TECHNICAL NOTE

Surface Temperature Measurement

A Comparison of Electrical, Infrared, and Fluoroptic® Techniques

Introduction

In order to determine the temperature of a solid object, it is generally necessary to measure the temperature of its surface. It would be preferable, for reliability of the measurement, to drill a small hole in the object and then insert the temperature sensor into the hole so as to “immerse” the sensor in material at the temperature of interest. However, if the object is an operating electronic component, a semiconductor wafer, or an extremely small device, this approach is not practical.

Meaningful measurements of surface temperature are very difficult. Good measurement procedures are typically tedious and time consuming. What is frequently needed, especially for use during electronic device manufacture or for operational testing of finished electronic components, is a technique which is both fast and convenient while, at the same time, being reasonably accurate and reliable. Until recently, no such technique has been available. This note will review briefly surface temperature measurement problems, historic approaches and their limitations, and the solutions recently provided by Luxtron’s Fluoroptic® thermometry technology.

Basic Problems of Contact Measurements Using Electrical Sensors

To measure the temperature of a hot object with a contact sensor, one must first bring the sensor into good thermal contact with the surface. Heat will then flow from the object to the sensor, raising its temperature in the process. The sensor and object will eventually reach thermal equilibrium. The equilibrium temperature of the sensor will depend on (1) the quality of the thermal contact; (2) the thermal mass of the sensor relative to that of the object, and; (3) the degree of thermal isolation of the sensor and object from the surrounding environment.

With a “hard” sensor such as a thermocouple, thermistor, or RTD, the only simple way to achieve reasonably good thermal contact with the surfaces is to epoxy the sensor directly to the surface. This provides not only a secure attachment but a thermally insulating barrier over the sensor so that the sensor sees primarily the temperature of interest. This is not a rapid attachment procedure and it does increase thermal mass. Furthermore, it may be difficult to remove the sensor once the measurement is complete.

There are several other difficulties in using a thermocouple, thermistor, or RTD for making surface measurements.

If the thermal contact is imperfect or if the sensor has significant thermal mass relative to that of the object being measured, the equilibrium temperature of the sensor will be measurably below that of the surface prior to contact with the sensor.

If the material whose surface is being measured is a poor conductor of heat, the rate of replacement of heat drawn away by the sensor may also be a factor both with regard to the time it takes to reach equilibrium and the final equilibrium temperature.

Last, but not least, if the sensor itself is attached to electrically-conducting metallic leads, as would be true of all electrical sensors, these leads, since they are also good conductors of heat, will conduct heat away from the sensor thereby lowering its temperature further. (This effect is illustrated dramatically in Figure 1c to be discussed later in this note.)

The above problems apply regardless of the type of measurement environment. They are made worse if the measurement must be made in a vacuum. In such an environment, thermal contact is typically worse since there are no air molecules present to help conduct heat from the surface to the sensor. If the measurement environment is also electrically hostile (i.e. if it involves a strong RF or microwave field, an RF plasma, or a high voltage gradient), the electrical sensors will experience other serious problems as well.

The Infrared Approach

One obvious approach to solving the above problems is to find a way to make a measurement of surface temperature from a distance without any physical contact. This is possible using infrared radiometry. With this approach thermally-generated infrared radiation from the surface is collected and focused onto an infrared detector. Since all materials emit infrared radiation in an amount and energy range which are well-defined functions of their absolute temperature and their infrared emission efficiency (emissivity), it is possible, in principle, to interpret the received infrared radiation in terms of the temperature of the emitting surface.

Why is this then not an adequate solution to the surface temperature measurement problem? In some case, it may be. However, the infrared radiometric approach has major limitations. First, the total infrared energy emitted by the surface varies as the fourth power of its absolute temperature. While there may be plenty of photons available at high temperature, there may not be at moderate to low temperatures. Hence, sensitivity may be poor at such temperatures. Furthermore, there are frequently problems of screening out reflected energy from other adjacent warmer objects.

The peak of the emitted infrared radiation shifts to shorter wavelengths at higher temperatures. Thus while substantial visible radiation is emitted by the hot tungsten filament of an electric light bulb, a room temperature object has most of its emission at a wavelength of 10 microns in the infrared – some 20 times the wavelength of visible light. Detectors are noisier and less sensitive at such long wavelengths and many materials, including water, plastics, and glass or quartz fibers are not transparent at such wavelengths.

There are several other difficulties in using an infrared system:

Line of sight access to the surface is required. It may be difficult to achieve direct access to the region to be measured.

The collecting optics of infrared systems are typically quite large. In electrically active environments, the large optics provide a direct path for RF or microwave energy to reach the very sensitive front end electronics of the radiometer, further contributing to noise and sensitivity problems.

The most serious problem of all, however, is the wide variability of the infrared characteristics of typical materials of interest. Emissivities can vary from nearly unity for water or organic materials such as human skin to as little as .01 for a highly reflective polished silver surface. All metals, in fact, have low emissivities and hence may appear much “colder” in the infrared than they are. However, a thin layer of oxide or a thin film of an organic material on the metal surface can change the emissivity drastically. Since, in may electronics fabrication applications the surface is being coated or etched, the surface emissivity is continuously changing with time. Furthermore, in finished devices, the surface may contain a wide variety of materials which are optically not resolvable from one another so the average (observed) emissivity may not be known.

Silicon, germanium, and gallium arsenide, like most semiconductor materials, are transparent throughout most of the infrared, further contributing to measurement problems. The majority of observed infrared energy, for example, may be transmitted through the semiconductor material from a source somewhere behind it (or at a depth within it).

All of this says that while infrared radiometric techniques may be of qualitative value for device-to-device comparisons, they are of limited use for absolute measurements of electronic circuits during fabrication or testing.

The Fluoroptic® Alternative(s)

Luxtron's most recent fiberoptic thermometry technology utilizes the measurement of the fluorescent decay time of a luminescent sensor. This technology, described in more detail in other Tech Notes and articles, offers not one but two possible solutions to the surface temperature measurement problem. The first solution utilizes a novel type of contact sensor which eliminates most of the drawbacks mentioned earlier for electrical contact sensors. The second solution involves a remote measurement technique which operates in the visible rather than the infrared region of the spectrum and provides absolute rather than qualitative temperature information.

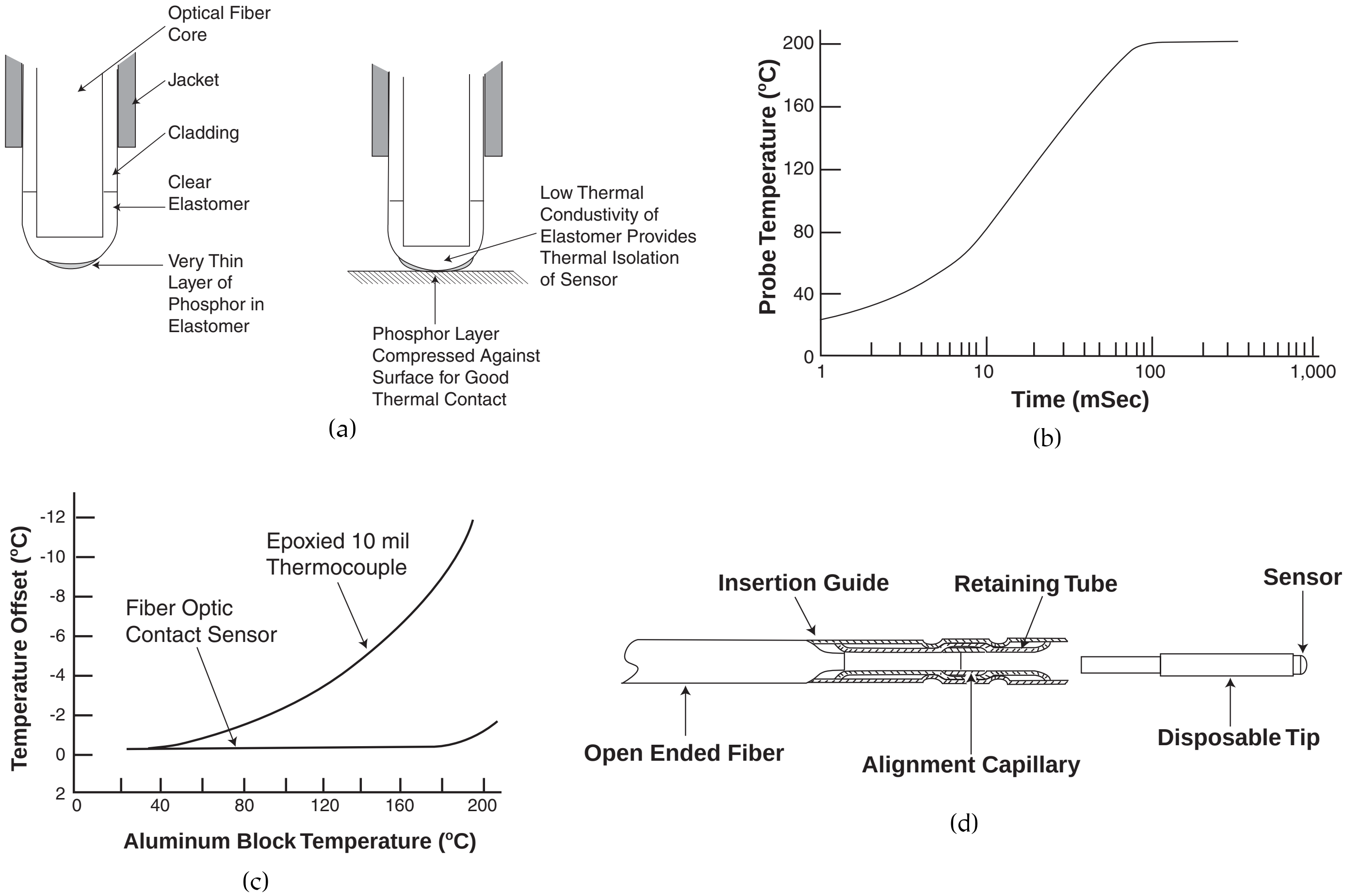
In the first solution, a very thin layer of the sensing material is coated onto the exterior of a transparent elastomeric hemisphere constructed at the tip of an optical fiber. When this sensor is touched to a surface, the elastomer deforms so that the phosphor layer is then held in intimate contact with the surface. Since the thermal mass of the sensing layer is very small and since the thermal conductivity of the elastomer and optical fiber are quite low, the sensor responds very quickly, reaching a temperature which is essentially the same as that of the surface within 100ms. No permanent attachment of the sensor to the solid surface is required and the measured offset is quite small (at least up to 200 C). (At temperatures above 250 C, the elastomer loses its elasticity and the tip becomes permanently deformed.) Figure 1 shows the design of the elastomer-tipped probe, its response time and its offset relative to that of a thermocouple of similar size epoxied to the surface. Note the pronounced offset of the thermocouple reading at high temperatures. This is the result of heat conducted away from the sensor by the metallic leads.

The probe tip if not overheated, retains its elasticity indefinitely. However, abrasion of the tip can lead to loss of the thin sensing layer. As a result, this probe is designed with an easily replaceable sensing tip (see Fig. 1d).

In the second approach, the sensing material is coated directly onto the surface of interest and viewed remotely. Since the fluorescent decay time measurement technique is totally optical, it can be used for measurement at a distance provided there is no interference from any flickering background light as might be caused, for example, by light reflected from a fluorescent lamp. If such background light is screened out, the remote approach can be used either with an open-ended fiber brought close to but not touching the sensing layer or, if longer distances are required, with a lens assembly to reimage more efficiently the fiber end on the sensing surface.

The remote approach retains the absolute measurement capability of the technology while eliminating most of the contact problems. If the presence of the phosphor layer on the surface of a part being processed is objectionable, as it might be in the case of semiconductor device fabrication, the sensor material can be coated onto a witness sample and then overcoated with an acceptable (transparent) passivating layer. Figure 2 illustrates the remote measurement concept and the resulting accuracy of the measurement. Tech Note TN86-7 discusses the remote technique in more detail.

Figure 1: (a) Elastomer-tipped probe showing surface-sensing design features; (b) Time response of elastomer-tipped probe when touched to a 200 C surface; (c) Temperature offset of elastomer-tipped probe touched lightly against an instrumented test block as compared with that of a thermocouple epoxied to the same test surface; (d) Design of the replaceable tip of the elastomer-tipped probe.



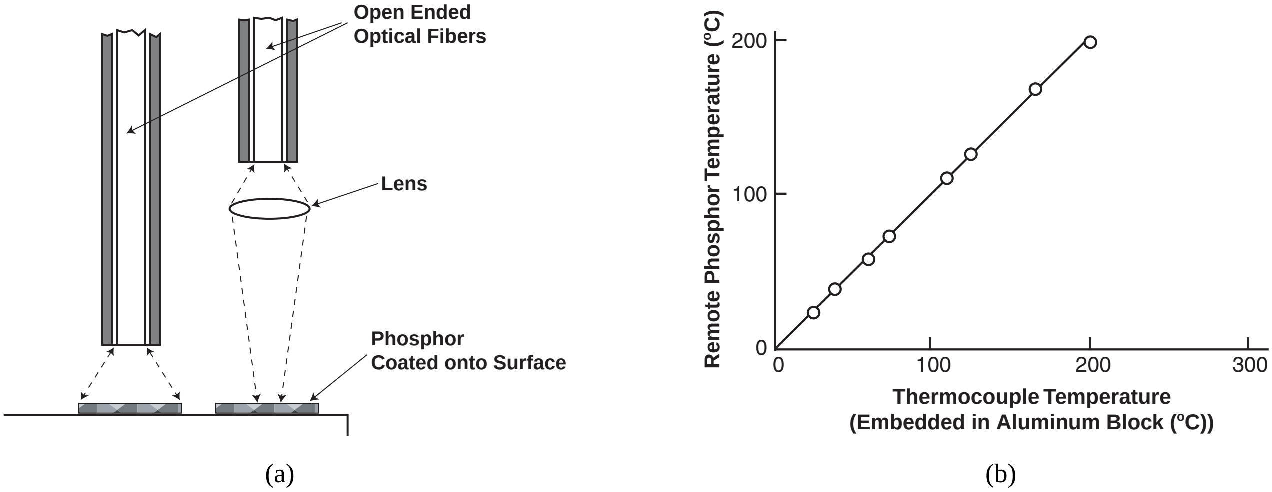
(a)

(b)

(c)

(d)

Figure 2: (a) Methods of making a remote Fluoroptic® surface temperature measurement; (b) Agreement between known surface temperature of an instrumented test block and the measured temperature using remote Fluoroptic® techniques.



(a)

(b)