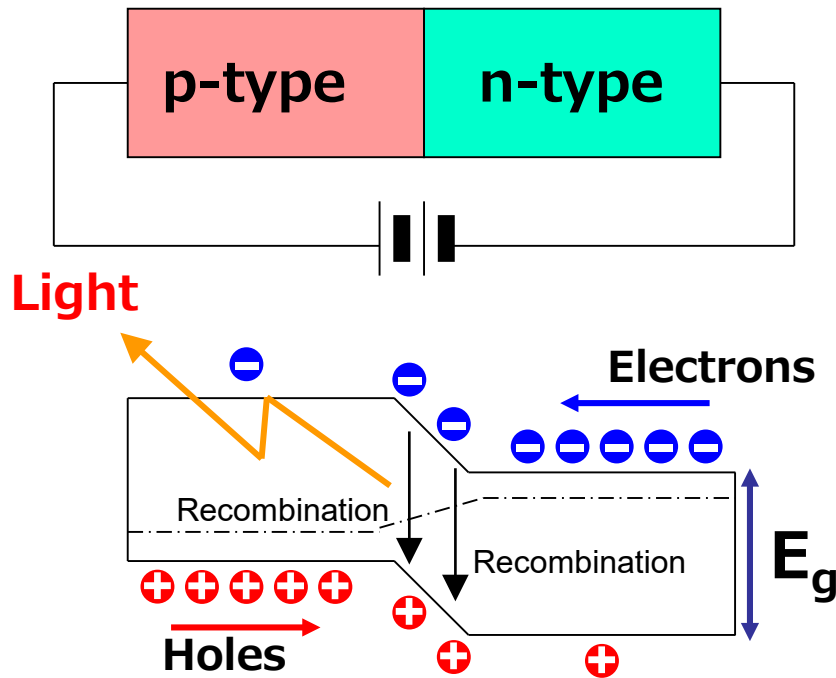


Light-Emitting Principal of LEDs

A light-emitting diode (LED) emits light by applying a forward current to the pn junction of a compound semiconductor.

When forward current is passed through the light-emitting diode, carriers (electrons and holes) move. The holes in the p-type region move to the n-type region and the electrons in the n-type region move to the p-type region. The injected carriers recombine, and the energy difference before and after recombination is released as light. The emitted light depends on the energy band gap (E_g) of the compound semiconductor.

(Remark: Conventional Si diodes do not emit light because the recombination energy becomes thermal energy.)

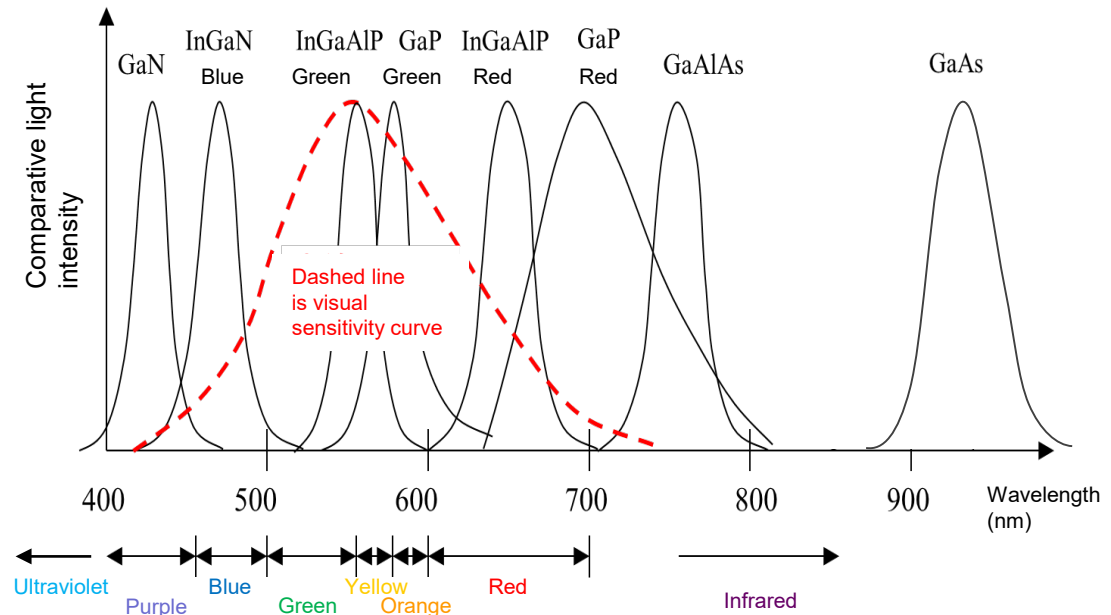


The wavelength range of LEDs

The LED emits ultraviolet light to infrared light with various wavelengths. This emission wavelength is expressed by the following equation using the energy band gap (E_g) of compound semiconductor material.

$$\lambda \text{ (nm)} = 1240/E_g \text{ (eV)}$$

Larger E_g materials emit shorter wavelengths, and materials with smaller E_g emit longer wavelengths. For infrared LEDs used in television remote controls etc., GaAs (gallium arsenide) is the material used; for red/green indicator LEDs, GaP or InGaAlP is used; and for blue LED, InGaN or GaN is used.



Material	Energy Band gap E_g @300K (eV)	Wavelength(λ)	Color
GaAs	1.4	885 nm	Infrared
GaP	1.8 to 2.26	549 to 700 nm	Green to red
InGaAlP	1.9 to 2.3	539 to 653 nm	Green to red
InGaN	2.1 to 3.2	388 to 590 nm	Ultraviolet to green
GaN	3.4	365 nm	Ultraviolet to blue

What Is a Photocoupler?

Photocoupler:

A photocoupler is a device incorporating a light-emitting diode (LED) and a photodetector in one package. Unlike other optical devices, light is not emitted outside the package. The external appearance is similar to that of non-optical semiconductor devices. Although a photocoupler is an optical device, it does not handle light, but handles electrical signals.

Examples of a photocoupler's operation:

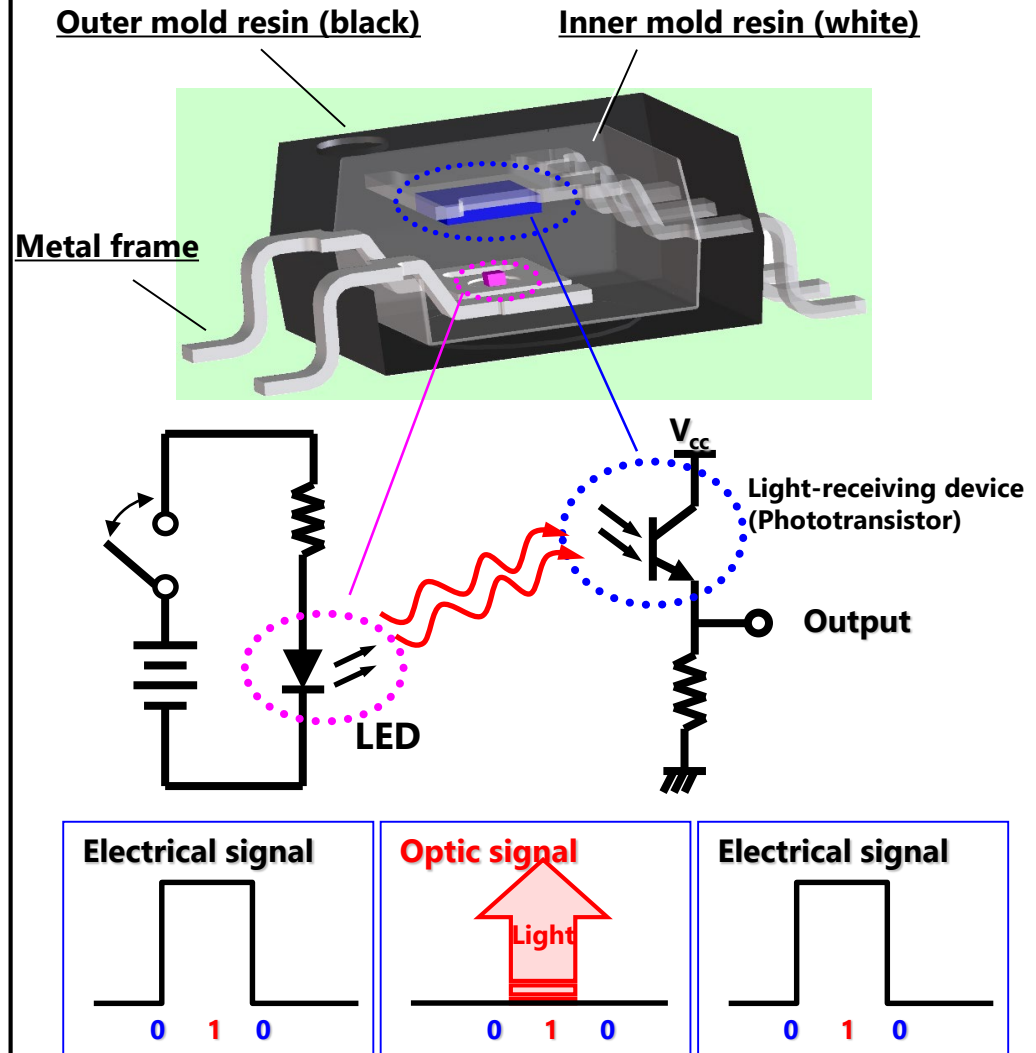
- (1) The LED turns on ($0 \Rightarrow 1$).
- (2) The LED light enters the phototransistor.
- (3) The phototransistor turns on.
- (4) Output voltage changes $0 \Rightarrow 1$.

(1) The LED turns off ($1 \Rightarrow 0$).

(2) The LED stops light emission to the phototransistor.

- (3) The phototransistor turns off.
- (4) Output voltage changes $1 \Rightarrow 0$.

*The cutaway image on the right shows a transistor-output photocoupler of the transmissive type in a double-mold structure.

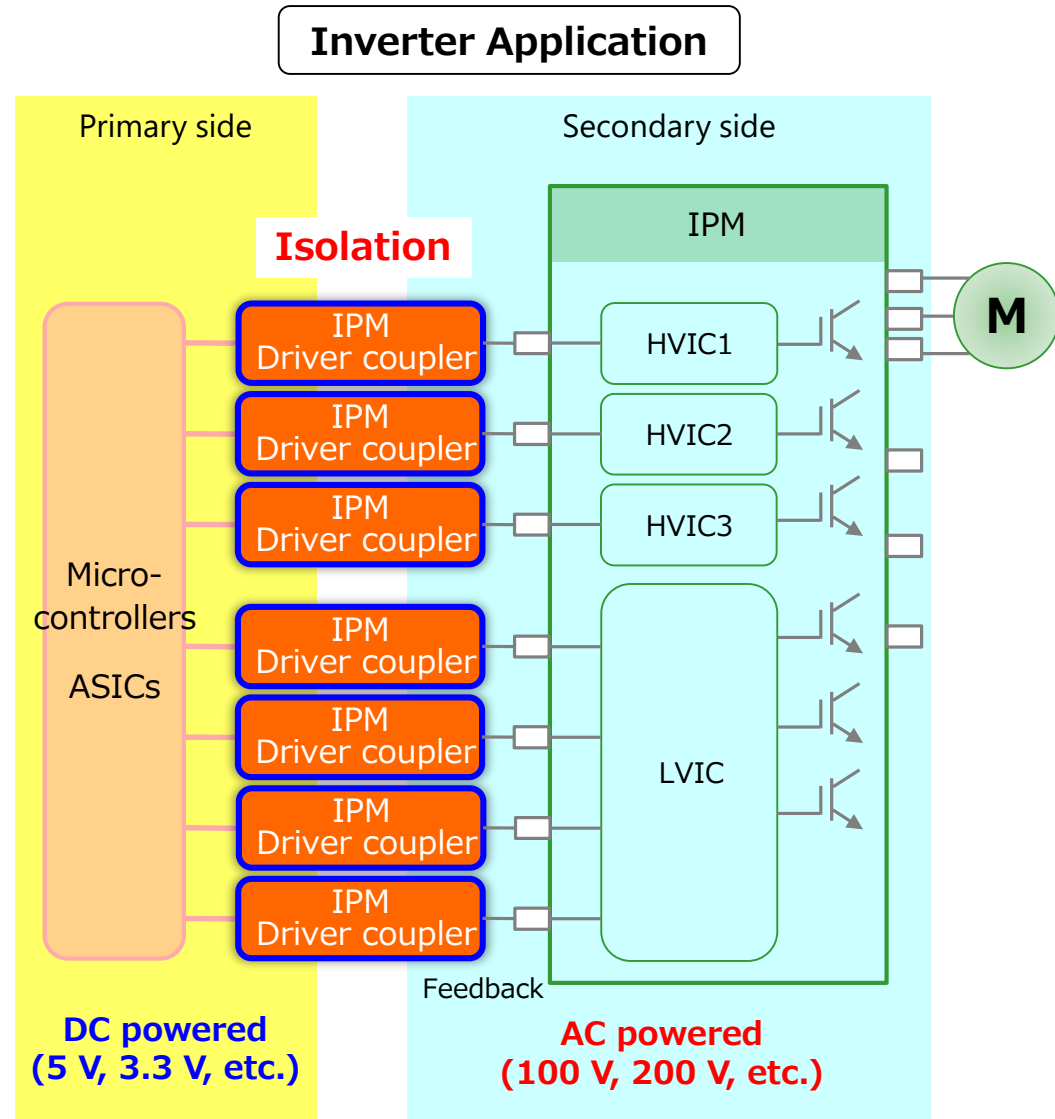


Why Are Photocouplers Necessary?

In the photocoupler, the primary side (LED side) and the secondary side (light-receiving-device side) are electrically insulated. Therefore, even if the potentials on the primary side and the secondary side (even GND potential) are different, the primary side electrical signal can be transmitted to the secondary side.

In the inverter application shown in the figure on the right, a controlling unit such as a microcontroller operates usually at low DC voltage. On the other hand, IPMs and IGBTs drive loads that need high voltage such as 200 V AC. High-voltage system parts can be controlled directly from the microcomputer via a coupler.

*Various output types of photocouplers are prepared according to your needs.



Types of Photocouplers

An LED is used for input of the photocoupler. On the other hand, various devices are used for output.

Transistor output

A phototransistor is a detector. Darlington type is also available.

IC output

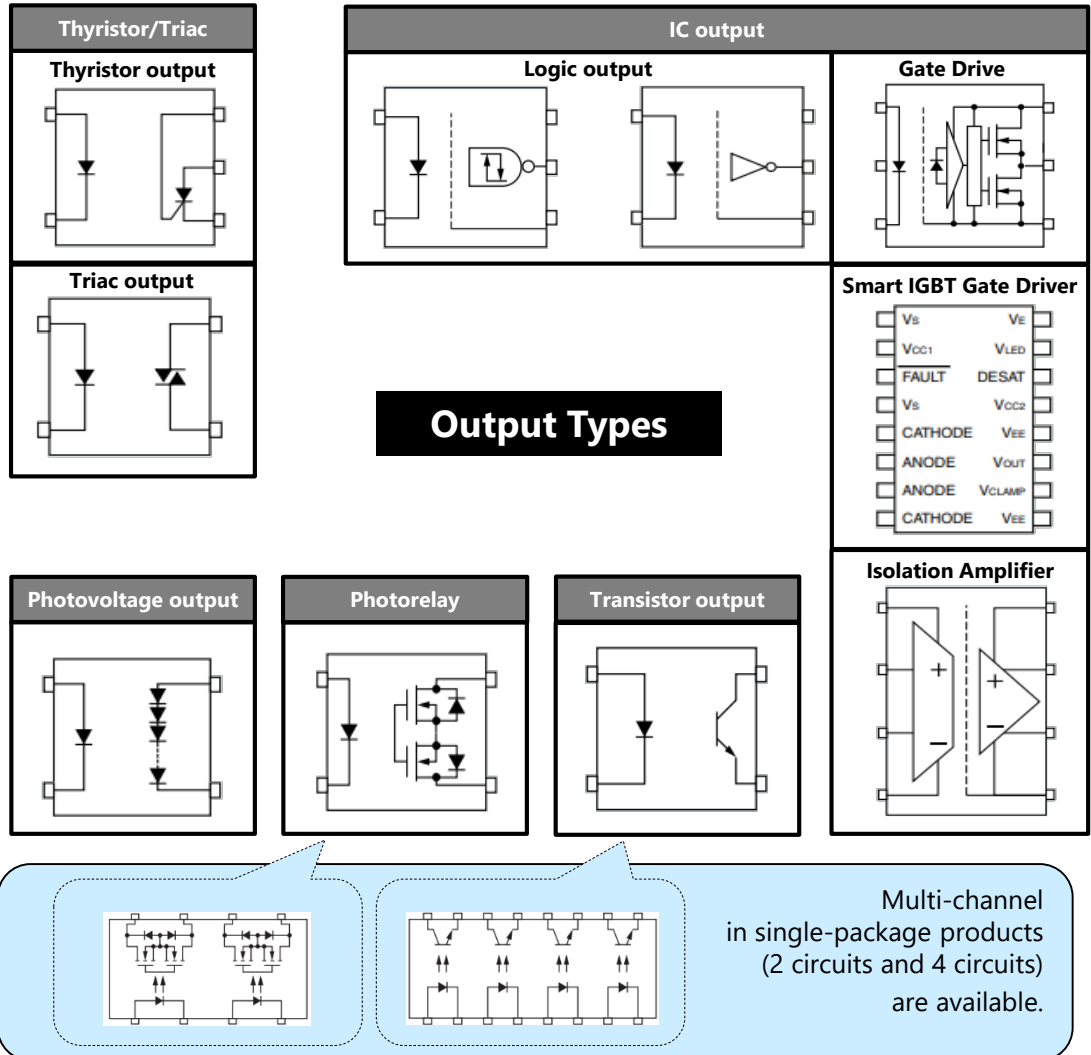
There are products using photodiodes as light-receiving devices, output products such as logic, products with high-current output for gate-drive driving of IGBT and MOSFET, and high-function products such as isolation amplifiers.

Triac/Thyristor output

A photothyristor or a phototriac is used for output. They are mainly used for control of AC line.

Photorelay (MOSFET output)

The photovoltaic array (photodiode array) drives the gate of the MOSFET to turn the output ON/OFF. By this operation, it can be used as a relay switch of MOSFET output.



Multi-channel
in single-package products
(2 circuits and 4 circuits)
are available.

Types of Photocouplers (Packages)

Photocouplers are required to have a package shape and dielectric strength based on safety standards. When designing in accordance with safety standards, you need to check the following items.

Creepage distance of isolation

The shortest distance along the surface of the insulator between two conductors (primary and secondary).

Clearance

The shortest distance between two conductors measured through air.

Insulation thickness

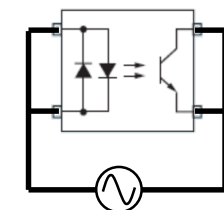
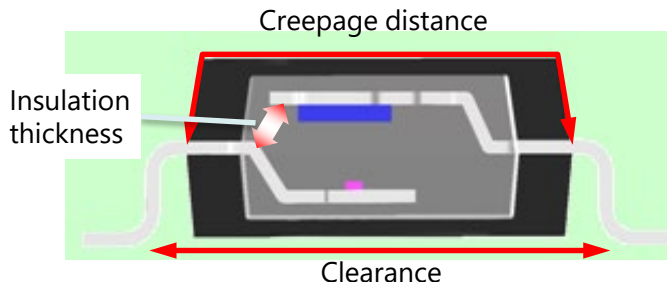
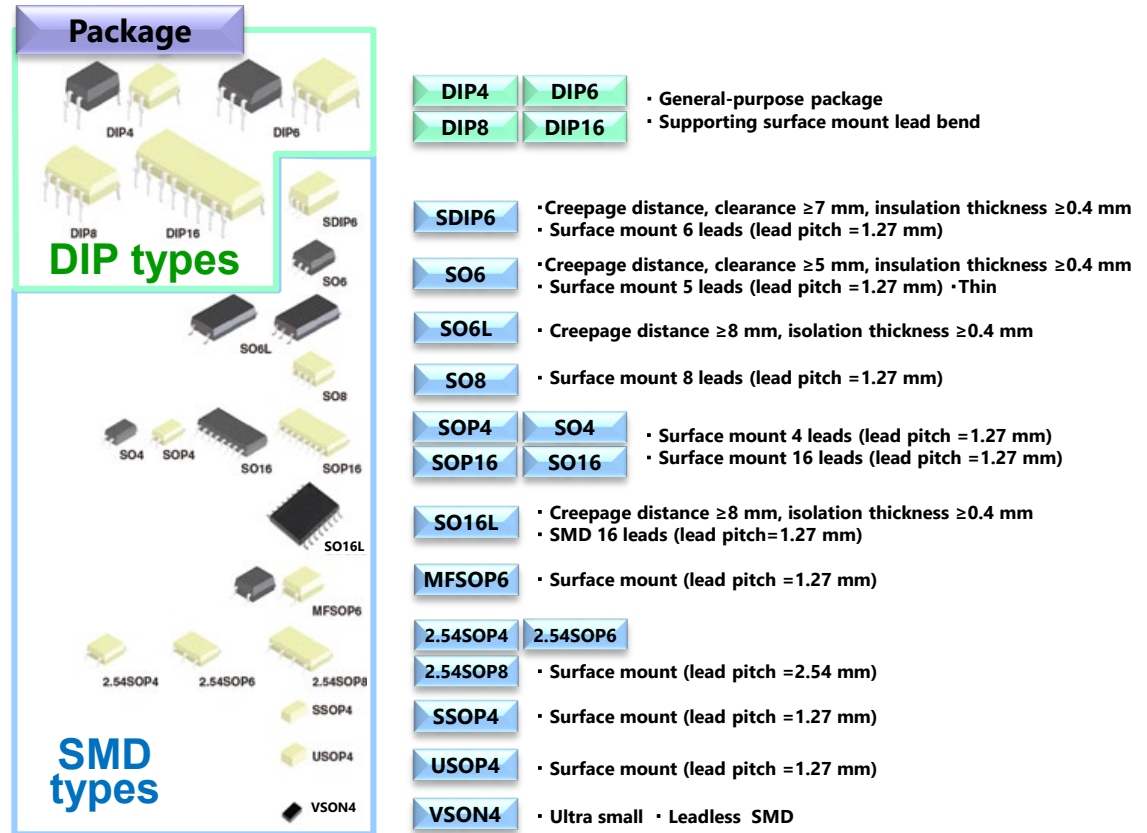
The minimum distance of insulator between two conductors

Isolation voltage

Isolation voltage between two conductors *

In the case of UL, the AC voltage that does not break the insulation even if it is applied for 1 minute is specified.

* Products with isolation voltage ranging from 2,500 Vrms to 5,000 Vrms are mainstream.



Types of Photocouplers (Internal Structure)

Photocouplers have various types of internal package structure because of various restrictions such as required insulation performance, package size, and size of internal chip.

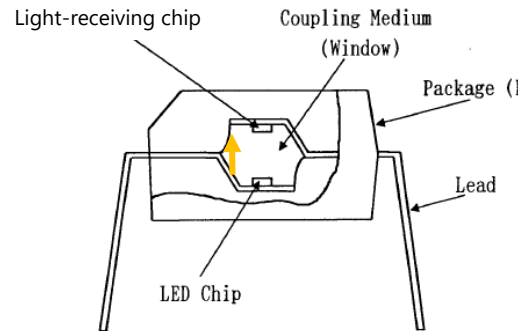
Transmissive type in single mold: Frame-mounted LED and frame-mounted photodetector face each other in the same molded package. Silicon resin is used for the optical transmission part between LED and photodetector.

Transmissive type in single mold with film: To raise isolation voltage, polyimide film is inserted between LED and photodetector.

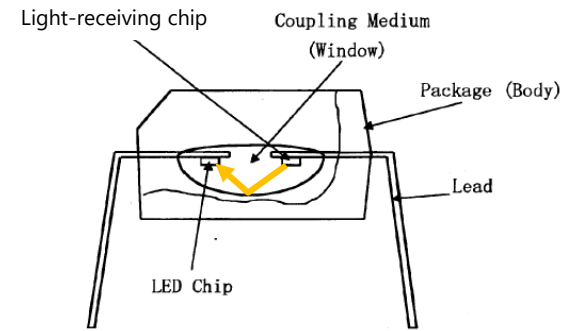
Transmissive type in double mold: In this transmissive structure, inner mold is white, and outer mold is black. Resin with high infrared light transmittance is used for white mold of the optical transmission part.

Reflective type: Frame-mounted LED and frame-mounted photodetector are on the same plane. LED light reflected in silicon resin reaches the photodetector. Thus, it is called reflective type.

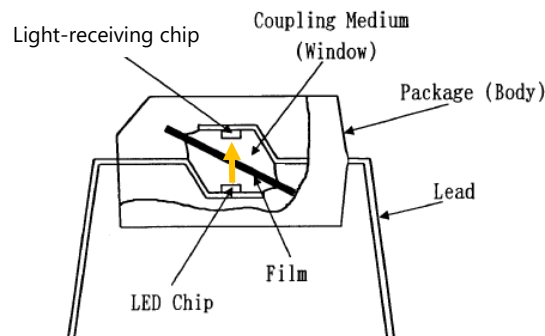
Transmissive type in single mold



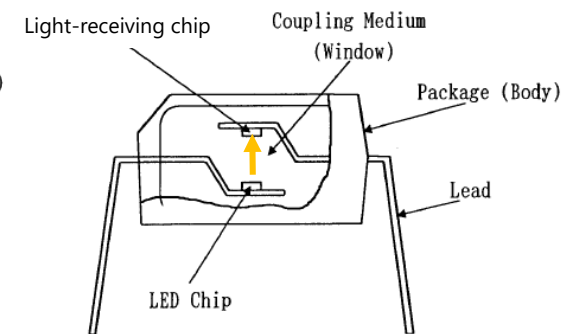
Reflective type



Transmissive type in single mold with film



Transmissive type in double mold



Safety Standards of Photocouplers

When mounted in electrical equipment as a means of isolation to protect the human body from electric shock, **photocouplers may be subject to various regulations in terms of safety standards.**

Various regulations and standards for ensuring safety exist.

From the perspectives of design and manufacturing, safety standards can be categorized into "Equipment standards" and "Component standards".

"Equipment standards" are the basis for designing and manufacturing equipment. Equipment standards differ according to equipment type, isolation method and its class, driving voltage, etc.

"Component standards" specify measurement methods or specifications of the isolation voltage etc. for photocouplers.

Major safety standards

Component standards

UL 1577

→ **Safety standard for optical isolators**

isolation voltage-withstand test (1 min), etc.

Certification body: **UL** (USA)

EN IEC 60747-5-5

→ **Standard for Optoelectronic devices – Photocouplers**

maximum operating isolation voltage, maximum transient isolation voltage, partial discharge test, etc.

Certification body : **VDE** (Germany)、**TUV** (Germany)

Equipment standards

EN IEC 62368-1

→ **Standard for Audio/Video, Information and Communication Technology Equipment**

Certification body: **VDE** (Germany), **SEMKO** (Sweden), etc.)

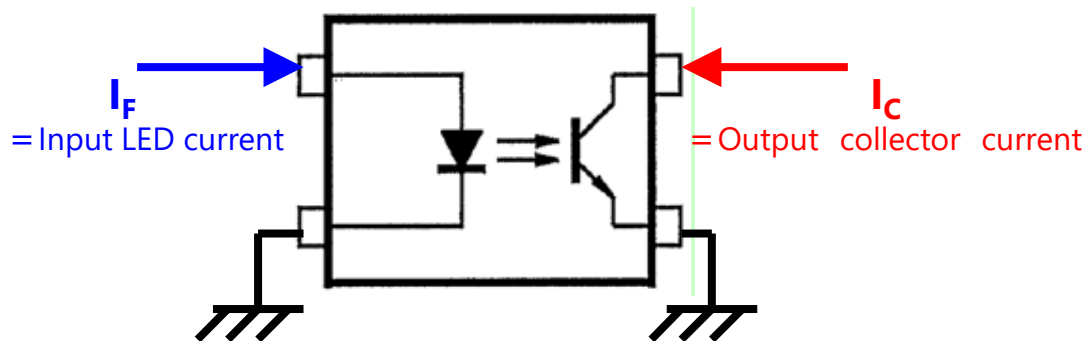


Characteristics of Photocouplers (Current Transfer Ratio: CTR)

Current transfer ratio of transistor coupler: It is expressed by the amplification ratio of the output current with respect to the input current like the transistor h_{FE} .

Current Transfer Ratio=CTR

$$= I_C / I_F = \text{Output (collector) current} / \text{input current} \times 100 (\%)$$



Reference: h_{FE} of bipolar transistor

h_{FE} (DC current gain)
= Collector current (I_C)/base current (I_B)

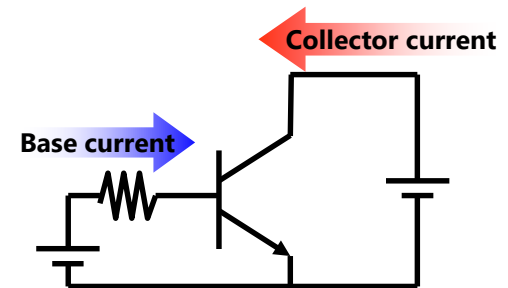
E.g.)

When $I_F = 5 \text{ mA}$ is input, $I_C = 10 \text{ mA}$ is obtained.

$$\text{CTR} = I_C / I_F = 10 \text{ mA} / 5 \text{ mA} \times 100 (\%) = 200\%$$

Coupled Electrical Characteristics (Unless otherwise specified, $T_a = 25^\circ\text{C}$)

CHARACTERISTIC	SYMBOL	TEST CONDITION	MIN	TYP.	MAX	UNIT
Current transfer ratio	I_C / I_F	$I_F = 5 \text{ mA}, V_{CE} = 5 \text{ V}$ Rank GB	50	-	600	%
			100	-	600	



Principal Characteristics of Photocouplers (Trigger LED Current)

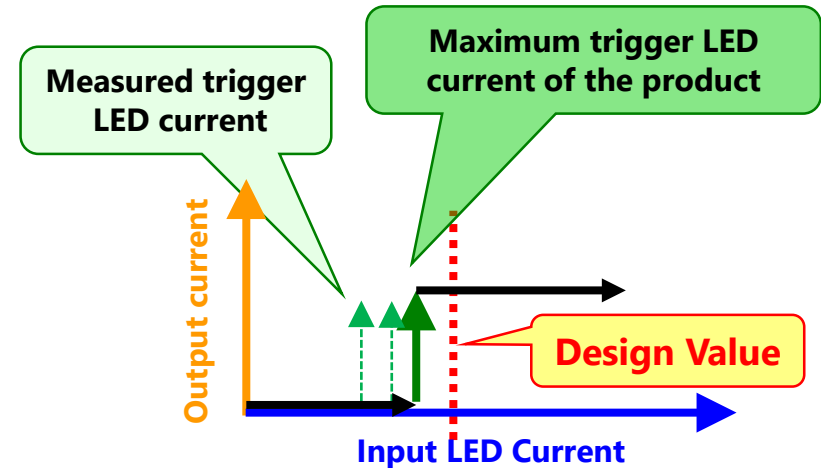
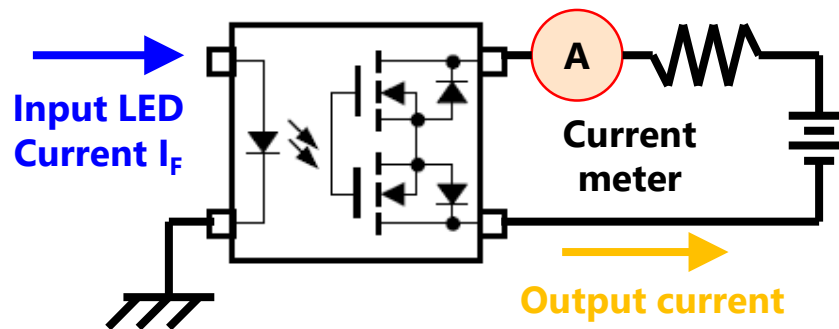
Trigger LED current

Trigger LED current is specified for products that perform binary operation of output ON/OFF such as IC coupler of logic output, photorelay, and triac output coupler.

“Trigger LED current” means “LED current that triggers change in the status”.

I_{FT} , I_{FLH} , I_{FHL} , etc., are used as symbols.

The trigger LED current indicated in the datasheet is the value specified by the product. For stable operation, the designer must design so that at least the trigger LED current (maximum) flows.



The input LED current I_F is gradually increased from 0 mA,

If the output shifts to the on state at 1 mA, $I_{FT} = 1$ mA.

In the following data sheet, the I_F required to shift the output to the ON state

It means that the maximum value is 3 mA.

Characteristics	Symbol	Note	Test Condition	Min	Typ.	Max	Unit
Trigger LED current	I_{FT}		$I_{ON} = 1.4$ A	—	1	3	mA

Trigger LED current is an important item for circuit design and lifetime design.

Aging Variation Data of Photocouplers

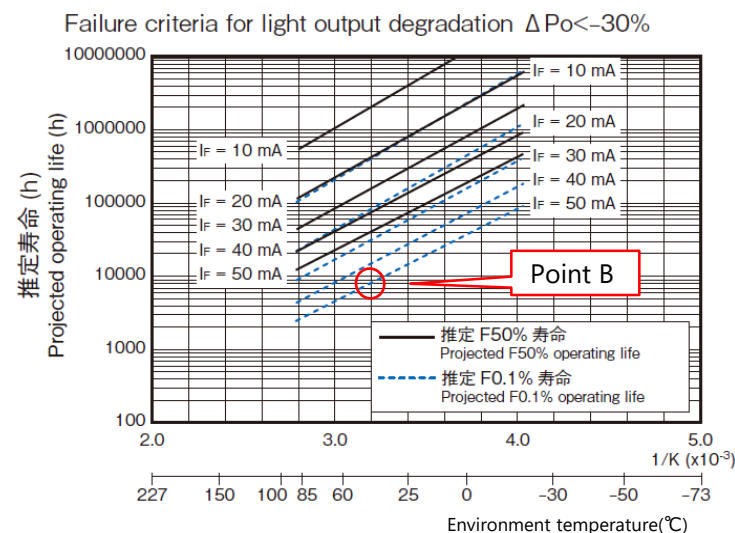
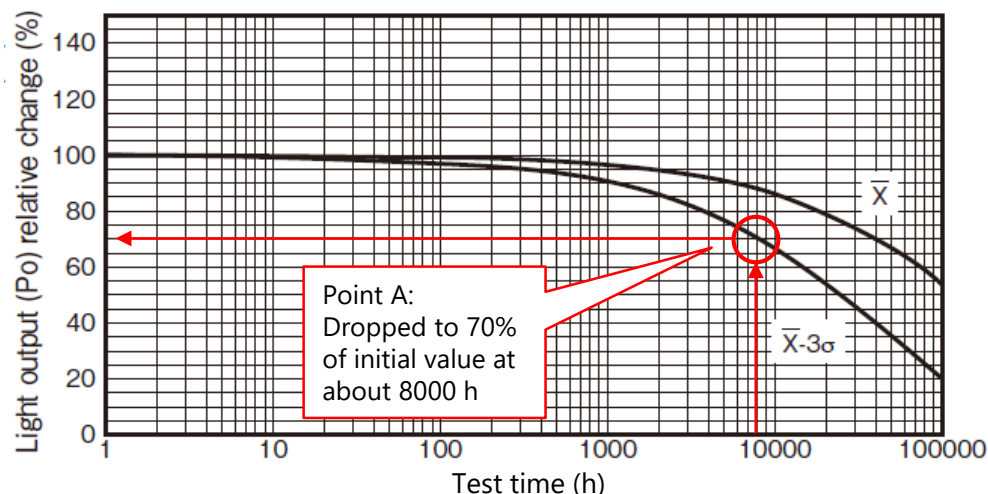
Aging variation data of photocouplers

The optical output of the light-emitting element (LED) decreases with the passage of time. In photocouplers, aging variation of optical output of LED is more dominant than that of optical receiving devices. Therefore, the designer needs to estimate the decrease in the light emission level using the data of aging variation of the adopted photocoupler. The designer calculates the light output change of the LED from the usage environment of the equipment to be used and the total operating time of the LED. It is necessary to reflect this value in the initial value of forward current (I_F) of the LED.

* For example, when duty (time duration of light emission) is 50% and working hours are 1,000 h, total operating time is calculated to be 500 hours.

Example of aging variation of optical output of GaAs

Test conditions: $I_F = 50 \text{ mA}$, $T_a = 40^\circ\text{C}$



The left-hand figure shows aging variation data of LED optical output.

The right-hand figure shows the operating time when LED optical output drops below a certain criterion.

For example, point A in the left-hand figure and point B in the right-hand figure show aging variation under the same conditions. ($I_F = 50 \text{ mA}$, $T_a = 40^\circ\text{C}$, 8000 h).

How to Use a Photocoupler

Design example of signal interface using phototransistor coupler

The figure below shows an example of an interface circuit that converts a 5 V signal into a 10 V signal using a phototransistor coupler.

How should we design the resistor R_{IN} on the LED input side and the resistor R_L on the phototransistor output side?

And how should we select CTR of the phototransistor coupler?

We will explain from the next page with the following steps.

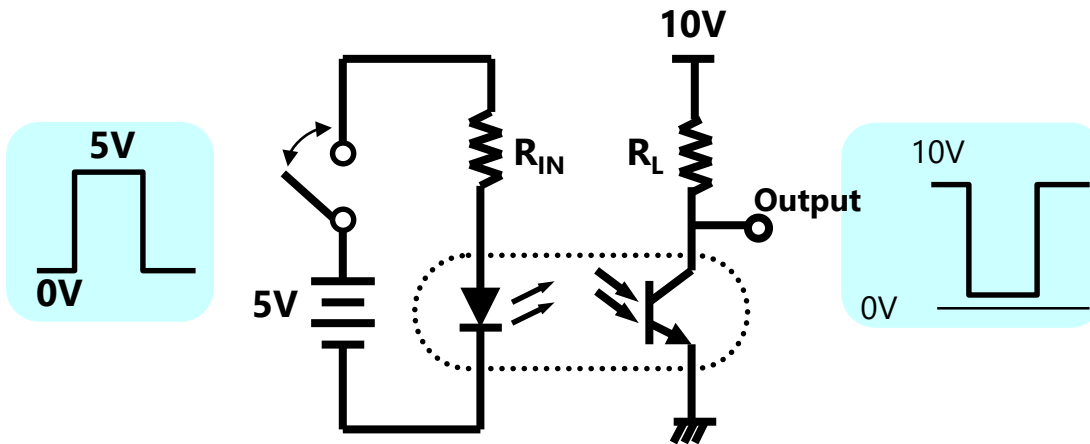
Step 1. Design of LED input-current I_F and input-side resistor R_{IN}

Step 2. Calculate output current from I_F and CTR

Step 3. Design of output-side resistor R_L

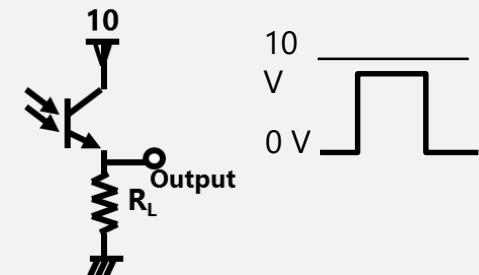
Step 4. Check each designed constant

Interface circuit of DC5V and DC10V



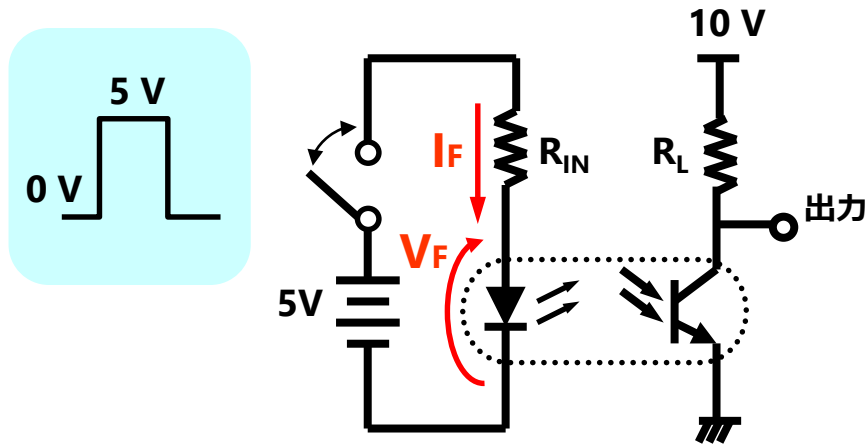
Note:

In the left figure, the output signal is inverted, but if the output is an emitter follower as shown below, it is possible to obtain the same positive phase output as the input.

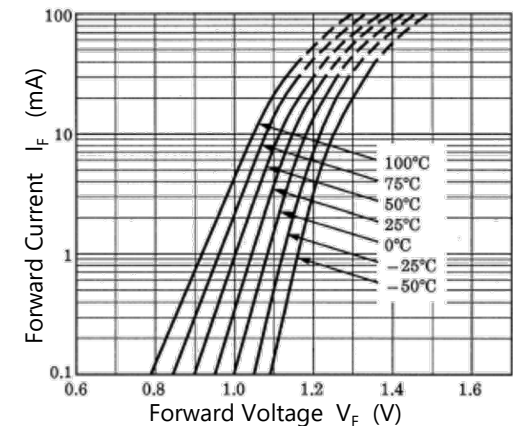


How to Use a Photocoupler “Input Current”

Step 1. Design LED input current and input resistor R_{IN} .



Forward voltage characteristic
 I_F - V_F characteristic changes according to temperature.
 Designers have to take temperature range into consideration.



What is the input current (I_F) of the photocoupler?

It is determined by (1) input power supply voltage (5 V), (2) current limiting resistor (R_{IN}), and (3) forward voltage (V_F) of LED.

From the specification example, determine the current limiting resistor and the input current (I_F).

$$R_{IN} = (V_{CC} - V_F) / I_F = (5 \text{ V} - 1.3 \text{ V}) / 10 \text{ mA} = 370 \Omega$$

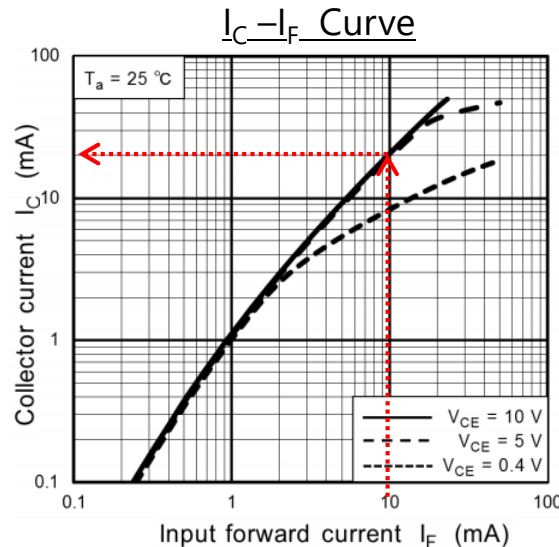
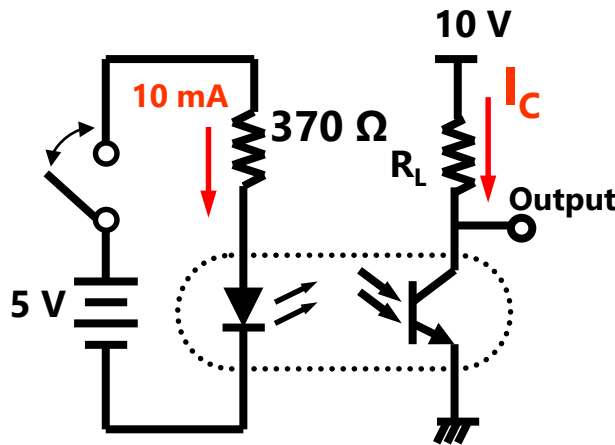
(Specification example)

Forward voltage	V_F	$I_F = 10 \text{ mA}$	1.0	1.15	1.3	V
-----------------	-------	-----------------------	-----	------	-----	---

How to Use a Photocoupler “Output Current”

Step 2. Calculate output current of the phototransistor from I_F and CTR.

Current transfer ratio (CTR) rank
Transistor photocouplers are classified by CTR.



Classification (Note1)	Current Transfer Ratio (%) (I_C / I_F)	
	$I_F = 5 \text{ mA}, V_{CE} = 5 \text{ V}, T_a = 25^\circ\text{C}$	
	Min	Max
Blank	50	600
Rank Y	50	150
Rank GR	100	300
Rank GB	100	600
Rank BL	200	600
Rank YH	75	150
Rank GRL	100	200
Rank GRH	150	300
Rank BLL	200	400

What is the value of the photocoupler's output current (I_C)?

Calculate the variation of the output current (I_C) at the input current (I_F) = 10 mA from the current transfer ratio ($\text{CTR} = I_C / I_F$). From the $I_C - I_F$ curve, you can see that $I_C = 10 \text{ mA}$ (@ $I_F = 5 \text{ mA}$, $V_{CE} = 5 \text{ V}$, $T_a = 25^\circ\text{C}$). So the CTR of this sample is 200%, which is the same value of minimum BL rank (200% to 600%). Also you can see that $I_C = 20 \text{ mA}$ (@ $I_F = 10 \text{ mA}$, $V_{CE} = 5 \text{ V}$, $T_a = 25^\circ\text{C}$).

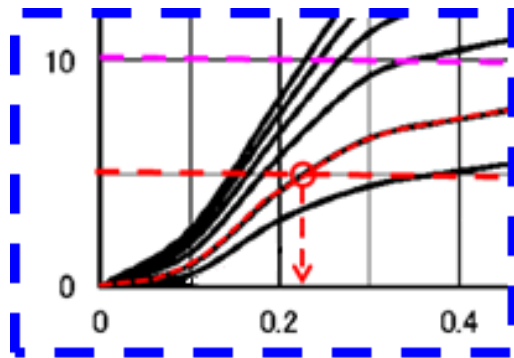
Next, we derive R_L using the value of I_C obtained here. In this calculation, design the value of R_L so that V_{CE} becomes saturation voltage even at the minimum value of I_C .

How to Use a Photocoupler "Output-Side Resistor"

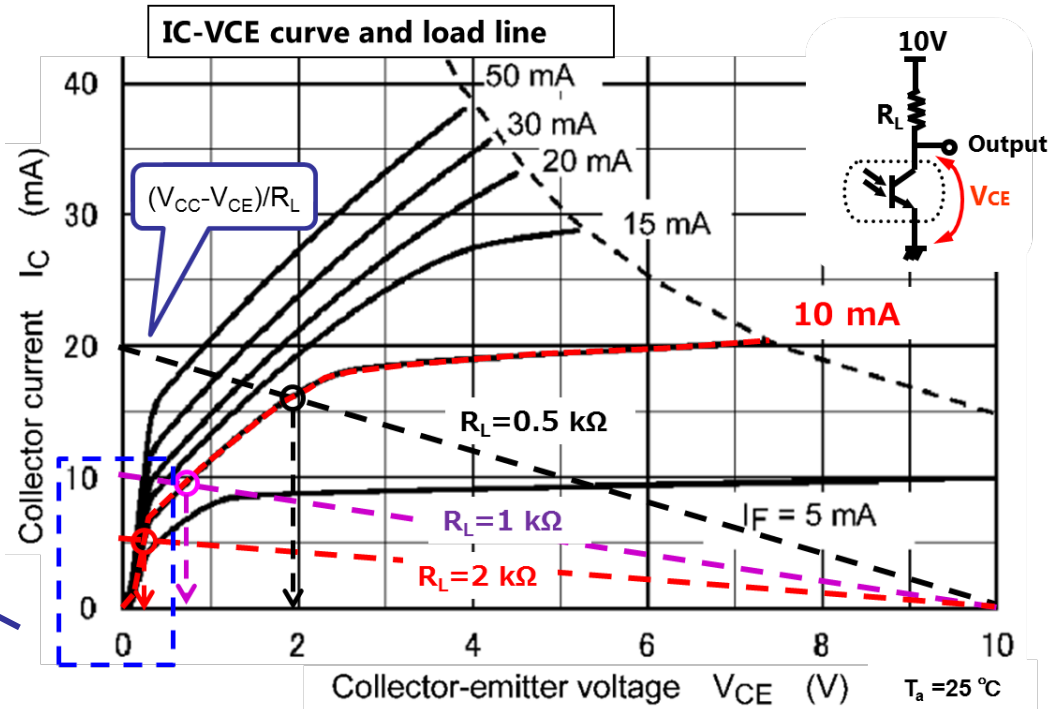
Step 3. Design output-side resistor R_L

Determine R_L from the I_C - V_{CE} characteristics of the output transistor. In order to use for signal transmission, it is necessary to fully satisfy the "L" level of the device connected to the load side. Here, we set $V_{CE} = 0.3$ V as the target value.

When $I_F = 10$ mA, $V_{CE} = 0.9$ V at $R_L = 1$ k Ω , which is insufficient. At $R_L = 2$ k Ω , $V_{CE} =$ about 0.2 V, which satisfies the target value. Therefore, choose $R_L = 2$ k Ω . In actual design, the impedance on the load side must also be considered.



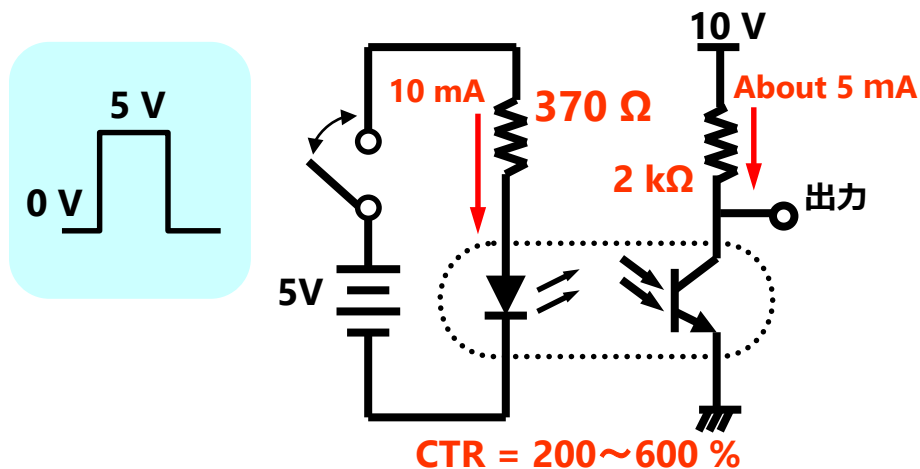
Enlarged view



How to Use a Photocoupler Check

Step 4. Check each constant.

Consider whether there is sufficient margin for operating temperature, speed, lifetime design, tolerance of resistor, etc.



Temperature range $\Rightarrow V_F$, CTR, allowable current, etc.

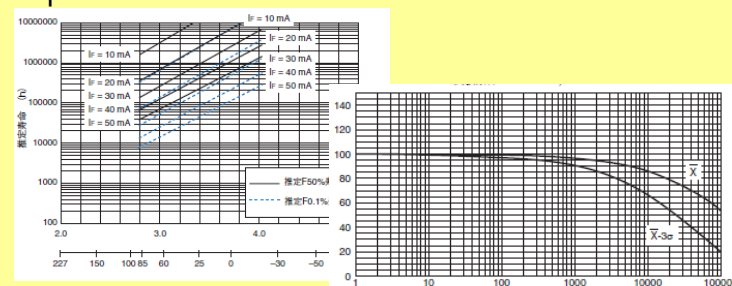
Load resistance \Rightarrow switching speed, influence of dark current, etc.

Confirmation of lifetime of the set

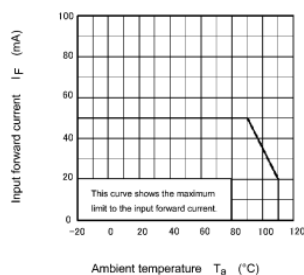
The optical output of the input LED of photocoupler decreases with the passage of time.

It is necessary to confirm that the characteristics are satisfied, for which purpose this deterioration during the lifetime target of the set must be included.

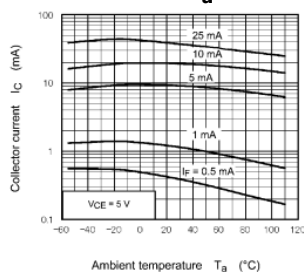
The aging variation of the optical coupler can be calculated from input current (I_F) and ambient temperature.



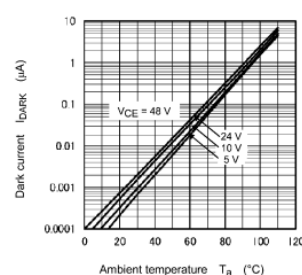
Allowable current



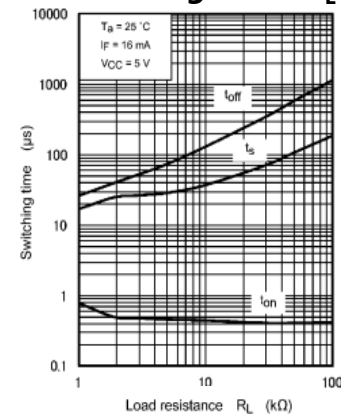
CTR- T_a



Dark current



Switching time - R_L



RESTRICTIONS ON PRODUCT USE

Toshiba Corporation and its subsidiaries and affiliates are collectively referred to as "TOSHIBA". Hardware, software and systems described in this document are collectively referred to as "Product".

- TOSHIBA reserves the right to make changes to the information in this document and related Product without notice.

- This document and any information herein may not be reproduced without prior written permission from TOSHIBA. Even with TOSHIBA's written permission, reproduction is permissible only if reproduction is without alteration/omission.

- Though TOSHIBA works continually to improve Product's quality and reliability, Product can malfunction or fail. Customers are responsible for complying with safety standards and for providing adequate designs and safeguards for their hardware, software and systems which minimize risk and avoid situations in which a malfunction or failure of Product could cause loss of human life, bodily injury or damage to property, including data loss or corruption. Before customers use the Product, create designs including the Product, or incorporate the Product into their own applications, customers must also refer to and comply with (a) the latest versions of all relevant TOSHIBA information, including without limitation, this document, the specifications, the data sheets and application notes for Product and the precautions and conditions set forth in the "TOSHIBA Semiconductor Reliability Handbook" and (b) the instructions for the application with which the Product will be used with or for. Customers are solely responsible for all aspects of their own product design or applications, including but not limited to (a) determining the appropriateness of the use of this Product in such design or applications; (b) evaluating and determining the applicability of any information contained in this document, or in charts, diagrams, programs, algorithms, sample application circuits, or any other referenced documents; and (c) validating all operating parameters for such designs and applications. **TOSHIBA ASSUMES NO LIABILITY FOR CUSTOMERS' PRODUCT DESIGN OR APPLICATIONS.**

- PRODUCT IS NEITHER INTENDED NOR WARRANTED FOR USE IN EQUIPMENTS OR SYSTEMS THAT REQUIRE EXTRAORDINARILY HIGH LEVELS OF QUALITY AND/OR RELIABILITY, AND/OR A MALFUNCTION OR FAILURE OF WHICH MAY CAUSE LOSS OF HUMAN LIFE, BODILY INJURY, SERIOUS PROPERTY DAMAGE AND/OR SERIOUS PUBLIC IMPACT ("UNINTENDED USE").** Except for specific applications as expressly stated in this document, Unintended Use includes, without limitation, equipment used in nuclear facilities, equipment used in the aerospace industry, lifesaving and/or life supporting medical equipment, equipment used for automobiles, trains, ships and other transportation, traffic signaling equipment, equipment used to control combustions or explosions, safety devices, elevators and escalators, and devices related to power plant. **IF YOU USE PRODUCT FOR UNINTENDED USE, TOSHIBA ASSUMES NO LIABILITY FOR PRODUCT.** For details, please contact your TOSHIBA sales representative or contact us via our website.

- Do not disassemble, analyze, reverse-engineer, alter, modify, translate or copy Product, whether in whole or in part.

- Product shall not be used for or incorporated into any products or systems whose manufacture, use, or sale is prohibited under any applicable laws or regulations.

- The information contained herein is presented only as guidance for Product use. No responsibility is assumed by TOSHIBA for any infringement of patents or any other intellectual property rights of third parties that may result from the use of Product. No license to any intellectual property right is granted by this document, whether express or implied, by estoppel or otherwise.

- ABSENT A WRITTEN SIGNED AGREEMENT, EXCEPT AS PROVIDED IN THE RELEVANT TERMS AND CONDITIONS OF SALE FOR PRODUCT, AND TO THE MAXIMUM EXTENT ALLOWABLE BY LAW, TOSHIBA (1) ASSUMES NO LIABILITY WHATSOEVER, INCLUDING WITHOUT LIMITATION, INDIRECT, CONSEQUENTIAL, SPECIAL, OR INCIDENTAL DAMAGES OR LOSS, INCLUDING WITHOUT LIMITATION, LOSS OF PROFITS, LOSS OF OPPORTUNITIES, BUSINESS INTERRUPTION AND LOSS OF DATA, AND (2) DISCLAIMS ANY AND ALL EXPRESS OR IMPLIED WARRANTIES AND CONDITIONS RELATED TO SALE, USE OF PRODUCT, OR INFORMATION, INCLUDING WARRANTIES OR CONDITIONS OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, ACCURACY OF INFORMATION, OR NONINFRINGEMENT.**

- Product may include products using GaAs (Gallium Arsenide). GaAs is harmful to humans if consumed or absorbed, whether in the form of dust or vapor. Handle with care and do not break, cut, crush, grind, dissolve chemically or otherwise expose GaAs in Product.

- Do not use or otherwise make available Product or related software or technology for any military purposes, including without limitation, for the design, development, use, stockpiling or manufacturing of nuclear, chemical, or biological weapons or missile technology products (mass destruction weapons). Product and related software and technology may be controlled under the applicable export laws and regulations including, without limitation, the Japanese Foreign Exchange and Foreign Trade Law and the U.S. Export Administration Regulations. Export and re-export of Product or related software or technology are strictly prohibited except in compliance with all applicable export laws and regulations.

- Please contact your TOSHIBA sales representative for details as to environmental matters such as the RoHS compatibility of Product. Please use Product in compliance with all applicable laws and regulations that regulate the inclusion or use of controlled substances, including without limitation, the EU RoHS Directive. **TOSHIBA ASSUMES NO LIABILITY FOR DAMAGES OR LOSSES OCCURRING AS A RESULT OF NONCOMPLIANCE WITH APPLICABLE LAWS AND REGULATIONS.**

TOSHIBA