TOSHIBA

Basic Knowledge of Discrete Semiconductor Device

Chapter V

Optical Semiconductors

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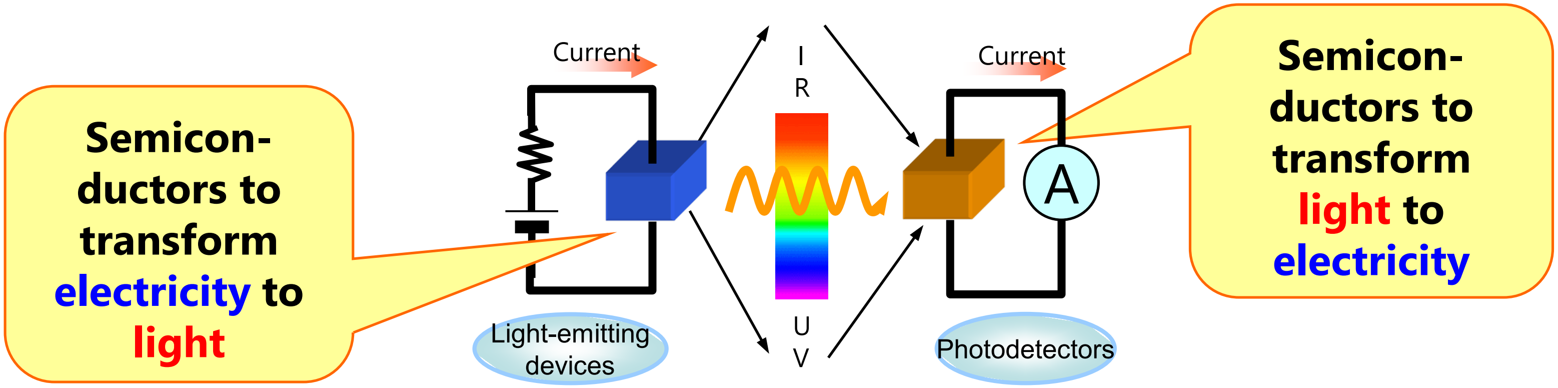
Toshiba Electronic Devices & Storage Corporation

Types of Optical Semiconductors

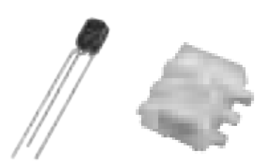
The types of optical semiconductors are as follows:

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

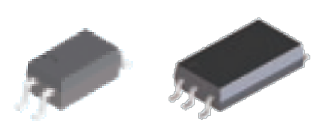


LED
Light-emitting element that emits light visible to the human eye such as purple to red or white

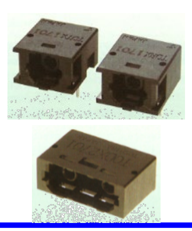
Light-receiving device
Photodiode, light-receiving IC, etc. Products that output changes in light as electrical signals



Photocouplers
Composite device packaged with a light-emitting device and a light-receiving device. Products that transmit electrical signals while keeping them electrically isolated



Fiber couplers
A product that performs electrical-to-optical conversion and vice versa for communication using an optical fiber.

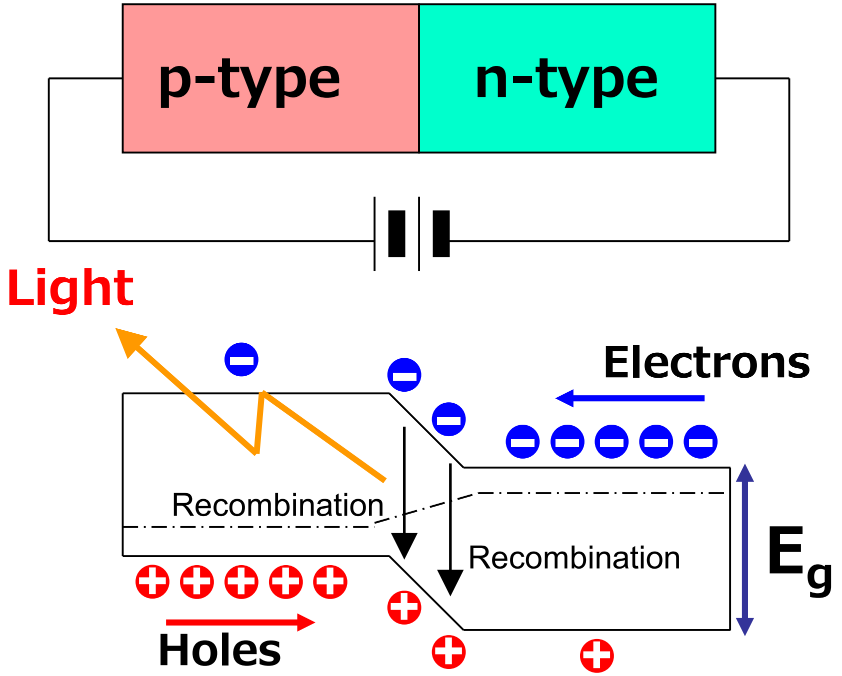


Light-Emitting Principal of LEDs

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 (Eg) of the compound semiconductor.

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

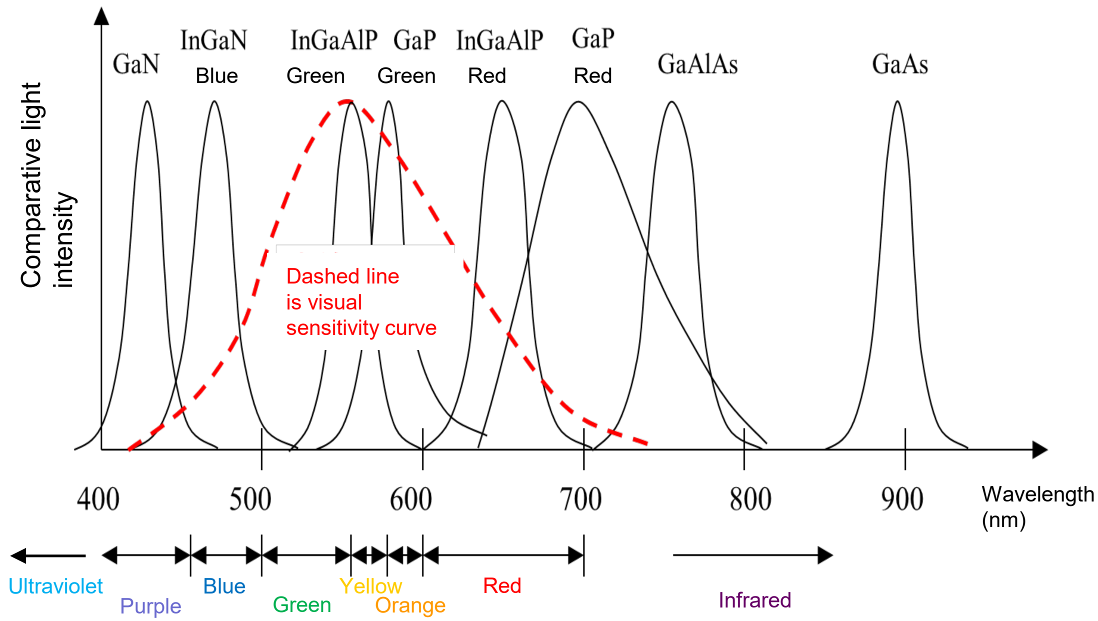


The wavelength range of LEDs

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 (Eg) of compound semiconductor material.

λ (nm) = 1240/Eg (eV)

Larger Eg materials emit shorter wavelengths, and materials with smaller Eg 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

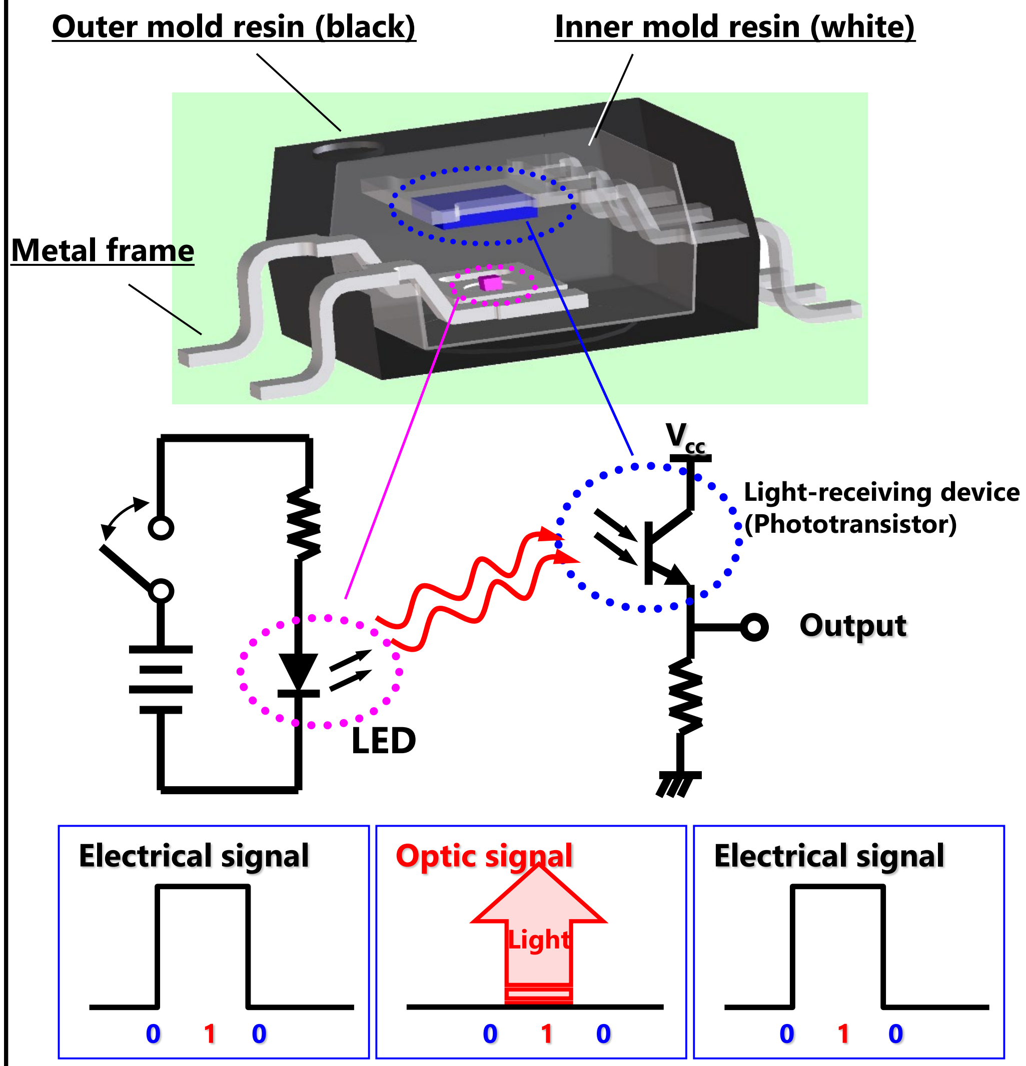
What Is a Photocoupler?

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 ⇒ 1).
(2) The LED light enters the phototransistor.
(3) The phototransistor turns on.
(4) Output voltage changes 0 ⇒ 1.

(1) The LED turns off (1 ⇒ 0).
(2) The LED stops light emission to the phototransistor.
(3) The phototransistor turns off.
(4) Output voltage changes 1 ⇒ 0.

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

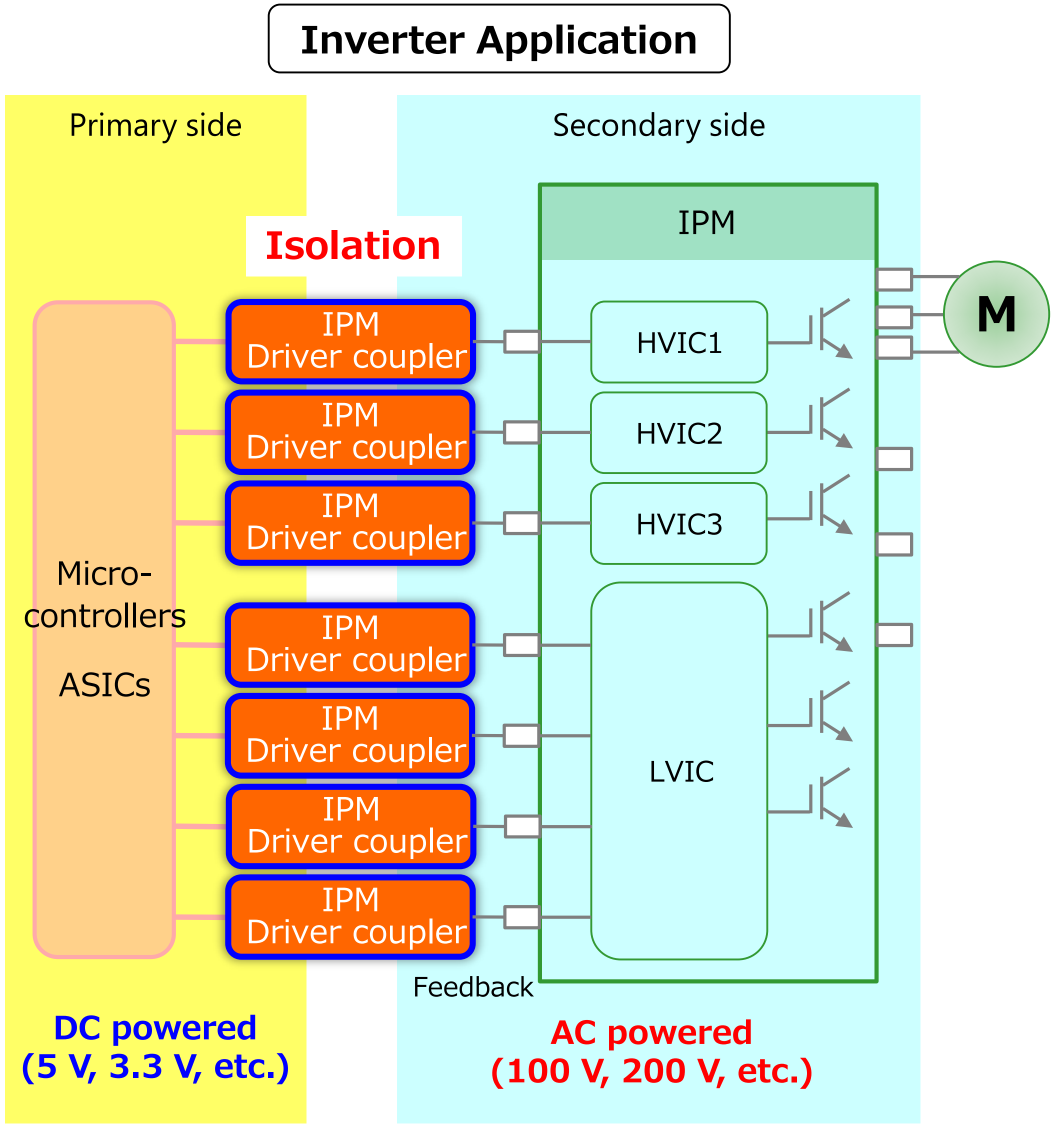


Why Are Photocouplers Necessary?

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

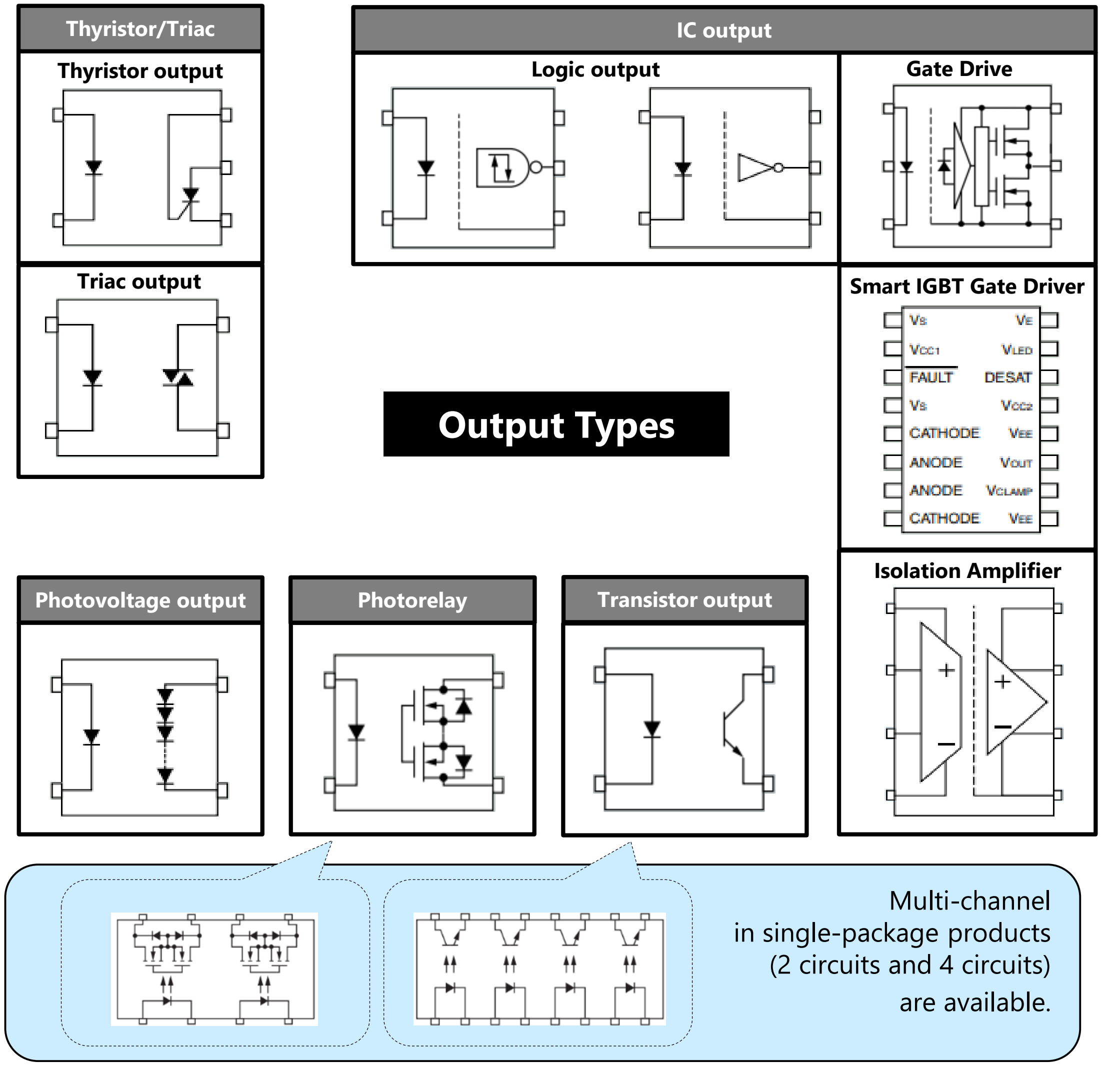
There are products using photodiodes as light-receiving devices, output products such as logic, products with high-current output for gate-drive driving of IGBT and MOSFET, and high-function products such as isolation amplifiers.

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.



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).

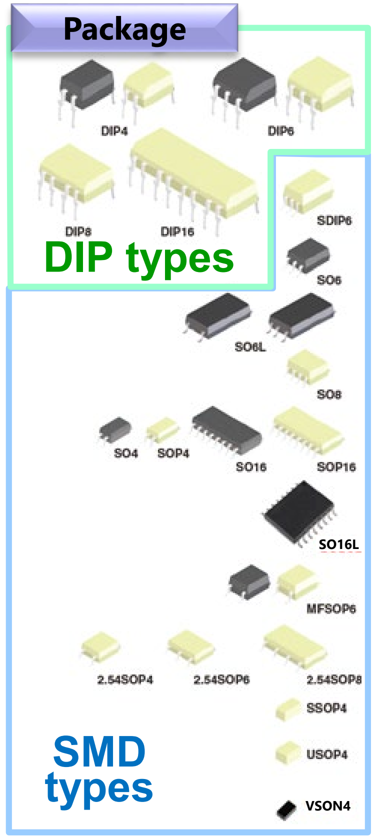
Clearance
The shortest distance between two conductors measured through air.

Insulation thickness
The minimum distance of insulator between two conductors

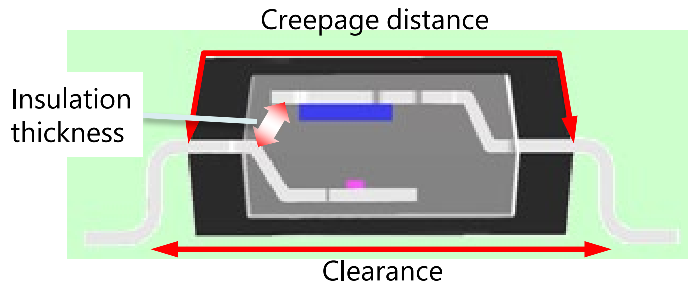
Isolation voltage
Isolation voltage between two conductors *
In the case of UL, the AC voltage that does not break the insulation even if it is applied for 1 minute is specified.

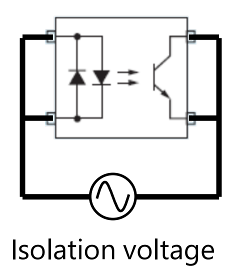
* Products with isolation voltage ranging from 2,500 Vrms to 5,000 Vrms are mainstream.

Package



DIP4, DIP6, DIP8, DIP16	・General-purpose package ・Supporting surface mount lead bend
SDIP6	・Creepage distance, clearance ≥7 mm, insulation thickness ≥0.4 mm ・Surface mount 6 leads (lead pitch =1.27 mm)
SO6	・Creepage distance, clearance ≥5 mm, insulation thickness ≥0.4 mm ・Surface mount 5 leads (lead pitch =1.27 mm) ・Thin
SO6L	・Creepage distance ≥8 mm, isolation thickness ≥0.4 mm
SO8	・Surface mount 8 leads (lead pitch =1.27 mm)
SOP4, SO4, SOP16, SO16	・Surface mount 4 leads (lead pitch =1.27 mm) ・Surface mount 16 leads (lead pitch =1.27 mm)
SO16L	・Creepage distance ≥8 mm, isolation thickness ≥0.4 mm ・SMD 16 leads (lead pitch=1.27 mm)
MFSOP6	・Surface mount (lead pitch =1.27 mm)
2.54SOP4, 2.54SOP6, 2.54SOP8	・Surface mount (lead pitch =2.54 mm)
SSOP4	・Surface mount (lead pitch =1.27 mm)
USOP4	・Surface mount (lead pitch =1.27 mm)
VSON4	・Ultra small ・Leadless SMD





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.

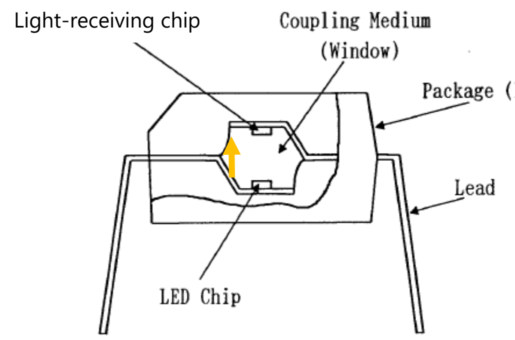
Transmissive type in single mold: Frame-mounted LED and frame-mounted photodetector face each other in the same molded package. Silicon resin is used for the optical transmission part between LED and photodetector.

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

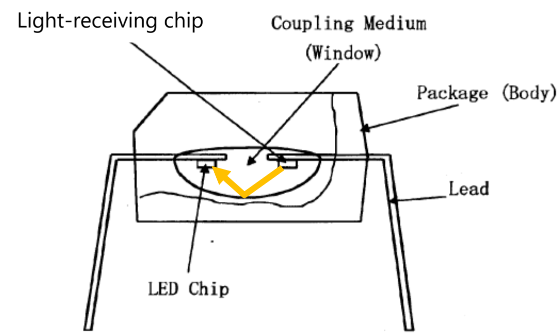
Transmissive type in double mold: In this transmissive structure, inner mold is white, and outer mold is black. Resin with high infrared light transmittance is used for white mold of the optical transmission part.

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.

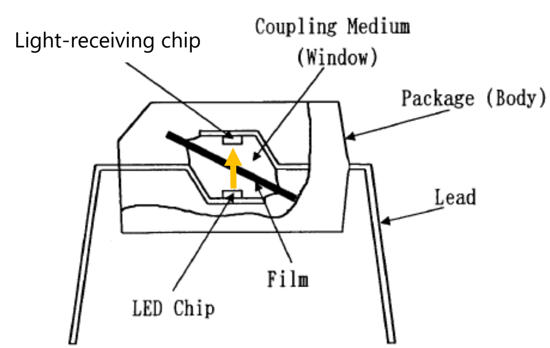
Transmissive type in single mold



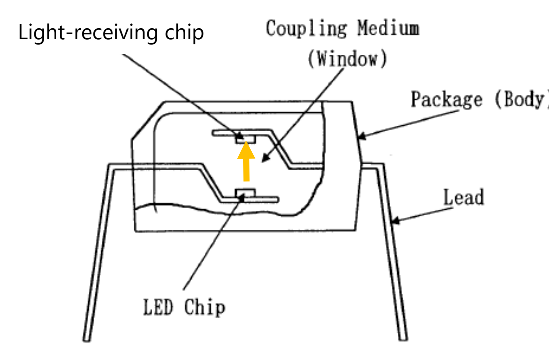
Reflective type



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 "set standards" and "parts standards". Set standards are the basis for designing and manufacturing equipment such as TVs, VTRs, and power source units. "**Set standards**" differ according to equipment type, isolation method and its class, driving voltage, etc. Also, the items (dielectric strength (isolation voltage), creepage distance, clearance, etc.) that must be maintained at the insulation portion are specified as "**Parts standards**".

Major safety standards

Parts standards

UL1577 (cUL)

Standard for isolation voltage (1 min)

Approval organization: **UL**

(Underwriters Laboratories Inc.)

EN60747-5-5

Standard for maximum operating isolation voltage and maximum overvoltage

Approval organization: **VDE**

(Verband Deutscher Elektrotechniker)

Approval organization: **TUV**

(Technischer Uberwachungs Verein)

Set standards

(Approval organization: **BSI** (UK), **SEMKO** (Sweden), etc.)

EN60950

Standard for telecommunication network equipment

(workstation, PC, printer, fax resistor, modem, etc.)

EN60065

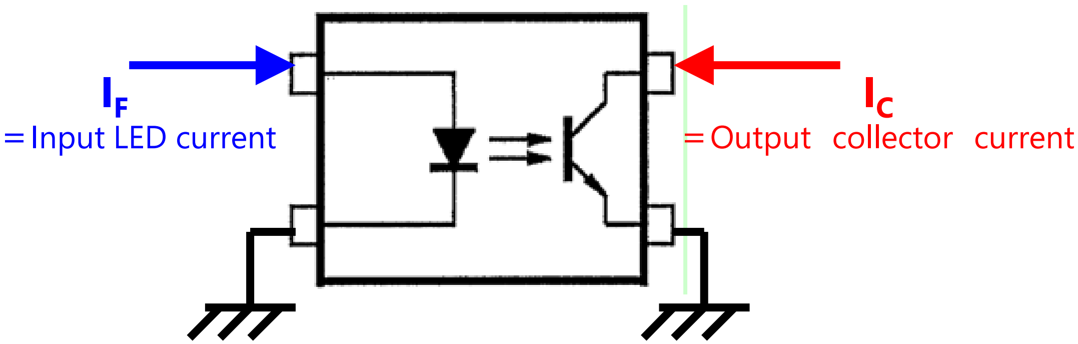
Standard of home appliance equipment.

(TV, radio, VTR, 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}.

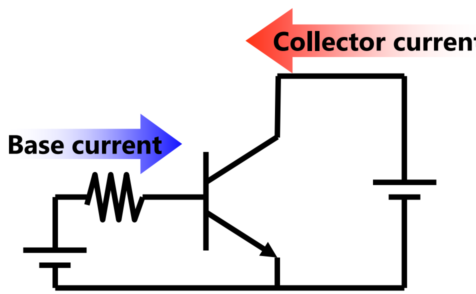
Current Transfer Ratio=CTR
$=I_C/I_E$ =Output (collector) current/input current ×100 (%)



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 mA** is input, **I_C = 10 mA** is obtained.
CTR = I_C/I_F = 10 mA/5 mA×100 (%) = **200%**

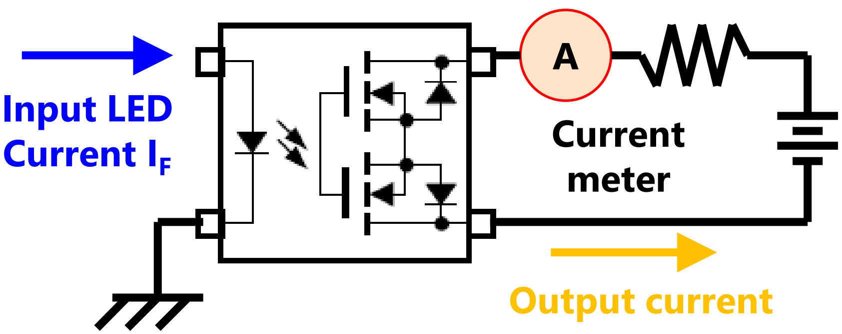


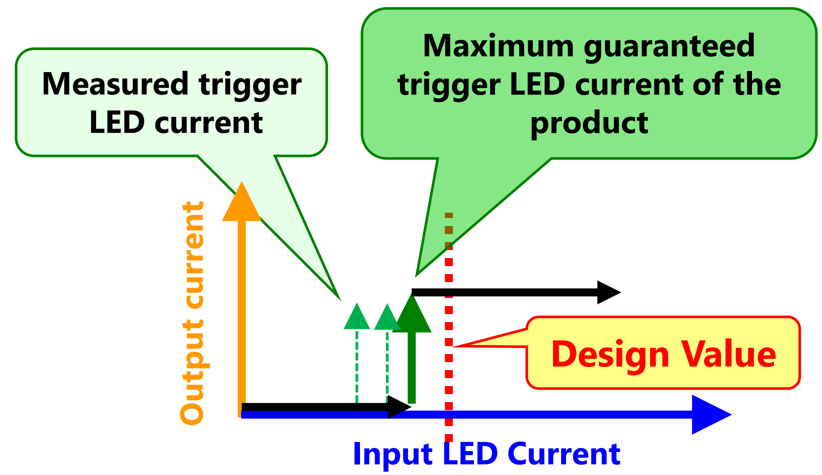
Coupled Electrical Characteristics (Unless otherwise specified, Ta = 25°C)

CHARACTERISTIC	SYMBOL	TEST CONDITION	MIN	TYP.	MAX	UNIT
Current transfer ratio	I_C / I_F	I_F = 5 mA, V_{CE} = 5 V	50	-	600	%
		Rank GB	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_{FH}, I_{FLH}, I_{FLH}, etc., are used as symbols.
The trigger LED current indicated in the datasheet indicates the current value guaranteed 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

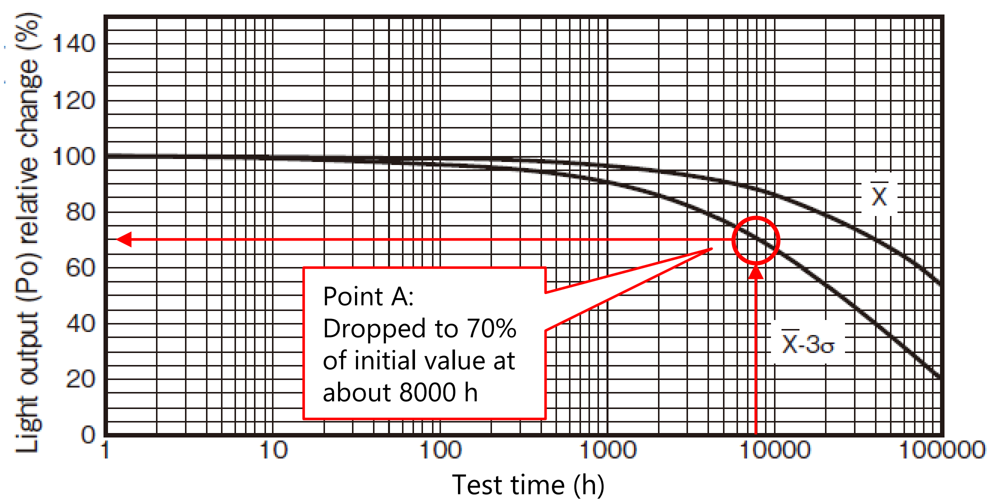
Aging variation data of photocouplers

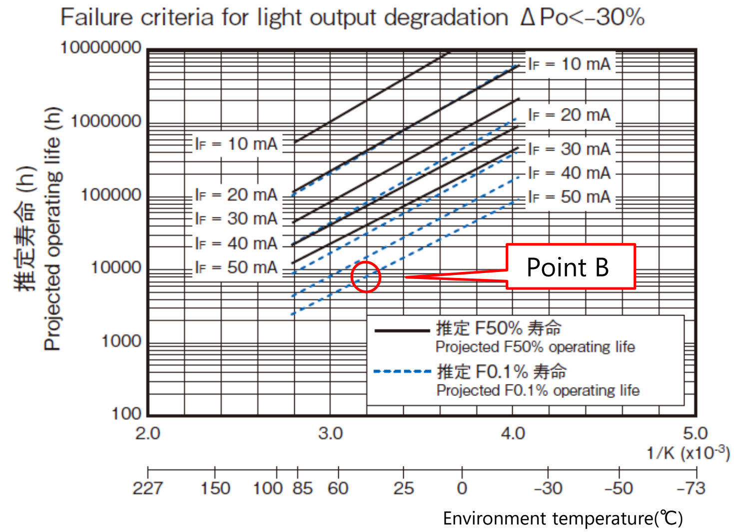
The optical output of the light-emitting element (LED) decreases with the passage of time. In photocouplers, aging variation of optical output of LED is more dominant than that of optical receiving devices. Therefore, the designer needs to estimate the decrease in the light emission level using the data 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 (IF) 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 mA, Ta = 40℃





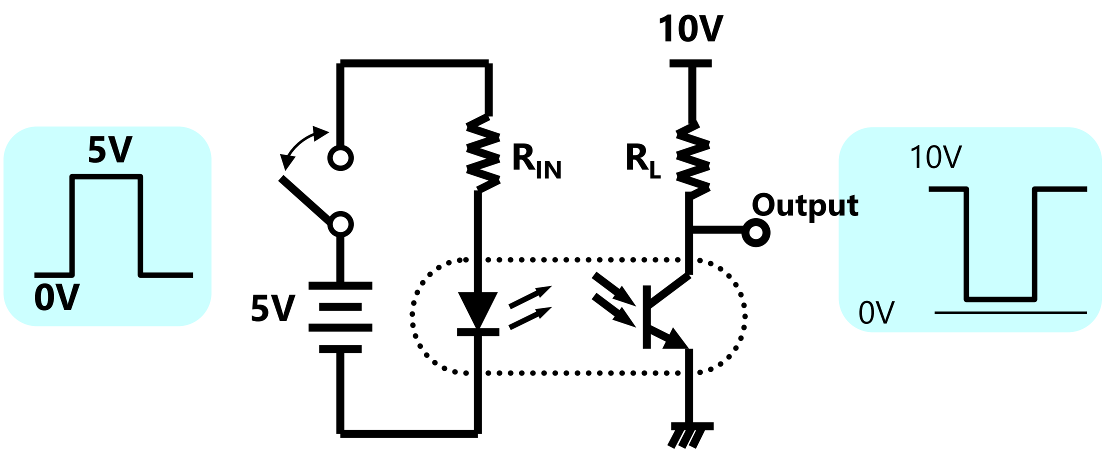
The left-hand figure shows aging variation data of LED optical output.
The right-hand figure shows the operating time when LED optical output drops below a certain criterion.
For example, point A in the left-hand figure and point B in the right-hand figure show aging variation under the same conditions. (I_F=50 mA, T_a=40℃, 8000 h).

How to Use a Photocoupler

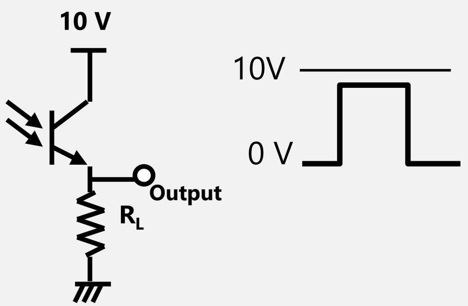
Design example of signal interface using phototransistor coupler
The figure below shows an example of an interface circuit that converts a 5 V signal into a 10 V signal using a phototransistor coupler.
How should we design the resistor R_{IN} on the LED input side and the resistor RL on the phototransistor 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 IF and CTR
Step 3. Design of output-side resistor RL
Step 4. Check each designed constant

Interface circuit of DC5V and DC10V

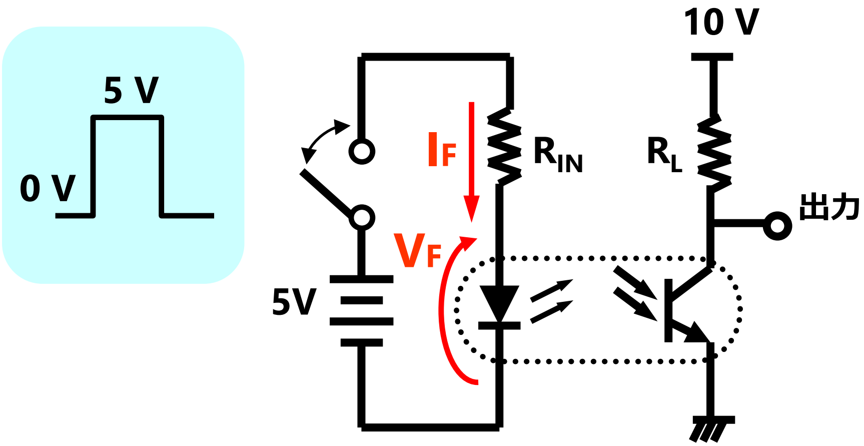


Note:
In the left figure, the output signal is inverted, but if the output is an emitter follower as shown below, it is possible to obtain the same positive phase output as the input.



How to Use a Photocoupler “Input Current”

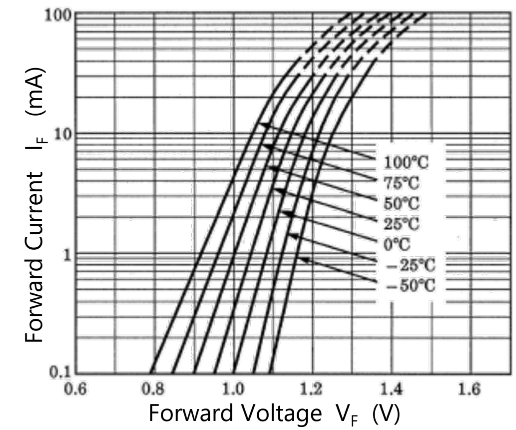
Step 1. Design LED input current and input resistor R_{IN}.



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).

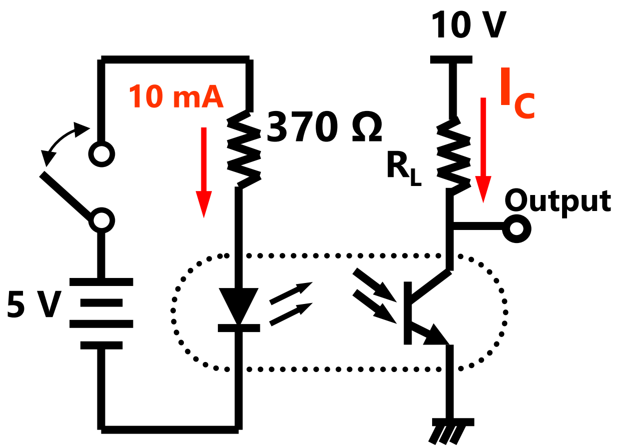
$$R_{IN}=(V_{CC}-V_F)/I_F=(5\text{ V}-1.3\text{ V})/10\text{ mA}=370\ \Omega$$

(Specification example)

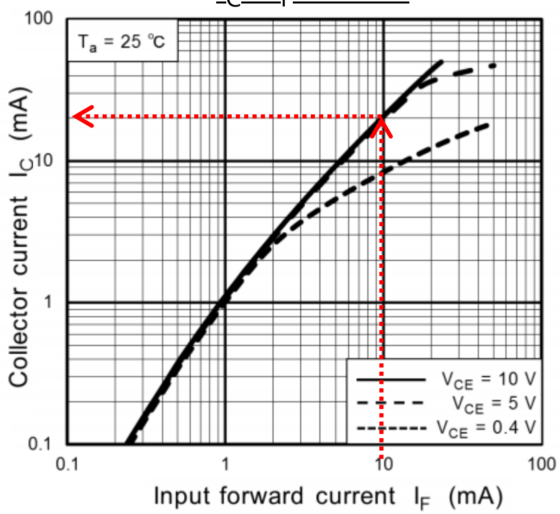
Forward voltage	V_F	I_F = 10 mA		1.0	1.15	1.3	V

How to Use a Photocoupler “Output Current”

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



I_C – I_F Curve



Current transfer ratio (CTR) rank

Transistor photocouplers are classified by CTR.

Classification (Note1)	Current Transfer Ratio (%) (I_C / I_F) I_F = 5 mA, V_{CE} = 5 V, Ta = 25°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 (I_C / I_F). When reading the I_C value at I_F = 10 mA from the I_C - I_F curve, you can see that I_C = 20 mA. Here, if we assume that the CTR is almost the same as I_F = 5 mA, it can be calculated as follows:

In the case of GR rank (100% to 300%)

$$I_C = 10 \text{ mA } (I_F) \times 100\% \text{ to } 300\% \text{ (CTR)} = 10 \text{ mA to } 30 \text{ mA}$$

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.

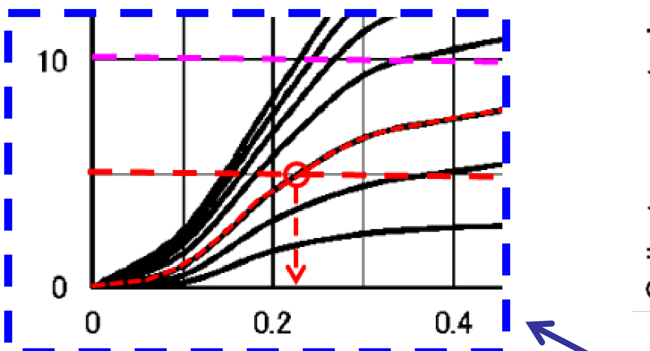
How to Use a Photocoupler "Output-Side Resistor"

Step 3. Design output-side resistor R_L

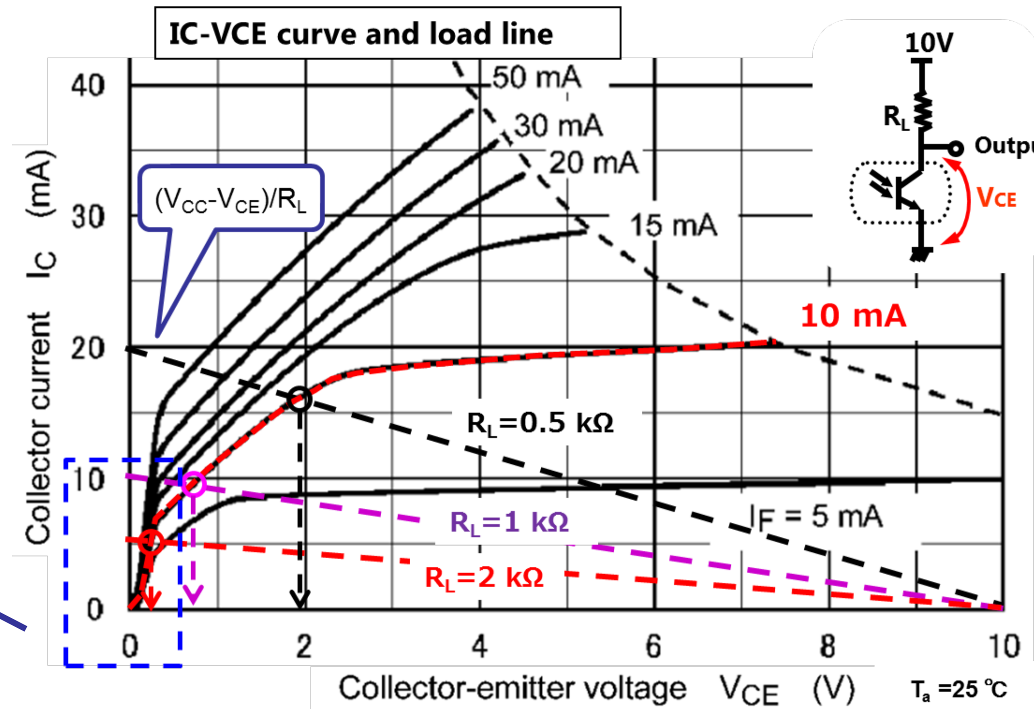
Determine R_L from the I_C-V_{CE} characteristics of the output transistor. In order to use for signal transmission, it is necessary to fully satisfy the "L" level of the device connected to the load side.

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 kΩ, which is insufficient. At R_L = 2 kΩ, V_{CE} = about 0.2 V, which satisfies the target value. Therefore, choose R_L = 2 kΩ. In actual design, the impedance on the load side must also be considered.

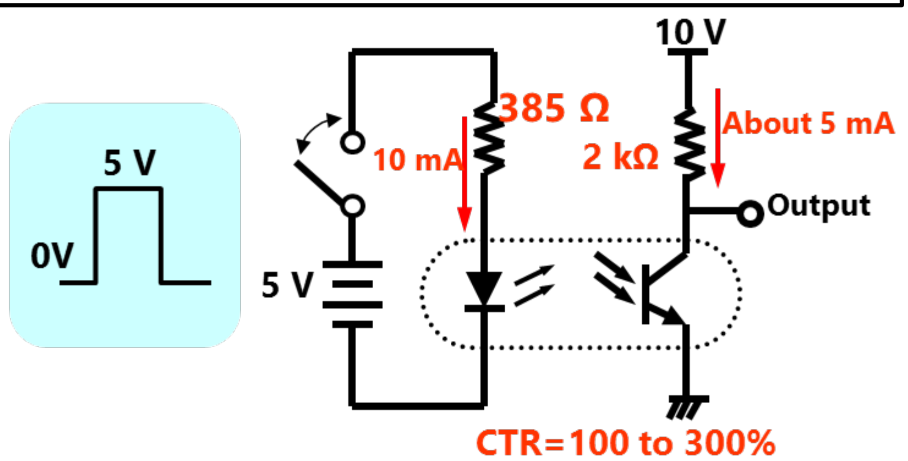


Enlarged view



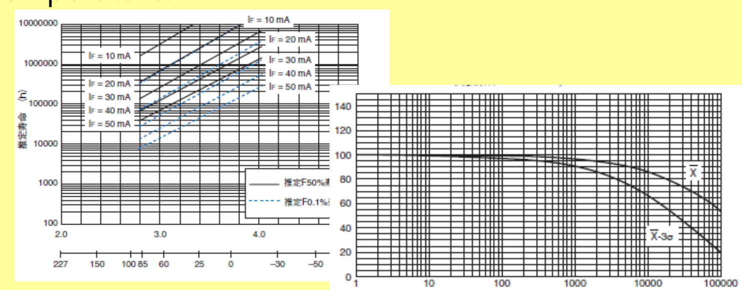
How to Use a Photocoupler Check

Step 4. Check each constant.
Consider whether there is sufficient margin for operating temperature, speed, lifetime design, tolerance of resistor, etc.



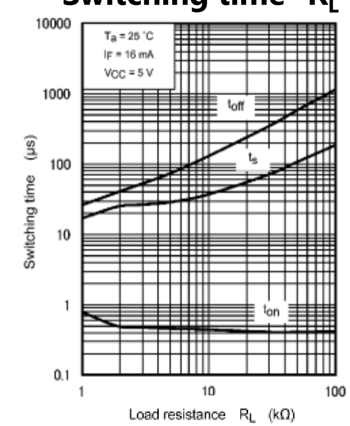
Confirmation of lifetime of the set

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 (IF) and ambient temperature.

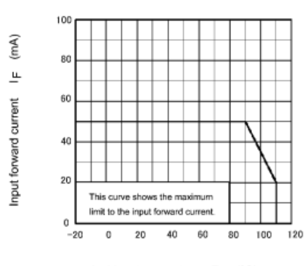


Temperature range ⇒ V_F, CTR, allowable current, etc.
Load resistance ⇒ switching speed, influence of dark current, etc.

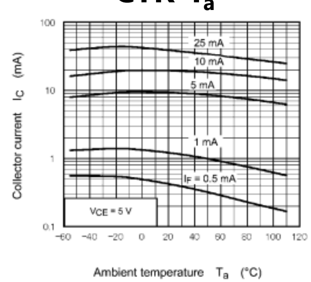
Switching time -R_L



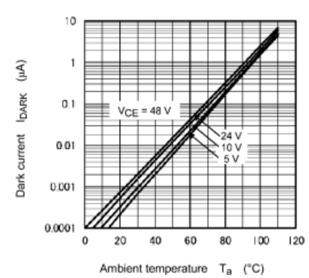
Allowable current



CTR-T_a



Dark current



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