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Literature Review of Optocouplers, Their Polymer Components and Current Applications

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ABSTRACT: Optocouplers, also called optoisolators and photocouplers, are devices that use a light emitting diode (LED) to conduct an electrical signal. The LED receives an electrical signal and emits light proportional to that signal. The light is then received by a photodetector and the signal is propagated. Optocouplers provide a high degree of electrical isolation and are therefore used extensively in commercial electronic equipment. Variations in optocouplers come from the type of photodetector used, the anatomy of the contents and the encapsulating polymers used. Current research involves investigating the tolerance of optocouplers to radiation for the purpose of improving spacecraft and satellites, as well as identifying failure mechanisms and improving design.

Introduction

Optocouplers, also called optoisolators, and photocouplers, are devices that employ two simple components for conducting an electric current: light-emitting diodes (LEDs) and a transistor, specifically a phototransistor.¹ Transistors are an essential part of most modern electrical devices because they are used extensively in memory chips. There are thousands of them in almost every electronic device. Most act as switches by receiving an input current and responding by turning on an output current. Some act as amplifiers by receiving a small input current and responding with the production of a much larger output current. The operation of a transistor relies on its base pin being triggered. Ideally, no current will pass through without the pin being triggered and all the current will be passed through when it is.² Transistors are frequently made from silicon, which is a semiconductor. This silicon can be treated with impurities, or “doped”, to alter its conductivity. This doping process is meant to either add free electrons to the system (n-type), or reduce the amount of free electrons in the system (p-type).³ As a result, there are excess electrons (n) or voids of electrons (p) that can be knocked around, increasing the conductivity of the material (Figure 1).³

Figure 1² Visual representation of n-doped silicon and p-doped silicon.

Phototransistors, used in optocouplers, take advantage of the fact that photons have the ability to move those electrons around in doped semiconductor materials. This means that a light source can be used as a signal current, and when directed at a phototransistor can trigger the base, making it conductive.^{4,5} In other words, a light can act as the input signal to a transistor without making any physical contact with

it. This concept of coupling a light emitter with a semiconductor detector was established by Akmekalns et. al in 1963 and became the foundation for optocouplers which revolutionized the world of electronics.⁶

It is crucial for most electronic equipment to be protected from high voltages and electrical surges, which can happen when there is a sudden buildup of electrical potential energy, resulting in a rapid increase of energy flow into a circuit. This excessive energy flow can destroy or weaken sensitive electronic equipment, especially at semiconductor junctions.⁷ In order to protect these devices from electrical surges, the input and the output voltages must somehow be isolated, meaning they must be different signals.⁸ This is usually achieved with transformers, which exchange information on the basis of magnetic flux and are quite effective.⁹ However, as Akmekalns discovered, total electrical isolation can also be achieved when an electrical current is transformed into a photocurrent. Thus, optocouplers are effective in protecting sensitive electronic components because the electrical surge stays on the LED side and everything on the transistor side stays isolated.^{8,9}

Current Technology

There are currently four different types of optocouplers: the phototransistor, photo-darlington, photo-SCR (silicon-controlled rectifier) and the photo-triac.¹⁰ All of them use an LED as the output but the type of sensor for the input varies, as shown in Figure 2. The sensor can be either a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a photo-triac. For direct currents (DC), a phototransistor or photo-darlington is usually used. For alternating currents (AC), a photo-triac or photo-SCR is used.^{10,11}

Figure 2.¹⁰ The four classes of optocouplers and their different sensors.

The phototransistor operates like a switch for direct current. A base current is passed along to the LED, the LED then emits light with an intensity that is proportional to the signal that it received. This light signal is directed to the phototransistor, which receives the light, switches ON and propagates the electrical signal.⁸ The photo-darlington operates similarly, but is only used when low frequencies are required. The darlington has an initial transistor acting as the photodetector and that transistor has an emitter which is coupled to the second transistor, making it very sensitive, yet very slow.¹¹ The photo-triac operates by the same principle of receiving a photocurrent proportional to the original electrical current, however it conducts current in both directions. Because it can conduct current bi-directionally, the photo-triac is commonly used for power control in devices with alternating current.¹² The photo-SCR is similar to the photo-triac but the current is only allowed to flow in one direction.¹⁰

The anatomy of an optocoupler is relatively simple. Typically, an optocoupler has a lead frame and a black epoxy housing. However, there are variations to the layout of the interior depending on the desired isolation voltage (the highest voltage that may be applied across a device for one second without the isolation of the device being compromised).^{13,14} Devices that are rated for smaller voltages have components that are stacked, as seen in Figure 3.

Figure 3.¹⁴ Planar configuration of an optocoupler. The yellow wire represents the base signal, the red box represents the LED, the grey box represents the glass/plastic and the

green represents the photosensor. The arrow represents the flow of the electrical current.

In this configuration, the photosensor sits directly on the frame, then a glass or plastic film is stacked on top of the sensor and the LED sits on top of the film. The glass/plastic film is referred to as the optical channel, and is made as thin as possible while still achieving the required breakdown voltage, or the minimum voltage needed for the insulator to become conductive.¹⁴ It is important to note that photosensors may also be referred to as “die,” depending on the context.

Optocouplers that require higher voltages use a different layout called the “silicone dome” or planar configuration, as shown in Figure 4. This configuration places the LED and the photosensor on opposite sides of the frame, with free space in between. A dome of transparent silicone encapsulates the LED, the sensor and the gap between them. This silicone dome is not only a physical protector, but also serves as a way to retain stray light emitted from the LED by reflecting it back onto the surface of the sensor. This optical channel is longer than that of the planar layout (Figure 3), therefore this reflective material helps minimize light loss and maintain maximum efficiency.¹⁵

Figure 4.¹⁴ Silicone Dome configuration of an optocoupler. The red box represents the LED, the grey circle is the silicone dome and the green represents the photosensor. The arrow represents the flow of the electrical current.

In another layout called the over/under single mold type (Figure 5), a film is inserted between the LED and the sensor, usually glass or polyamide, both of which improve isolation voltage and noise rejection.¹⁴

Figure 5.¹⁴ Representation of the over/under configuration. The dotted line represents the glass or polyamide film.

The double mold device seen in Figure 6 is very similar to the over/under single mold except that it has an additional inner mold. This inner mold is usually white epoxy resin

with high dielectric properties that acts similarly to a light pipe or an optical waveguide.¹⁴ For both of these molded designs, all contents and the inner mold are housed in light-blocking black epoxy resin.

Figure 6.¹⁴ Double mold design of an optocoupler. The outer mold is the black epoxy and the inner mold is the white epoxy, represented by the grey shaded area.

The polymers used in optocouplers all have specific properties that are crucial to the efficiency of the device. Silicone resins are often used because they have high reflectance properties at a wide range of wavelengths. They also have good thermal conductivity and heat resistance.¹⁵ Polyimides are used frequently as optical waveguides because of their mechanical, thermal and optical properties. They are extremely stable under high-intensity light sources and tend to show low optical insertion loss, which means that the light lost between two fixed points is very minimal.¹⁴ Epoxy resins are generally used as the dielectric because they are good insulators and provide additional protection for the fragile electrical components. Epoxy resins also typically have low shrinkage while curing, so the risk of damaging the sensitive contents during the cure is low.¹⁶

Aside from the structure of the device, polymers can also be found in the LED and photodetector components. Within the past thirty years, the use of polymers in electronics has increased tremendously, due to their versatility and low cost. The first organic optocoupler was made in 1994 by combining a polymer light emitting diode (PLED) comprised of poly(2-methoxy5-2-ethyl-hexyloxy-phenylenevinylene) (MEH-PPV) and an organic photoresistor made of poly(3-octyl-thiophene), or P3OT.⁸ Since then, the development of organic and polymeric optocouplers has improved greatly. There have been big advances in organic phototransistors, PLEDs and OLEDs (organic light emitting diode) as photoemitters and semiconducting diodes made from conjugated polymers. Conjugated polymers are desirable in these applications because they have the advantage of color tunability via chemical modification, as well as being lightweight, low-cost, and flexible at a wide range of temperatures. Compared to 1994, it is now a lot more common to find commercial devices with PLEDs and semiconducting polymers, though MEH-PPV and P3OT are still some of the most common materials used.⁸

Current Research and Future Directions

Optocouplers currently have a well-established role in commercial electronics. That is not to say, however, that

there are no opportunities for improvement. One of the biggest areas of research right now involves optocouplers' ability to tolerate radiation. Optocouplers are used extensively in electronic devices used in satellites and other spacecraft. Being part of such devices exposes them to the ionizing radiation of space, which can be quite harsh. The components in an optocoupler are very sensitive and depend on intricate, precise structures and designs. These delicate features do not have a good tolerance for radiation because radiation transfers energy to the device and causes the properties of its materials to change. These material changes can cause the optocoupler to give false signals, and can cause its components to degrade, permanently damaging the optocoupler. Unfortunately, many of the common polymers used in optocouplers are not great at shielding the sensitive optocoupler components from radiation.¹⁸

A great deal of current research is focused on trying to identify which components of the optocoupler are most sensitive to which types of radiation, and how to avoid radiation damage. A study done by Chernyak et. al shows that the most critical temperature for a digital optocoupler to be exposed to radiation is -60 °C, and the most sensitive region on the chip is the routing block (where the signal is transferred from the transistor to the rest of the device). They found that modifying this region by using p-well (donor) for routing rather than n-wells (acceptor) tripled the device's tolerance to radiation.¹⁸ Davydov et. al similarly concluded that the most radiation-sensitive component of an optocoupler is in fact the transistor or MOSFET. This is because the radiation significantly affects the crystal lattice structure of the doped silicon.¹⁹ Though it is important that the sensitive areas are identified, it is equally important that effective and accurate tests are developed to run on these devices before they are used in space crafts. This is a growing area of interest and is very involved since it requires an effective way of simulating the impact of protons and electrons in outer space.^{17, 20} Optocouplers will continue to be a powerhouse in the world of electronics and with the development of potentially radiation-tolerant devices, the demand for their application in space will most likely increase.

In addition to space applications, there is research being done on the failure mechanisms of optocouplers used in everyday life. Wu et. al studied the failure of various optocouplers and divided the failures into extrinsic and intrinsic categories. The extrinsic failures are the result of improper management of the devices, while intrinsic failures stemmed from the actual properties of the materials being used. These properties include coefficient of thermal expansion (CTE), thermal resistance, poor adhesion, and wire bonding. They found that one of the most overlooked causes of optocoupler failure is poor attachment of the die components. Ideally, die are attached with some form of adhesive that has high thermal conductivity and low thermal resistance so that heat may be dissipated. Furthermore, the adhesive must be strong enough to resist the stress caused by a difference in CTE between the die and the submount. They found that a common failure was the adhesive itself. It was often not strong enough to combat peel stress, so delamination (Figure 7) was occurring between the die and the sub mount, resulting in weak or missing signals.²¹

Figure 7.21 Locations where delamination occurred due to weak adhesive.

My Project Involvement

I am currently involved in a project with a group who wants to manufacture their own optocouplers after experiencing several failures from commercial suppliers. The group suspects that the polymers involved in the commercial optocouplers are causing them to fail thermal stress testing and they are also finding that the supplier is unwilling to disclose the exact polymeric encapsulants they use. Therefore, this group is hoping to select new, better polymers in the hopes of producing an in-house optocoupler that better meets their rigorous, unique requirements. I will be investigating the thermal/mechanical properties and the cure profile of different materials as well as expansion/contraction via thermomechanical analysis (TMA), dynamic mechanical analysis (DMA) and differential scanning calorimetry (DSC).

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