



PHOTOMOS RELAYS

Bringing reliable and
fast switching to future
industries



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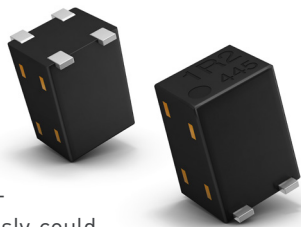
INTRODUCTION

Whether in cars, buildings, or automated machines, switching devices have become indispensable for industries and in everyday life. From centuries, relay technology has played a crucial role in this development. Since the first electromechanical relays (EMRs) were applied in long telegraph lines in the 1840s, the requirements for such switching devices, however, have changed dramatically – and so has the technology available. Making use of the swift advances in semiconductor and LED technology in the 1960s, the first solid-state relay (SSR) saw the light of day in the early 1970s. Getting rid of any moving elements, the technology allowed for more reliable and faster switching operations and substantially expanded switching life. Nevertheless, EMRs remained the gold standard for certain applications, e.g. where linear on-resistance or AC and DC switching are required.

“PhotoMOS relays are popular in applications which previously could only be served by signal level EMRs.”

A new subgroup of SSRs set out to change this: In the early 1980s, a solid-state relay that uses metal oxide semiconductor field effect transistors (MOSFETs) as output devices was introduced. These transistors effectively combine metal as an electrical conductor with an oxide film serving as an insulator and semiconductor material. In contrast to SSRs with bipolar transistors or TRIACs, these MOSFET or PhotoMOS relays use an inverse series of two MOSFETs and can switch DC and AC up to high frequencies. Furthermore, the static and commutating rate of voltage change over time (dV/dt) effects are not inherent and turn-off is not related to the phase of the AC current. Compared with bipolar transistors, MOSFETs also have a lower on-state offset voltage, much lower off-state leakage currents and, most important, an infinite static forward current gain.

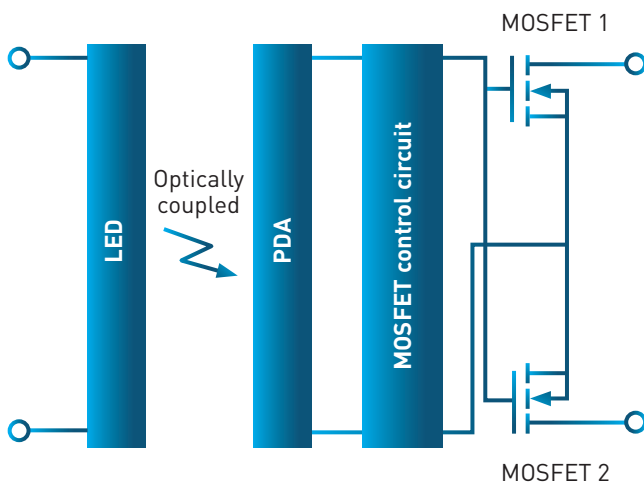
These particular characteristics have made PhotoMOS relays popular in applications which previously could only be served by signal level EMRs, particularly industrial machines and process control. With the rise of the Internet of Things, e-mobility, and energy management applications in general, the demand is sure to rise in the future.



BASICS OF A PHOTOMOS RELAY

Topology

A typical PhotoMOS relay consists of several elements: An input LED optically coupled to a photodiode array (PDA), a control circuit, and two power MOSFETs that function as output devices. When the LED is operated, the PDA translates the light into electrical current and voltage, which drive the power MOSFETs on the output. The intermediate control circuit is responsible for the safe and reliable turn-on and turn-off of the output MOSFETs once a certain trigger current is reached. The MOSFETs in turn form an inverse series connection, enabling them to switch both DC and AC.



Advantages of PhotoMOS relays

PhotoMOS relays are made entirely of semiconductor material and do not have moving parts, making them especially suitable for applications that need to worry about package size, power consumption, or operating speed.

In mechanical relays, the kinetic energy produced by closing the contact leads to a bounce-back of the operated contact. This causes contact interruption and typical arcing phenomena. A fluctuating contact resistance and electromagnetic circuit noise can be the consequence. PhotoMOS relays, on the other hand, guarantee a **bounce-free operation** and are **immune to electromagnetic interference (EMI)**. Furthermore, the mechanical parts in EMRs impose a natural limit to **switching speed**: closing a contact takes 2 to 3 ms. PhotoMOS relays, on the other hand, come without such restrictions – they can switch far below 1 ms. No moving parts inside a PhotoMOS relay also lead to much better **shock and vibration resistance** of more than 1000 g. For EMRs, the limit is reached at 30 g.

Although PhotoMOS relays are not entirely immune to deterioration, **reliable** switching can be extended almost indefinitely when operated at moderate temperature and within the rated junction temperature. Likewise, mechanical wear does not occur, further extending the **switching life** of a PhotoMOS relay.

The physical properties of this type of semiconductor relay also allow for unusually **high isolation voltages** of up to 5000 VAC, while comparable signal relays reach their limit at 2000 VAC. As PhotoMOS relays do not have to worry about arcing, **maximum switching voltage** is increased more than tenfold compared to EMRs, from 200 V to over 2000 V. And as they can switch both AC and DC, they are especially versatile.

PhotoMOS relays additionally offer advantages in terms of energy consumption and package dimensions. Due to the low input current required by the LED, power consumption of around 10 mW are standard. Especially sensitive products with less than 5 mW are also available for designated applications. And while EMR only come in DIP, PhotoMOS relays can go down to VSSOP or even TSON packages for low-current devices – a big advantage when board space is limited.

Advantages	Disadvantages
bounce-free operation	contact resistance
reliable	output capacitance
switching speed	overload
immune to electromagnetic interference (EMI)	galvanic isolation at the output
switching life	
high isolation voltages	
maximum switching voltage	

Advantages of electromechanical relays

While these benefits make PhotoMOS relays a perfect choice for many applications, they are by no means about to completely replace EMRs. Where a low **contact resistance** in the on-state is required, for example, mechanical relays reign supreme with a resistance of around 30 mΩ. While special PhotoMOS relays with values below 50 mΩ are available, the typical range is around 3 Ω. EMR also perform better in high frequency applications, although recent technologies are starting to change this. As of now, EMRs have an **output capacitance** of less than 1 pF in the open state whereas PhotoMOS relays are in the range of nanofarads. Furthermore, PhotoMOS relays are more prone to **overcurrent** and **overvoltage**, which can damage internal bond wires or the pn-junction of the MOSFET. Lastly, full **galvanic isolation at the output** is currently only possible with an electromagnetic relay.

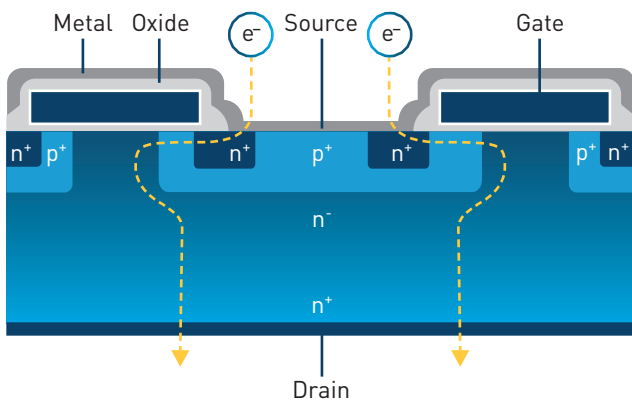
Nevertheless, PhotoMOS relays are better able to replace EMRs than other SSRs with optical coupling (such as an opto-TRIAC) for several reasons: They offer linear on-resistance, are able to switch both AC and DC, and show no self-trigger mechanism for overhead firing.

PHOTOMOS RELAY COMPONENTS

Power MOSFETS

Power MOSFETs function as the output switching element in a PhotoMOS relay due to their robustness, temperature stability, high switching speed and high gain current level. In a typical MOSFET, the gate and source terminals are located on the chip top surface while the drain terminal is located at the bottom. Layers of n^+ Si connected to the source are contained within two p-type high-impurity concentration wells (p^+). These wells in turn are embedded in an n-type low-impurity concentration region (n^-). The gate is encased in a thin SiO_2 insulation layer above the p-channel. The load current is conducted vertically through the chip outside the channel.

Cross-section of a power MOSFET with vertical structure and planar gate



When no current is applied between the gate and source (VGS), the connection between source and drain is blocked. Once the gate voltage reaches a certain threshold, an n-conducting channel is formed within the p^+ region, directing electrons from the source through the n^- drift zone to the drain.

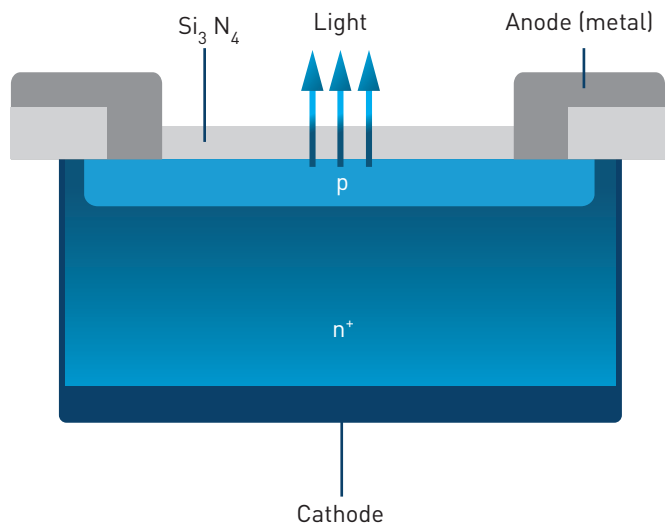
PhotoMOS relays use MOSFETs with a double-diffused structure, so-called DMOSFETs. When put in inverse connection, they are able to also switch AC loads. The vertical structure of the transistor allows it to sustain both high blocking voltage and high current.

If the gate voltage is below the threshold voltage required for conduction, the MOSFET is in a cut-off state: the channel current from source to drain (I_{DS}) is zero. Once the threshold is reached, conduction ensues and the gate gets charged. The on-state is reached once saturation occurs and the gate capacitance is fully charged. Switching between the off- and the on-state as quickly as possible is central for high-speed operation and to ensure that minimal turn-on losses are generated in the transition period.

LED

PhotoMOS relays typically feature a GaAs LED as an input device. This type of LED chip includes an n-type high-impurity concentration GaAs layer (n^+) with a p-type diffusion layer on the top. Both sides are metallized with an aluminum layer, forming the cathode and an anode connection. Infrared light is emitted when the internal pn-junction is activated in forward bias. In order to maximize light output, this area is moved as close to the surface as possible.

Cross-section of a GaAs LED

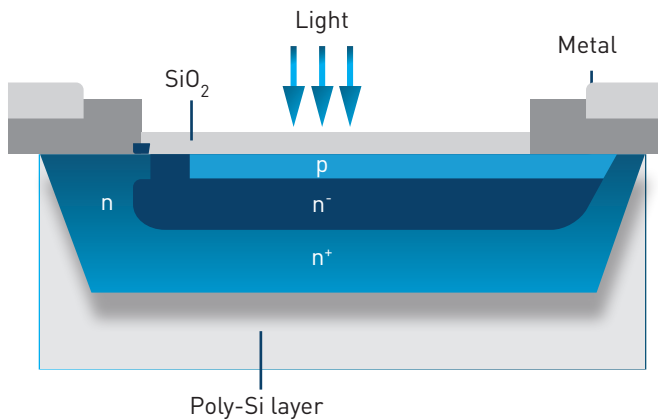


For optimal operation, a GaAs LED requires an input current of around 3 to 5 mA. While lower currents are possible, they will lead to dimmer light and consequently affect the switch-on time of the PhotoMOS relay. As the voltage across a GaAs LED in its forward biased condition is just over 1 V, an external resistor is needed to adjust the current to a correct level in order not to damage the LED. Light output will also decrease with higher ambient temperatures and increasing operating time under constant current.

PDA

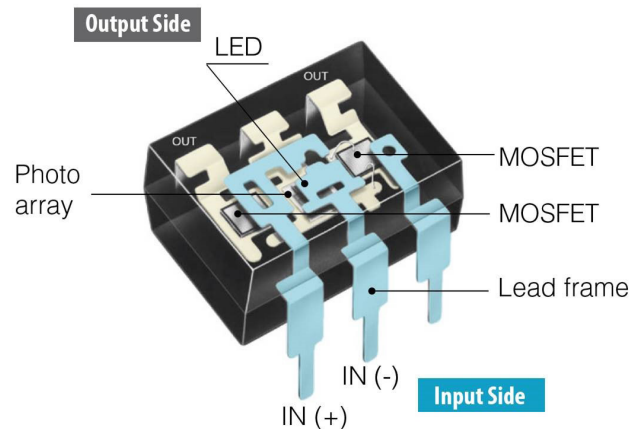
Photodiodes generate a current by absorbing the photons emitted by the LED into the pn-junction area. GaAs LEDs typically emit photons with an energy in the range of 1.4 eV, which is a perfect match to an Si photodiode with an energy gap of 1.1 eV. These photodiodes also feature a p-type diffusion layer and an n-type high-impurity concentration (n^+), with an undoped intrinsic (i) or an n-type low-impurity concentration layer (n^-) implemented between the positively and negatively doped regions – a so-called pin-diode. A polycrystalline Si layer serves as a physical substrate for the whole PDA, while a SiO_2 film on the surface acts as a passivation and as an anti-reflector for the incoming light.

Cross-section of an Si pin diode: side view (top) and top view (bottom)



“In a standard PhotoMOS relay, fifteen separate photodiode cells are combined into a single PDA.”

Such a pin-type PDA with an increased depletion region reduces the capacitance of the pn-junction. As a result, it can generate more electric current than a standard pn-diode from the same amount of light. Until saturation occurs, the value of the current develops linear to the incidence of light. However, several photodiodes are needed to reach the threshold voltage of the MOSFET gate. In a standard PhotoMOS relay, fifteen single cells (each 1 mm × 1 mm) are combined into a single PDA in order to reach the 8 V and 2.5 μA required for full conduction of the MOSFET.



Control circuit

The main function of the control circuit inside a PhotoMOS relay is to avoid the intermediate or linear operating state of the output MOSFETs, mimicking as closely as possible the two operation states of an EMR. This control circuit consists of a normally-on transistor (driver transistor) connected in parallel to the gate-drain capacitance of the output MOSFETs. A resistor is connected in series to the MOSFET's gate of the normally-on transistor. Through this construction, the gate voltage threshold will not be reached until enough current has accumulated to achieve saturation, effectively skipping the linear state. Only when the LED input current reaches a certain level (LED input current) will the MOSFETs be switched. A constant voltage of 7.5 V is applied at the gates of the output MOSFETs, which keeps them in the saturation state. Once no more current is generated by the PDA, the transistor will return to its on-state, quickly decreasing gate voltage and turning off the MOSFETs within a fraction of a millisecond.

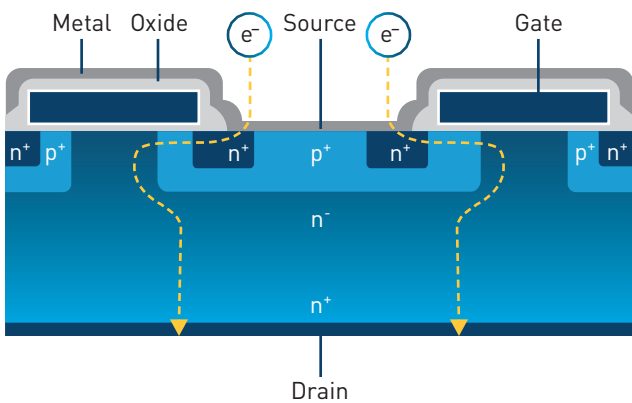
DIVERSITY OF PHOTOMOS RELAYS

Normally-closed PhotoMOS relays

Normally-closed (1-Form-B) PhotoMOS relays use depletion-type MOSFETs on the output side in order to keep them in a conducting state at zero input current. This type of MOSFET has a thin layer of n-type Si just below the gate-insulating layer, which forms a conducting channel between source and drain. Therefore, a current can occur even without gate-source voltage. Due to this structure, the on-resistance is higher than for normally-open types, leading to a smaller load current while maintaining the same switching voltage.

Normally-closed PhotoMOS relays are typically used for alarm contacts, but they can also be combined with normally-open PhotoMOS relay to realize changeover contacts (1-Form-C). In such configurations, however, the turn-off time of normally-closed PhotoMOS relay is longer than the turn-on time of their normally-open counterparts. In order to avoid a situation where both contacts are closed for a short time, a delay element, e.g. a speed-down circuit, is inserted in the control unit.

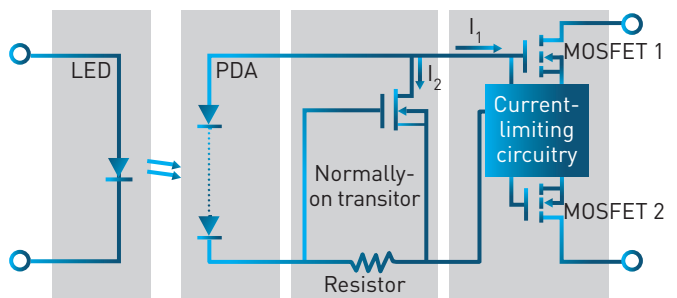
Cross-section of depletion-type MOSFET for 1-Form-B MOSFET relay



Current-limiting PhotoMOS relays

A current-limiting circuit can be installed in certain PhotoMOS relays in order to prevent damage from overcurrent. It is activated as soon as overcurrent occurs and automatically reduces the voltage at the gates of the MOSFET. This lower gate voltage will consequently increase the on-resistance, therefore limiting the current. Once the overcurrent is removed, the PhotoMOS relay will immediately resume normal operation. However, the current-limiting circuit can only be operated for a limited time before the power dissipation caused by the high on-resistance and current flow reaches a self-destructing level.

Equivalent circuit diagram of current-limiting PhotoMOS relay



Short-circuit-protected PhotoMOS relays

Short-circuit-protected PhotoMOS relays protect both the output MOSFETs and the load circuit against overcurrent. A protective circuit detects if the load current increases above a certain limiting value, threatening a short-circuit. To this effect, shunts are located at the output side of the PhotoMOS relay. Excessive current in the event of an error leads to a voltage drop across the shunt, triggering the MOSFET control circuit. After the output disturbance has disappeared, these relays behave like normal semiconductor switches again. Short-circuit protected PhotoMOS relays therefore offer 100 percent protection against overcurrent. There are two basic ways of achieving the switch-off function:

Latching-type: The load circuit is switched off completely. The voltage drop at the shunts activates an asymmetrical flip-flop gate, which switches off the output. The load current remains interrupted even if continuous input current is supplied. Normal switching operations can only resume after the LED input current has been removed and then reapplied.

Non-latching-type: The output in this relay closes and opens the load circuit alternately, leading to an oscillating load current. This decreases the load current's root mean square (RMS) value in such a way that the resulting power dissipation does not exceed the component's maximum permissible energy dissipation.

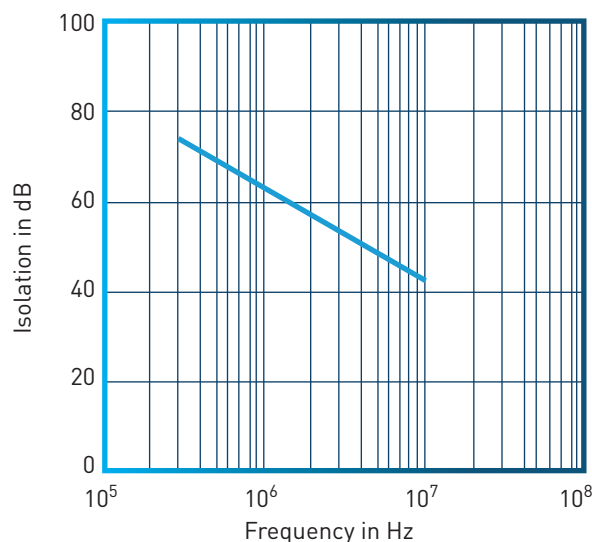
“Short-circuit protected PhotoMOS relays offer 100 percent protection against over-current.”

Low CxR PhotoMOS relays

In a Low CxR PhotoMOS relay, both the output resistance and the output capacitance of the transistors are extremely low. In DMOSFETs with a conventional vertical structure, there is a trade-off between load voltage, resistance and capacitance - reducing output resistance will result in a higher output capacitance. Low CxR PhotoMOS relays manage to avoid this conundrum by resorting to a U-shaped DMOSFET technology, bringing down capacitance value from several hundred pF to less than 1 pF, while also keeping the output resistance low.

This makes them ideally suited for applications that operate with high frequencies, such as signal applications in the medical field, measuring or communication technology. Due to the output capacitance, high frequencies cannot be blocked well and only lower frequencies can be restrained (high pass).

Isolation-frequency characteristic of a 1 pF MOSFET relay



High-sensitivity PhotoMOS relays

The amount of current generated inside a PhotoMOS relay can be boosted by simply increasing the number of photodiodes used in the PDA. This in turns allows for the LED operating current to be reduced, making the device more energy efficient. For battery-driven applications, this also comes with a longer operating life.

High-power PhotoMOS relays

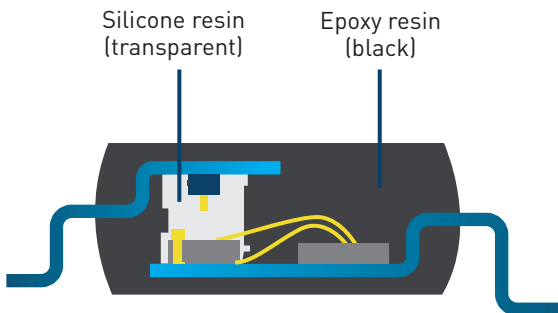
A higher load current also means higher power dissipation is required. As PhotoMOS relays cannot be cooled from the outside, all power dissipation must be processed inside the component. In order to increase load current, the packaging size inevitably needs to be increased. High-power PhotoMOS relays are therefore offered mainly in SIL or PD packages - current models allow load currents of up to 10 A in a SIL package whilst keeping the on-resistance below 10 mΩ.

Package types

PhotoMOS relays come in many different sizes, the nomenclature of which varies from manufacturer to manufacturer. At the heart, however, there are two general ways of building up the package: single- or double-molding.

Single-molding structure: The whole housing is made of a homogeneous black epoxy resin, with only a narrow path of transparent silicone resin for the light of the LED to travel to the control circuit. As the silicone path transmits light much better than the black epoxy resin, operation time is extremely short. Furthermore, very little to no light reaches the output MOSFETs, bringing down any unintended offset voltage. On the other hand, the bonding wires are in contact with two different materials, epoxy resin and silicone. The different behaviour of these materials during temperature cycling can put stress on the bonding wire and make it less heat-resistant. And as the withstand voltage of silicone resin is lower than for epoxy, the I/O isolation of the relay is also lower. Single-molded relays are typically used in measurement technology.

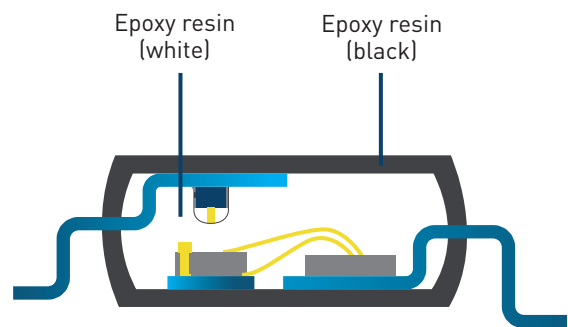
Single-molding package



Double-molding structure: The inside of the housing is filled up with a transparent epoxy; only the outer part is covered by impermeable black epoxy. While the resulting higher offset voltage can be problematic for certain applications, this structure has a higher withstand voltage and less stress is put on the bonding wires.

Starting from DIP, the I/O isolation voltage is up to 5 kV. These characteristics make double-molded PhotoMOS relays ideal for most automotive applications.

Double-molding package



Package type	Single-molding	Double-molding
Operating time	++	+
Offset voltage	++	+
Heat resistance	+	++
Withstand voltage	+	++
Typical application	Measurement	Automotive

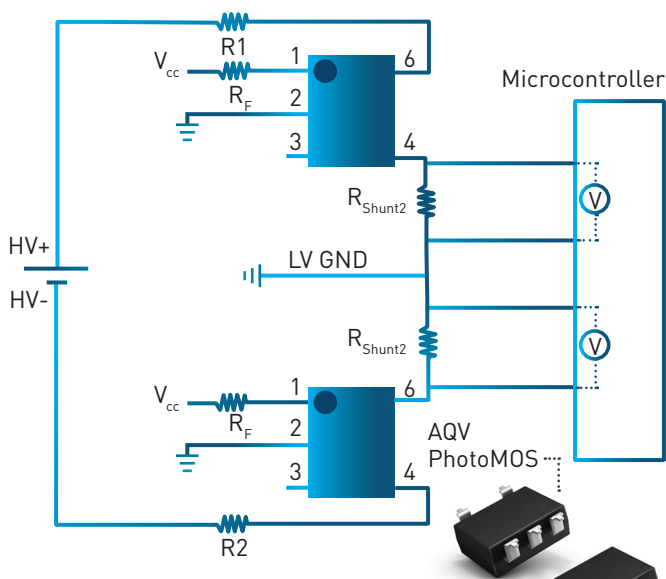
Comparison between single- and double-molding packages
+ good, ++ very good

APPLICATION SCENARIOS

Electric mobility

With the rise of e-mobility, PhotoMOS relays have increasingly found their way into the automotive industry. While galvanic isolation is usually not needed in internal combustion engine vehicles, electric cars operate with high-voltage systems of between 450 VDC and up to 1000 VDC. Here, a safe separation of low voltage in the chassis and high voltage in the power train is essential. As PhotoMOS relays offer both high I/O isolation voltage up to 5000 V and high output switching voltage up to 2000 V, their most common application in the automotive field is isolation monitoring. If a leakage between high and low voltage occurs, current flows through the high-ohmic resistor shunts, leading to a voltage drop. Once the microcontroller registers this, a cutoff function for the traction battery is immediately activated.

Isolation monitoring circuit



In order to meet the high demands on quality and reliability of the automotive sector, there are types of PhotoMOS relays especially dedicated to this industry. Among other things, these relays can withstand ambient temperatures between -40°C and $+105^{\circ}\text{C}$, undergo special reliability and quality checks, and come with a special lead frame that meets the clearance and creepage requirements on the PCB.



Scan the QR code for more information about Automotive PhotoMOS relays.

Energy management

PhotoMOS relays are also used in the energy management sector, for similar reasons. Storage systems require cell balancing and isolation monitoring, just like electric vehicles do. Additionally, PhotoMOS relays are ideally suited for the use in smart meters due to their low control current and long switching life. Their main function in this application is to control the signal line to the power supplier.

“Storage systems require cell balancing and isolation monitoring, just like electric vehicles do.”



Building automation

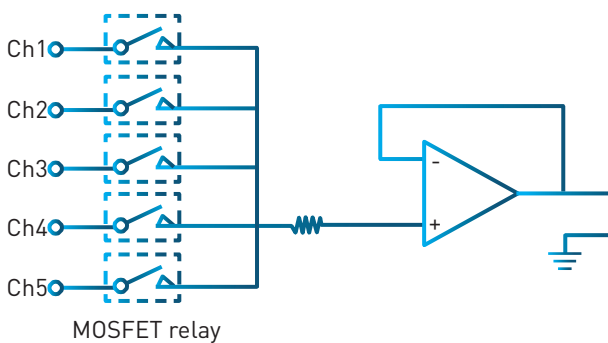
The low control current, high reliability and long operating time of PhotoMOS relays make them the perfect fit for security applications that need to run for a long time. Thus, these relays are used in battery-driven applications like smoke detectors or burglar alarm sensors. Depending on the application, PhotoMOS relays can function as input interfaces for system sensors and output interfaces for alarm contacts. Additionally, the ability to switch AC and DC enables free connectable switching outputs for different kinds of loads.

Industrial automation

Analog I/O module

PhotoMOS relays are often used for signal multiplexing, i.e. switching analog signals from several input or output channels inside the device to one A/D converter. In the realm of industrial automation, this is the case for programmable logic controllers (PLC) or industrial PCs (IPC). This task is helped by the linear output characteristics of the PhotoMOS relays, allowing them to transmit signals without distortion.

Equivalent circuit diagram of multiplexer:



Relay terminal

Relay terminals profit from the ability of PhotoMOS relays to switch AC and DC. This feature allows free connectable switching outputs for low-voltage loads (e.g. 12 VDC) up to mains voltage at 230 VAC. When operated within their maximum ratings, PhotoMOS relays are protected against inrush current without the need for additional snubber circuits. Furthermore, PhotoMOS make for more compact controllers: In the industrial field, high-power SIL packages are usually used for PLC or IPC relay terminals.

Panasonic FP7



Measurement equipment

Automatic test equipment (ATE)

Nowhere do PhotoMOS relays get to display the whole range of their qualities more than in semiconductor testing. Again, they are used for multiplexing, but with especially high requirements on the switching elements. This is where Low CxR PhotoMOS relays with their low output resistance and capacitance can offer a solution. Depending on the need of the individual measurement path, the user can select C- or R-optimized types to build up T or Pi circuits. Small packaging size for multichannel design and almost unlimited switching cycles further establish PhotoMOS relays as ideal components for ATE. Together with low overall energy consumption, this semiconductor relay increases reliability while reducing cost and maintenance.



Multimeter

The multiplexing capabilities of PhotoMOS relays also come into play with multimeters and other handheld measurement devices. In addition to the linear output characteristic, low control current, small size and high reliability, the very high shock resistance plays an important role for these components, contributing significantly to a multimeter's resilience.

OUTLOOK

For future markets like the solar, storage battery and electric vehicle industries, PhotoMOS relays are likely to become a staple. However, as demands for higher currents and higher working voltage rise, MOSFET devices also have to evolve. In order to stay successful in these fast-growing markets, PhotoMOS relays are bound to focus on:

- » **Increasing the switching performance (voltage > 2500 V, current > 10 A)**
- » **Expanding the operating temperature range to 125°C**
- » **Finer structure to reduce chip area**
- » **Low energy consumption**
- » **Low system cost.**

To this effect, several technological advancements are currently under way. Thus, replacing silicon (Si) with wide-band-gap silicon carbide (SiC) in the output MOSFETs could make PhotoMOS relays more economical for high-power applications. First high-power PhotoMOS relays, which allow switching currents of more than 10 A, are already available. At the same time, new MOSFETs with gate-source capacities in the range of picofarads could open the door for HF applications. The input LED is also a focus of researchers: Highly efficient GaAlAs diodes promise to reduce energy consumption by more than 50 percent, while also overcoming the temperature limit of traditional GaAs LEDs.

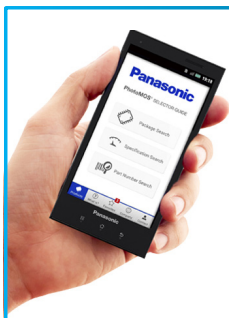
With these developments on the horizon, PhotoMOS relays can be expected to remain in high demand in the next decades. As the technology becomes ever more advanced, they not only stand to increasingly replace conventional switching solutions – they could play a crucial role in the development of new and smarter products.

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