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AN EVALUATION OF LIGHT EMITTING DIODES AS SOURCE LAMPS IN PHOTOELECTRIC SMOKE DETECTORS

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ABSTRACT

This paper discusses the factors to be considered in evaluating light emitting diodes when used as unsupervised source lamps in photoelectric smoke detectors. Primary failure modes of the devices are covered as well as methods and design parameters intended to minimize these failure modes. The paper provides a basis for, and concludes with the requirements now being established by Underwriters Laboratories Inc. for light emitting diodes used in this application.

Key Words - Arrhenius Law, Light Emitting Diode, Light Degradation Rate, Photoelectric Smoke Detector.

REFERENCES

(1) Optoelectronics application seminar manual, Hewlett Packard, Palo Alto, CA (no date), P29.

(2) Standard For Single And Multiple Station Smoke Detectors. Underwriters Laboratories Inc., Northbrook, Ill., UL217 (February, 1975 draft revised) P25 through 27.

Reliability is obviously an important factor in the design of smoke detectors, especially for residential applications. Field data received from many sources indicate that, by far, the major cause of nonoperating residential smoke detectors is the lack of regular required maintenance, such as battery replacement, lamp replacement, cleaning of chamber, etc.

In the case of battery-operated ionization type detectors one would feel that changing of batteries would be a familiar process to a homeowner since almost any home has many battery-operated appliances (e.g., toys, flashlights, radios, etc.). Fire alarm installers and manufacturers find, however, that many people simply let the detector units go dead and do not bother to replace the batteries even when reminder cards are sent.

Photoelectric detectors currently being produced generally use incandescent lamps with an expected life to 1 to 3 years. It appears that these too are not always replaced by the homeowner even though at least one spare bulb is provided with each detector. One photoelectric manufacturer indicated that more than half of the detectors returned to the factory as inoperative, had only burned out source lamps.

It is interesting to note that statistically for detectors employing a part which requires annual replacement, less than half of the detectors in the field will still be operating within 10 years after installation.

Most of these data have been gathered on detectors which have been purchased through catalog or door-to-door sales, resulting in what could be termed as a "conscious purchase." One may ask what the effect will be with the adoption of new building codes requiring detectors in all new living units where people have a device they did not buy directly and may or may not even realize they have.

Based on the above, it would appear that it is imperative to design detectors which require minimum or no maintenance to be performed by the homeowner. Since many present building codes allow battery-powered detectors only in existing construction, the battery replacement factor is somewhat limited to those cases where the homeowner makes a "conscious purchase." Thus a major step in rectifying this situation in the legislated market would be to manufacture photoelectric detectors with a source lamp which will last the life of the detector without replacement.

A major step in that direction is the present trend toward the development by manufacturers of detectors which employ light emitting diodes as source lamps.

LED's are semiconductor junction devices with much the same electrical characteristics as the common silicon diode. They emit light energy due to the recombination of minority carriers under forward bias conditions. Under the influence of a forward bias potential, electrons in the semiconductor crystal are raised from the valance band to the conduction band, flow across the junction, and recombine with holes to reach equilibrium. In this recombination they pass from the conduction band through discrete levels or quanta back to the valance band. It is in this band-gap transition that the energy of the electron is released in the form of a photon whose energy is equal to the band-gap energy.

The photon wavelength is inversely related to its energy according to:

$$E = \frac{1240}{\lambda}$$

E = Photon energy (ev).
λ = Wavelength (NM).

There are three basic types of LEDs used at present. These are Gallium Phosphide (GaP), Gallium Arsenide (GaAs) and Gassium Arsenide Phosphide (GaAsP). These basic crystals along with various dopants used to vary their band-gap energy can be used to produce devices with light outputs from infrared (0.9 microns) to green (0.55 microns). Since the amount of doping required to adjust the band-gap energy and thus the wavelength of an LED affects the cost and photon emission efficiency of the device, the most popular current LEDs are of the red or infrared type.

As stated earlier, the reason for the transition from incandescent lamps to LEDs is the reduction of lamp replacement maintenance. Where the normal expected life of an incandescent lamp is 1 to 3 years, a good quality LED, properly applied, is believed at last 50 years or more based on accelerated tests and projected data. Proper application and careful manufacturing techniques to achieve long life on a production basis is, however, a fairly complex subject.

Light emitting diodes have two basic failure modes. These are: (1) catastrophic failures, and (2) gradual light output degradation.

Catastrophic failures are usually caused by manufacturing flaws and misapplication of devices. These failures may be mechanical or electrical in nature such as:

Mechanical Failures - (1) Die-attachment (die-bond) fracture.
(2) Anode lead bond fracture.
(3) Separation of anti-reflection coating or index matching encapsulation.
(4) Separation of the anode contact metalization.

Electrical Failures - (1) Anode lead burnout.
(2) Shorts or leakage external to the die.
(3) Bulk failure at the semiconductor junction.

Since the catastrophic failure modes and fabrication techniques of transistors and integrated circuits are similar to those of LEDs, production and testing methods used to reduce failures and increase overall reliability of other semiconductor devices can be applied to LEDs. Using these methods, failure rates for LEDs of as low as 0.1 percent per 1000 hour are easily achieved while maintaining a reasonable device cost.

While most LED manufacturers are able to manufacture devices with these failure rates, it has been the experience of many users that the reliability and performance of individual units from a given manufacturer are quite variable. Therefore, a strict quality assurance (QA) program, both by the LED manufacturer and by the smoke detector manufacturer, is essential.

To meet these goals it should be required that the LED manufacturer provide lot sample testing of the chips for important optical efficiency, conduction, reverse breakdown, and anode bond and chip peel tests. They should also conduct 100 percent production tests of light output, conduction, leakage, and reverse breakdown on the finished product.

The detector manufacturer should be required to conduct a burn-in at an elevated temperature on all units to weed out those devices which would fail early. After such a burn-in, 100 percent inspection of light output, conduction, leakage and reverse breakdown parameters should be conducted. This type of program, in conjunction with an LED with a failure rate of not greater than 0.25 percent per 1000 hour, should result in a minimum of failures before the epxected end-of-life of the detector.

The second major LED failure mode is that of gradual light output degradation. Although all LEDs decrease in light output with time the rate of decrease depends to a great extent on the cleanliness of the manufacturing process.

Mobile contaminant ions diffuse under forward conduction into the semiconductor junction where they combine with light producing centers resulting in a reduction in the quantum efficiency. By maintaining a clean process, the number of contaminant ions can be reduced, resulting in a reduced degradation rate.

The degradation rate is also dependant on the operating junction temperature of the device. Reducing the junction temperature will reduce the mobility of these contaminant ions and also reduce the rate of decrease in light output.

Since the failure rates of nearly all semiconductor devices are primarily dependant on the junction temperature, mathematical methods havy been developed for predicting rates based on accelerated testing. One such method is the Arrhenius Law which states:

$$R = Ae^{-B/T}$$

Where: R = Degradation rate at temperature T.
A = Constant for a given device.
B = Arrhenius coefficient, constant for a given device.
T = Absolute junction temperature.

Since average life is the reciprocal of the failure rate, the constants A and B can be determined by conducting accelerated life tests on identical LEDs under the same electrical operating conditions at various elevated temperatures, and plotting log time to failure vs $\frac{1}{T}$.

This plot is a straight line for LEDs, allowing easy extrapolation to normal temperatures.

It is generally accepted among LED producers that the end-of-life in terms of light degradation occurs when the light output reaches 50 percent of the original. Since the degradation rate for most devices is exponential, the greatest reduction is experienced in the first few years of operation. Thus, it would appear that some type of compensation for this reduction would be necessary in a smoke detector in order to maintain a stable sensitivity. it would also be necessary to operate the LED at a junction temperature such that the 50 percent light output point would not be reached before the predicted end-of-life of the detector, and at that time, the sensitivity of the detector would be required to be within acceptable limits.

These predictions would be based on the assumption of a uniform level of cleanliness maintained by the LED manufacturer. This reinforces the need for a strict QA program by both the LED and detector manufacturers.

The design considerations are the last major factor in assuring reliable operation of smoke detectors with LED sources.

Hewlett Packard, a major manufacturer of LEDs, makes the following statements: (1)

> "For direct current operation, the drive current source should be designed such that it remains less than the maximum direct current rating at any temperature.
>
> In alternating current operation, or with pulsed sources, the LED will tolerate peak currents such higher than the direct current rating if pulse duration is less than one millisecond and the duty factor is less than 50 percent. Under these conditions, the direct current rating applies to the average rather than the peak current. Such operation is more efficient for light production than direct current.
>
> If pulse duration exceeds one millisecond, the direct current rating must apply to peak current."

In addition, it appears reasonable in alternating current or pulsed operation, that all negative voltages such as negative transients and pulse undershoot should be eliminated so as not to subject the diode to reverse bias.

Another constraint on pulsed operation would be pulse rise and fall times and pulse width. If rise and fall times are small, high current densities could be achieved, which may cause stress failures in the area of the high density. If pulse widths are long, excessive thermal stresses may be generated from rapid temperature cycling which may also lead to early failures.

In conclusion, it can be said that the proper design of an LED detector along with strict QA programs can produce a highly reliable detector which requires minimum or no maintenance. Observance of these constraints would result in a light source which is at least as reliable as the other components in the detector circuit. Since the LED would be as unlikely to fail as other components, supervision requirements could be reduced or eliminated, resulting in a substantial reduction in cost and an increase in overall reliability of the detector. This increase in overall reliability would be achieved since the primary factor affecting the overall MTBF of an electronic device is the number of electronic components it contains. The cost reduction would also make detection more easily available to the public.

Based on the reasons outlined above, Underwriters Laboratories Inc. is establishing the following requirements for smoke detectors employing light emitting diodes as source lamps:

Light Emitting Diode (LED) Source Lamps (2)

15.27 In photoelectric detectors employing a LED light source not considered reliable, the source shall be supervised for an open short and greater than 50 percent light degradation by means of a trouble signal. Failure of the light source shall not result in an alarm signal.

15.28 A trouble signal for greater than 50 percent light degradation is not required if light degradation data is supplied by the LED manufacturer to show that, for the conditions under which it is to be operated, the LED will not reach 50 percent light output for at least 30 years.

15.29 When the light output of a LED source lamp is reduced to the 50 percent level, the sensitivity of the detector shall not be reduced by more than 50 percent of the value at full output but in no case shall it exceed 4 percent per foot for grey smoke and 10 percent per foot for black smoke.

15.30 In photoelectric detectors employing a LED light source considered reliable, the source need not be supervised. Failure of a reliable LED may result in an alarm signal.

15.31 To be considered reliable, a LED shall have a predicted failure rate of less than 0.25 percent per 1000 hours, and shall comply with the requirements in paragraphs 15.28 and 15.29. In addition, the operating conditions of the LED in the detector circuit, as well as the diode and detector manufacturer's quality assurance (QA) programs, are to be evaluated as to the level of reliability they provide.

Operating Conditions

15.32 For direct-current operation, the drive current shall not exceed 75 percent of the direct current forward current rating.

15.33 For pulsed operation, where the pulse duration is less than one millisecond and the duty factory is less than 50 percent, the peak current shall not exceed 75 percent of the peak forward current rating and the average current shall not exceed 75 percent of the direct-current forward current rating.

15.34 For pulsed operation, where the pulse duration exceeds one millisecond or the duty cycle is greater than 50 percent, the peak current shall not exceed 75 percent of the direct-current forward current rating.

15.35 For all pulsed applications, the pulse rise and fall time shall be greater than 15 nanoseconds.

15.36 For all applications, the LED shall be electrically protected from negative voltages from transients or pulse undershoot exceeding 25 percent of the rated reverse voltage.

Quality Assurance Program

LED Manufacturer

15.37 Verification shall be provided by the LED manufacturer to indicate compliance with the following minimum quality assurance program:

A. Lot sample testing of optical efficiency, anode bond, and chip peel tests are performed on diode chips.

B. 100 percent production tests of light output, forward conduction, leakage, and reverse breakdown on the finished product.

Detector Manufacturer

15.38 The detector manufacturer shall conduct the following minimum quality assurance program on the LED lamps:

A. An incoming LEDs, in a de-energized condition, are to be subjected to a thermal stress consisting of 10 cycles of temperature variation from -40 to +85°C with 30 minutes at each extreme and 5 minutes between extremes. Each cycle consists of starting at -40°C, going to +85°C, and returning to -40°C. Following the thermal stress the LEDs are to be subjected to a minimum 16 hours burn-in period at 110 percent of normal circuit current at rated circuit voltage under room temperature ambient conditions prior to inspection.

B. Following the burn-in, 100 percent inspection of light output, forward conduction, leakage, and reverse breakdown shall be conducted.