Temperature Measurements of Semiconductor Devices - A Review

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Abstract

There are numerous methods for measuring the temperature of an operating semiconductor device. The methods can be broadly placed into three generic categories: electrical, optical, and physically contacting. The fundamentals underlying each of the categories are discussed, and a review of the variety of techniques within each category is given. Some of the advantages and disadvantages as well as the spatial, time, and temperature resolution are also provided.

Keywords

Electrical, measurements, optical, semiconductor, temperature

1. Introduction

'Operating' temperature has important consequences for the performance and reliability of semiconductor devices. For instance, the speed, or maximum operating frequency, of a microprocessor typically decreases as the temperature increases, and the gain or transconductance of a transistor may either increase or decrease with increasing temperature, depending upon the device type and operating conditions. It is also commonly assumed that the safety margin or reliability of a semiconductor device decreases as the temperature increases. It is not surprising, then, that a significant amount of effort goes into accurately measuring the temperature at which devices operate.

The topic of measuring the temperature of semiconductor devices is in many ways 'mature' in that people have been trying to measure the temperature of semiconductor devices from the time of the invention of the transistor. It remains, though, a very relevant topic in that people are still inventing new methods to address temperature measurement issues that previously had no solutions and because thermal management and temperature control are probably more of a concern today than ever before [1-3]. Moore's law dictates that devices and circuits will continue to shrink in size, be packed more densely, operate at higher switching speeds, and dissipate more power overall [4]. The major temperature measurement challenges associated with these advances include improvements in the spatial and temporal resolution of the measurements.

The act of 'measuring' the temperature is in reality the measurement of some physical phenomena which itself is affected or changed by temperature. The physical phenomena by which the temperature of a device 'makes itself known' are many and varied, and thus a wide range of methods have been employed for measuring and predicting the temperature at which devices operate. For semiconductor devices, the useful temperature measurement methods can be divided into the broad, generic categories of electrical methods, optical methods, and physically contacting methods. In the first two categories, the temperature variation of some property of the device (an electrical or optical property) is used as a thermometer. In the third category, a temperature transducer (such as a thermocouple) assumes the temperature of the device through intimate contact, and it is the temperature of the transducer that is actually measured.

It is the intent here to briefly review a number of commonly used and useful methods for measuring device temperature. The physical basis underlying the measurement will be presented, some indication of accuracy and spatial and temporal resolution will be provided, and any special requirements or precautions associated with each measurement will be discussed.

2. Generic Methods

There are many different ways to measure the temperatures within a semiconductor device or circuit. A wide variety of electrical and optical phenomena associated with semiconductor materials and the devices fabricated from them are temperature sensitive and can be used as thermometers. Also, there are a variety of temperature transducers that when in contact with the device can be used to indicate the temperature of the device. In the following, each of the generic types will be described briefly before looking later at more specific methods belonging to each type. Figure 1 shows each of the generic types being used on a typical chip.

2.1. Optical

To use the optical properties as a thermometer, either naturally emitted radiation, reflected radiation, or stimulated emitted radiation is measured. As an example, an optical beam (of photons) is focused at a point on the device, and the incident photons will interact with the device in the region of the point of focus. (If there is no interaction, then the photons will travel unimpeded through the object, and the object is transparent to the photons - a situation that is rather uninteresting for our discussion.) One interaction among several that may occur is that some fraction of the incident photons will be reflected, or scattered back, from the surface (or from a thin surface region) of the object. The actual reflection or scattering results from a complicated interaction between the incident photons and the lattice phonons (and maybe the electrons) of the object being probed. The distribution in energy of the lattice phonons is a strong

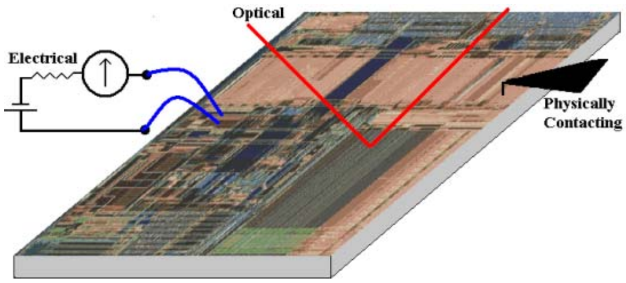


Figure 1. Examples of generic methods for measuring temperatures of semiconductor chips.

function of the local temperature of the object, and the net result of the photon-phonon interaction is that the relative number, and maybe the energy and phase of reflected photons (with respect to the incident photons), changes with temperature of the object. Clearly, if these changes are carefully measured, they might be used to infer the temperature of the probed object in the region of the point being probed. Optical methods can be considered to be non-contacting in the sense that only photons interact with the device, and the effect on the device operation or its temperature due to the interaction can usually be neglected. Spatial resolution of optical methods is determined by the size of the optical probe and the region over which it interacts with the device. The time response is determined ultimately by the response time of the optical phenomena to changes in temperature, but also practically by instrumentation response. Advantages of optical methods include that they can have very high spatial resolution, can often measure rapid variations in temperature, and are non-contacting. Also, temperature maps of the surface of a device can usually be easily made from a matrix of measurements. Disadvantages are that one must have optical access to the device, something not usually possible if the device is packaged, and the equipment required is often expensive and difficult to use.

2.2. Electrical

Many of the electrical properties of semiconductor devices and circuits can be strong functions of temperature. PN-junction forward voltage, threshold voltage, leakage current and gain, to name but a few, are examples of electrical temperature sensitive parameters (TSP). Obviously, a careful measurement of any of these quantities can also be used to infer the temperature of an operating semiconductor device [5]. There are fundamental and conceptual differences, though, between these electrical measurements of temperature, and the previously described optical probe techniques. Conceptually at least, the optical probe can be made very small and thus be used to probe the temperature of a very small, well defined region of the device. A point-by-point map of the temperature at different positions on the device might even be made.

Electrical methods, though, by their very nature, are lumped, or averaging, methods. For instance, the forward voltage of a pn-junction at a constant current is known to vary with temperature in a predictable way. Thus, the forward voltage can be used to infer the temperature of the junction but not necessarily the temperature anywhere else in the device. In many instances, the device temperature is nearly the same everywhere; therefore, this is of little consequence. However, in other instances, this is not the case. Even the junction temperature may not be the same everywhere in the junction. The model used to determine the variation of the forward voltage of a junction with temperature should be considered a 'lumped' model in that the distributed nature of the electrical and thermal behavior of the junction is lumped into a model with a single temperature, single voltage, and single current density. This idea is shown pictorially in Figure 2.

Although electrical methods sacrifice some specificity of the measured temperature, their advantage is that no special sample preparation is required because all the necessary electrical connections are already available, since they are required for normal device operation. Electrical methods are thus considered to be non-contacting because the electrical contacts required to make the measurement are those already required for the device to operate.

The spatial resolution of electrical methods is often difficult to determine. As evidenced from the discussion above, the temperature indicated is some lumped average temperature of the actual temperature distribution. The time resolution is practically determined by measurement interferences and parasitic effects that will be discussed later. Advantages of electrical methods are that they are non-contacting and are the only type that can be made on fully packaged devices. The major disadvantages are the fact that the spatial resolution can not usually be well determined and that only a single, averaged temperature is measured for a device that usually has some temperature distribution (i.e., temperature maps cannot be made).

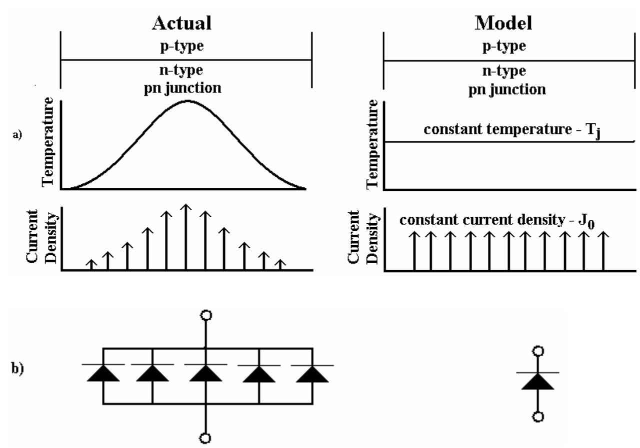


Figure 2. An illustration of the actual and modeled situation for a pn-junction. a) the temperature and current density, and b) the diode models (distributed and lumped).

2.3. Physically Contacting

Methods that rely on physically contacting the device include point contacting, such as thermocouples and scanning thermal probes, and multiple contacting or blanket coatings, such as liquid crystals and thermographic phosphors. All rely upon a transfer of thermal energy, or heat, from the device of interest to the object contacting the device, the thermometer. The nature of that energy transfer and the possible effect on the device temperature of conducting heat from the device are important considerations with these methods. Spatial resolution for contacting measurements are determined by the size of the probe or coating particles being used, and time response depends upon the thermal response times of the probe or particles. Advantages of contacting methods are that they can have very good spatial resolution, less than 100 nm in some instances, and, like the optical probes, temperature maps can be made. Temperature maps require a matrix of measurements for the point contact methods and are an inherent feature in the blanket coating methods. Disadvantages are the fact that the surface of the device being measured must be available for contacting (thus packaged chips can not be measured) and the thermal response depends upon the response of the probe, which may be considerably slower than that of the device.

This has been intended as an introduction to the generic methods that can be used to measure the temperature of an operating semiconductor device. In summary, there are methods that use: i) an optical probe, ii) temperature sensitive electrical device parameters, or iii) a physically contacting probe to measure the temperature. Table I shows some of the characteristics and relative advantages and disadvantages of the generic types of measurements. In the following sections, more detailed discussion is given of specific methods of each generic type.

Method	Examples	Advantages	Disadvantages
Electrical	♦Junction voltage ♦Threshold voltage ♦Resistance	♦Packaged device ♦No contact ♦Potentially subsurface	♦Averages ♦May require special device operation
Optical	♦Infrared emission ♦Reflectance ♦Raman	♦Temperature map ♦No contact ♦Good Spatial resolution	♦Need surface view ♦Potentially expensive
Physical Contact	♦Scanning nanoprobe ♦Liquid crystals ♦Thermographic phosphors	♦Temperature map ♦Potentially high spatial resolution	♦Need surface view ♦Contact may disturb temperature.

Table I. Generic methods for measuring temperature of semiconductor devices.

3. Electrical Measurements

Electrical methods for measuring temperature are attractive because they can be made on packaged devices; i.e., visual or mechanical access to the chip is not required. The major disadvantage is that only a representative average chip temperature can usually be determined and temperature maps can not be made. A major concern with the use of electrical parameters as thermometers is the separation of the effects of temperature from the inherent electrical variations of these parameters. As an example, for a diode, when the current is increased the temperature will also increase (due to the increased power dissipation). The effects on the diode voltage will be that the voltage will tend to *increase* due to the increasing current, but it will also tend to *decrease* due to the increasing temperature. The electrical effect must be isolated or eliminated to use the temperature variation of the voltage as a thermometer for the diode.

Another concern with electrical measurements is the calibration process. As with all temperature measurements, the electrical parameter that is to be used as the thermometer must be calibrated with respect to temperature. Calibration is usually performed by setting the device to a series of known temperatures (e.g., by using a temperature-controlled oven or hot plate, the temperature of which is measured with a thermocouple) and measuring the electrical parameter while the device is set to each temperature. It is assumed that the device is at the same temperature as the oven or hot plate. For non-electrical methods, there is no self heating of the device during calibration, and all of the heat is being supplied externally by the oven or hot plate. It is usually a very good assumption that the temperature of the hot plate or oven is the same as the device temperature when no self heating is occurring. For electrical measurements, though, by necessity, heat is dissipated within the device during the calibration process because some heat is always dissipated by the device when it is electrically active.

3.1. Switched and Non-Switched Measurements

As a result of the two concerns mentioned above, i) separation of the thermal from the electrical effects and ii) the effect of self-heating during calibration, there are two broad categories of electrical measurement: a) switched (pulsed) and b) non-switched (continuous). With switched measurements, the effects of self heating during calibration are minimized, but the effects of electrical interferences during measurement are increased. For non-switched measurements, the effects of electrical interference during measurement are minimized, but the effects of self-heating during calibration are increased.

Switched Measurements

For switched measurements, self-heating during calibration is minimized by keeping the dissipated power very low. Since the calibration and measurement must be performed for identical electrical conditions, this requires that, during the measurement phase, the device heating power must be momentarily switched to this very low value; thus the term, switched measurement. The major problems with switched measurements are:

1.) During the switching event, transient electrical signals interfere with the measurement. It takes some delay time (of the order of microseconds) for the electrical signals to 'settle down' to those of the calibration process. These electrical transients are a result of measurement circuit response time, charge storage in the device under test [6], and even parasitic effects due to the device package [7].

2.) During the delay time for the electrical transient to subside, the device cools (because the power has been reduced to the very low measurement level from the heating level).

Because of these two problems, the measured device temperature is less than the actual device temperature. Methods have been developed that can, by modeling the initial cooling of the device as a one-dimensional transient, compensate for the effects of the electrical transients and make improved estimates of the actual temperature [8].

Non-switched Measurements

For non-switched measurements, the parameter used as the thermometer is measured at the same conditions under which the device is being heated. This eliminates the problems with the switching transients during the measurements, but the problems now appear during the calibration. Because temperature changes due to self-heating must be kept as small as possible during calibration, the calibration process must now be performed under switched conditions; i.e., the high power used during the measurement must be switched on only momentarily during the calibration at each set temperature. The problems are:

1.) The temperature does rise by some amount during the calibration phase due to the large, momentary self heating effect. Thus, the actual device temperature during calibration is not the same, known temperature of the oven or hot plate.

2.) Electrical transients also interfere with the switching during calibration.

The issues with switched and non-switched measurements are summarized in Table II. Brief discussions will now follow of some of the electrical parameters that have been used to measure temperature.

3.2. PN-Junction Forward Voltage

The forward voltage of a pn-junction is probably the most commonly used electrical parameter for measuring the temperature of a semiconductor device. The relationship between the current through, the voltage across, and the temperature of an ideal pn-junction is given by the well known relation [9]:

$$I_{pn} = I_s[\exp(\frac{qV_{pn}}{kT}) - 1]$$

where I_{pn} is the current, q is the electron charge ($1.6 \cdot 10^{-19}$ C), k is Boltzmann's constant ($1.381 \cdot 10^{-23}$ J/K), V_{pn} is the voltage across the junction, T is the temperature, and:

$$I_s = I_0 T^{\gamma} \exp(\frac{-E_g}{kT})$$

where γ is a constant equal to about 3, E_g is the bandgap of Si (1.12 eV at T=275 K), and I_0 is a constant not dependent upon temperature. From the above equations, the variation of junction voltage with temperature at a constant current I_{pn} is found to be:

$$\left[\frac{\partial V_{pn}}{\partial T}\right]_{I_{pn}} = -\gamma \frac{k}{q} + \frac{\left(V_{pn} - E_g / q\right)}{T}$$

Measurement	Calibration	Issues
Pulsed	Continuous	* Time must elapse after switch to measurement condition before reliable measurement of the TSP can be made * Device cools before a measurement can be made
Continuous	Pulsed	* Time must elapse after calibration pulse is applied before a reliable measurement of the TSP can be made. * Device heats before calibration can be made.

Table II. Summary of switched and non-switched measurement characteristics.

Plots of the junction voltage and its temperature derivative versus temperature for a typical junction are shown in Figure 3 for three currents, each an order of magnitude apart. Figure 3b shows that the 'calibration constant,' $\frac{dV_{pn}}{dT}$, is approximately -2 mV/K and varies by about 7 % between 275 K and 475 K.

The forward voltage of any pn-junction can be used as a thermometer if it can be electrically accessed from the device's electrical leads. Some examples of the use of the forward junction voltage as a thermometer include the emitter-base junction of Si bipolar and GaAs heterojunction bipolar transistors [6,10-16], the gate-source voltage of GaAs field effect transistors (FETs) [17-21], the integral diode in Si power MOSFETs [22,23], and laser diodes [21,24,25].

3.3. Threshold Voltage

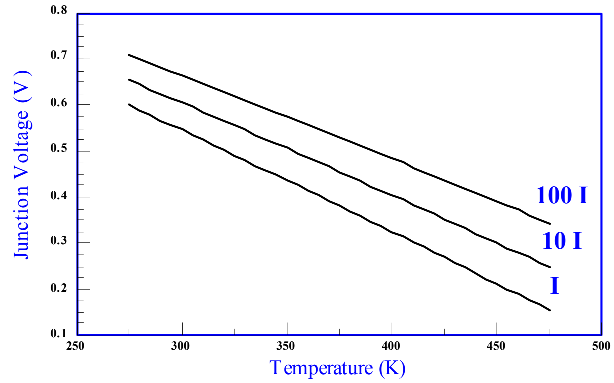
The temperature variation of the threshold voltage is given by [26]:

$$\frac{dV_T}{dT} = \frac{d\psi_B}{dT} \cdot \left(2 + \frac{1}{C_{ox}}\sqrt{\frac{\varepsilon_{Si} q N_A}{\psi_B}}\right)$$

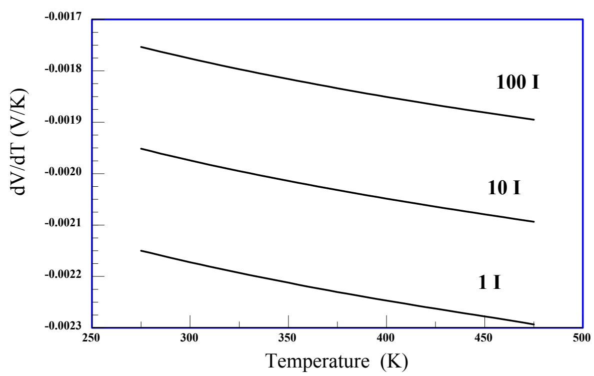
where:

$$\frac{d\psi_B}{dT} \approx \frac{1}{T}\left[\frac{E_g(0)}{2q} - |\psi_B|\right]$$

where V_T is the threshold voltage, ψ_B is the distance of the Fermi level from mid-gap, ε_{Si} is the dielectric constant of Si, N_A is the doping density, E_g is the band-gap at T=0, and C_{ox} is the intrinsic gate-channel oxide capacitance. A plot of the threshold voltage and $\frac{dV_T}{dT}$ versus temperature are shown in Figure 4 for two different combinations of oxide thickness, t_{ox}, and channel dopant density. As can be seen, the threshold voltage itself and its variation with temperature are functions of the oxide thickness and doping density. The curves in Figure 4a are representative of a discrete power MOSFET and those in Figure 4b more representative of a low power discrete or IC MOSFET. An advantage of using the threshold voltage is that the electrical circuit used for the measurement can be

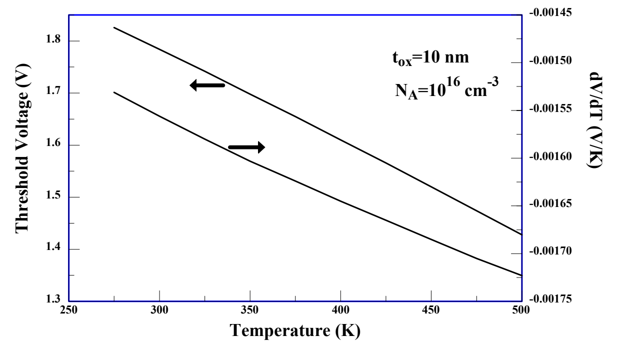


a)

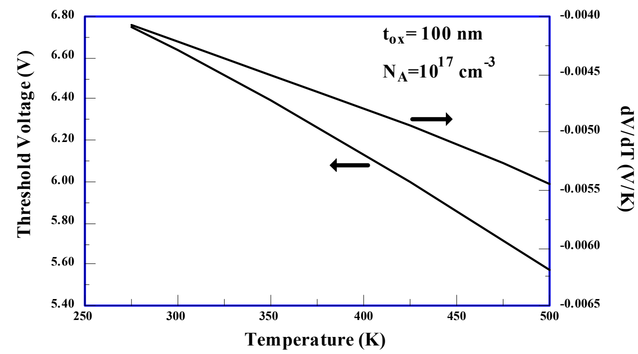


b)

Figure 3. Temperature variation for different currents of a) forward voltage of a pn junction, and b) the temperature derivative of the voltage.



a)



b)

Figure 4. Temperature variation of threshold voltage and temperature derivative of threshold voltage for representative a) power MOSFET and b) integrated circuit MOSFET.

made nearly identical to the one for using the emitter-base junction forward voltage for bipolar transistors [23]. A disadvantage is that the temperature derivative of V_T is a strong function of doping, as seen in Figure 4b, and thus varies significantly from device to device. In addition to power MOSFETs [23], V_T has been used for measuring the temperature of power Insulated Gate Bipolar Transistors (IGBTs) [22].

3.4. Electrical Resistance

The electrical resistance, R (ohms), between the ends of a bar of length, L(m), and cross-sectional area, A(m^2), is given by:

$$R = \frac{\rho \cdot L}{A}$$

where ρ (ohm-meter) is the resistivity and is given by:

$$\rho = \left[\sum n_i \cdot q_i \cdot \mu_i \right]^{-1}$$

where i represents the number of different types of charges present (electrons and holes in a semiconductor, only electrons in a metal), n (m^{-3}) is the number density of each particle type, q (C) is the charge each particle carries, and μ ($m^2V^{-1}s^{-1}$) is the particle mobility. The mobility is a measure of how easily the particle moves under the influence of an electric field. The value of both n and μ can be temperature dependent. In a semiconductor, n increases and μ decreases with increasing temperature. In a metal, μ decreases with increasing temperature, but n is not temperature dependent. At typical operating temperatures for semiconductors, the decreasing μ dominates, and thus the resistance of both semiconductors and metals increase with increasing temperature for the operating temperatures of semiconductor devices.

The resistance of the bar is easily measured by passing a current, I (A), through the bar and measuring the applied voltage, V (V), where R is given by Ohm's law:

$$R = \frac{V}{I}$$

Thus, changes in the measured R can be used as a thermometer.

Most semiconductor devices do not have a specific parameter that obeys Ohm's law because they have pn-junctions that usually dominate with their exponential I,V relationship. An exception is very high voltage devices, particularly power MOSFETs, that have a region of their I,V characteristic that closely follows Ohm's law. The temperature variation of this region of the device, known as the on-resistance region, can be used to measure the device temperature [23]. The resistance of the characteristics of

Gunn diodes was also used for measuring the characteristics of these early devices [27].

There are other instances where resistance has been used as a thermometer, but they all have required that special contacts or structures be fabricated on the device of interest. In one instance, special contacts were made to the gate of a GaAs MESFET to use the variation of the metal gate's electrical resistance as a thermometer [28], and in another, the resistance of a polysilicon line was used to measure the temperature of an SOI MOSFET [29,30]. In numerous other instances, special resistance structures have been fabricated on thin films in order to measure the thermal properties of the films [31-33].

3.5. Current Gain

The current gain of bipolar transistors, β, is often a strong function of temperature. The gain is defined by:

$$\beta = \frac{i_C}{i_B}$$

where i_C (A) and i_B (A) are the collector and base currents respectively. The values of β and its temperature variation are complex functions of the device construction, doping levels, and temperature [9]. Generally it is not a well behaved, monotonic function of temperature; in fact, the temperature variation of β is intentionally minimized as much as possible in the device design in order to improve device stability and performance. For some GaAs-based heterostructure bipolar transistors (HBTs), though, β does decrease monotonically with temperature and has often been used to measure the HBT's temperature [13,14,34-38]. The gain has also been used to measure the temperature of GaAs MESFETs [34,39] and SiGe heterostructures [40].

3.6. Other Electrical Methods

A number of other methods, all related to the electrical output characteristics of a transistor, have been recently used for measuring the temperature of a device. The saturation current has been used to measure the temperature of Insulated Gate Bipolar Transistors (IGBTs) [41]. In an IGBT, or a MOSFET, changes in the saturation current with temperature are due primarily to changes in the threshold voltage. Self heating effects in silicon-on-insulator (SOI) MOSFETS are a problem of considerable interest today. A number of researchers have used the ac, or small signal, output conductance of these devices to measure their temperature [42-45]. The temperature variability of the output conductance of these devices is dominated by changes in the threshold voltage and mobility with temperature. Other techniques that have been used include noise thermometry to measure the temperature of SOI MOSFETs [46], and Deep Level Transient Spectroscopy (DLTS) to measure the temperature of MESFETs [47] and LEDs [48].

4. Optical Methods

There are a large variety of temperature sensitive physical phenomena that can be sensed by optical methods for indicating the temperature of a semiconductor device. Objects spontaneously emit radiation, the intensity and spectrum of which depend upon temperature (infrared radiation), and objects interact with incident radiation through absorption, reflection, and/or stimulated emission, all of which are often temperature dependent. The most commonly used optical technique is the measurement of the naturally emitted infrared radiation from a heated body. Recently, thermal reflectance has been used by several researchers as a method with potentially improved spatial and temporal resolution.

4.1. Luminescence

Luminescence is emission of radiation due to some external stimulation, such as an electric field or by photo excitation. The emitted radiation is due to recombination of electron and holes with the peak energy occurring in direct band gap materials at the band gap energy. For GaAs, for instance, the band gap and its temperature variation are given by [49]:

$$E_g = 1.519 - 5.405 \cdot 10^{-4} \cdot \frac{T^2}{(T + 204)}$$

where the energy is given in eV. Thus the peak energy of the luminescence depends upon the temperature.

The source of electrons and holes can be through injection across a pn junction (Electroluminescence) or by external optical excitation (Photoluminescence). Both electroluminescence [49] and photoluminescence [50-52] have been used for measuring temperature of compound semiconductor devices. It is claimed [50,52] that the resolution of the photoluminescence method can be 0.5 µm - 1 µm and 1 °C. The spatial resolution of the electroluminescence peak would be expected to be on the order of the area of the pn junction generating the signal, whereas the resolution of the photoluminescence peak could be of the order of the size of the incident optical excitation. Luminescence is only useful for direct band-gap semiconductors such as GaAs.

4.2. Raman

Raman scattering occurs when a photon scatters inelastically from a crystal, with the creation or annihilation of one or more phonons. The spectra of the scattered photon, which will be different than that of the incident photon, is dependent upon the temperature of the crystal because the phonon spectra is temperature dependent. The temperatures of Si MOSFETS [53,54], GaAs and other compound semiconductor devices [53,55], and Si rf power semiconductor devices [56] have been measured using the Raman effect. The spatial resolution of the Raman effect for measuring the temperature has been claimed to be 1 µm [55] and the temperature resolution 1-2 °C [56].

4.3. Reflectance

Reflectance of light from a surface can also be temperature dependant. In contrast to Raman scattering, in optical reflectance, the incident and reflected photons will have the same wavelength, but the intensity of the reflected photon will depend upon temperature. The relative change in optical reflectance with temperature is quite small [57], being of the order of 10^{-5} to 10^{-4} K^{-1}. Thermoreflectance has been used to measure the temperature of interconnects [57-59], devices [58,60-63], and thin films [61,64,65]. For the measurement of the temperature of self-heated devices and interconnects, a single optical probe is used. For thin-film measurements, two probes are used, one to heat the film and the other to sense the temperature. The temperature of thin films is measured in order to determine the thermal conductivity and specific heat of the film. Thermoreflectance can be used to measure very short thermal transients, with a 10 ns resolution being claimed [59,62]. The spatial resolution has been claimed to be 1 μm [61].

4.4. Thermo-Optic Effect

Thermo-optic effects are changes in the optical index of refraction of a material with temperature. Like thermoreflectance, the change is small, being of the order of 10^{-5}/°C [66,67]. A method based upon measuring the gradient of the optical index has been used to find the temperature profile through the depth of a power gate-turn-off thyristor [68]. Also, the temperature in waveguide modulators has been found using the thermo optic effect [69].

4.5. Infrared

Infrared radiation is probably the most common optical technique that is used for measuring temperature [20,70-73]. A portion of the spectrum of the naturally emitted infrared radiation is used for determining the temperature. This is the only optical method which has readily available commercial instrumentation.

The spectral emittance, W(Watt/m^3), of a black body as a function of wavelength, λ(μm), and temperature, T (K), is given by Planck's law of radiation:

$$W = \frac{2\cdot\pi\cdot h\cdot c^2}{\lambda^5\cdot\left(\exp\left(\frac{h\cdot c}{\lambda\cdot k\cdot T}\right)-1\right)} ,$$

where h is Planck's constant ($6.6\cdot10^{-34}$ J sec) and c is the speed of light ($3\cdot10^8$ m/s). This well known relation is shown as a function of wavelength for several temperatures in Figure 5. The obvious features are that, as the temperature increases, the total emitted radiation over all wavelengths increases and the wavelength at which the emittance peaks decreases as the temperature increases. Integrating the above equation over all wavelengths yields the Stefan-Boltzmann equation for the total emitted energy:

$$W = \sigma\cdot T^4$$

where σ= ($5.7\cdot10^{-8}$ Wm^{-2}K^{-4}). The above has been for an ideal black body. Black bodies are said to have an emissivity, ε, equal to 1. Real emitters have an emissivity of $0<\varepsilon<1$, and the above equation is rewritten:

$$W = \varepsilon\cdot\sigma\cdot T^4$$

Thus, by measuring the total emitted radiation from a body, the temperature can be determined. In real systems, only a portion of the energy spectrum shown in the figure is measured, but an equation similar to the above is valid for this slice of the spectrum.

Probably the major concern with infrared temperature measurements is the emissivity. The values for ε of the materials on a chip can range from 0.1 (aluminum) to 0.6 (polysilicon) or so. Without taking these variations into account, quantitative measurements of temperature are not possible.

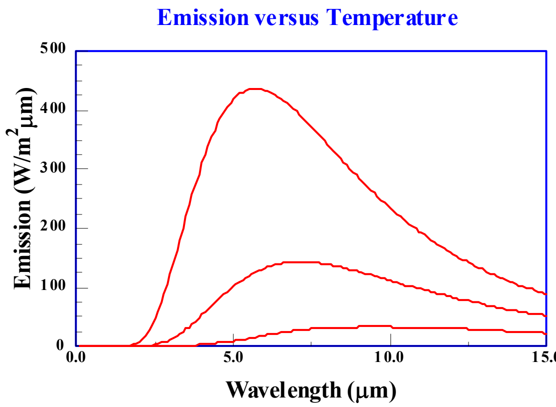


Figure 5. The infrared emission as a function of wavelength for a black body.

The spatial resolution is generally limited to no better than the wavelength of radiation being detected and in commercial systems is at best about 3 μm to 5 μm. This is the slice of the energy spectrum that is being measured. A major reason that detectors sensitive to radiation in this wavelength range are used is that the radiation from bodies in the temperature range that microelectronics operates (about 300 K to 600 K), peaks over this range.

5. Physically Contacting Methods

Contacting methods actually measure the temperature of an object or material that is making thermal contact to the device under study. There are single point contact methods such as thermocouples and scanning thermal microprobes, and multi-point or 'blanket cover' methods such as liquid crystals and thermographic phosphors. There has been an extensive review published of temperature measurements using scanning probe methods [74], so these methods will only be briefly mentioned here. Liquid crystal thermography is a popular method of chip-level temperature measurement as well as board-level microelectronic temperature measurements [75,76]. Thermographic phosphors have not been extensively used for chip-level temperature measurements, but potentially offer some advantages [77]. The spatial resolution of contacting methods can be the smallest of all the methods available. A resolution of 30 nm to 50 nm has been demonstrated for scanning thermal probes [2].

5.1. Liquid Crystals

Liquid crystals (LCs) are organic compounds that exist as a phase between that of a solid and an isotropic liquid. They scatter incident light selectively by wavelength, with the selectivity being temperature dependent. The LC molecules have a helical structure the repeat distance of which is of the order of the wavelength of visible light and which changes with temperature. The wavelength of the light that is reflected back is determined by the pitch of the helix and thus changes with temperature. Thus, the apparent color of the region being observed changes as the temperature of the region changes. The color range of LCs can be tailored by modifying the chemical composition. Tailored LCs are available commercially in the temperature range of -30 ºC to 120 ºC with temperature bands between 0.5 ºC and 30 ºC [78]. Spatial resolution of 1 µm [79] and temperature resolution of 0.1 ºC [80] have been demonstrated.

5.2. Thermographic Phosphors

Thermographic phosphors have not been extensively used for measuring the temperature of microelectronic chips. In many respects, though, they are similar in use to liquid crystals and might be expected to have similar resolution [77]. The most extensive applications of phosphors to temperature measurement is high temperature turbine blades and other surfaces. The material is a ceramic powder that is doped with rare earths. When illuminated with ultraviolet radiation, the phosphors fluoresce, the intensity of which is temperature sensitive, decreasing in intensity as the temperature increases. For electronics, the phosphor can either be applied as a powder or from a slurry.

5.3. Scanning Thermal Probes

Scanning thermal probes are in effect atomic force microscopes for which the probe has been modified with a temperature sensitive element such as a thermocouple or thermistor [81-89]. This method potentially offers the highest spatial resolution of any of the methods because of the small size of the probe tip.

6. Conclusions

A wide variety of methods exist for measuring the temperature of an operating semiconductor device. Methods that use electrical parameters of the device as the thermometer have the advantage that the temperature of fully packaged devices can be measured, but they do not allow two-dimensional temperature maps to be made. Another advantage of electrical techniques is that they only require the use of standard electronic instrumentation for the measurement. Optical methods have the advantage that they are non-contacting and that high spatial and temporal resolution temperature maps can be made. Methods that rely upon physical contact to the device by a probe or blanket film can also make high spatial resolution (perhaps the highest of any of the generic methods), but not with high temporal resolution. Both optical and contacting methods have the disadvantages that the semiconductor chip must be visible so that fully packaged devices can not be measured and that special optical or other equipment is needed to make the measurements. The particular method chosen by the researcher or engineer will depend upon the specific needs of the measurement, such as the desirability of temperature maps, the availability of packaged or unpackaged chips, as well as personal experience and expertise.

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