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Radiative properties of silicon

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ABSTRACT

RADIATIVE PROPERTIES OF SILICON

by
Anamika Patel

The objective of this thesis was 1) to study the radiative properties of silicon in the wavelength range of 1 to 20 microns and temperature range of 30 to 1000°C for the development of a multi-wavelength pyrometer 2) to develop a methodologies for deconvolution of the measured optical properties to yield fundamental optical constants of bulk materials. A novel spectral emissometer has been utilized for measurement of the temperature dependent radiative properties of silicon. The temperature determination capability of the emissometer was tested and verified using a standard thermocouple embedded in a silicon wafer. The temperature measurement accuracy, with the emissometer, was found to be within ± 10°C of the thermocouple temperature for a temperature range of 30 to 300°C. The experimental results presented in this thesis showed that the measurement of high temperature optical properties could be performed reliably with a novel non-contact, real-time approach using the spectral emissometer. The optical properties of n and p-type lightly and heavily doped silicon wafers were investigated. These studies have led us to establish spectral emissometer as a reliable technique for simultaneous measurements of radiative properties and temperature in the 1-20 μm wavelength range.

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This Thesis is dedicated to

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CHAPTER 1

INTRODUCTION

In silicon device manufacturing, the current trend has been to increase the physical dimensions of silicon wafers and reduce device size. As a result, it is more important now to minimize a) the temperature-time product or the thermal budget, 2) the process-induced contamination, and 3) device failure. This has led to some novel processes such as Rapid thermal processing (RTP), Rapid thermal chemical vapor deposition (RTCVD) and Metal organic molecular beam epitaxy (MOMBE). By the end of the century, it appears that single-wafer and cluster-based tools will be the manufacturing approach taken by the silicon device industry. It is anticipated that the silicon wafers will be 300 mm in diameter, thus making it difficult for batch-mode manufacturing that is currently practiced in horizontal furnaces.

The most important process parameter in these techniques is the wafer temperature and small changes in temperature can severely affect the rate of the process. Rapid thermal oxidation (RTO) of silicon represents the most demanding process, requiring temperature measurement and control to $\pm 1°C$[1]. Thermal modeling of RTP also requires a very good understanding of the thermal radiative properties of the wafer, chamber walls, the quartz sleeves and the quartz window. Most of the processing in the RTP systems occurs by radiation, and hence accurate modeling calls for a detailed knowledge of the total emissivity of a wafer, and its absorbtivity for the lamp radiation incident on it. Variation in these quantities has been shown to have a strong influence on power coupling and temperature uniformity. From these considerations, it can be seen that the advancement of RTP technology requires a complete understanding of the radiative properties of semiconductor materials at elevated temperatures. Although silicon is among the most intensely studied materials in the history of science, there have been remarkably few studies of its optical properties at elevated temperature, especially in the infrared range of wavelength, which determine the radiative properties of interest.

The objective of this thesis was to develop a reliable muti-wavelength pyrometer for simultaneous measurement of the wafer temperature and its optical properties in the wavelength range of 1 to 20 microns and temperature range of 30 to 1000°C. The spectral emissometer was utilized for the measurement of the radiative properties of silicon. A C++ program was used for deconvolution of the measured radiative properties. It has been demonstrated in this thesis that this emissometer yields reliable values of optical properties as a function of temperature and wavelength but it suffers from limitations in terms of sources of heating. Work aimed at replacing the currently used source of heating in the form of oxy-acetylene or propane torch is in progress. Two possible solutions are being investigated - 1) Possible use of CO_2 laser and 2) Tungsten halogen lamp assisted heating. Both the solutions offer the possibility of non-contact heating of semiconductor wafers in the emissometer.

The investigation of the temperature dependent optical properties of silicon, in this thesis, has been distributed over the next six chapters. In chapter 2, the background of semiconductors and their properties, particularly silicon is discussed. A comparative study of silicon and germanium is also presented. In chapter 3 the fundamentals of radiative properties are discussed along with their link to optical and electrical properties. The equations employed to deconvolute the measured radiative properties to yield the refractive index (n) and extinction coefficient (k) are presented. The reason for the interest in the radiative properties is also discussed. The fundamentals of temperature sensors are discussed in chapter 4. Temperature sensors include contact methods such as thermocouples and non-contact method such as pyrometry and some recently proposed temperature sensors based on optical fiber. In chapter 5, experimental details and methodology employed for the measurement of radiative properties of materials has been discussed. In chapter 6, the measured high temperature optical properties of silicon are presented and discussed. These measured properties have been compared with those in the literature. Conclusions and recommendations based on these studies are presented in chapter 7.

CHAPTER 2

BACKGROUND

2.1 Fundamentals

2.1.1 Semiconductor Materials

The study of semiconductor materials began in the early nineteenth century [2]. Over the years, many semiconductors have been investigated. Semiconductor materials are found in column IV and neighboring columns of the periodic table (Table 1) [3].

Table 1. Portion of Periodic table related to Semiconductors

Period	column II	III	IV	V	VI
2		B Boron	C carbon	N Nitrogen	
3	Mg Magnesium	Al Aluminum	Si Silicon	P Phosphorus	S sulfur
4	Zn Zinc	Ga Gallium	Ge Germainum	As Arsenic	Se Selenium
5	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium
6	Hg Mercury		Pb Lead		

The column IV semiconductors, silicon and germanium, are elemental semiconductors. In addition to the elemental materials, compounds of column III and column V atoms, as well as certain combinations from II and VI, make up the intermetallic, or compound semiconductors.

There are numerous semiconductor materials. The wide variety of electronic and optical properties of these semiconductors provide the device engineer with great flexibility in the design and fabrication of electronic and optoelectronic devices. The elemental semiconductor Ge was widely used in the early days of semiconductor development for transistors and diodes. Silicon is now used for majority of rectifiers, transistors and integrated circuits. However, the III-V compounds are widely used in high-speed devices requiring the emission or absorption of light. III-V compounds such as GaAs and GaP are commonly utilized in the fabrication of light emitting diodes (LEDs). Ternary compounds such as GaAsP and quadrinary compounds such as InGaAsP can be grown to provide added flexibility in choosing materials properties. Fluorescent materials such as those used in television screens usually are II-VI compounds such as ZnS. Light detectors are commonly made with InSb, CdSe, or other compounds such as PbTe and HgCdTe. Silicon and Ge are also widely used as infrared and nuclear radiation detectors. An important microwave device, the Gunn diode, is usually made of GaAs or InP. Semiconductor lasers are made using GaAs, AlGaAs, and other ternary and quadrinary compounds.

2.1.2 Properties of Semiconductors

Semiconductors are a group of materials having electrical conductivity intermediate between metals and insulators (Fig. 1) [4].

It is significant that the conductivity of these materials can be varied over orders of magnitude by changing the temperature, optical excitation and impurity content. The electronic and optical properties of semiconductor materials are strongly affected by impurities, which may be added in precisely controlled amounts. Such impurities are used to vary the conductivity of semiconductors over a wide range and even to alter the nature of the conduction process. For example, an impurity concentration of one part per million can change a sample of silicon from poor conductor to a good conductor of electric current. This process of controlled addition of impurities is called *doping*. Another important characteristic of a semiconductor, which distinguishes it from metals and insulators, is its energy band gap. Semiconductor materials at 0K have the same structure as insulator- a filled valence band separated from an empty conduction band (fig.2a). The difference lies in the size of the band gap Eg, which is much smaller in semiconductors than in insulators. The relatively small band gaps of semiconductors allow for excitation of electrons from the lower (valence) band to the upper (conduction) band by reasonable amounts of thermal or optical energy. For example, at room temperature, a semiconductor with a 1 eV band gap will have a significant number of electrons excited thermally across the energy gap into the conduction band, whereas an insulator with 10 eV bandgap will have a negligible number of excitations.

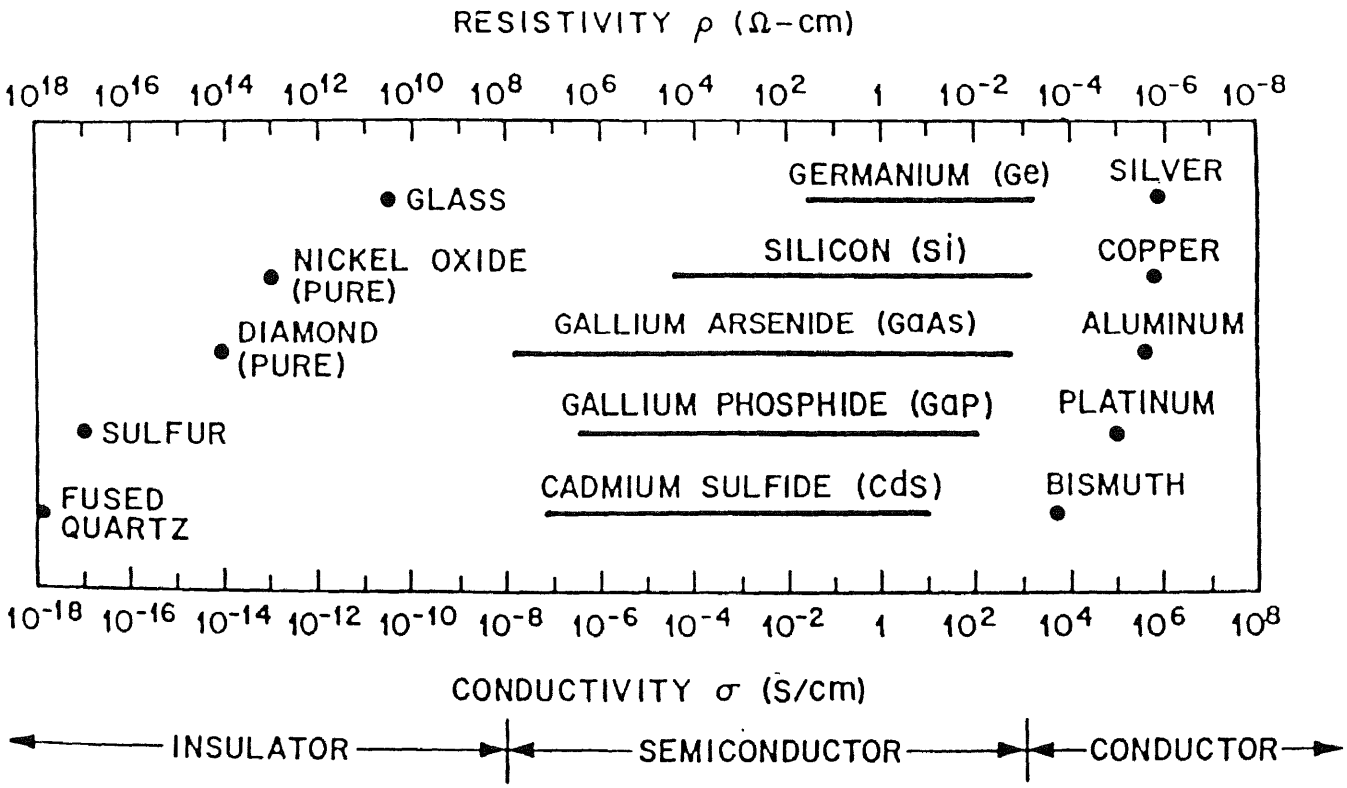
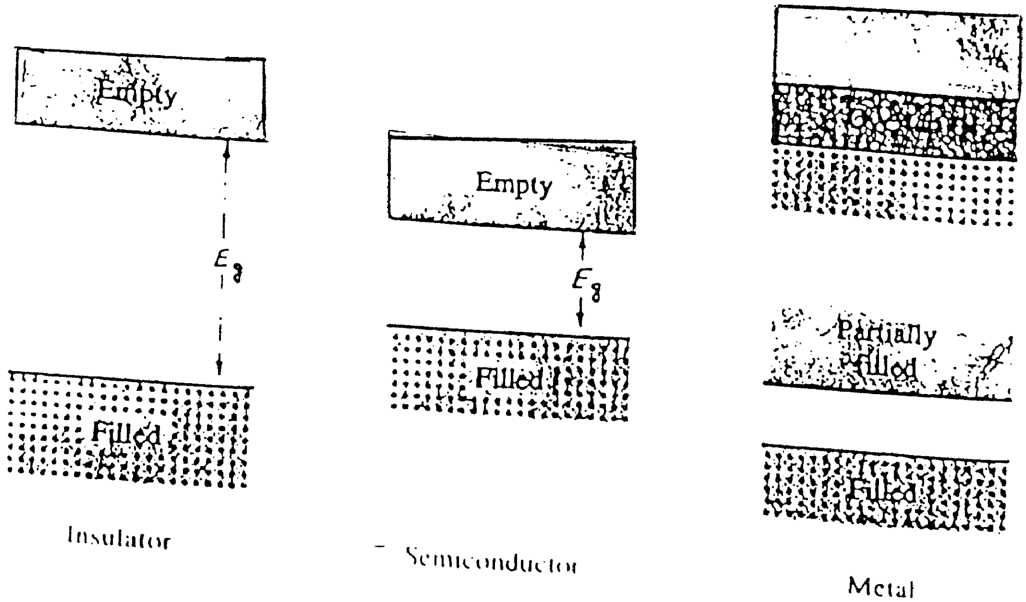
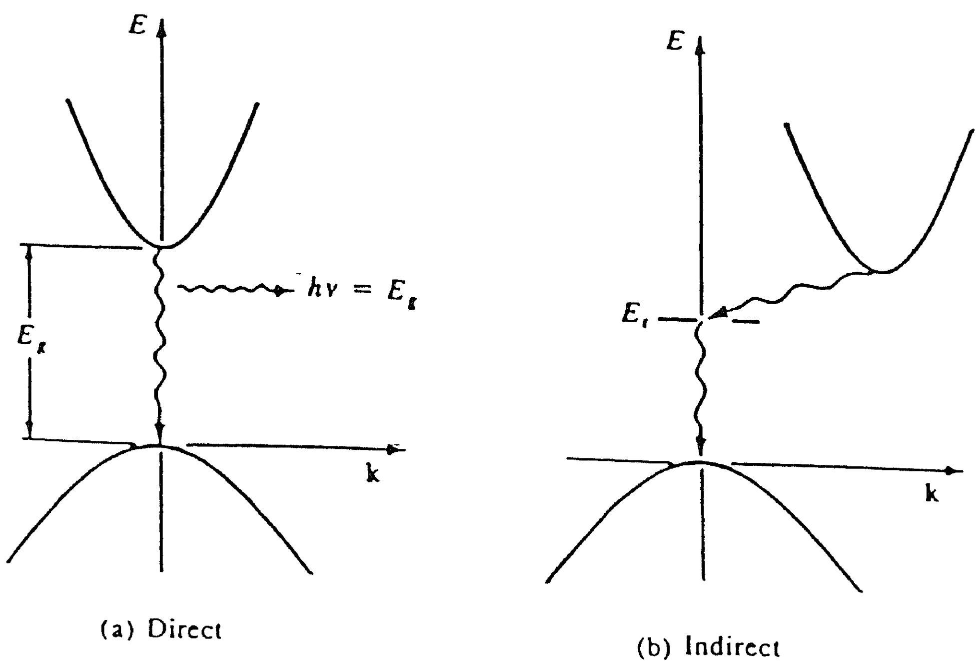


Figure 1 Typical range of conductivities for insulators, semiconductors and conductors.



(a)



(b)

Figure 2 (a)Band structure of metal, semiconductor and insulator at 0 K. (b)Direct and indirect electron transitions in semiconductors: (a)direct transition with accompanying photon; (b) indirect transition via a defect level

Thus, an important difference between semiconductors and insulators is that the number of electrons available for conduction can be increased greatly in semiconductors by thermal or optical energy. As the temperature of a semiconductor is raised from 0K, some electrons in the valence band receive enough thermal energy to be excited across the band gap to the conduction band. The result is a material with some electrons in an otherwise empty conduction band and some unoccupied states in an otherwise filled valence band. For convenience, an empty state in the valence band is referred to as ***hole.*** If the conduction band electron and the hole are created by excitation of a valence band electron to the conduction band, they are called an electron-hole pair (EHP). There are two classes of semiconductor energy bands: direct and indirect (Fig.2b). Here, allowed values of energy can be plotted vs. the propagation constant k. An indirect transition, which involves a change in k, requires a change in momentum for electron. Some direct and indirect semiconductors are identified in the Table 2 given below.

Table 2 Few direct and indirect band-gap semiconductors

	E_g	Transition
Si	1.11	Indirect
Ge	0.67	Indirect
AlP	2.45	Indirect
AlAs	2.16	Indirect
AlSb	1.6	Indirect
GaP	2.26	Indirect

Table 2 (continued)

GaAs	1.43	Direct
GaSb	0.7	Direct
InP	1.35	Direct
InAs	0.36	Direct

2.2 Summary of Properties of Silicon

2.2.1 Material Properties

Although many elements and intermetallic compounds exhibit semiconducting properties, silicon is used almost exclusively in the fabrication of semiconductor devices and microcircuits. Of many reasons of choice, the most important are the following: a) Silicon is an elemental semiconductor. It can be subjected to a large variety of processing steps without the problem of decomposition that are ever present with compound semiconductors; b) Consequently it can be fabricated into microcircuits capable of operation at higher temperatures. At the present time, the upper operating temperature for silicon microcircuits is between 125°C to 175°C, which is entirely acceptable for both commercial and military applications. c) Silicon lends itself readily to surface passivation treatments. This takes the form of a layer of thermally grown SiO_2, which provides a high degree of protection to the underlying device. The fabrication of devices such as metal-oxide-semiconductor(MOS) transistors has emphasized that this oxide falls short of providing perfect control of surface phenomena [5]. Because of the above, a significant technological base has been established to take advantage of its characteristics. This includes the development of a number of advanced processes for deposition and doping of silicon layers, as well as sophisticated equipment for forming and defining intricate patterns for very-large-scale integration (VLSI). Although silicon is the workhorse of the semiconductor industry, it is not an optimum choice in every respect. Indirect band-gap does not allow many functions to be performed by silicon. These include transferred electron oscillators, lasers, light-emitting devices, and a variety of highly efficient, lightweight, photovoltaic devices for space as well as terrestrial applications.

2.2.2 Physical Properties

In single-crystal form, silicon adopts the diamond lattice structure, with 5.2×10^{22} atoms/cm^3 and each atom covalently bonded to four nearest neighbors. Many of its physical properties result from this strong covalent bonding. In pure form, its lattice constant is 5.43086 A° at 300 K, increasing by +0.02% with doping. The nearest neighbor distance between silicon atoms in the diamond lattice is 2.35163 A°. The intrinsic carrier concentration for silicon is about 10^{10} cm^{-3} at 300 °K. Thus silicon cannot be made semi insulating(SI). When thermally oxidized, silicon has a significantly lower density of surface states. The electron mobility of lightly doped silicon is 1350 cm^2/V s and that of hole mobility is 475 cm^2/V s at 300 K. Shear stress for silicon is 3.61×10^7 dyn cm^{-2}. Because of this property of silicon, it is possible to handle a 300mm wafer. The minimum separation between conduction bands-which is the thermal activation energy is 1.1 eV, but the minimum vertical transition is ~2.5 eV. As in any semiconductor, the band-gap Eg(T) is expected to depend on temperature T, through two effects, lattice dilation and electron-phonon interaction[6].

Direct transitions will thus only be possible with visible photons. Any infrared absorption must arise from indirect transitions[7].

2.2.3 Silicon and Germanium a Comparison

Prior to the invention of the bipolar transistor in 1947, semiconductors were used only as two - terminal devices, such as rectifiers and photodiodes. In the early 1950s, germanium was the major semiconductor material. The narrow bandgap of Ge (0.66 eV), however, causes large leakage currents in Ge devices. This limits Ge device operation, to temperatures below 100°C. In addition, integrated circuit planar processing requires the capability, of fabricating a passivation layer on the semiconductor surface, Germanium oxide, GeO_2, could act as such a layer but it is difficult to form as it is water soluble, and dissociates at 800°C. These limitations make germanium an inferior material for fabrication of integrated circuits, compared to silicon. Since the early 1960s, silicon has become a practical substitute and has now replaced germanium as a material for VLSI fabrication. The relatively larger band-gap of silicon (1.1 eV) results in smaller leakage currents SiO_2, is also easy to form and also, chemically very stable. Electronic grade silicon is about one tenth as costly as germanium. Silicon in the form of silica and silicates comprises 25% of the Earth's crust, and silicon is second only to oxygen in abundance. Moreover, silicon technology is by far the most advanced among all semiconductor technologies.

CHAPTER 3

FUNDAMENTALS OF RADIATIVE PROPERTIES

3.1 Background

The development of Rapid Thermal Processing (RTP) techniques for fabrication of advanced electronic devices requires a detailed understanding of the thermal radiative properties of semiconductor wafers. Fig. 3 illustrates the main reasons for interest in these properties:

a) The spectral emissivity of a wafer affects the amount of radiation emitted at the pyrometer wavelength, and determines the temperature measurement and its errors in pyrometry.

b) The total hemispherical emissivity of a wafer affects the total heat loss by radiation from a wafer at any given temperature.

c) The total absorptivity is related to the efficiency of coupling lamp radiation to a wafer.

Much of our interest in this subject stems from the challenge in performing accurate temperature measurements in an RTP chamber. In an RTP chamber, the wafer is not in thermal equilibrium with its surroundings, and as a result, traditional temperature measurement techniques involving the use of thermocouples cannot be applied, unless the thermocouples are physically embedded in the wafer, which is not practical for production process. Usually, pyrometry is employed for temperature measurement in RTP. However, this introduces some problems because successful pyrometry requires accurate knowledge of the spectral emissivity of the target at the pyrometer wavelength

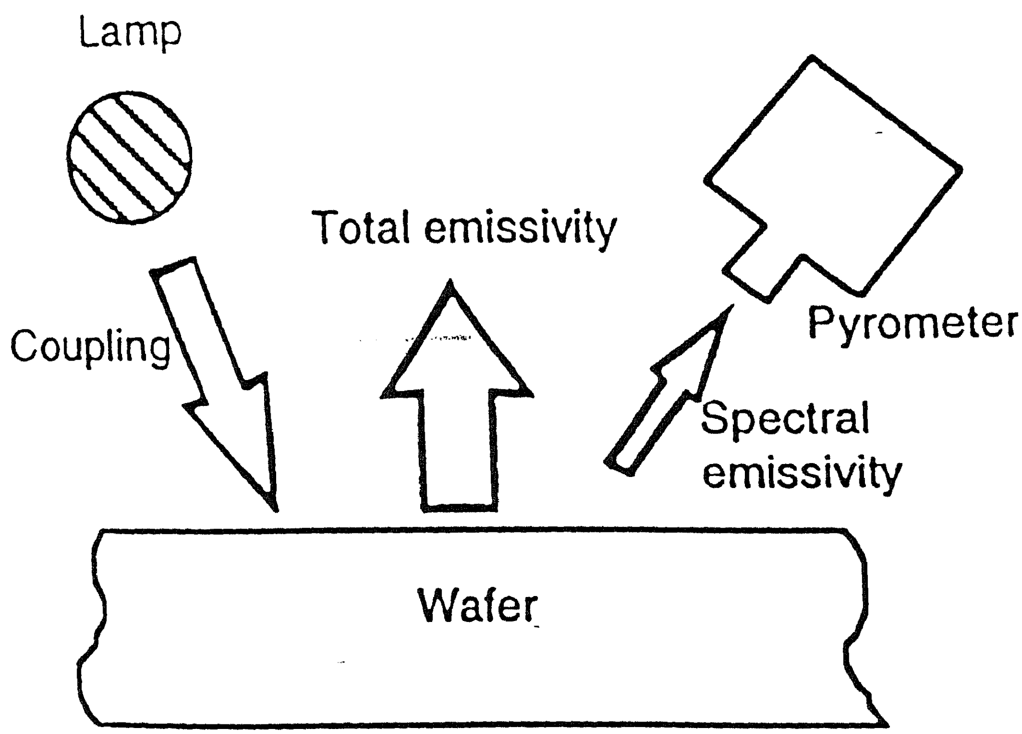


Figure 3 The thermal radiative properties of semiconductor play a key part in RTP.

The emissivity is a physical quantity not only basic to the theory of thermal radiation but also important in the practice of optical pyrometry. The Non-contact temperature measurements are based on the detection and analysis of thermal radiation emitted by an object. The underlying idea of all techniques is based on the concept of the black body radiator, which is defined as an ideal surface that emits more thermal radiation than any other surface at the same temperature[8].

3.2 Blackbody Radiation

A Blackbody is a perfect absorber of electromagnetic energy. It is also a perfect emitter. The spectrum of radiation emitted from a blackbody is described by the Planck radiation function. Actually, it is the mathematical function for the spectral radiance of blackbodies.

$$W_{bb}(\lambda,T) = \frac{c1}{\lambda^5(\exp(c2/\lambda T)-1)}, \qquad \ldots \qquad (2)$$

Where, $W_{bb}(\lambda,T)$ is known as spectral radial exitance, and describes the power per unit area and wavelength radiated into the forward hemishere from a blackbody at the absolute temperature T in K, at the wavelength λ in μm[10]. The equation gives $W_{bb}(\lambda,T)$ in units of $Wm^{-2}\mu m^{-1}$, and c1, c2 are constants, with the values 3.7418×10^8 $W\mu m^4 m^{-2}$ and 1.4388×10^4 μmK respectively. The total energy emitted by a blackbody at any temperature can be found by summing up the energy emitted at each wavelength. This can be done mathematically by integrating this Planck function with respect to wavelength.

The result is that the total energy radiation by a blackbody is proportional to its absolute temperature to the fourth power (T^4). This is called the Stefan-Bolzmann radiation law,

$$W_{tot,bb} = \sigma T^4 \quad \ldots \quad (3)$$

Where, W_{tot} is the total power radiated per unit area, $\sigma = 5.67\times10^{-8}$ $Wm^{-2}K^{-4}$ is the Stefan Bolzmann constant and T is in K.

3.3 Link between Radiative and Optical Properties

3.3.1 Optical Properties

The optical response of a material can be described using various interrelated properties. The response of a solid to electromagnetic radiation is generally regarded as a consequence of its microscopic elements with the electric field, and hence it can be summarized by defining the dielectric "constant", $\varepsilon_r(\nu)$, which is a function of the frequency of the wave, ν[11].

$$\varepsilon_r(\nu) = \varepsilon_1(\nu) + j\varepsilon_2(\nu) \quad \ldots \quad (4)$$

The dielectric constant is not usually measured directly, and a number of other properties are used to describe the optical response of a material. The complex refractive index, n_c, is defined by the relation,

$$n_c = (\varepsilon_r)^{1/2}, \quad \ldots \quad (5)$$

Where, frequency dependence of ε_r has been dropped for simplicity. The complex refractive index can be written as

$n_c = n + jk$, ... (6)

Where, n is the refractive index and k is the extinction coefficient. The refractive index is equal to the ratio of phase velocity of the wave in vacuum to that in the material. The relationships between the dielectric function and n and k is summarized by the equations,

$\varepsilon_1 = n^2 - k^2$ ... (7)

$\varepsilon_2 = 2nk$ ... (8)

For many practical problems, it is convenient to consider loss in a material as being described by the absorption, α, which is defined by,

$\alpha = 4\pi k/\lambda$ ... (9)

Where, λ is the wavelength. α is a useful quantity to know because it is closely related to the penetration depth of radiation in a given medium, since the intensity of the radiation decreases according to $\exp(-\alpha z)$, where z is the depth beneath the surface of the medium. α is usually expressed in units of cm^{-1}.

3.3.2 Emissivity

In general, in order to infer the temperature of the target from the measurement of emitted radiation, the value of the surface emissivity should be known. Emissivity is an important parameter in radiation thermometry. It is defined as the ratio of the radiance of a given object to that of a blackbody at the same temperature and for the same spectral and directional conditions. It is a function of wavelength and temperature. Hence, it is a property, which must be known for accurate temperature determination of an object by measurement of its emitted electromagnetic radiation with a radiation thermometer. For RTP, there are three reasons to know wafer emissivity:

1) Pyrometry
2) Thermal modeling and
3) For wafer design and fabrication to test the robustness of an RTP chamber or process[12].

For normal incidence, the emissivity $\varepsilon(\lambda)$ of a plane parallel specimen is given by[13]

$$\varepsilon(\lambda) = [1-R(\lambda)]\,\{1-T(\lambda)]\,/\,[1-R(\lambda)T(\lambda)] \qquad \ldots \qquad (10)$$

Where, λ is the wavelength, $R(\lambda)$ is the true reflectivity and $T(\lambda)$ is the true transmissivity. $R(\lambda)$ and $T(\lambda)$ are related to the fundamental optical parameters-$n(\lambda)$, the refractive index and $k(\lambda)$, the extinction coefficient by the following relations:

$$R(\lambda) = [\{n(\lambda)-1\}^2 + k(\lambda)^2]\,/\,[\{n(\lambda)+1\}^2 + k(\lambda)^2] \qquad \ldots \qquad (11)$$

$$T(\lambda) = \exp[-\,\alpha(\lambda)t/\lambda] = \exp[-4\pi k(\lambda)t/\lambda] \qquad \ldots \qquad (12)$$

α is the absorption coefficient and t is the thickness of the material. When the radiant heat transfer is in an equilibrium state, the emissivity of a perfectly opaque body is given by Kirchoff's law as $1-R(\lambda)$ from(10) for a perfect opaque body, since $T(\lambda) = 0$. Hence

$$\varepsilon(\lambda) = [1-R(\lambda)] \qquad \ldots \qquad (13)$$

The experimentally measured values of transmittance and reflectance include effects such as light trapping and multiple internal reflections depending on the angle of incidence, surface roughness, presence of grains, grain boundaries, interface roughness, etc as in Fig.4. These apparent transmittance $T(\lambda)^*$ and apparent reflectance $R(\lambda)^*$ are related to real or true transmittance $T(\lambda)$ and true reflectance $R(\lambda)$, respectively, by the following well known equations[13] :

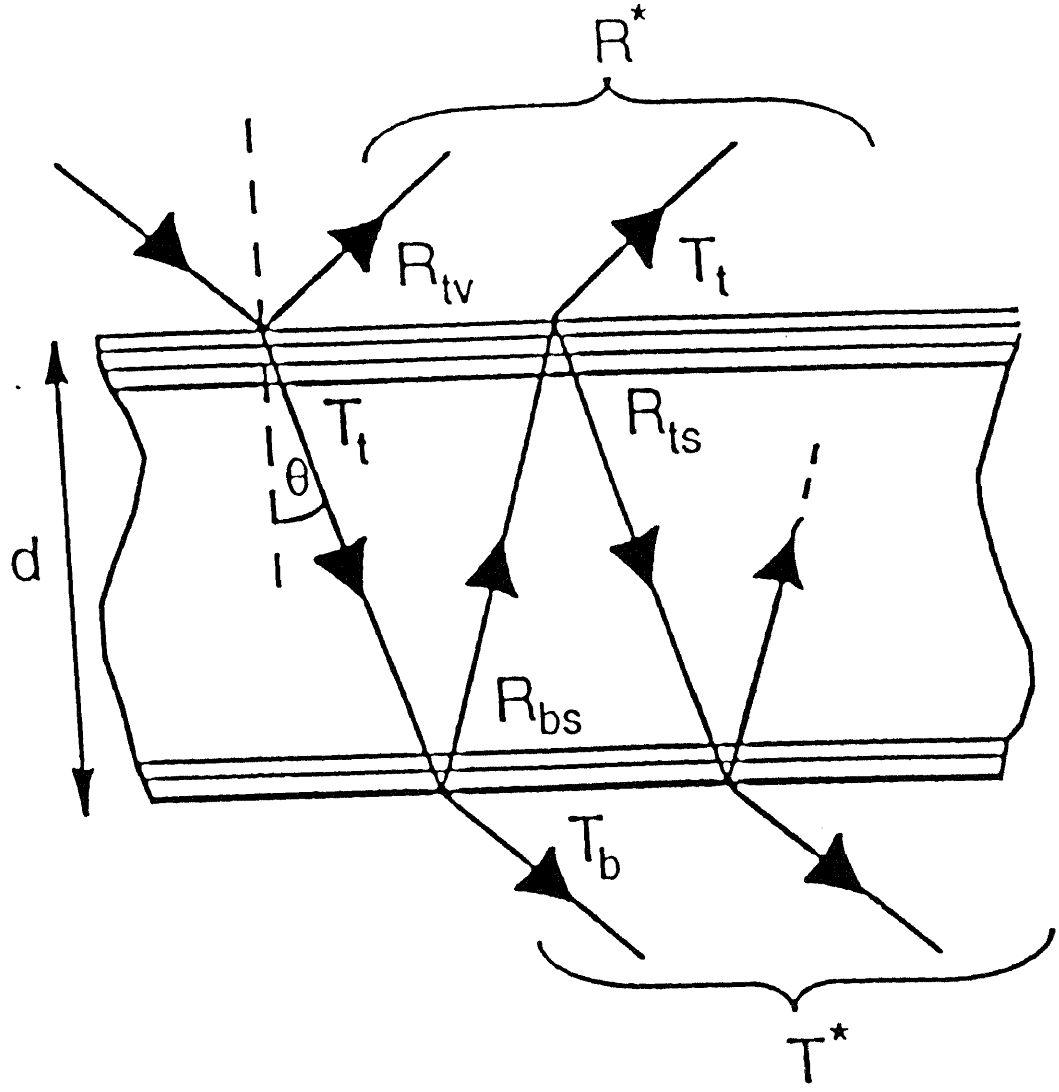


Figure 4 The effect of multiple internal reflections on the apparent reflectivity, R* and transmissivity T*.

$T(\lambda)^* = T(\lambda)\{(1-R(\lambda))^2/(1-R(\lambda)^2T(\lambda)^2)\}$ ... (14)

$R(\lambda)^* = R(\lambda)\{ 1+ [T(\lambda)^2(1-R(\lambda))^2]/[1-R(\lambda)^2T(\lambda)^2]\}$ ... (15)

Equations (14) and (15) are the result of considering multiple internal reflections. A simultaneous measurement of reflectance and transmittance can yield true values of reflectance and transmittance and therefore, the refractive index, n(λ) and the extinction coefficient, k(λ) of single substrate materials. Using equations (14) and (15) we get real R and T from the apparent R* and T* and is given by,

$$R = \frac{T^{*2} - R^{*2} + 2R^* + 1 \pm \sqrt{T^{*2}(T^{*2} + 2(-R^{*2} + 2R + 1)) + (R^* - 1)^4}}{4 - 2R^*},$$

$$T = \frac{\frac{R^*}{R} - 1}{T^*},$$

$$n = \frac{R + 1 \pm \sqrt{4R - k^2 * (1-R)^2}}{(1-R)},$$

$$\alpha = \frac{4\pi . k}{\lambda},$$

$$k = \frac{\alpha . \lambda}{4\pi}$$

With the choice of appropriate models, n(λ) and k(λ) of multilayers can also be resolved from experimentally measured spectral properties[14]. Emissivity models can convey to a process engineer information about films and thickness to achieve the desired emissivity. The total contribution to emissivity, ε(λ, T), is given by[14],

$\varepsilon(\lambda, T)_{total} = \varepsilon(\lambda, T)_{free\ carrier} + \varepsilon(\lambda, T)_{absorption\ edge} + \varepsilon(\lambda, T)_{phonon}$ ... (16)

For photon energy, $E_{photon} \geq E_g$, E_g is the bandgap, i.e., $\lambda_{photon} \leq \lambda_E$, the wavelength corresponding to absorption edge; emissivity contributions are due to bandgap or above bandgap absorption. For $E_{photon} < E_g$, the emissivity contributions are due to below bandgap absorption. The free carrier absorption mechanism plays the dominant role in doped semiconductors in the short-wavelength range[9]. In the long-wavelength range(>10μm), phonons contribute to emissivity changes. These properties are function of temperature.

CHAPTER 4

FUNDAMENTALS OF SENSORS FOR PROCESS MONITORING

4.1 Contact Sensors

Thermocouples: A junction of two dissimilar materials will, when heated, produce a voltage across the two open leads. This effect is called thermovoltaic effect and such a junction is referred to as thermocouple. When more than one of these junctions are combined in a single responsive element, it is termed as thermopile. The most important features of thermocouples are the following:

(a) Thermocouple does not measure the junction temperature. It will measure the temperature gradient of the wire.

(b) Thermocouple does not measure wafer temperature directly. Only a close approximation is the output of the thermocouple, as determined by the thermal resistance between the wafer and the thermocouple[15].

(c) The signal produced by the thermocouple is translated into temperature by a number of methods. The most common conversion is the use of a standard reference table, international temperature standard, ITS-90 and interpolation from a number of ITS-90 fixed points[16-17].

Although thermocouples are inexpensive and easy to use, they suffer from some limitations. The main problem with the thermocouple is its way of operation. For a thermocouple to operate, it has to be in physical contact with the surface of the wafer. This leads to risk of contamination of the wafer. In order to minimize the contamination, real-time measurements must not involve contacting the wafer. Thermocouples can be used as temperature measurement tools in batch reactor furnaces where the wafer is in total equilibrium with its surroundings. Thus, by determining the furnace temperature, the wafer temperature can be found. In processes like RTP, the thermocouple should be embedded inside the wafer in order to find the wafer temperature since wafer temperature is not in equilibrium with the furnace temperature. In order to obtain uniform temperature, several thermocouples have to be embedded across the wafer to measure the wafer temperature spatially, which could introduce more contamination. On the other hand, this technique cannot be used in processes such as rapid thermal oxidation (RTO) where a layer of thermal oxide is grown on the surface of the substrate. Although there are many limitations in using the thermocouples including the associated large time constants, it is not likely to see the disappearance of thermocouples in the semiconductor industry in the near future. The major problems with thermocouples are low reproducibility and speed. They offer a simple measurement solution if some of their disadvantages can be overcome.

4.2 Non-Contact Sensors

Methodologgies based on infrared detection have been well established as a method for temperature monitoring. Their major advantage is the ability to accurately measure temperature without physical contact and therefore in real-time. Another important advantage of infrared temperature sensors is their fast response times, typically in the region of 10 to 50 milliseconds, with some as fast as 2 microseconds.

Pyrometry: It is a non-contact optical technique used to monitor the temperature of the wafer during semiconductor processing. Pyrometers are all fundamentally based on

Planck's blackbody radiation equation. A pyrometer does not measure the temperature of the wafer directly. Instead, it measures the intensity of the radiation coming from the wafer, which can later be converted into temperature by using an appropriate correction factor. Thermometry using pyrometry involves measuring the thermal distribution of photons, often within a narrow wavelength band. Pyrometers are also called as photon detectors. In photon detectors, incident infrared photons are absorbed producing free charge carriers, which change electrical characteristics without causing any temperature change of the responsive element[18]. Radiation pyrometry is a valuable tool for non-contact measurement of temperature. The main advantages of using pyrometers are the following:

(a) pyrometers look directly at the wafer

(b) can be located outside the process chamber

(c) need no contact with the wafer

(d) exhibit low time constants and high resolution

Pyrometers can also give other information such as transmittance, reflectance and emittance of the wafer. However, there are some limitations such as sensitivity to changing emissivity and background light. They are costly and complex and they need calibration. Wavelength, photodetector and collection optics are some key considerations to be evaluated for pyrometers. A number of sensors are placed looking at the sample depending on the location of the wafer to collect the radiated thermal energy from the wafers because of the spatial limitation of each sensor.

Thermal radiance is characterized by Planck's blackbody spectral radiance $M_{\lambda,b}$ (T, λ), the wafer emissivity $\varepsilon(\lambda, T)$, and is given by[13]:

$$P\rho = A\, f(h)\, \varepsilon(\lambda, T)\, M_{\lambda,b}\, (T,\lambda) \qquad \ldots \qquad (17)$$

Where, T is the temperature, λ is the pyrometer operating wavelength, A is the area of the wafer that contributes directly to the pyrometer signal, and f(h) is a function dependent on the distance (h) between the wafer and the pyrometer. As can been seen from the above equation, the emissivity of the wafer should be known precisely in order to measure the accurate temperature of the wafer. Although there are some limitations, pyrometers are still being used as the standard technique in monitoring the wafer temperature in many semiconductor processes such as RTP, MBE and MOCVD[15,17]. The limitations of pyrometers have compelled researchers to investigate other non-contact techniques like the ripple technique, which has solved the two largest pyrometer problems such as undesired background light and unknown wafer emissivity[19].

A pyrometer measures the amount of radiation emitted from a wafer. The emitted radiation is a function of both the wafer temperature and the optical properties of the side of interest. The most important radiative property is the wafer emissivity.

In semiconductor processes such as RTP, problem of measuring the temperature and its uniformity can be reduced greatly by emissivity reduction techniques[20]. However, most of these techniques seek virtual blackbody cavity. If a wafer is placed into a virtual blackbody, the effective emissivity is forced up towards one. A new technique introduced by AG Associates minimizes emissivity errors and improves temperature uniformity by placing a highly reflective surface very close to the wafer, to enhance its emissivity.

A fiber sensor can be inserted through a hole in the bottom reflector of an RTP system and can be focussed at the wafer to acquire real-time emissivity data.

4.3 Fiber Optics in Infrared Thermal Monitoring

With the advent of fiber optics, a new generation of infrared sensors have come into existence which allow for greater flexibility and ease of implementation and applications[21]. Typically, fiber optic infrared sensors are used in applications where a conventional direct viewing instrument cannot be applied because of the physical size of the sensor, or because of harsh environments. Instruments with fiber optic probes may be used in areas of high ambient temperatures or hazardous conditions due to harsh environments or high levels of electromagnetic or nuclear radiation. Using a fiber optic cable, the actual infrared detector and electronics may be located at a safe distance from the process with only a non-electrical lens assembly or fiber optic tip located in the vicinity of the process area. Fiber optic tips supplied with sapphire elements encased in a ceramic tube may be exposed to ambient temperatures as high as 1000°C. Fiber optic cable lengths from 1 to 40 feet are common with some as long as 60 feet. The most commonly used fiber optic material today is lead alkaline silica glass encased in a cladding of soda lime silica glass; this glass fiber material is easily produced. Its major drawback is the longer the cable, the higher the minimum detectable temperature, due to losses in the glass fiber.

CHAPTER 5

EXPERIMENTAL DETAILS

5.1 Emissometer

The schematic of the spectral emissometer is presented in Fig.5. It consists of a hemiellipsoidal mirror providing two foci, one for the exciting source in the form of a diffuse radiating near blackbody source and the other for the sample under investigation. A microprocessor controlled motorized chopper facilitates in simultaneous measurement of the sample spectral properties such as radiance, reflectance and transmittance. A carefully adjusted set of five mirrors provides the optical path for the measurement of the optical properties. The source of heating of the samples is provided by oxy-acetylene/propane torch. The sample size is typically in the range of 0.5 to 1 inch in diameter. The spot size for the optical signal collection from the sample is ~3 mm in diameter. Thus the temperature estimation, using the emissometer, is assumed to be uniform over this small region of the sample. However, because of safety considerations and potential sample contamination, various alternatives to heat the samples, uniformly in a controlled environment, are being investigated.

The spectral emissometer consists of three GaAs lasers to facilitate in aligning the sample at the appropriate focus. A high resolution Bomem FTIR, consisting of Ge and HgCdTe detectors, interfaced with a pentium processor, permits data acquisition of the measured optical properties. Fourier Transform Infrared Spectroscopy involves a special mathematical treatment of the experimentally measured spectral data[22]. Markham et.al. [23] have designed and constructed a bench top FTIR instrument which allows for

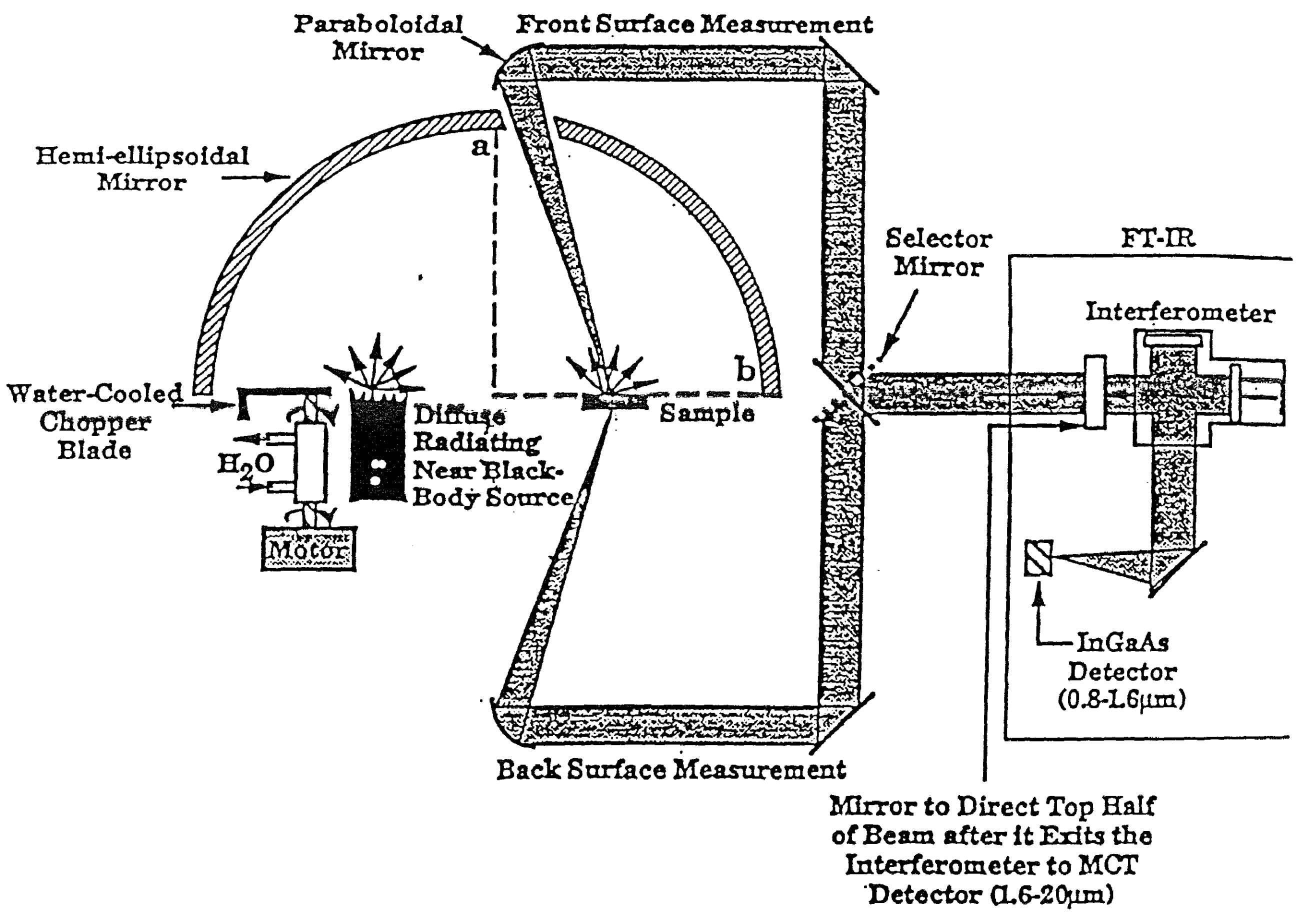


Figure 5 Schematic of Benchtop Emissometer.

measurement of radiance, directional-hemispherical reflectance and directional hemispherical transmittance of materials at elevated temperatures from 50 to 1000 °C over a wide spectral range from 12,500 to 500 cm^{-1} (0.8 to 20 μm). This on-line computer enables the user to flip the mirrors to acquire transmission/reflection spectra via software configurations such as Spectra Calc and GRAMS. This system from On-Line Technologies is third of its kind in United States and the first of its kind in a university environment.

5.2 Methodology

The spectral emissometer allows for simultaneous measurements of radiance R, reflectance ρ, transmittance τ and the temperature T of the sample at the measured point. The theoretical background and methodology is as follows[23]. A sample is placed at one of the foci of the hemispherical ellipsoidal mirror while the source, a blackbody at 900°C, is at the other focus. The chopper (in Fig 5) permits the simultaneous acquisition of the radiative properties of interest including the sample temperature. A front-surface sample measurement, with the chopper closed, yields the sample's directional spectral radiance:

$$R_\nu(T) = \varepsilon_\nu(T) R_\nu^b(T) \qquad \ldots \; (18)$$

Where, $\varepsilon_\nu(T)$ is the emissivity of the sample at temperature T, and R_ν^b is the theoretical Planck function at temperature T. The subscript ν denotes the spectral frequency.

When the chopper is open, the measured radiation M_o will include that emitted by the sample and the blackbody source radiation reflected by the sample in spectral directional hemispherical mode:

$$Mo = R_v(T) + \rho_v(T)R_v^b(T_{bb}) \qquad \ldots \quad (19)$$

Where, T_{bb} is the constant blackbody source temperature, which is maintained at 900°C and ρ_v is the spectral directional-hemispherical reflectivity. The difference in two measurements is thus $q_v(T)\ R_v^b(T_{bb})$. The constant source radiation $R_v^b(T_{bb})$ is quantified by replacing the sample with a perfect reflector (a gold mirror, $q_v^{gold} \sim 1.0$) and measuring the spectrum in the chopper open condition. Thus, the directional-hemispherical reflectance of the sample, ρ_v (T), can be determined.

For an opaque sample, the spectral emittance, $\varepsilon_v = 1-\rho_v$. By rearranging equation (10), $R_v^b(T)=R_v(T)/\varepsilon_v(T)$, the surface temperature of the sample can be determined by direct integration over the entire spectral region:

$$\int R_v^b(T)\, dv = \sigma T^4 \qquad \ldots \quad (20)$$

Where, Stefan Bolzmann constant $\sigma = 5.67 \times 10^{-12}$ W $cm^{-2}K^{-4}$. The sample temperature can be obtained to within $\pm$10°C. For nonopaque samples, the directional-hemispherical transmittance, τ_v, is measured by flipping the selector mirror and measuring the backsurface radiance and backsurface radiance plus transmittance. The source radiation is quantified with the sample absent, and the analysis to determine τ_v follows that for q_v. The more extensive closure relationship, $\varepsilon_v = 1-q_v-\tau_v$, is then used to determine ε_v. The temperature of the samples can also be determined simultaneously by fitting the sample's radiance to the Planck's black body curves.

CHAPTER 6

RADIATIVE AND BULK PROPERTIES OF SILICON

6.1 Background

The optical properties of silicon at room temperature have been studied extensively, partly because of its fundamental interest and importance as an electronic material, and partly because it is an important material for infra-red (IR) optics. In general, for silicon, the high emissivity in the visible region can be attributed to band-to-band transitions. For low temperatures, Si is transparent for λ greater than 1.2μm leading to low emissivity in near IR. For $\lambda > 6$ μm, the high emissivity of silicon is due to lattice vibrations. For temperature greater than 870 K, emissivity is constant in the entire IR region[23,24].

6.2 Effects on the Emissivity of Silicon

The emissivity of a wafer, outside a process chamber and without the influence of reflections from other radiation sources, is referred as ex-situ emissivity also known as intrinsic emissivity. It is a fundamental property that is only dependent on the wafer. The intrinsic emissivity of a Si-wafer is defined as the emissivity in a non-reflective, non-radiating environment, which is only dependent on the wafer parameters. Three major parameters influence this emissivity: (1) the surface reflectivity, which can be drastically changed by surface layers, (2) the transmittance of the bulk, which lowers the emissivity at temperatures below 700°C and (3) the roughness of the surface, which can increase the emissivity. The effect of backside roughness on temperature measurement was also demonstrated and it was observed that with an anti-reflective backside layer (e.g quarter wavelength oxide or oxynitride) behave like a nearly perfect blackbody at a particular pyrometer wavelength[25]. When the wafer is placed inside a reflecting process chamber, the emissivity increases because of multiple reflections inside the chamber so the effective emissivity in an RTP system is higher than the intrinsic radiation from the wafer. Reflected radiation is added to the intrinsic radiation from the wafer. This addition of reflected radiation decreases the influence of dielectric layers on the effective emissivity. Wafer backside roughness is a problem for temperature measurement system using pyrometry and determination of optical constants due to emissivity and reflectivity variations[26]. Hence, the drawback is that the emissivity becomes more sensitive to backside roughness. Addition of reflected radiation to the pyrometer signal might change the effective emissivity, which is also known as in situ emissivity. It is strongly dependent on the chamber geometry and the materials used. Reflectance is least dependent on the temperature as compared to transmittance. When a pyrometer is used for temperature measurements, the emissivity must be measured in-situ for accurate results[27].

6.3 Literature Data on Radiative and Optical Properties

It has been found that a highly doped Si wafer has a high emissivity, which is independent of temperature[28]. The Optical functions of silicon have been discussed in many reviews. Li [29] provides refractive index values from 1.2 to 14 microns with comprehensive description of samples and measurement conditions. The review of Edwards [30] provides refractive index and extinction coefficient from 0.62 to 333 microns. Sato[13] has performed the first detailed measurement of temperature dependent spectral emissivity of silicon. Using a spectrophotometer, Sato measured the emissivity of comparatively pure and heavily doped n-type silicon in the temperature range of 543 to 1073 K and in the spectral region from visible to 15 μm. The results of his measurements are shown in Fig.6. His result shows that emissivity increases with increasing temperature for pure silicon in the 2 – 15 μm region. For n silicon, emissivity decreases with increasing temperature.

For photon energies less than the direct band-gap of silicon, the refractive index of silicon at any given wavelength can be approximated as being a linear function of temperature. Jellison and Modine[31] found that a good fit could be obtained using the expression (25) for temperature dependence of the refractive index:

$$n(h\nu,T)=\sqrt{4.386-0.00343T+(99.14+0.062T)/(Eg^2-(h\nu)^2)} \quad \text{.... (21)}$$

Where, Eg = 3.652eV. Li[29] has performed a detailed review of the refractive index of silicon in the infra-red range of wavelength in 1980, and analyzed the data available, covering the wavelength range from 1.2 to 14 μm, for temperatures between 100 to 750 K. Over the temperature range of 293 to 750 K, the refractive index could be described by the relation:

$$n(\lambda,T)=\sqrt{\varepsilon r(T)+\frac{L(T)}{\lambda^2}(A_0+A_1T+A_2T^2)} \quad \text{...(22)}$$

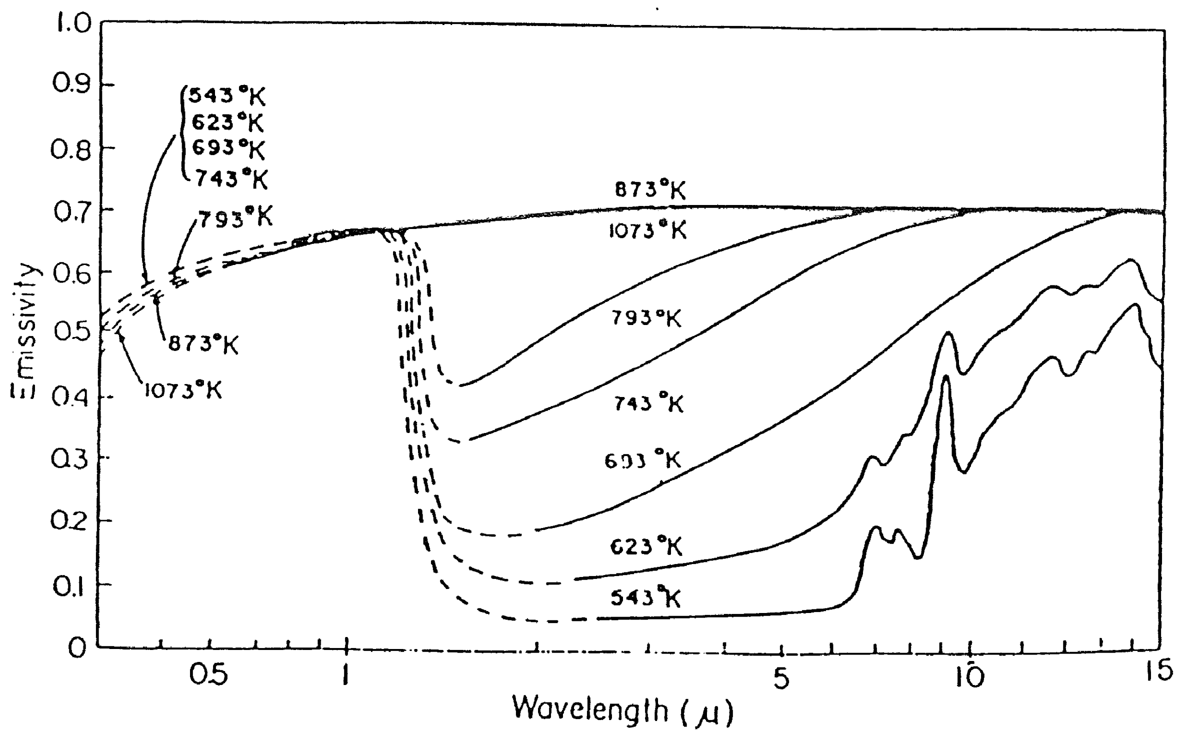


Figure 6 Sato's result of spectral emissivity for silicon.

Where, $\varepsilon r(T) = 11.4445+2.7739 \times 10^{-4} T+1.705 \times 10^{-6}T^2 - 8.1347 \times 10^{-10}T^3$,

$L(T) = \exp(-3\Delta L(T) / L_{293})$,

and A1 = 0.8948, A2 = 4.3977x 10-4, A3 = 7.3835 X 10-8 and $\Delta L(T)/L_{293}$ is the linear expansion coefficient, which is given by

$\Delta L(T)/L_{293} = -7.1 \times 10^{-4} + 1.887 \times 10^{-6} T + 1.934 \times 10^{-9} T^2 - 4.544 \times 10^{-13} T^3.$

Where, wavelengths are in micrometer and the temperatures are in K. Hence, the simple expressions given by Jellison and Modine[31] for wavelengths between 0.4 and 0.84μm and by Li[29] for wavelengths between 1.2 and 14μm, provide a reasonable approach for calculation of the refractive index of silicon across the whole wavelength range of interest here. In addition to the room temperature measurements, Icenogle et al[32] have measured the refractive index for a number of temperatures between 100 and 296K for the wavelength range from 2.554 to 10.27 μm. For a given wavelength their temperature-dependent indices were fit to a polynomial from which dn/dT can be evaluated. This dn/dT are given in Table 6 below for four wavelengths. dn/dT for T = 100 to 296 K is:

$$dn/dT = B_1 + B_2T + B_3T^2 \quad \ldots \quad (23)$$

Table 3. Temperature Dependence of Index of Refraction.

Wavelength, (μm)	B_1	B_2	B_3
2.554	-1.1127×10^{-4}	2.0722 x 10-6	-4.0×10^{-9}
2.732	-1.0255×10^{-5}	9.6748×10^{-7}	-1.2145×10^{-9}
5.19	-4.0089×10^{-5}	1.3368×10^{-7}	-2.3458×10^{-9}
10.27	-6.5198×10^{-5}	1.6358×10^{-7}	-3.2457×10^{-9}

6.4 Experimental Data of Optical Properties

6.4.1 p-type Silicon

The results of emissivity measurements on p-type silicon, with front-side polished, as function of wavenumber for temperatures in the range of 58°C to 962°C, are presented in Fig.7. These wafers have resistivities in the range of 1x 10^{-2}-2x10^{-2} Ω.cm and are 0.61-0.64 mm in thickness. The observed sharp features in the infrared spectra in the wavelength range of 1μm (10,000 cm^{-1}) to 20μm (500 cm^{-1}) are due to the presence of the following infrared sensitive molecules: (a) C in Si-607 cm^{-1} (b) SiO_2-1110cm^{-1} (c) interstitial oxygen in Si-1130 cm^{-1} (d) H_2O-1600 and 3500 cm^{-1} (e) CO_2-2400 cm^{-1} (f) Si_3N_4-1206 cm^{-1}. The narrow bandgap features below 1000 cm^{-1} are due to lattice vibrations in silicon. Spectrum (i), in Fig.7, at 196°C was measured after heating the wafer to the maximum temperature of 962°C. Comparison of the emittance spectrum (i) to that in (b) indicates reversibility in emittance changes. The most pronounced change in all these measurements is the loss of transmissivity at elevated temperatures, due to increase in free carrier density, with increase in temperature. Results of the temperature dependent emissivity of silicon, in Fig. 8, lead us to a numerical model[33-34] that represents the best fit to experimental data. This equation is given by:

$$\varepsilon(\lambda, T) = A_o + (A1/\lambda) + (A2/\lambda^2) \quad \ldots \quad (24)$$

Where,

$$A_o = 0.64326 + (0.1264 \times 10^{-3})T - 0.67955\times10^{-7})T^2$$

$$A1 = 0.66789 - (0.1506 \times 10^{-2})T + 0.65442\times10^{-6})T^2$$

$$A2 = -1.2978 + (0.30243\times 10^{-2})T - (0.15119\times10^{-5})T^2$$

λ is the wavelength in microns and T is the temperature in Kelvin. The results of the calculations of ε of silicon as a function of λ for temperatures in the range of 400-1200 K, based on the above equations, are presented in Fig. 8. As can be seen in this figure, below 2 microns, emissivity is highly sensitive to temperature. The trend in its variation is characteristic of temperature making it difficult for modeling the changes in emissivity. However above two microns, emissivity increases with temperature irrespective of λ. Qualitatively, the non-linearities in the variation of emissivity with T for $\lambda > 2$ μm may be attributed to the presence of impurity states within the gap of the material and electron-phonon interaction. The calculated value of ε of silicon is in accord with expectations. The change in the extinction coefficient, k, with temperature is shown in Fig. 9. The extinction coefficient shows the same trend with temperature but with wavelength, its value is increasing. The change in ε_1 and ε_2 with temperature is plotted in Figs. 10 and 11 respectively. ε_1 follows the trend of the refractive index and ε_2 follows that of extinction coefficient. This is expected because

$\varepsilon_1 = n^2 - k^2$,

$\varepsilon_2 = 2nk$.

As $k << n$, thus ε_1 is proportional to n^2 and ε_2 proportional to k.

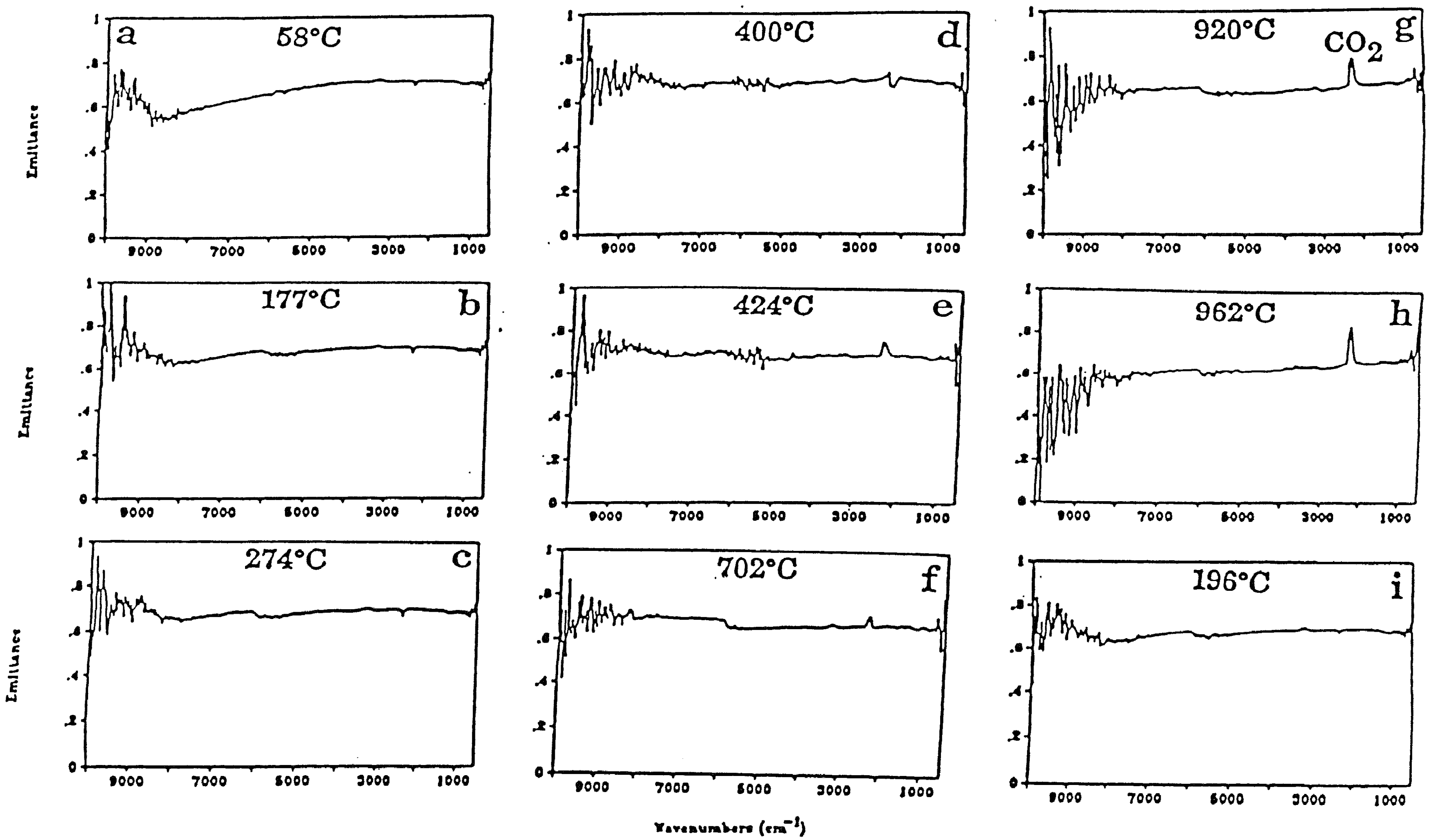


Figure 7 Spectral Emittance for p-type silicon wafer with front-side polished.

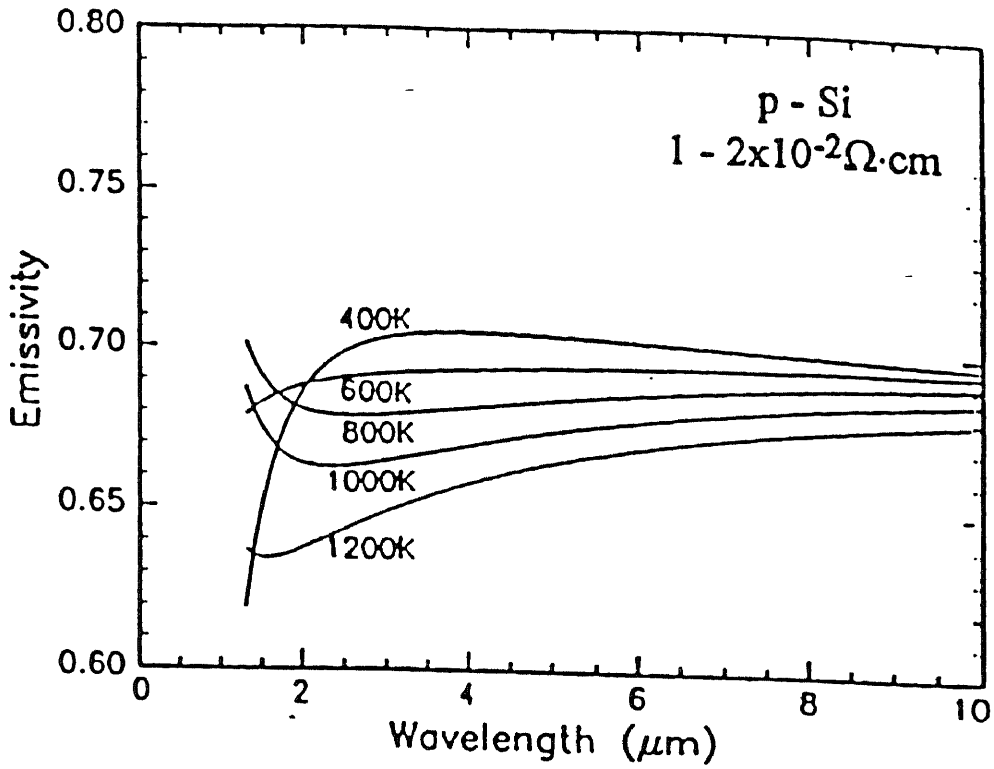


Figure 8 Calculated emissivity for p-type doped silicon.

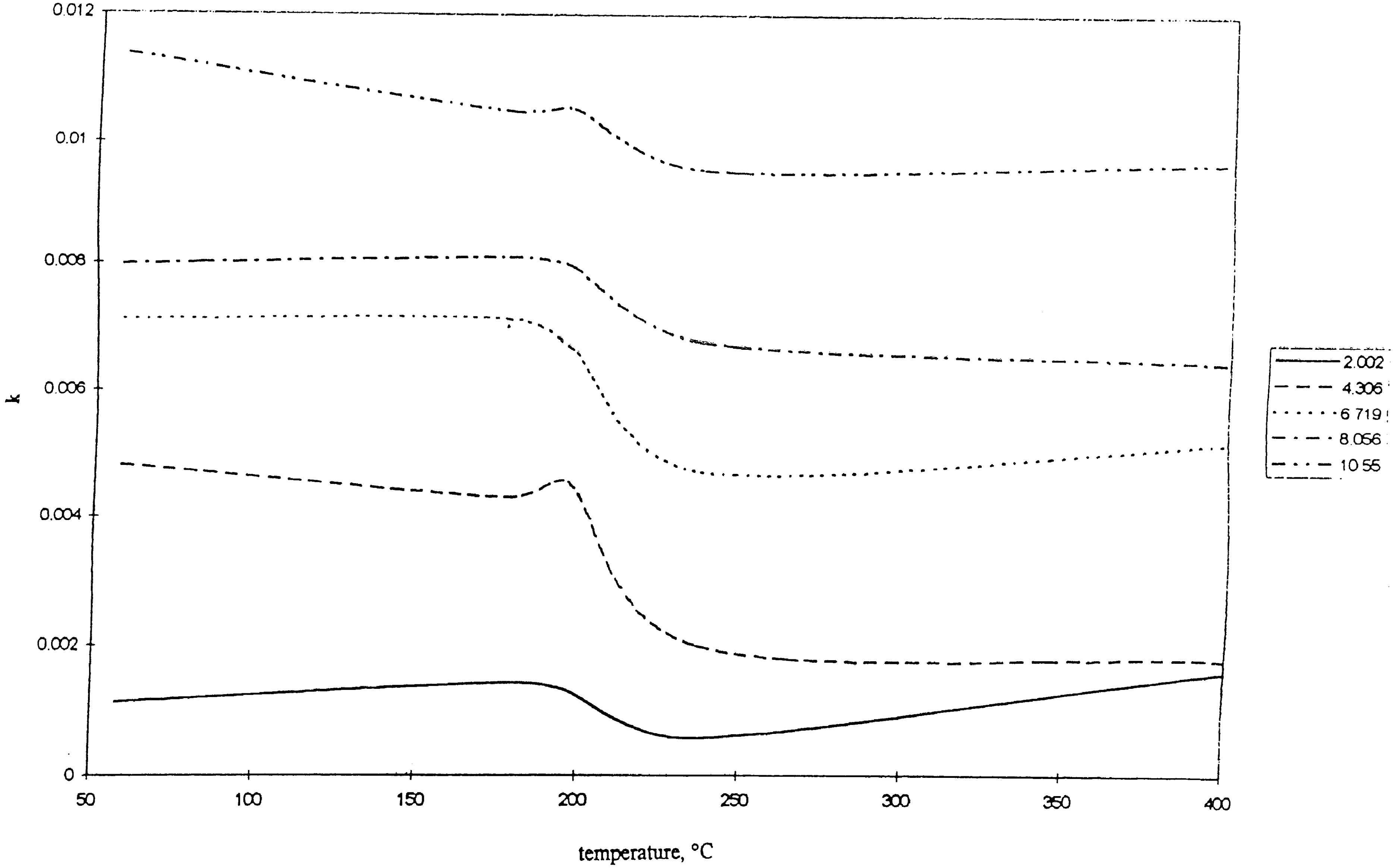


Figure 9 Extinction coefficient Vs temperature plot of p-type silicon with front side polished.

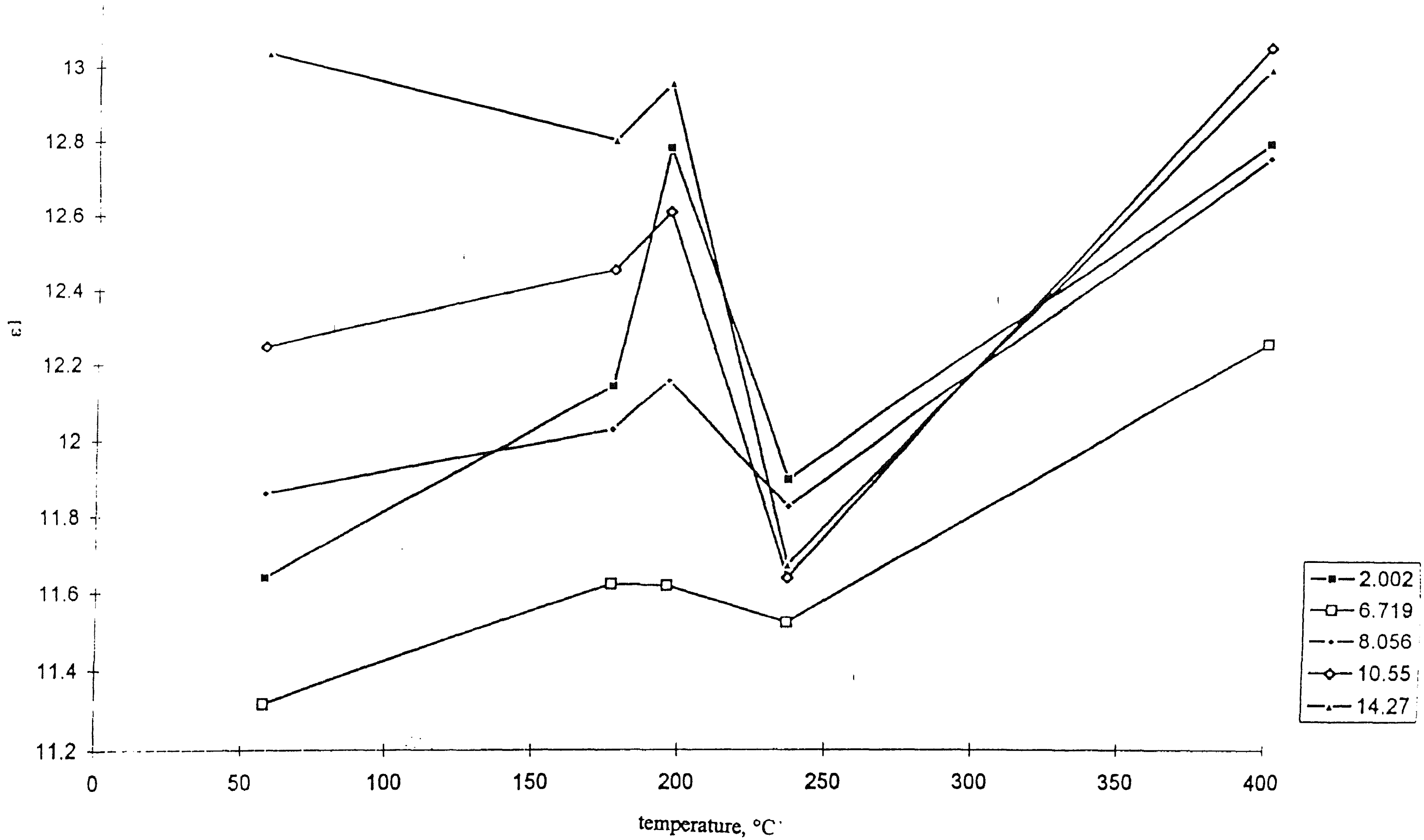


Figure 10 Epsilon1 Vs temperature plot of p-type silicon with front side polished.

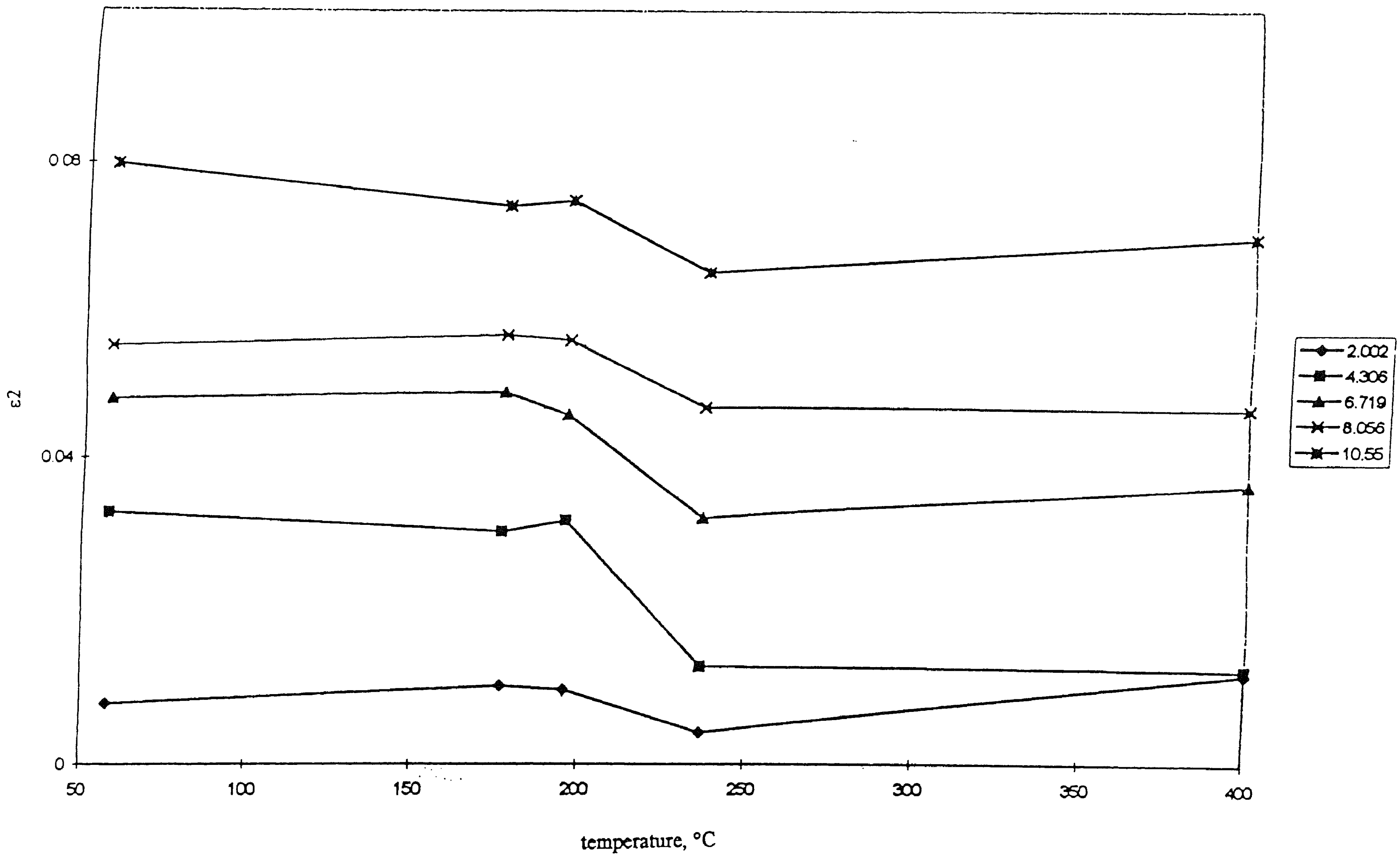


Figure 11 Epsilon2 Vs temperature plot of p-type silicon with front side polished.

6.4.2 n-type Silicon

A double side polished, n-type lightly doped wafer exhibits interesting properties. As seen in Fig.12, the emissivity of this wafer is negligible at room temperature while at high temperatures, it approaches that of single side polished silicon. The most change in this measurement is the loss of transmissivity at elevated temperatures, due to increase in free carrier density, with increase in temperature. In Fig.13, the calculated value of α are compared with those in the literature[34-35].

6.4.3 Effect of Thickness and Roughness on Wafer Emissivity

Emissivity has been evaluated as a function of wavelength for silicon wafer thickness in the range of 0.2 to 2 mm. The results are shown in Fig 15. Emissivity is a volume effect – larger wafer thickness leads to higher values of emissivity. It was found that the influence of backside roughness on the emissivity is different for partially transparent and opaque wafers. For opaque wafers, only a slight dependence of the emissivity on the backside roughness is observed, except for an extremely rough backside. For partially transparent wafers, a strong dependence of the emissivity on the backside roughness is observed. The model[37], which worked well, gave an effective transmittance Tr*, which can be written as $Tr^* = Fe^{-\alpha t}$ where, the factor F lies between 1 and 0 according to varying back-side roughness. The effect of roughness is to cause light trapping thereby reducing the transmittance and increasing the reflectance. Double side polished wafers seems to exhibit unusually low emissivities at low temperatures[14]. The emissivity is

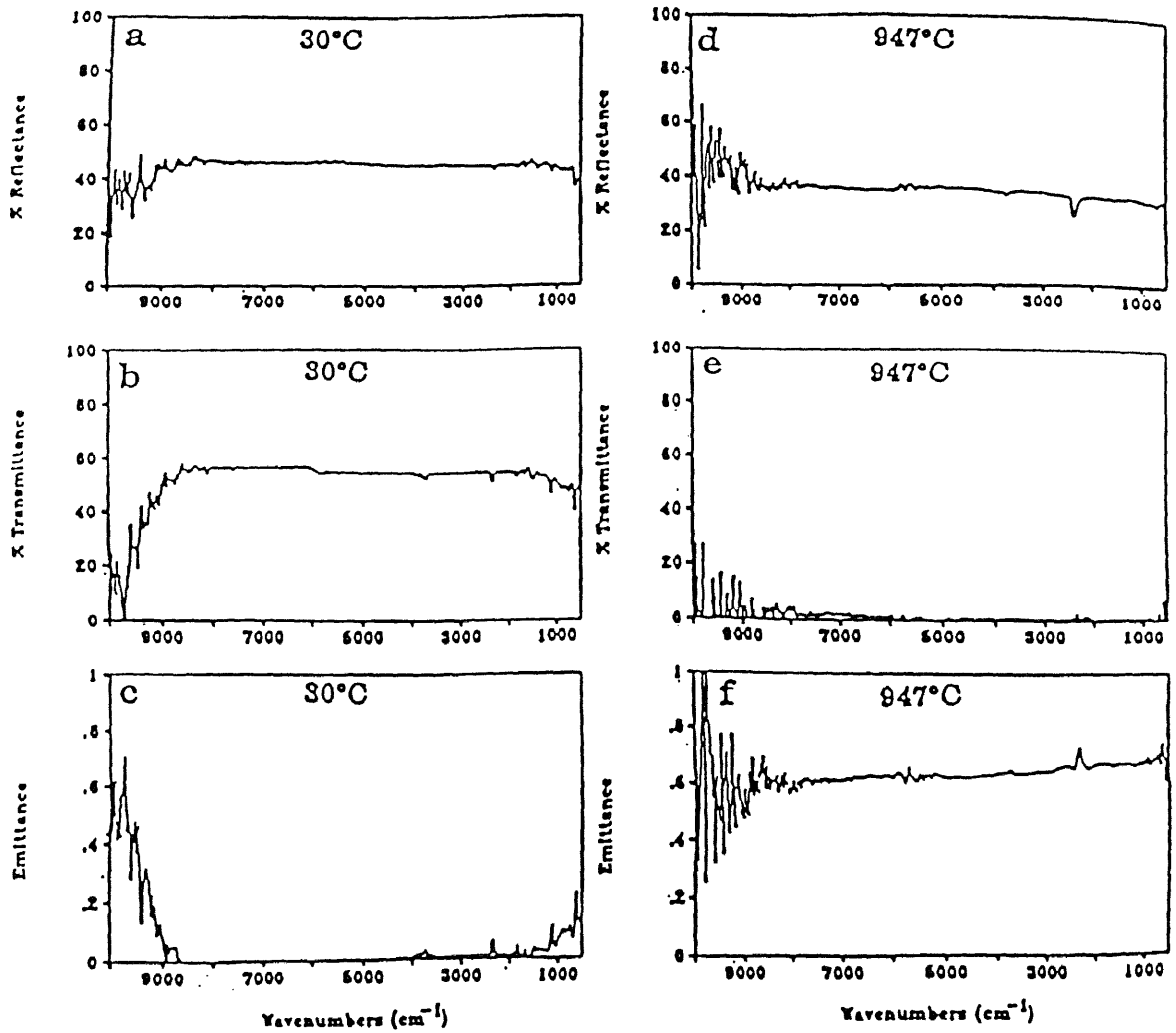


Figure 12 Reflectance, Transmittance and Emittance of double side polished n-type silicon wafer.

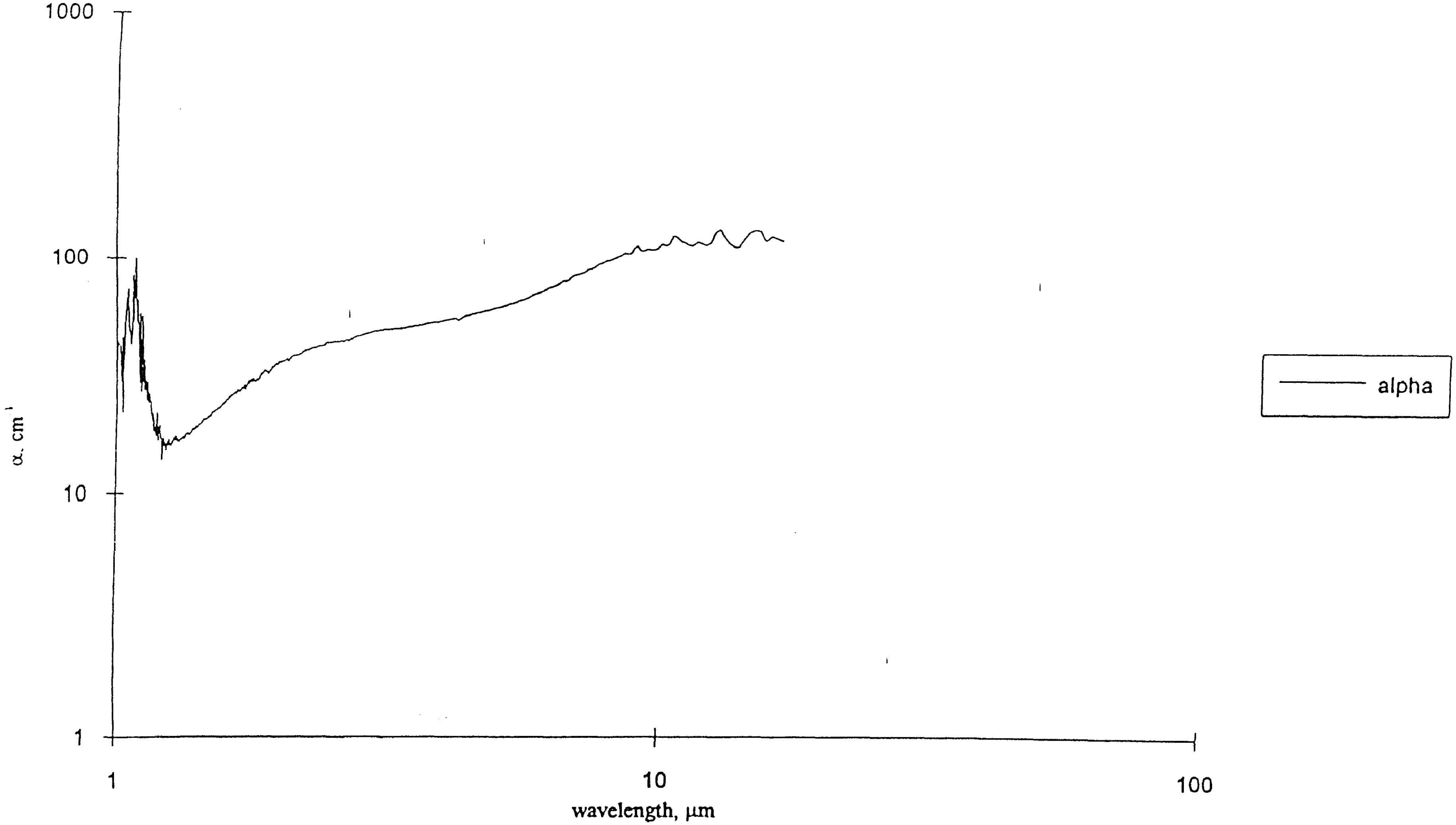


Figure 13 Alpha Vs wavelength of n-type silicon wafer with front side polished.

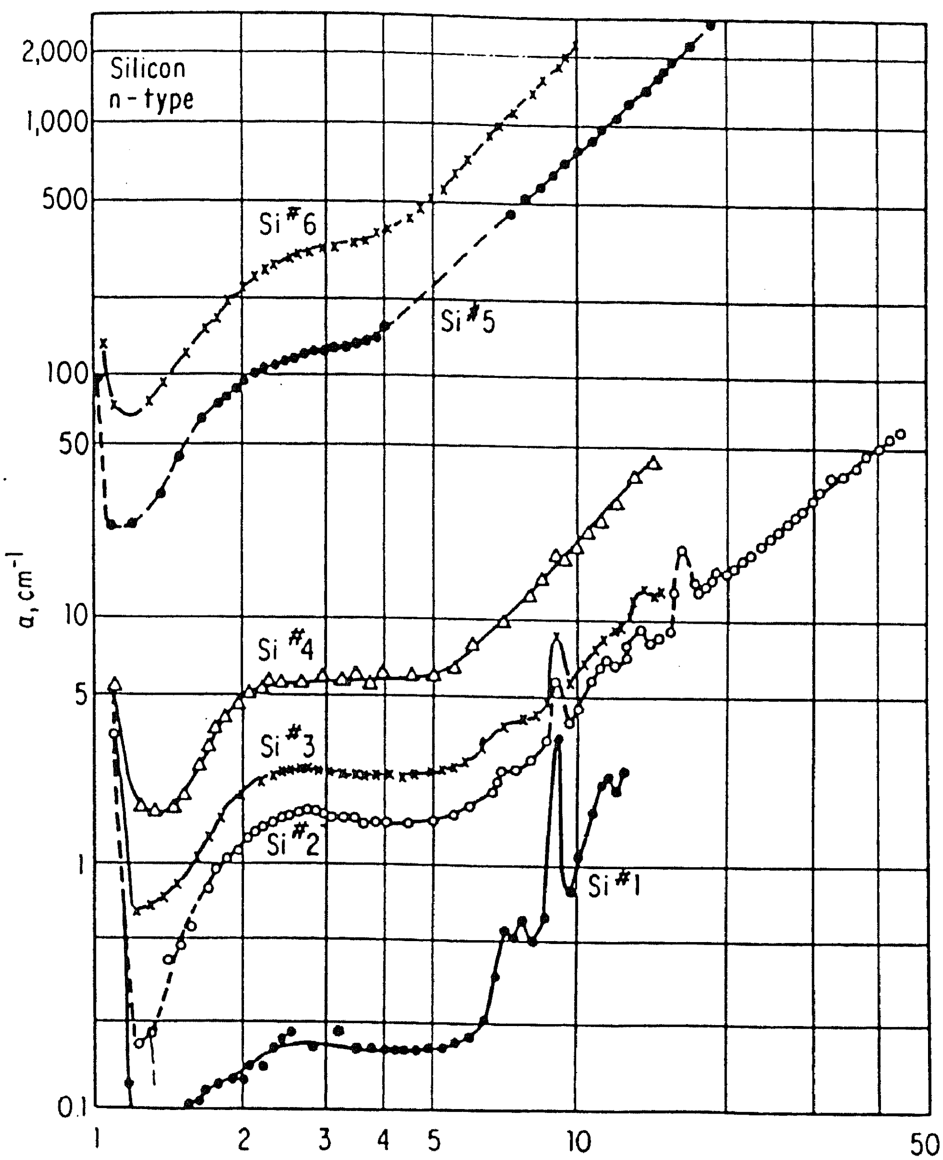


Figure 14 Alpha Vs Wavelength of n-type silicon from literature.

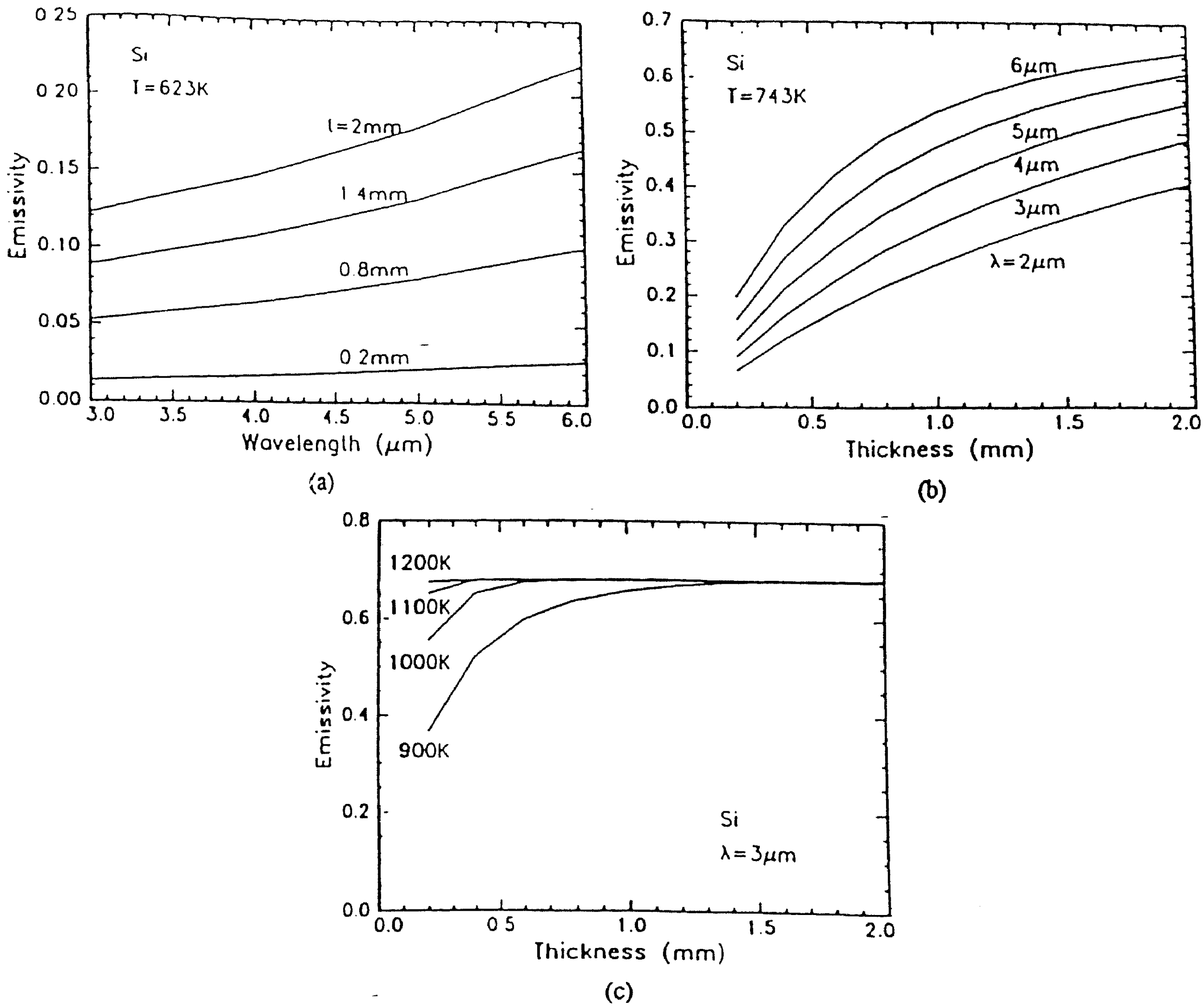


Figure 15 Calculated emissivity of lightly doped silicon as a function of (a)wavelength of samples with thickness of 0 2, 0.8, 1.4 and 2 mm at 623 K. (b)thickness for wavelength from 2 to 6 microns at 743 K. (c)thickness for temperature 900, 1100 and 1200 K at wavelength of 3 micron

not strongly dependent on the backside roughness, except for extreme back roughness. In situ emissivity measurements in a reflective chamber yielded higher emissivity values, which are also more sensitive to moderate roughness variations[37].

6.5 Comparative Study

The low temperature emissivity data has been compared with that of the Sato's[13] results and the summary of that comparison is presented in Table 4.

Table 4. Low Temperature Emissivity Data.

p – Si	n – Si	n – Si	Si	Sato[5]
polished one side	polished bothsides	polished one side	pure (polished both	n – Si sides)
300K	303K	461K	543K	543K
1.4-10 μm	1.4-10 μm	1.4-10 μm	1.5-6.5 μm	2-15μm
ε = 0.6-0.75	ε ≈ 0	ε=0.5-0.8	ε ≈ 0.05	ε= 0.7-0.8
ρ = 1-2x10-2 Ωcm	ρ = 1-3 Ωcm	ρ =0.005-0.02 Ωcm	ρ = 15 Ωcm	ρ=7x10-3 Ωcm
t = 0.61-0.64 mm	t = 0.27-0.29 mm	t = 0.41-0.46 mm	t = 1.77 mm	t = 3.71 mm

Emissivity of n-type and p-type silicon is compared at 183 °C and ~ 250 °C. A study on optical-absorption data for a series of heavily doped silicon samples has been performed[38] and conclusion of the study is that the electron-impurity interactions in heavily doped silicon are strong and beyond the powers of perturbation theory. The effect of doping, in general, is to reduce the transmittance. Thus, intrinsic Si exhibits high transmittance. Unlike pure silicon, the effect of free carriers/doping is to reduce the emissivity of silicon with increasing temperature. The comparison of the literature data with that of the deconvoluted value is presented in the table below:

Table 5 Comparison between the literature value of refractive index and that of the deconvoluted value

Wavelength, μm	n [31]	n (deconvoluted)
1.4	3.48	3.40
2.0	3.44	3.412
4.0	3.42	3.404
6.0	3.43	3.349
8.05	3.422	3.444
10.0	3.42	3.392
12.05	3.42	3.434
14.08	3.421	3.411
16.13	3.43	3.464

CHAPTER - 7

CONCLUSIONS

The experimental results presented in this thesis showed that the measurement of high temperature radiative properties over the wavelength range of 1 to 20 microns and temperature range of 300 to 2000 K could be performed reliably with a novel approach based on the use of a spectral emissometer. Methodology of obtaining temperature from simultaneous measurement of reflectance, transmittance and radiance has been shown with applications to silicon. The temperature measurement accuracy, with the emissometer, was found to be within ± 10 °C of the thermocouple temperature in the temperature range of 30 to 300 °C. In general, results of the temperature and wavelength dependent emissivity of silicon and comparison with studies in literature, lead to following observations:

- The effect of doping in general is to reduce the transmittance. Thus, intrinsic Si exhibits high transmittance.
- As temperature increases, silicon becomes opaque. This characteristic is useful in designing heating sources (contact or non-contact) to measure high temperature optical properties of silicon.
- Unlike pure silicon, the effect of free carriers/doping is to reduce the emissivity of silicon with increasing temperature.
- The effect of roughness is to cause light trapping reducing, thereby, the transmittance.

Much work needs to be performed to understand the effect of roughness. Double side polished wafers seems to show low emissivities at low temperatures.

Recommendations:

Spectral emissometer has thus been established as a reliable technique for simultaneous measurement of temperature and optical properties of semiconductors. In order to make this technique user-friendly and clean, the following improvements in the measurement systems need to be incorporated:

Much of the work on emissivity studies on semiconductors in the literature has focused on silicon. Since silicon is transparent below 600 °C, several approaches are being investigated to establish noncontact and noninterfering methods of heating silicon so that reliable temperature-dependent study of the optical properties may be performed. These methods include the use of lamps, lasers, e-beams and flames. The anticipation is that the heat-source signal can be completely eliminated in the measurement process. The present approach of using flames is appropriate for the measurement technique since the infrared spectra of the flames are very well known. On the other hand, flames will invariably modify the surface conditions of the samples under study. Ideally, the method of choice would be the one that does not modify the surface and bulk composition of the material at the same time permitting the required optics to measure the radiance from all possible angles. A sample chamber with a controlled environment would be very useful in keeping the measurement process and surface conditions of the samples free of contaminants.

It is proposed that future work be aimed at integrating a portable emissometer with a rapid thermal processing chamber for in-line, real-time measurement and control of process temperature and thickness of grown/deposited films.

APPENDIX A1

Data of Optical Constants p-type Silicon at 58 °C

LAMBDA	EXTCOEF	REFINDEX	EPSILON1	EPSILON2	ALPHA	EXTCOEF
1.005	0.000331	3.326	11.064	0.0022	0.004137	0.000331
1.006	0.000142	4.796	23.004	0.00136	0.001772	0.000142
1.008	0.000387	4.961	24.616	0.00384	0.004825	0.000387
1.01	0.000235	5.241	27.464	0.00246	0.002923	0.000235
1.011	0.000202	4.87	23.717	0.00197	0.002509	0.000202
1.013	0.000255	3.834	14.703	0.00195	0.003163	0.000255
1.014	0.000239	3.845	14.782	0.00183	0.002956	0.000239
1.016	0.000369	2.99	8.941	0.00221	0.004565	0.000369
1.021	0.000427	3.519	12.385	0.003	0.005256	0.000427
1.022	0.000402	3.106	9.646	0.0025	0.004941	0.000402
1.026	0.00055	3.54	12.529	0.00389	0.006736	0.00055
1.027	0.000291	3.583	12.84	0.00209	0.003566	0.000291
1.029	0.000353	3.719	13.834	0.00263	0.004317	0.000353
1.037	0.000299	3.11	9.672	0.00186	0.003628	0.000299
1.039	0.000306	2.895	8.382	0.00177	0.0037	0.000306
1.04	0.000449	3.018	9.105	0.00271	0.005429	0.000449
1.047	0.000869	3.713	13.79	0.00645	0.010433	0.000869
1.051	0.000542	3.433	11.788	0.00372	0.006484	0.000542
1.052	0.000467	3.812	14.529	0.00356	0.005582	0.000467
1.054	0.000482	3.806	14.486	0.00367	0.005752	0.000482
1.056	0.000393	3.537	12.511	0.00278	0.004678	0.000393
1.057	0.00048	3.382	11.44	0.00325	0.005707	0.00048
1.059	0.000615	3.373	11.378	0.00415	0.007305	0.000615
1.061	0.000375	3.458	11.959	0.0026	0.004447	0.000375
1.063	0.0003	3.331	11.094	0.002	0.003551	0.0003
1.064	0.00027	3.407	11.608	0.00184	0.003184	0.00027
1.066	0.000335	3.911	15.294	0.00262	0.003945	0.000335
1.068	0.001149	4.196	17.604	0.00964	0.013528	0.001149
1.07	0.000736	3.271	10.702	0.00482	0.008652	0.000736
1.071	0.000474	2.993	8.956	0.00284	0.00556	0.000474
1.073	0.00058	3.253	10.582	0.00377	0.006794	0.00058
1.079	0.000335	3.442	11.848	0.00231	0.003907	0.000335
1.08	0.000291	3.331	11.094	0.00194	0.003387	0.000291
1.082	0.000277	3.245	10.53	0.0018	0.003217	0.000277
1.084	0.000307	3.215	10.336	0.00198	0.003563	0.000307
1.086	0.000323	3.112	9.682	0.00201	0.003743	0.000323
1.088	0.000312	2.949	8.696	0.00184	0.003607	0.000312
1.089	0.000295	3.226	10.408	0.0019	0.003407	0.000295
1.091	0.000338	3.418	11.686	0.00231	0.003898	0.000338
1.093	0.000427	3.362	11.3	0.00287	0.004906	0.000427
1.095	0.000362	3.525	12.422	0.00255	0.004156	0.000362
1.097	0.000349	3.467	12.023	0.00242	0.003998	0.000349
1.099	0.000365	3.417	11.678	0.00249	0.004176	0.000365
1.101	0.000411	3.568	12.729	0.00293	0.004692	0.000411
1.102	0.000358	3.656	13.364	0.00261	0.004077	0.000358
1.104	0.000266	3.351	11.229	0.00178	0.00303	0.000266
1.106	0.000297	3.428	11.753	0.00203	0.00337	0.000297
1.108	0.000446	3.718	13.825	0.00332	0.005058	0.000446
1.11	0.000309	3.58	12.82	0.00221	0.0035	0.000309
1.112	0.000291	3.472	12.058	0.00202	0.003291	0.000291

APPENDIX A1 (continued)

1.114	0.000293	3.439	11.828	0.00202	0.003309	0.000293
1.116	0.000254	3.47	12.04	0.00176	0.002861	0.000254
1.118	0.000321	3.434	11.792	0.0022	0.003606	0.000321
1.12	0.000327	3.39	11.495	0.00222	0.003677	0.000327
1.121	0.000294	3.446	11.875	0.00203	0.003298	0.000294
1.123	0.000294	3.492	12.191	0.00205	0.003287	0.000294
1.125	0.000266	3.534	12.488	0.00188	0.002975	0.000266
1.127	0.00024	3.584	12.848	0.00172	0.002678	0.00024
1.129	0.000234	3.484	12.14	0.00163	0.002607	0.000234
1.131	0.000209	3.469	12.033	0.00145	0.002325	0.000209
1.133	0.000199	3.563	12.697	0.00142	0.002206	0.000199
1.135	0.000244	3.605	12.998	0.00176	0.0027	0.000244
1.137	0.000238	3.567	12.726	0.0017	0.00263	0.000238
1.139	0.000243	3.485	12.143	0.00169	0.00268	0.000243
1.141	0.000271	3.336	11.13	0.00181	0.00298	0.000271
1.143	0.000241	3.392	11.503	0.00164	0.002653	0.000241
1.145	0.000218	3.467	12.023	0.00151	0.002393	0.000218
1.147	0.000218	3.531	12.465	0.00154	0.002392	0.000218
1.149	0.000242	3.533	12.484	0.00171	0.002645	0.000242
1.151	0.00024	3.47	12.044	0.00167	0.002625	0.00024
1.153	0.00023	3.508	12.305	0.00162	0.002511	0.00023
1.155	0.000256	3.421	11.701	0.00175	0.002781	0.000256
1.158	0.000254	3.369	11.351	0.00171	0.002759	0.000254
1.16	0.000259	3.398	11.547	0.00176	0.002813	0.000259
1.162	0.000263	3.429	11.758	0.0018	0.002841	0.000263
1.164	0.000244	3.521	12.398	0.00172	0.00264	0.000244
1.166	0.000229	3.544	12.56	0.00162	0.002467	0.000229
1.168	0.000221	3.482	12.123	0.00154	0.002378	0.000221
1.17	0.000235	3.469	12.033	0.00163	0.002526	0.000235
1.172	0.000253	3.508	12.307	0.00178	0.002715	0.000253
1.174	0.000246	3.351	11.228	0.00165	0.002631	0.000246
1.176	0.000226	3.351	11.232	0.00152	0.002418	0.000226
1.179	0.000235	3.449	11.898	0.00162	0.002509	0.000235
1.181	0.000246	3.414	11.657	0.00168	0.002615	0.000246
1.183	0.000234	3.544	12.557	0.00166	0.002491	0.000234
1.185	0.000237	3.541	12.54	0.00168	0.002509	0.000237
1.187	0.000238	3.512	12.336	0.00167	0.00252	0.000238
1.189	0.00024	3.499	12.24	0.00168	0.002539	0.00024
1.192	0.000239	3.393	11.512	0.00162	0.002516	0.000239
1.194	0.000235	3.401	11.566	0.0016	0.002473	0.000235
1.196	0.000243	3.393	11.513	0.00165	0.00255	0.000243
1.198	0.000258	3.314	10.982	0.00171	0.002706	0.000258
1.2	0.000257	3.333	11.11	0.00172	0.002695	0.000257
1.203	0.000248	3.445	11.87	0.00171	0.002588	0.000248
1.205	0.000253	3.471	12.051	0.00176	0.002642	0.000253
1.207	0.000269	3.452	11.917	0.00186	0.0028	0.000269
1.209	0.000267	3.47	12.04	0.00185	0.002773	0.000267
1.212	0.000248	3.478	12.094	0.00172	0.002571	0.000248
1.214	0.000242	3.454	11.934	0.00167	0.002506	0.000242
1.216	0.00026	3.343	11.175	0.00174	0.00269	0.00026
1.219	0.000294	3.328	11.075	0.00196	0.003034	0.000294

APPENDIX A1 (continued)

1.221	0.000297	3.393	11.511	0.00202	0.00306	0.000297
1.223	0.00028	3.452	11.918	0.00193	0.002878	0.00028
1.225	0.000279	3.404	11.589	0.0019	0.002864	0.000279
1.228	0.000269	3.388	11.481	0.00182	0.002753	0.000269
1.23	0.000271	3.448	11.887	0.00187	0.00277	0.000271
1.232	0.000293	3.398	11.548	0.00199	0.002984	0.000293
1.235	0.000277	3.373	11.379	0.00187	0.002824	0.000277
1.237	0.000256	3.336	11.129	0.00171	0.002599	0.000256
1.24	0.000272	3.297	10.867	0.00179	0.002758	0.000272
1.242	0.000284	3.341	11.163	0.0019	0.002879	0.000284
1.244	0.000276	3.34	11.158	0.00184	0.002786	0.000276
1.247	0.000278	3.36	11.292	0.00187	0.002805	0.000278
1.249	0.000278	3.414	11.653	0.0019	0.002801	0.000278
1.252	0.000285	3.413	11.649	0.00195	0.002864	0.000285
1.254	0.000286	3.395	11.526	0.00194	0.002865	0.000286
1.256	0.000282	3.376	11.396	0.0019	0.002817	0.000282
1.259	0.000285	3.336	11.128	0.0019	0.002848	0.000285
1.261	0.000298	3.303	10.909	0.00197	0.002974	0.000298
1.264	0.000308	3.338	11.144	0.00206	0.003066	0.000308
1.266	0.000308	3.374	11.386	0.00208	0.003062	0.000308
1.269	0.000314	3.399	11.554	0.00213	0.003108	0.000314
1.271	0.000308	3.386	11.465	0.00209	0.00305	0.000308
1.274	0.000304	3.376	11.401	0.00206	0.003005	0.000304
1.276	0.000309	3.437	11.812	0.00212	0.003041	0.000309
1.279	0.000313	3.458	11.959	0.00217	0.003079	0.000313
1.281	0.000315	3.421	11.7	0.00216	0.003091	0.000315
1.284	0.000311	3.392	11.508	0.00211	0.003043	0.000311
1.286	0.000314	3.383	11.447	0.00212	0.003066	0.000314
1.289	0.000318	3.374	11.387	0.00215	0.003105	0.000318
1.291	0.000317	3.365	11.326	0.00213	0.003084	0.000317
1.294	0.000315	3.369	11.351	0.00212	0.003056	0.000315
1.297	0.000322	3.347	11.202	0.00216	0.003124	0.000322
1.299	0.000322	3.348	11.208	0.00215	0.003114	0.000322
1.302	0.000315	3.371	11.365	0.00212	0.003039	0.000315
1.304	0.000321	3.358	11.277	0.00216	0.003096	0.000321
1.307	0.000318	3.384	11.449	0.00215	0.003056	0.000318
1.31	0.000314	3.409	11.62	0.00214	0.003013	0.000314
1.312	0.00032	3.384	11.449	0.00217	0.00307	0.00032
1.315	0.000325	3.38	11.428	0.00219	0.003102	0.000325
1.318	0.000325	3.383	11.447	0.0022	0.003104	0.000325
1.32	0.000327	3.369	11.351	0.00221	0.003116	0.000327
1.323	0.00034	3.369	11.348	0.00229	0.003233	0.00034
1.326	0.000356	3.39	11.495	0.00241	0.003372	0.000356
1.329	0.000349	3.377	11.405	0.00236	0.003302	0.000349
1.331	0.000339	3.377	11.402	0.00229	0.003197	0.000339
1.334	0.000351	3.368	11.347	0.00236	0.003305	0.000351
1.337	0.00035	3.381	11.433	0.00237	0.003289	0.00035
1.34	0.000341	3.423	11.714	0.00233	0.003197	0.000341
1.342	0.000351	3.412	11.639	0.00239	0.003283	0.000351
1.345	0.00035	3.408	11.612	0.00238	0.00327	0.00035
1.348	0.00035	3.384	11.453	0.00237	0.003263	0.00035

APPENDIX A1 (continued)

1.351	0.000354	3.365	11.324	0.00238	0.003298	0.000354
1.354	0.000352	3.415	11.66	0.00241	0.003272	0.000352
1.356	0.000356	3.428	11.754	0.00244	0.003298	0.000356
1.359	0.000365	3.389	11.482	0.00248	0.003379	0.000365
1.362	0.000366	3.368	11.345	0.00247	0.003383	0.000366
1.365	0.000363	3.389	11.486	0.00246	0.003348	0.000363
1.368	0.000362	3.413	11.649	0.00247	0.00333	0.000362
1.371	0.000368	3.398	11.544	0.0025	0.003372	0.000368
1.374	0.000374	3.384	11.452	0.00253	0.00342	0.000374
1.377	0.000377	3.397	11.543	0.00256	0.00344	0.000377
1.38	0.000377	3.398	11.544	0.00256	0.003437	0.000377
1.382	0.000383	3.386	11.466	0.00259	0.003479	0.000383
1.385	0.000386	3.391	11.501	0.00262	0.003504	0.000386
1.388	0.000382	3.384	11.453	0.00259	0.003459	0.000382
1.391	0.00038	3.397	11.539	0.00258	0.003433	0.00038
1.394	0.000378	3.406	11.603	0.00258	0.00341	0.000378
1.397	0.000385	3.396	11.53	0.00262	0.003464	0.000385
1.4	0.000399	3.401	11.566	0.00271	0.003581	0.000399
1.403	0.00041	3.39	11.495	0.00278	0.003669	0.00041
1.406	0.000403	3.367	11.336	0.00271	0.003599	0.000403
1.41	0.0004	3.376	11.399	0.0027	0.003567	0.0004
1.413	0.000402	3.364	11.318	0.00271	0.003581	0.000402
1.416	0.000401	3.368	11.346	0.0027	0.00356	0.000401
1.419	0.000408	3.367	11.339	0.00275	0.003613	0.000408
1.422	0.000418	3.366	11.332	0.00281	0.003692	0.000418
1.425	0.00042	3.38	11.425	0.00284	0.003705	0.00042
1.428	0.000417	3.371	11.36	0.00281	0.00367	0.000417
1.431	0.000416	3.375	11.388	0.00281	0.003654	0.000416
1.435	0.000418	3.385	11.457	0.00283	0.00366	0.000418
1.438	0.000419	3.37	11.355	0.00282	0.00366	0.000419
1.441	0.000426	3.372	11.37	0.00287	0.003717	0.000426
1.444	0.00043	3.375	11.393	0.0029	0.003741	0.00043
1.447	0.000431	3.369	11.351	0.00291	0.003747	0.000431
1.451	0.000435	3.369	11.352	0.00293	0.003766	0.000435
1.454	0.000431	3.37	11.355	0.00291	0.00373	0.000431
1.457	0.00044	3.369	11.352	0.00297	0.003796	0.00044
1.46	0.000445	3.398	11.544	0.00302	0.003828	0.000445
1.464	0.000448	3.403	11.583	0.00305	0.003852	0.000448
1.467	0.000449	3.383	11.445	0.00304	0.003847	0.000449
1.47	0.000447	3.385	11.461	0.00303	0.003823	0.000447
1.474	0.000448	3.384	11.453	0.00303	0.003819	0.000448
1.477	0.000449	3.388	11.48	0.00304	0.003823	0.000449
1.48	0.00046	3.406	11.599	0.00314	0.00391	0.00046
1.484	0.000469	3.407	11.609	0.00319	0.003971	0.000469
1.487	0.000473	3.392	11.505	0.00321	0.003996	0.000473
1.491	0.000478	3.406	11.603	0.00326	0.004031	0.000478
1.494	0.000479	3.41	11.631	0.00327	0.004033	0.000479
1.498	0.000475	3.401	11.568	0.00323	0.003991	0.000475
1.501	0.000476	3.409	11.619	0.00324	0.003985	0.000476
1.505	0.000483	3.397	11.542	0.00328	0.004037	0.000483
1.508	0.000489	3.385	11.46	0.00331	0.004075	0.000489

APPENDIX A1 (continued)

1.512	0.000496	3.387	11.473	0.00336	0.004127	0.000496
1.515	0.000506	3.402	11.575	0.00344	0.004196	0.000506
1.519	0.000494	3.412	11.641	0.00337	0.004087	0.000494
1.522	0.000487	3.399	11.551	0.00331	0.004021	0.000487
1.526	0.000497	3.391	11.501	0.00337	0.004095	0.000497
1.529	0.000506	3.397	11.54	0.00344	0.004159	0.000506
1.533	0.000514	3.405	11.595	0.0035	0.004212	0.000514
1.537	0.000511	3.399	11.553	0.00347	0.004179	0.000511
1.54	0.000511	3.398	11.546	0.00347	0.004172	0.000511
1.544	0.000516	3.42	11.695	0.00353	0.004205	0.000516
1.548	0.00052	3.424	11.727	0.00356	0.004224	0.00052
1.551	0.000528	3.41	11.626	0.0036	0.00428	0.000528
1.555	0.000535	3.409	11.624	0.00365	0.004324	0.000535
1.559	0.000537	3.405	11.597	0.00366	0.004331	0.000537
1.563	0.000544	3.406	11.602	0.0037	0.004373	0.000544
1.566	0.000545	3.414	11.657	0.00372	0.00437	0.000545
1.57	0.000554	3.4	11.557	0.00377	0.004438	0.000554
1.574	0.000561	3.397	11.542	0.00381	0.004481	0.000561
1.578	0.00056	3.417	11.673	0.00383	0.004463	0.00056
1.582	0.000565	3.414	11.652	0.00386	0.00449	0.000565
1.586	0.000565	3.414	11.654	0.00386	0.004479	0.000565
1.589	0.000564	3.42	11.695	0.00386	0.00446	0.000564
1.593	0.000563	3.414	11.656	0.00385	0.004445	0.000563
1.597	0.000573	3.414	11.657	0.00391	0.004511	0.000573
1.601	0.000583	3.407	11.609	0.00397	0.004577	0.000583
1.605	0.000575	3.41	11.629	0.00392	0.004506	0.000575
1.609	0.000582	3.41	11.628	0.00397	0.00455	0.000582
1.613	0.000596	3.411	11.633	0.00407	0.004645	0.000596
1.617	0.000601	3.417	11.678	0.00411	0.004674	0.000601
1.621	0.000605	3.41	11.631	0.00413	0.004694	0.000605
1.625	0.000605	3.409	11.625	0.00413	0.004681	0.000605
1.629	0.000608	3.41	11.629	0.00415	0.00469	0.000608
1.634	0.000621	3.412	11.645	0.00424	0.004783	0.000621
1.638	0.000629	3.421	11.705	0.0043	0.004827	0.000629
1.642	0.00063	3.427	11.744	0.00432	0.004824	0.00063
1.646	0.000636	3.434	11.794	0.00437	0.004854	0.000636
1.65	0.000632	3.444	11.861	0.00436	0.004818	0.000632
1.654	0.000625	3.442	11.85	0.0043	0.004746	0.000625
1.659	0.000633	3.424	11.726	0.00433	0.004795	0.000633
1.663	0.000647	3.409	11.624	0.00441	0.004894	0.000647
1.667	0.000644	3.426	11.736	0.00441	0.004857	0.000644
1.672	0.000646	3.428	11.748	0.00443	0.004862	0.000646
1.676	0.000666	3.408	11.616	0.00454	0.004999	0.000666
1.68	0.00067	3.437	11.816	0.00461	0.005015	0.00067
1.685	0.00065	3.474	12.067	0.00451	0.004848	0.00065
1.689	0.000655	3.452	11.913	0.00452	0.004876	0.000655
1.693	0.000668	3.45	11.902	0.00461	0.004962	0.000668
1.698	0.000655	3.445	11.865	0.00451	0.004848	0.000655
1.702	0.000652	3.41	11.628	0.00445	0.004815	0.000652
1.707	0.000689	3.359	11.282	0.00463	0.005076	0.000689
1.711	0.000702	3.373	11.378	0.00474	0.005159	0.000702

APPENDIX A1 (continued)

1.984	0.001132	3.398	11.544	0.00769	0.007174	0.001132
1.99	0.00111	3.419	11.688	0.00759	0.007014	0.00111
1.996	0.001147	3.413	11.648	0.00783	0.007223	0.001147
2.002	0.001126	3.412	11.641	0.00769	0.007072	0.001126
2.009	0.001109	3.411	11.637	0.00756	0.006938	0.001109
2.015	0.001159	3.413	11.645	0.00791	0.007234	0.001159
2.021	0.001241	3.406	11.602	0.00845	0.007717	0.001241
2.027	0.001264	3.404	11.586	0.0086	0.007836	0.001264
2.034	0.001231	3.399	11.555	0.00837	0.00761	0.001231
2.04	0.001192	3.395	11.523	0.0081	0.007347	0.001192
2.047	0.001162	3.385	11.459	0.00787	0.007137	0.001162
2.053	0.001175	3.376	11.396	0.00793	0.007195	0.001175
2.06	0.001185	3.4	11.561	0.00806	0.007234	0.001185
2.066	0.001222	3.414	11.657	0.00834	0.007433	0.001222
2.073	0.001282	3.391	11.502	0.0087	0.007775	0.001282
2.08	0.001322	3.378	11.412	0.00893	0.007989	0.001322
2.086	0.001303	3.399	11.552	0.00886	0.007852	0.001303
2.093	0.001264	3.402	11.576	0.0086	0.00759	0.001264
2.1	0.001271	3.379	11.417	0.00859	0.00761	0.001271
2.107	0.001282	3.383	11.447	0.00868	0.007651	0.001282
2.113	0.001319	3.408	11.615	0.00899	0.007847	0.001319
2.12	0.001362	3.405	11.594	0.00928	0.008076	0.001362
2.127	0.001379	3.391	11.5	0.00935	0.008149	0.001379
2.134	0.001386	3.39	11.49	0.0094	0.008165	0.001386
2.141	0.00134	3.4	11.563	0.00911	0.007867	0.00134
2.148	0.001419	3.397	11.537	0.00964	0.008301	0.001419
2.156	0.001531	3.39	11.491	0.01038	0.008929	0.001531
2.163	0.001415	3.389	11.484	0.00959	0.008224	0.001415
2.17	0.001389	3.373	11.377	0.00937	0.008048	0.001389
2.177	0.00142	3.373	11.379	0.00958	0.008199	0.00142
2.185	0.001446	3.385	11.457	0.00979	0.008322	0.001446
2.192	0.001443	3.376	11.398	0.00974	0.008275	0.001443
2.2	0.001465	3.359	11.286	0.00984	0.00837	0.001465
2.207	0.001543	3.358	11.274	0.01036	0.008789	0.001543
2.215	0.001583	3.352	11.234	0.01061	0.008987	0.001583
2.222	0.001584	3.339	11.147	0.01058	0.008962	0.001584
2.23	0.001584	3.344	11.179	0.0106	0.008933	0.001584
2.238	0.001633	3.357	11.273	0.01097	0.009175	0.001633
2.245	0.001721	3.361	11.294	0.01157	0.009636	0.001721
2.253	0.00165	3.364	11.317	0.0111	0.009207	0.00165
2.261	0.001614	3.372	11.37	0.01089	0.008975	0.001614
2.269	0.001588	3.365	11.324	0.01069	0.008799	0.001588
2.277	0.001566	3.362	11.303	0.01053	0.008646	0.001566
2.285	0.00162	3.365	11.325	0.0109	0.008912	0.00162
2.293	0.001611	3.367	11.34	0.01085	0.00883	0.001611
2.301	0.001642	3.363	11.307	0.01104	0.008969	0.001642
2.309	0.001731	3.358	11.279	0.01162	0.009421	0.001731
2.318	0.001787	3.366	11.332	0.01203	0.009691	0.001787
2.326	0.001818	3.37	11.359	0.01226	0.009827	0.001818
2.334	0.001828	3.364	11.314	0.0123	0.009846	0.001828
2.343	0.001878	3.357	11.269	0.01261	0.010076	0.001878

APPENDIX A1 (continued)

2.351	0.001816	3.352	11.233	0.01217	0.009711	0.001816
2.36	0.001705	3.351	11.228	0.01142	0.009081	0.001705
2.369	0.00178	3.354	11.251	0.01194	0.009448	0.00178
2.377	0.001932	3.351	11.227	0.01294	0.010214	0.001932
2.386	0.001914	3.343	11.178	0.0128	0.010085	0.001914
2.395	0.00191	3.35	11.222	0.0128	0.010027	0.00191
2.404	0.001946	3.356	11.262	0.01306	0.010175	0.001946
2.413	0.001897	3.347	11.199	0.0127	0.009887	0.001897
2.422	0.001919	3.344	11.182	0.01284	0.009963	0.001919
2.431	0.001994	3.351	11.231	0.01336	0.010311	0.001994
2.44	0.002137	3.356	11.26	0.01434	0.011012	0.002137
2.449	0.002166	3.348	11.211	0.01451	0.011119	0.002166
2.458	0.002079	3.348	11.21	0.01392	0.01063	0.002079
2.468	0.002161	3.351	11.229	0.01448	0.011009	0.002161
2.477	0.0022	3.344	11.184	0.01472	0.011167	0.0022
2.487	0.002286	3.339	11.146	0.01526	0.011554	0.002286
2.496	0.002263	3.34	11.158	0.01512	0.011397	0.002263
2.506	0.002181	3.343	11.176	0.01458	0.010938	0.002181
2.516	0.002238	3.337	11.135	0.01494	0.011184	0.002238
2.526	0.002152	3.337	11.133	0.01436	0.01071	0.002152
2.536	0.002107	3.336	11.13	0.01406	0.010445	0.002107
2.545	0.002197	3.334	11.115	0.01465	0.010848	0.002197
2.556	0.002266	3.336	11.132	0.01512	0.011147	0.002266
2.566	0.002437	3.337	11.135	0.01626	0.011942	0.002437
2.597	0.002575	3.345	11.186	0.01722	0.012467	0.002575
2.607	0.002397	3.338	11.143	0.01601	0.011561	0.002397
2.617	0.002497	3.332	11.099	0.01663	0.011991	0.002497
2.628	0.002469	3.337	11.133	0.01647	0.011808	0.002469
2.639	0.00235	3.336	11.126	0.01568	0.011195	0.00235
2.65	0.003151	3.333	11.109	0.021	0.014949	0.003151
2.671	0.003052	3.348	11.21	0.02044	0.014364	0.003052
2.694	0.002745	3.348	11.206	0.01838	0.012812	0.002745
2.705	0.00258	3.343	11.175	0.01725	0.011989	0.00258
2.716	0.002397	3.338	11.139	0.016	0.011092	0.002397
2.728	0.002264	3.336	11.131	0.01511	0.010435	0.002264
2.739	0.002403	3.335	11.119	0.01603	0.011029	0.002403
2.751	0.002705	3.344	11.185	0.01809	0.01236	0.002705
2.763	0.002841	3.357	11.269	0.01907	0.012926	0.002841
2.775	0.002703	3.356	11.261	0.01814	0.012246	0.002703
2.786	0.002685	3.345	11.192	0.01796	0.012112	0.002685
2.799	0.002957	3.34	11.157	0.01976	0.013285	0.002957
2.811	0.003502	3.335	11.124	0.02336	0.015665	0.003502
2.823	0.003118	3.335	11.123	0.02079	0.013884	0.003118
2.835	0.00267	3.338	11.141	0.01782	0.011837	0.00267
2.848	0.002697	3.336	11.132	0.018	0.011908	0.002697
2.86	0.003121	3.341	11.162	0.02085	0.013716	0.003121
2.873	0.00331	3.341	11.162	0.02212	0.014486	0.00331
2.886	0.003466	3.334	11.114	0.02311	0.015099	0.003466
2.899	0.002929	3.332	11.105	0.01952	0.012701	0.002929
2.912	0.00268	3.329	11.08	0.01784	0.011571	0.00268
2.925	0.002764	3.324	11.052	0.01838	0.011879	0.002764

APPENDIX A1 (continued)

2.938	0.003002	3.318	11.009	0.01992	0.012844	0.003002
2.952	0.00312	3.316	10.997	0.0207	0.013291	0.00312
2.965	0.002981	3.313	10.976	0.01975	0.01264	0.002981
2.979	0.003573	3.301	10.897	0.02359	0.01508	0.003573
3.02	0.00353	3.292	10.84	0.02324	0.014692	0.00353
3.035	0.003012	3.284	10.785	0.01978	0.012476	0.003012
3.049	0.003057	3.272	10.709	0.02001	0.012606	0.003057
3.063	0.003182	3.263	10.645	0.02077	0.01306	0.003182
3.107	0.003903	3.266	10.669	0.0255	0.015792	0.003903
3.122	0.003594	3.272	10.706	0.02352	0.014469	0.003594
3.138	0.003696	3.281	10.763	0.02425	0.01481	0.003696
3.153	0.00383	3.288	10.812	0.02519	0.015271	0.00383
3.168	0.00389	3.297	10.868	0.02565	0.015434	0.00389
3.2	0.003926	3.314	10.982	0.02602	0.015425	0.003926
3.215	0.003327	3.326	11.061	0.02213	0.013008	0.003327
3.231	0.003412	3.329	11.081	0.02271	0.013273	0.003412
3.281	0.003779	3.337	11.136	0.02522	0.014482	0.003779
3.331	0.003917	3.334	11.118	0.02612	0.014783	-0.003917
3.348	0.003706	3.338	11.144	0.02475	0.013915	0.003706
3.383	0.004076	3.338	11.143	0.02721	0.015146	0.004076
3.401	0.003803	3.339	11.152	0.0254	0.014057	0.003803
3.419	0.003658	3.337	11.136	0.02441	0.013448	0.003658
3.437	0.003981	3.336	11.128	0.02656	0.014561	0.003981
3.456	0.003975	3.339	11.15	0.02655	0.014461	0.003975
3.474	0.004348	3.34	11.153	0.02904	0.015735	0.004348
3.531	0.004136	3.334	11.113	0.02757	0.014724	0.004136
3.55	0.003997	3.332	11.104	0.02664	0.014151	0.003997
3.57	0.004107	3.333	11.11	0.02738	0.014462	0.004107
3.59	0.004115	3.334	11.115	0.02744	0.014412	0.004115
3.61	0.004283	3.331	11.093	0.02853	0.014917	0.004283
3.63	0.003982	3.326	11.063	0.02649	0.013789	0.003982
3.65	0.004145	3.325	11.055	0.02756	0.014274	0.004145
3.692	0.004513	3.324	11.052	0.03001	0.015368	0.004513
3.713	0.003965	3.326	11.063	0.02638	0.013424	0.003965
3.735	0.003881	3.324	11.047	0.0258	0.013064	0.003881
3.756	0.004063	3.323	11.04	0.027	0.013599	0.004063
3.778	0.004269	3.324	11.046	0.02838	0.014204	0.004269
3.8	0.004193	3.326	11.06	0.02789	0.013869	0.004193
3.823	0.004562	3.327	11.07	0.03036	0.015003	0.004562
3.846	0.004827	3.325	11.056	0.0321	0.015779	0.004827
3.869	0.00458	3.323	11.041	0.03044	0.014884	0.00458
3.892	0.004206	3.322	11.033	0.02794	0.013587	0.004206
3.915	0.004072	3.319	11.014	0.02703	0.013073	0.004072
3.939	0.004651	3.321	11.026	0.03089	0.014844	0.004651
3.963	0.004532	3.327	11.066	0.03015	0.014374	0.004532
3.988	0.004378	3.325	11.053	0.02911	0.013802	0.004378
4.012	0.004419	3.319	11.016	0.02933	0.013846	0.004419
4.037	0.004295	3.319	11.017	0.02851	0.013374	0.004295
4.063	0.004434	3.321	11.027	0.02945	0.013719	0.004434
4.088	0.004619	3.321	11.031	0.03068	0.014201	0.004619
4.114	0.005168	3.322	11.037	0.03434	0.015789	0.005168

APPENDIX A1 (continued)

4.141	0.004889	3.323	11.041	0.03249	0.014843	0.004889
4.167	0.004643	3.333	11.11	0.03095	0.014007	0.004643
4.194	0.004727	3.381	11.429	0.03196	0.014167	0.004727
4.306	0.004813	3.404	11.585	0.03276	0.01405	0.004813
4.394	0.005004	3.33	11.091	0.03333	0.014319	0.005004
4.424	0.005313	3.327	11.069	0.03535	0.015098	0.005313
4.485	0.005099	3.324	11.05	0.0339	0.014292	0.005099
4.516	0.005728	3.327	11.066	0.03811	0.015946	0.005728
4.548	0.005473	3.326	11.059	0.0364	0.015128	0.005473
4.58	0.00508	3.323	11.043	0.03376	0.013944	0.00508
4.613	0.005291	3.323	11.04	0.03516	0.01442	0.005291
4.646	0.00527	3.323	11.042	0.03502	0.014261	0.00527
4.679	0.005793	3.324	11.046	0.03851	0.015563	0.005793
4.713	0.00528	3.325	11.055	0.03511	0.014081	0.00528
4.748	0.005931	3.325	11.058	0.03945	0.015705	0.005931
4.819	0.005515	3.328	11.073	0.0367	0.014388	0.005515
4.855	0.005217	3.329	11.079	0.03473	0.013508	0.005217
4.891	0.006038	3.329	11.084	0.0402	0.015517	0.006038
4.966	0.006007	3.331	11.094	0.04001	0.015205	0.006007
5.044	0.006072	3.329	11.08	0.04042	0.015134	0.006072
5.083	0.006442	3.33	11.09	0.04291	0.015932	0.006442
5.165	0.006018	3.329	11.085	0.04008	0.01465	0.006018
5.206	0.006496	3.331	11.095	0.04328	0.015687	0.006496
5.424	0.006585	3.338	11.143	0.04396	0.015262	0.006585
5.47	0.006532	3.337	11.134	0.04359	0.015012	0.006532
5.564	0.006498	3.334	11.115	0.04333	0.014683	0.006498
5.612	0.006124	3.336	11.131	0.04087	0.013719	0.006124
5.661	0.006051	3.34	11.156	0.04042	0.013437	0.006051
5.711	0.005697	3.342	11.166	0.03807	0.01254	0.005697
5.762	0.005847	3.338	11.14	0.03903	0.012758	0.005847
5.814	0.006548	3.338	11.139	0.04371	0.014159	0.006548
5.866	0.006858	3.343	11.177	0.04586	0.014696	0.006858
5.92	0.006563	3.346	11.196	0.04392	0.013937	0.006563
5.975	0.007045	3.349	11.219	0.04719	0.014823	0.007045
6.145	0.007237	3.348	11.209	0.04846	0.014806	0.007237
6.204	0.00665	3.349	11.217	0.04455	0.013477	0.00665
6.264	0.006886	3.354	11.25	0.04619	0.01382	0.006886
6.325	0.006995	3.362	11.3	0.04703	0.013904	0.006995
6.451	0.007541	3.347	11.201	0.05048	0.014696	0.007541
6.516	0.006844	3.348	11.207	0.04582	0.013204	0.006844
6.582	0.0075	3.352	11.236	0.05028	0.014325	0.0075
6.65	0.007394	3.358	11.279	0.04966	0.013979	0.007394
6.719	0.007113	3.364	11.315	0.04785	0.013309	0.007113
6.789	0.007138	3.363	11.308	0.04801	0.013218	0.007138
6.861	0.00784	3.356	11.263	0.05262	0.014365	0.00784
6.934	0.00859	3.352	11.236	0.05758	0.015572	0.00859
7.01	0.008307	3.358	11.275	0.05579	0.014899	0.008307
7.165	0.008319	3.377	11.401	0.05618	0.014597	0.008319
7.245	0.00766	3.37	11.358	0.05163	0.013293	0.00766
7.327	0.007621	3.362	11.303	0.05124	0.013076	0.007621
7.411	0.007756	3.362	11.302	0.05215	0.013157	0.007756

7.496	0.007602	3.374	11.385	0.0513	0.012748	0.007602
7.584	0.007623	3.393	11.515	0.05173	0.012635	0.007623
7.674	0.008341	3.4	11.563	0.05672	0.013663	0.008341
7.766	0.009197	3.392	11.504	0.06239	0.014888	0.009197
7.86	0.008613	3.384	11.452	0.05829	0.013775	0.008613
7.957	0.00807	3.401	11.568	0.0549	0.01275	0.00807
8.056	0.007986	3.444	11.861	0.05501	0.012462	0.007986
8.158	0.008298	3.475	12.077	0.05767	0.012787	0.008298
8.262	0.008691	3.474	12.068	0.06039	0.013226	0.008691
8.368	0.008645	3.449	11.898	0.05964	0.012987	0.008645
8.478	0.0084	3.425	11.733	0.05755	0.012456	0.0084
8.59	0.008282	3.429	11.755	0.05679	0.012119	0.008282
8.706	0.008552	-3.461	11.98	0.0592	0.012349	0.008552
8.825	0.008984	3.486	12.156	0.06264	0.012798	0.008984
8.947	0.009725	3.474	12.069	0.06757	0.013665	0.009725
9.072	0.010053	3.435	11.8	0.06907	0.013932	0.010053
9.201	0.01044	3.411	11.633	0.07122	0.014265	0.01044
9.333	0.01017	3.431	11.77	0.06978	0.013698	0.01017
9.47	0.009541	3.473	12.061	0.06627	0.012665	0.009541
9.61	0.009676	3.493	12.199	0.06759	0.012657	0.009676
9.755	0.010365	3.458	11.955	0.07167	0.013357	0.010365
9.904	0.009677	3.392	11.507	0.06566	0.012283	0.009677
10.058	0.009542	3.368	11.343	0.06427	0.011926	0.009542
10.217	0.01041	3.413	11.647	0.07105	0.012809	0.01041
10.381	0.010972	3.482	12.125	0.07641	0.013287	0.010972
10.55	0.011397	3.5	12.248	0.07977	0.01358	0.011397
10.725	0.011277	3.441	11.842	0.07762	0.013219	0.011277
10.905	0.010966	3.369	11.352	0.0739	0.012642	0.010966
11.092	0.011215	3.363	11.307	0.07542	0.012711	0.011215
11.285	0.011318	3.44	11.834	0.07787	0.012607	0.011318
11.486	0.011512	3.527	12.437	0.0812	0.012601	0.011512
11.693	0.011973	3.526	12.43	0.08443	0.012873	0.011973
11.908	0.012566	3.434	11.792	0.0863	0.013266	0.012566
12.131	0.012444	3.349	11.217	0.08335	0.012896	0.012444
12.363	0.013013	3.378	11.409	0.08791	0.013233	0.013013
12.603	0.013022	3.508	12.303	0.09135	0.012989	0.013022
12.854	0.013251	3.607	13.013	0.09561	0.01296	0.013251
13.114	0.01308	3.563	12.697	0.09322	0.012539	0.01308
13.385	0.012855	3.411	11.638	0.08771	0.012074	0.012855
13.668	0.013524	3.323	11.039	0.08987	0.01244	0.013524
13.962	0.013629	3.411	11.634	0.09297	0.012271	0.013629
14.27	0.01307	3.611	13.039	0.09439	0.011514	0.01307
14.592	0.013815	3.713	13.783	0.10257	0.011902	0.013815
14.928	0.014507	3.563	12.691	0.10336	0.012217	0.014507
15.28	0.013913	3.324	11.049	0.09249	0.011446	0.013913
15.65	0.014795	3.233	10.453	0.09567	0.011885	0.014795
16.037	0.01536	3.364	11.319	0.10336	0.012041	0.01536
16.444	0.015301	3.549	12.594	0.1086	0.011697	0.015301
16.873	0.015903	3.541	12.537	0.11262	0.011848	0.015903
17.324	0.01606	3.295	10.855	0.10583	0.011654	0.01606
17.801	0.015696	3.038	9.231	0.09538	0.011085	0.015696

APPENDIX A1 (continued)

18.304	0.016228	3.034	9.205	0.09847	0.011146	0.016228
18.836	0.016238	3.279	10.754	0.1065	0.010837	0.016238

APPENDIX A2

Data of Optical Constants n-type Silicon at 183 °C

LAMBDA	EXTCOEF	REFINDEX	EPSILON1	EPSILON2	ALPHA
1	0.000227	4.01	16.08	0.00182	0.002847
1.002	0.00026	4.556	20.754	0.00237	0.003264
1.003	0.000583	2.529	6.395	0.00295	0.007299
1.005	0.000713	1.952	3.809	0.00278	0.008922
1.008	0.000554	2.965	8.792	0.00328	0.006906
1.029	0.00081	3.648	13.305	0.00591	0.009898
1.03	0.000326	3.62	13.107	0.00236	0.003971
1.032	0.000258	4.069	16.557	0.0021	0.003139
1.034	0.000281	3.561	12.683	0.002	0.003422
1.035	0.0004	3.144	9.887	0.00252	0.004861
1.04	0.000656	3.751	14.067	0.00492	0.007927
1.042	0.000332	3.098	9.6	0.00205	0.004
1.044	0.00031	3.115	9.702	0.00193	0.003733
1.045	0.000456	3.324	11.052	0.00303	0.005484
1.047	0.000634	3.129	9.788	0.00397	0.007614
1.049	0.000408	3.723	13.859	0.00304	0.004891
1.051	0.000383	3.811	14.525	0.00292	0.004589
1.056	0.000646	3.029	9.173	0.00391	0.007691
1.057	0.000474	2.807	7.881	0.00266	0.005631
1.073	0.000674	3.26	10.628	0.00439	0.007896
1.077	0.000436	3.398	11.546	0.00296	0.005087
1.079	0.000494	3.416	11.67	0.00337	0.005753
1.082	0.000527	3.257	10.611	0.00343	0.006122
1.084	0.000452	3.293	10.843	0.00298	0.005242
1.095	0.000431	3.403	11.58	0.00294	0.004953
1.097	0.000355	3.37	11.359	0.00239	0.004071
1.099	0.000408	3.293	10.846	0.00269	0.004666
1.101	0.000531	3.366	11.332	0.00358	0.006069
1.102	0.000729	3.33	11.092	0.00485	0.008309
1.104	0.000494	3.19	10.175	0.00315	0.005623
1.106	0.000434	3.107	9.655	0.0027	0.004936
1.108	0.000455	3.308	10.943	0.00301	0.005164
1.11	0.00048	3.355	11.253	0.00322	0.005442
1.112	0.000649	3.438	11.817	0.00446	0.007337
1.114	0.001001	3.334	11.115	0.00668	0.011299
1.116	0.000883	3.221	10.373	0.00569	0.009953
1.118	0.000757	3.149	9.919	0.00477	0.00852
1.12	0.000595	3.167	10.03	0.00377	0.006685
1.121	0.00054	3.361	11.294	0.00363	0.006052
1.123	0.000391	3.338	11.143	0.00261	0.00437
1.125	0.000385	3.286	10.8	0.00253	0.004298
1.127	0.000545	3.349	11.214	0.00365	0.006082
1.129	0.000542	3.23	10.432	0.0035	0.006038
1.131	0.000433	3.168	10.036	0.00274	0.004812
1.133	0.00036	3.278	10.747	0.00236	0.003995
1.135	0.000386	3.271	10.702	0.00252	0.004272
1.137	0.000449	3.252	10.576	0.00292	0.004964
1.139	0.000405	3.267	10.676	0.00264	0.004464
1.141	0.000439	3.192	10.187	0.0028	0.004838
1.143	0.000458	3.255	10.592	0.00298	0.005034

APPENDIX A2 (continued)

1.145	0.000425	3.383	11.447	0.00288	0.00467
1.147	0.000452	3.394	11.521	0.00307	0.004952
1.149	0.000462	3.337	11.135	0.00309	0.005057
1.151	0.000461	3.257	10.607	0.00301	0.005038
1.153	0.000425	3.26	10.626	0.00277	0.004637
1.155	0.000427	3.303	10.909	0.00282	0.00465
1.158	0.000373	3.219	10.361	0.0024	0.004047
1.16	0.000317	3.228	10.418	0.00205	0.003438
1.162	0.000378	3.298	10.876	0.00249	0.004092
1.164	0.000452	3.229	10.427	0.00292	0.004885
1.166	0.000387	3.211	10.312	0.00249	0.004174
1.168	0.000357	3.226	10.406	0.00231	0.003847
1.17	0.000388	3.237	10.48	0.00251	0.00417
1.172	0.000443	3.256	10.603	0.00288	0.004747
1.174	0.000497	3.316	10.993	0.00329	0.005319
1.176	0.000382	3.361	11.293	0.00257	0.004082
1.179	0.000349	3.367	11.337	0.00235	0.003722
1.181	0.000374	3.318	11.008	0.00248	0.003977
1.183	0.000354	3.314	10.986	0.00235	0.003766
1.185	0.000329	3.204	10.268	0.00211	0.003495
1.187	0.000302	3.214	10.327	0.00194	0.003198
1.189	0.000345	3.324	11.051	0.0023	0.00365
1.192	0.000391	3.251	10.567	0.00254	0.004126
1.194	0.000342	3.215	10.336	0.0022	0.003599
1.196	0.000338	3.24	10.501	0.00219	0.003552
1.198	0.000341	3.159	9.976	0.00216	0.003579
1.2	0.000349	3.09	9.547	0.00216	0.003654
1.203	0.000362	3.197	10.223	0.00232	0.003785
1.205	0.000368	3.186	10.148	0.00235	0.003842
1.207	0.000371	3.125	9.768	0.00232	0.003868
1.209	0.000371	3.254	10.586	0.00241	0.003851
1.212	0.000343	3.288	10.809	0.00225	0.003558
1.214	0.000314	3.271	10.699	0.00205	0.003252
1.216	0.000331	3.27	10.692	0.00216	0.003418
1.219	0.000349	3.279	10.753	0.00229	0.003599
1.221	0.000355	3.396	11.53	0.00241	0.003653
1.223	0.000355	3.392	11.507	0.00241	0.003645
1.225	0.000353	3.3	10.891	0.00233	0.003618
1.228	0.000366	3.327	11.07	0.00243	0.003746
1.23	0.000371	3.361	11.299	0.00249	0.003787
1.232	0.000362	3.284	10.784	0.00238	0.003689
1.235	0.000366	3.212	10.32	0.00235	0.003724
1.237	0.000369	3.217	10.347	0.00238	0.003752
1.24	0.000365	3.27	10.693	0.00239	0.003703
1.242	0.000357	3.3	10.888	0.00236	0.003617
1.244	0.000359	3.246	10.537	0.00233	0.003622
1.247	0.000363	3.214	10.332	0.00233	0.00366
1.249	0.000349	3.222	10.38	0.00225	0.003509
1.252	0.000351	3.266	10.664	0.0023	0.00353
1.254	0.000368	3.299	10.886	0.00243	0.003689
1.256	0.000373	3.233	10.45	0.00241	0.003733

APPENDIX A2 (continued)

1.259	0.000374	3.205	10.272	0.00239	0.003731
1.261	0.000373	3.189	10.171	0.00238	0.003721
1.264	0.00037	3.171	10.053	0.00234	0.003678
1.266	0.000369	3.204	10.265	0.00237	0.003668
1.269	0.000377	3.256	10.602	0.00245	0.003734
1.271	0.000378	3.319	11.015	0.00251	0.003736
1.274	0.00037	3.347	11.205	0.00248	0.003657
1.276	0.000369	3.342	11.17	0.00247	0.003635
1.279	0.000372	3.336	11.127	0.00248	0.003658
1.281	0.000379	3.275	10.722	0.00248	0.003719
1.284	0.000398	3.238	10.487	0.00258	0.0039
1.286	0.000408	3.26	10.627	0.00266	0.003985
1.289	0.000398	3.242	10.51	0.00258	0.003885
1.291	0.000384	3.259	10.622	0.0025	0.003733
1.294	0.000391	3.28	10.758	0.00256	0.003797
1.297	0.000407	3.255	10.598	0.00265	0.003942
1.299	0.0004	3.261	10.632	0.00261	0.00387
1.302	0.000377	3.268	10.68	0.00247	0.003645
1.304	0.000377	3.291	10.833	0.00248	0.003632
1.307	0.000399	3.317	11.005	0.00265	0.00384
1.31	0.000408	3.309	10.947	0.0027	0.00392
1.312	0.000399	3.32	11.019	0.00265	0.003818
1.315	0.000396	3.315	10.989	0.00263	0.003788
1.318	0.000415	3.267	10.676	0.00271	0.003957
1.32	0.000422	3.25	10.566	0.00274	0.004014
1.323	0.000418	3.24	10.496	0.00271	0.003968
1.326	0.000423	3.234	10.46	0.00273	0.004008
1.329	0.000418	3.298	10.877	0.00275	0.003952
1.331	0.000417	3.301	10.899	0.00276	0.003941
1.334	0.000412	3.294	10.853	0.00271	0.003882
1.337	0.000413	3.29	10.825	0.00272	0.003887
1.34	0.000429	3.244	10.521	0.00278	0.004022
1.342	0.000428	3.233	10.45	0.00277	0.004007
1.345	0.000437	3.245	10.531	0.00284	0.004084
1.348	0.000436	3.27	10.695	0.00285	0.004068
1.351	0.000429	3.294	10.85	0.00282	0.003989
1.354	0.000432	3.283	10.781	0.00284	0.004014
1.356	0.000439	3.284	10.782	0.00288	0.004072
1.359	0.000455	3.284	10.782	0.00299	0.004204
1.362	0.000462	3.25	10.564	0.003	0.00426
1.365	0.000462	3.226	10.405	0.00298	0.004251
1.368	0.000451	3.232	10.449	0.00291	0.004143
1.371	0.000444	3.269	10.684	0.0029	0.004069
1.374	0.000439	3.263	10.644	0.00287	0.004021
1.377	0.000444	3.239	10.494	0.00287	0.004051
1.38	0.000455	3.238	10.486	0.00295	0.00415
1.382	0.000459	3.252	10.573	0.00299	0.004175
1.385	0.000466	3.267	10.673	0.00304	0.004228
1.388	0.000466	3.278	10.742	0.00305	0.004217
1.391	0.000471	3.271	10.701	0.00308	0.00426
1.394	0.000484	3.253	10.582	0.00315	0.004368

APPENDIX A2 (continued)

1.397	0.000479	3.262	10.64	0.00313	0.00431
1.4	0.00047	3.27	10.692	0.00308	0.004222
1.403	0.000478	3.255	10.592	0.00311	0.004281
1.406	0.000491	3.263	10.646	0.00321	0.004391
1.41	0.0005	3.279	10.752	0.00328	0.004456
1.413	0.000493	3.259	10.62	0.00322	0.004391
1.416	0.000483	3.255	10.596	0.00315	0.004292
1.419	0.000487	3.272	10.708	0.00319	0.004316
1.422	0.000515	3.258	10.612	0.00336	0.004554
1.425	0.000531	3.249	10.559	0.00345	0.004685
1.428	0.000512	3.271	10.7	0.00335	0.004505
1.431	0.000507	3.286	10.796	0.00333	0.004455
1.435	0.000523	3.263	10.65	0.00342	0.004586
1.438	0.000525	3.252	10.578	0.00342	0.004591
1.441	0.000519	3.263	10.646	0.00339	0.004526
1.444	0.000527	3.27	10.692	0.00344	0.004584
1.447	0.00054	3.263	10.649	0.00352	0.00469
1.451	0.000539	3.24	10.5	0.00349	0.004668
1.454	0.00054	3.261	10.632	0.00352	0.004672
1.457	0.000541	3.275	10.723	0.00354	0.00467
1.46	0.000541	3.265	10.663	0.00353	0.004658
1.464	0.000559	3.274	10.721	0.00366	0.004802
1.467	0.000555	3.277	10.738	0.00364	0.004755
1.47	0.000548	3.258	10.618	0.00357	0.004689
1.474	0.000552	3.257	10.609	0.00359	0.004707
1.477	0.000555	3.266	10.67	0.00363	0.004725
1.48	0.000558	3.265	10.659	0.00364	0.004734
1.484	0.000557	3.261	10.634	0.00363	0.004716
1.487	0.000565	3.275	10.724	0.0037	0.004775
1.491	0.000572	3.272	10.709	0.00375	0.004826
1.494	0.000578	3.249	10.558	0.00376	0.004862
1.498	0.000584	3.248	10.552	0.00379	0.0049
1.501	0.000584	3.25	10.562	0.0038	0.004892
1.505	0.000588	3.233	10.452	0.0038	0.004917
1.508	0.000592	3.24	10.5	0.00384	0.004935
1.512	0.000592	3.262	10.644	0.00386	0.004926
1.515	0.000596	3.269	10.689	0.0039	0.004945
1.519	0.000605	3.26	10.63	0.00394	0.005008
1.522	0.000605	3.254	10.588	0.00394	0.004996
1.526	0.000599	3.274	10.718	0.00392	0.004935
1.529	0.000609	3.278	10.745	0.00399	0.005007
1.533	0.000623	3.266	10.67	0.00407	0.005105
1.537	0.00063	3.254	10.59	0.0041	0.005154
1.54	0.000632	3.246	10.535	0.0041	0.005156
1.544	0.00063	3.254	10.589	0.0041	0.005134
1.548	0.000634	3.271	10.698	0.00415	0.005149
1.551	0.000634	3.271	10.701	0.00414	0.005134
1.555	0.000635	3.261	10.631	0.00414	0.005134
1.559	0.000642	3.267	10.672	0.0042	0.005179
1.563	0.00065	3.27	10.694	0.00425	0.005226
1.566	0.000661	3.263	10.646	0.00432	0.005308

APPENDIX A2 (continued)

1.57	0.000668	3.261	10.635	0.00436	0.00535
1.574	0.00067	3.261	10.632	0.00437	0.005354
1.578	0.000672	3.277	10.74	0.00441	0.005357
1.582	0.000678	3.28	10.756	0.00445	0.005386
1.586	0.000689	3.277	10.74	0.00452	0.005466
1.589	0.000686	3.272	10.706	0.00449	0.005422
1.593	0.000682	3.269	10.684	0.00446	0.00538
1.597	0.000684	3.279	10.753	0.00448	0.005382
1.601	0.000695	3.273	10.712	0.00455	0.005458
1.605	0.000704	3.268	10.682	0.0046	0.005516
1.609	0.000701	3.27	10.692	0.00459	0.00548
1.613	0.00071	3.281	10.763	0.00466	0.005537
1.617	0.000716	3.286	10.799	0.00471	0.005569
1.621	0.000709	3.282	10.774	0.00465	0.005498
1.625	0.000718	3.286	10.796	0.00472	0.005557
1.629	0.000734	3.286	10.8	0.00483	0.005664
1.634	0.000743	3.288	10.812	0.00489	0.005721
1.638	0.000749	3.288	10.814	0.00492	0.005747
1.642	0.000752	3.289	10.815	0.00495	0.005759
1.646	0.00076	3.283	10.776	0.00499	0.005807
1.65	0.000761	3.278	10.748	0.00499	0.005797
1.654	0.000749	3.306	10.927	0.00495	0.005692
1.659	0.000753	3.337	11.134	0.00502	0.005705
1.663	0.000762	3.369	11.347	0.00513	0.005761
1.667	0.000775	3.392	11.508	0.00526	0.005842
1.672	0.000817	3.376	11.4	0.00552	0.006148
1.676	0.000812	3.388	11.479	0.00551	0.006095
1.68	0.000849	3.434	11.789	0.00583	0.006349
1.685	0.000901	3.439	11.825	0.0062	0.006723
1.689	0.000874	3.429	11.757	0.00599	0.006503
1.693	0.000827	3.434	11.793	0.00568	0.006141
1.698	0.000856	3.457	11.95	0.00592	0.006336
1.702	0.000867	3.475	12.075	0.00603	0.006403
1.707	0.000782	3.509	12.314	0.00549	0.005758
1.711	0.000768	3.513	12.343	0.00539	0.005639
1.716	0.000849	3.506	12.292	0.00595	0.006218
1.72	0.000925	3.533	12.481	0.00654	0.006761
1.725	0.000935	3.564	12.699	0.00666	0.006814
1.73	0.000888	3.506	12.291	0.00622	0.006452
1.734	0.000888	3.456	11.946	0.00614	0.006438
1.739	0.000965	3.481	12.12	0.00672	0.006978
1.744	0.00087	3.513	12.341	0.00611	0.006274
1.748	0.000824	3.555	12.641	0.00586	0.005927
1.753	0.000813	3.568	12.731	0.0058	0.005833
1.758	0.000875	3.523	12.41	0.00616	0.006255
1.763	0.001126	3.524	12.421	0.00794	0.008032
1.767	0.001053	3.528	12.445	0.00743	0.007489
1.772	0.001019	3.518	12.374	0.00717	0.007231
1.777	0.001053	3.52	12.389	0.00741	0.007448
1.782	0.000939	3.535	12.496	0.00664	0.006622
1.787	0.000856	3.549	12.596	0.00607	0.006019

APPENDIX A2 (continued)

2.086	0.001511	3.51	12.318	0.01061	0.009106
2.093	0.001428	3.494	12.211	0.00998	0.008577
2.1	0.001388	3.504	12.277	0.00973	0.008312
2.107	0.00137	3.524	12.421	0.00965	0.008174
2.113	0.001372	3.513	12.341	0.00964	0.00816
2.12	0.001414	3.506	12.295	0.00991	0.008381
2.127	0.001493	3.507	12.299	0.01047	0.008823
2.134	0.001553	3.493	12.198	0.01085	0.009147
2.141	0.001654	3.492	12.194	0.01155	0.009707
2.148	0.001607	3.502	12.264	0.01126	0.009403
2.156	0.001456	3.508	12.305	0.01022	0.008491
2.163	0.001447	3.515	12.353	0.01017	0.008412
2.17	0.001609	3.507	12.297	0.01128	0.00932
2.177	0.001833	3.497	12.228	0.01282	0.010584
2.185	0.001779	3.492	12.194	0.01243	0.010238
2.192	0.001667	3.486	12.149	0.01162	0.009562
2.2	0.001673	3.471	12.047	0.01161	0.009561
2.207	0.001703	3.456	11.945	0.01177	0.009703
2.215	0.0017	3.475	12.073	0.01182	0.009651
2.222	0.001666	3.483	12.13	0.0116	0.009423
2.23	0.001636	3.478	12.098	0.01138	0.009224
2.238	0.00169	3.471	12.051	0.01174	0.009497
2.245	0.001863	3.463	11.992	0.0129	0.010431
2.253	0.001856	3.48	12.11	0.01291	0.010353
2.261	0.001705	3.488	12.167	0.0119	0.009481
2.269	0.001653	3.479	12.106	0.0115	0.009159
2.277	0.001783	3.478	12.094	0.0124	0.009846
2.285	0.002046	3.47	12.04	0.0142	0.011259
2.293	0.002068	3.477	12.093	0.01438	0.011335
2.301	0.001906	3.479	12.102	0.01326	0.010415
2.309	0.001862	3.479	12.103	0.01296	0.010137
2.318	0.001862	3.484	12.139	0.01297	0.010098
2.326	0.002019	3.476	12.085	0.01404	0.010913
2.334	0.002181	3.467	12.017	0.01512	0.011748
2.343	0.002045	3.458	11.96	0.01415	0.010974
2.351	0.002171	3.467	12.02	0.01505	0.011608
2.36	0.002069	3.476	12.081	0.01439	0.011024
2.369	0.00186	3.467	12.017	0.01289	0.00987
2.377	0.00191	3.461	11.982	0.01322	0.0101
2.386	0.002119	3.464	12.001	0.01468	0.011163
2.395	0.002062	3.459	11.966	0.01427	0.010827
2.404	0.001984	3.455	11.938	0.01371	0.010374
2.413	0.002077	3.456	11.944	0.01436	0.010821
2.422	0.002127	3.453	11.922	0.01469	0.011044
2.431	0.002028	3.455	11.934	0.01401	0.01049
2.44	0.002209	3.46	11.974	0.01529	0.011383
2.458	0.002904	3.464	11.999	0.02012	0.014849
2.468	0.00249	3.467	12.02	0.01727	0.012687
2.477	0.002218	3.463	11.991	0.01536	0.011256
2.487	0.002238	3.452	11.913	0.01545	0.011313
2.496	0.002453	3.45	11.9	0.01693	0.012355

APPENDIX A2 (continued)

2.506	0.002336	3.443	11.854	0.01609	0.011718
2.516	0.002352	3.446	11.872	0.0162	0.01175
2.526	0.002598	3.438	11.823	0.01787	0.012933
2.536	0.002747	3.437	11.814	0.01888	0.01362
2.545	0.002955	3.451	11.91	0.02039	0.014593
2.556	0.002761	3.446	11.878	0.01903	0.013581
2.566	0.002428	3.439	11.828	0.0167	0.011899
2.576	0.002633	3.436	11.807	0.0181	0.012852
2.586	0.002539	3.437	11.816	0.01746	0.012343
2.597	0.002615	3.443	11.857	0.01801	0.012659
2.607	0.003065	3.44	11.834	0.02108	0.014778
2.617	0.002828	3.438	11.817	0.01944	0.013583
2.628	0.002683	3.439	11.825	0.01845	0.012832
2.639	0.002988	3.437	11.81	0.02054	0.014236
2.661	0.003335	3.454	11.93	0.02304	0.015756
2.671	0.00313	3.462	11.983	0.02167	0.014731
2.683	0.00332	3.452	11.913	0.02292	0.01556
2.694	0.002879	3.441	11.839	0.01981	0.013438
2.705	0.002682	3.442	11.849	0.01847	0.012465
2.716	0.002724	3.439	11.824	0.01873	0.012607
2.728	0.003092	3.439	11.824	0.02126	0.014249
2.739	0.003015	3.446	11.874	0.02078	0.013836
2.751	0.002807	3.446	11.875	0.01935	0.012827
2.763	0.002955	3.453	11.92	0.0204	0.013446
2.775	0.002752	3.449	11.896	0.01899	0.012471
2.786	0.002648	3.439	11.827	0.01821	0.011946
2.799	0.00298	3.429	11.759	0.02044	0.013387
2.811	0.002946	3.433	11.788	0.02023	0.013176
2.823	0.002876	3.439	11.823	0.01978	0.012807
2.835	0.003043	3.432	11.778	0.02089	0.013493
2.848	0.003252	3.436	11.807	0.02235	0.014356
2.873	0.002908	3.436	11.808	0.01998	0.012723
2.886	0.002743	3.427	11.746	0.0188	0.01195
2.899	0.002938	3.424	11.722	0.02012	0.012743
2.912	0.003056	3.424	11.724	0.02093	0.013196
2.925	0.003405	3.418	11.682	0.02328	0.014636
2.952	0.003363	3.408	11.612	0.02292	0.014322
2.965	0.002995	3.406	11.601	0.0204	0.012699
2.979	0.002839	3.398	11.548	0.01929	0.011981
2.993	0.002864	3.393	11.514	0.01944	0.012032
3.006	0.002927	3.388	11.479	0.01983	0.012239
3.02	0.003245	3.377	11.403	0.02191	0.013506
3.035	0.003357	3.368	11.346	0.02262	0.013909
3.049	0.002934	3.367	11.339	0.01976	0.012096
3.063	0.003255	3.36	11.291	0.02188	0.013359
3.107	0.003536	3.355	11.254	0.02372	0.014305
3.122	0.003898	3.357	11.269	0.02617	0.015695
3.215	0.003687	3.409	11.624	0.02514	0.014416
3.231	0.00353	3.417	11.678	0.02412	0.013731
3.248	0.004025	3.421	11.701	0.02754	0.01558
3.264	0.003732	3.423	11.717	0.02555	0.014372

APPENDIX A2 (continued)

3.281	0.003817	3.429	11.756	0.02617	0.014626
3.314	0.003744	3.426	11.74	0.02566	0.014203
3.331	0.003859	3.427	11.747	0.02645	0.014563
3.348	0.003962	3.426	11.737	0.02715	0.014875
3.366	0.003506	3.424	11.725	0.02401	0.013095
3.383	0.003577	3.423	11.72	0.02449	0.013291
3.401	0.004238	3.425	11.728	0.02903	0.015665
3.419	0.003997	3.426	11.737	0.02738	0.014695
3.437	0.003646	3.425	11.732	0.02498	0.013335
3.456	0.003781	3.424	11.721	0.02589	0.013754
3.474	0.004083	3.421	11.703	0.02793	0.014773
3.493	0.003738	3.415	11.665	0.02554	0.013455
3.512	0.003701	3.41	11.628	0.02524	0.01325
3.531	0.003989	3.412	11.64	0.02722	0.014201
3.55	0.00413	3.415	11.665	0.02821	0.014624
3.63	0.004521	3.409	11.619	0.03082	0.015656
3.65	0.004258	3.407	11.607	0.02901	0.014663
3.671	0.003974	3.405	11.592	0.02706	0.013609
3.692	0.004198	3.406	11.599	0.02859	0.014294
3.713	0.004326	3.406	11.598	0.02947	0.014647
3.735	0.004005	3.405	11.595	0.02727	0.01348
3.756	0.004041	3.403	11.579	0.0275	0.013526
3.778	0.004466	3.401	11.567	0.03038	0.01486
3.8	0.004342	3.399	11.555	0.02952	0.014361
3.823	0.004285	3.399	11.552	0.02913	0.014093
3.846	0.004529	3.401	11.565	0.03081	0.014807
3.869	0.004082	3.401	11.565	0.02776	0.013265
3.892	0.004035	3.397	11.541	0.02742	0.013035
3.915	0.004609	3.396	11.536	0.03131	0.014798
3.939	0.004781	3.399	11.554	0.0325	0.015259
3.963	0.004372	3.397	11.542	0.02971	0.013867
3.988	0.004335	3.395	11.528	0.02944	0.013666
4.012	0.004514	3.395	11.526	0.03065	0.014143
4.037	0.005096	3.396	11.533	0.03461	0.015866
4.063	0.004648	3.397	11.539	0.03158	0.014382
4.088	0.005088	3.394	11.519	0.03454	0.015644
4.114	0.005136	3.395	11.524	0.03487	0.015693
4.141	0.005164	3.396	11.535	0.03507	0.015677
4.167	0.00473	3.407	11.61	0.03223	0.014269
4.194	0.004616	3.468	12.026	0.03202	0.013835
4.222	0.004336	3.611	13.043	0.03132	0.012913
4.249	0.004174	3.633	13.196	0.03032	0.012348
4.277	0.00406	3.597	12.936	0.02921	0.011933
4.306	0.004315	3.5	12.248	0.03021	0.012599
4.335	0.004826	3.436	11.805	0.03316	0.013997
4.364	0.005031	3.408	11.617	0.03429	0.014492
4.394	0.005057	3.403	11.578	0.03442	0.01447
4.424	0.005508	3.398	11.546	0.03743	0.015654
4.454	0.005256	3.391	11.5	0.03565	0.014834
4.485	0.005067	3.387	11.474	0.03432	0.014202
4.516	0.005338	3.388	11.477	0.03617	0.014861

APPENDIX A2 (continued)

4.548	0.00517	3.388	11.476	0.03503	0.014292
4.58	0.004867	3.386	11.466	0.03296	0.013358
4.613	0.004931	3.387	11.47	0.0334	0.013439
4.646	0.005118	3.387	11.475	0.03467	0.013848
4.679	0.005083	3.388	11.48	0.03444	0.013656
4.713	0.005209	3.388	11.48	0.0353	0.013893
4.748	0.005221	3.388	11.476	0.03537	0.013823
4.783	0.005298	3.389	11.486	0.03591	0.013924
4.819	0.005454	3.388	11.479	0.03696	0.01423
4.855	0.005323	3.388	11.475	0.03606	0.013783
4.891	0.005616	3.389	11.484	0.03807	0.014434
4.929	0.005532	3.39	11.491	0.0375	0.01411
4.966	0.005267	3.39	11.491	0.03571	0.013333
5.005	0.005347	3.389	11.482	0.03624	0.013431
5.044	0.005251	3.389	11.484	0.03559	0.013088
5.083	0.005378	3.389	11.485	0.03645	0.013299
5.124	0.006086	3.389	11.486	0.04125	0.014932
5.165	0.006107	3.391	11.5	0.04142	0.014867
5.206	0.005833	3.392	11.504	0.03957	0.014085
5.248	0.005673	3.389	11.487	0.03846	0.01359
5.291	0.005954	3.389	11.488	0.04036	0.014147
5.335	0.006147	3.389	11.487	0.04167	0.014486
5.379	0.005875	3.389	11.487	0.03983	0.013731
5.424	0.005882	3.392	11.504	0.0399	0.013632
5.47	0.005844	3.392	11.507	0.03965	0.013431
5.517	0.005908	3.389	11.486	0.04004	0.013463
5.564	0.00629	3.387	11.472	0.04261	0.014211
5.612	0.006558	3.391	11.497	0.04447	0.014691
5.661	0.005988	3.392	11.508	0.04062	0.013296
5.711	0.005964	3.395	11.526	0.0405	0.013128
5.762	0.006157	3.398	11.55	0.04185	0.013434
5.814	0.006265	3.397	11.54	0.04256	0.013547
5.866	0.00616	3.397	11.538	0.04185	0.0132
5.92	0.00636	3.398	11.546	0.04322	0.013506
5.975	0.007034	3.404	11.584	0.04788	0.0148
6.03	0.006899	3.411	11.635	0.04707	0.014382
6.087	0.006798	3.41	11.631	0.04637	0.014039
6.264	0.006607	3.398	11.548	0.04491	0.013261
6.325	0.006568	3.41	11.631	0.0448	0.013055
6.387	0.007146	3.414	11.655	0.04879	0.014064
6.451	0.007269	3.406	11.602	0.04952	0.014166
6.516	0.007005	3.4	11.557	0.04763	0.013515
6.582	0.006824	3.398	11.544	0.04637	0.013034
6.65	0.006831	3.404	11.585	0.0465	0.012915
6.719	0.00714	3.41	11.629	0.04869	0.01336
6.789	0.007147	3.416	11.667	0.04882	0.013234
6.861	0.006801	3.408	11.617	0.04636	0.012462
6.934	0.006938	3.4	11.559	0.04717	0.012577
7.01	0.006798	3.401	11.569	0.04625	0.012192
7.086	0.00676	3.41	11.627	0.0461	0.011992
7.165	0.007072	3.424	11.722	0.04842	0.012409

APPENDIX A2 (continued)

7.245	0.007356	3.427	11.743	0.05041	0.012764
7.327	0.007586	3.414	11.658	0.0518	0.013016
7.411	0.007673	3.405	11.592	0.05225	0.013017
7.496	0.007791	3.41	11.627	0.05313	0.013065
7.584	0.0077	3.429	11.755	0.0528	0.012764
7.674	0.007676	3.443	11.857	0.05286	0.012574
7.766	0.008187	3.442	11.848	0.05636	0.013253
7.86	0.008705	3.435	11.797	0.0598	0.013922
7.957	0.00856	3.44	11.837	0.0589	0.013525
8.056	0.008126	3.469	12.035	0.05638	0.01268
8.158	0.008307	3.501	12.259	0.05817	0.012802
8.262	0.008259	3.512	12.337	0.05802	0.012567
8.368	0.008207	3.498	12.239	0.05742	0.012329
8.478	0.008418	3.471	12.047	0.05844	0.012483
8.59	0.008212	3.459	11.962	0.05681	0.012018
8.706	0.008123	3.479	12.106	0.05653	0.01173
8.825	0.008417	3.511	12.326	0.0591	0.01199
8.947	0.008757	3.52	12.389	0.06164	0.012305
9.072	0.008845	3.493	12.2	0.06179	0.012258
9.201	0.008687	3.46	11.971	0.06011	0.011869
9.333	0.008867	3.458	11.959	0.06133	0.011943
9.47	0.009358	3.489	12.171	0.06529	0.012422
9.61	0.009939	3.518	12.375	0.06993	0.013001
9.755	0.009885	3.503	12.271	0.06925	0.012738
9.904	0.009586	3.45	11.902	0.06614	0.012168
10.058	0.010208	3.409	11.62	0.0696	0.012759
10.217	0.010181	3.428	11.749	0.0698	0.012528
10.381	0.010132	3.49	12.178	0.07072	0.01227
10.55	0.01049	3.53	12.461	0.07406	0.0125
10.725	0.010669	3.503	12.268	0.07474	0.012507
10.905	0.01084	3.43	11.764	0.07436	0.012496
11.092	0.011482	3.393	11.512	0.07791	0.013013
11.285	0.011973	3.442	11.846	0.08242	0.013337
11.486	0.012182	3.534	12.491	0.08611	0.013334
11.693	0.012438	3.568	12.731	0.08876	0.013372
11.908	0.012145	3.499	12.243	0.08499	0.012822
12.131	0.01267	3.401	11.565	0.08618	0.01313
12.363	0.012894	3.387	11.471	0.08734	0.013112
12.603	0.012714	3.487	12.159	0.08867	0.012681
12.854	0.012708	3.606	13.007	0.09166	0.012429
13.114	0.01411	3.616	13.078	0.10206	0.013527
13.385	0.016664	3.495	12.215	0.11648	0.015651
13.668	0.01444	3.377	11.407	0.09754	0.013282
13.962	0.013796	3.405	11.595	0.09396	0.012422
14.27	0.013665	3.579	12.809	0.09781	0.012039
14.592	0.013548	3.73	13.911	0.10106	0.011673
14.928	0.013589	3.653	13.345	0.09928	0.011444
15.28	0.014327	3.422	11.709	0.09805	0.011787
15.65	0.016019	3.274	10.722	0.10491	0.012868
16.037	0.015944	3.343	11.178	0.10661	0.012499
16.444	0.014911	3.521	12.4	0.10501	0.011399

APPENDIX A2 (continued)

16.873	0.015461	3.573	12.768	0.11049	0.01152
17.324	0.015328	3.399	11.553	0.1042	0.011123
17.801	0.014445	3.142	9.873	0.09077	0.010201
18.304	0.015157	3.078	9.476	0.09332	0.01041
18.836	0.015019	3.258	10.613	0.09785	0.010023

REFERENCES

1. J. Wortman, "Technical summary", in *Semiconductor Research Corporation Workshop on Temperature Measurements*, J.R. Burke, J. Wortman, and S.A Rizvi, Eds. Semiconductor Research Corp., Research Triangle Park, NC, p.1, Feb 1990.

2. R.A. Smith, *Semiconductors*, 2nd ed., Cambridge University Press, London, 1979.

3. B.G. Streetman, *Solid State Electronic Devices*, 4th ed., Prentice Hall of India, New Delhi, 1995.

4. S.M. Sze, *Semiconductor Devices, Physics and Technology*, John Wiley & Sons, NewYork,1985.

5. S.K. Gandhi, *VLSI Fabrication Principles, Silicon and Gallium Arsenide*, 2nd ed., John Wiley & Sons, NewYork, 1994.

6. D.J. Dunstan, "Indirect energygap of Si, temperature dependence", Properties of Silicon, *INSPEC*, The Institute of Electrical Engineerings, pp. 171-172, 1988.

7. T.S. Moss, *Optical Properties of Semiconductors*, Butterworth Scientific Publications, London, 1959.

8. M.B. Kaplinsky, Jun Li, N.J. McCaffrey, E.S. Hou and W.F. Kosonocky, "Progress on the development of multi-wavelength imaging pyrometer," *Proc. of SPIE*, vol. 2764, pp.178-189, 1996.

9. N.M. Ravindra, F.M. Tong, S.Abedrabbo, W. Chen, W. Schmidth, A. Nanda, T. Speranza and A. M. Tello, "Applications of spectral emissometry to silicon related materials," in *4th Int. RTP Conf.*, Boise, ID, pp. 190-204, Sept.1996.

10. R.Siegel and J.R. Howell, *Thermal Radiation Heat Transfer*, 3rd ed., Hemisphere Publishing Corporation, Washington, 1992.

11. J.N. Hodgson, *Optical Absorption and Dispersion in Solids*, Chapman and Hall, London, 1970.

12. C. Schietinger and B.Peuse "Wafer Emissivity for RTP- modeling and measured," in *3rd Int. RTP Conf.*, RTP'95, pp. 225-227, Sep. 1995.

13. K. Sato, "Spectral emissivity of silicon," *Jpn. Journal. App. Phys.*, vol. 6, no. 3, pp. 339-347, Mar. 1967.

REFERENCE
(continued)

14. N.M. Ravindra, S. Abedrabbo, W. Chen, F.M. Tong, A. Nanda and C. Speranza,"Temperature-dependent emissivity of silicon-related materials and structures," *IEEE tran. on semicond. manuf.*, vol. 11, no. 1, pp. 30-39, Feb. 1998.

15. N. Hajji and J. E. Spruiell, "Radiation pyrometry of semi transparent sheets I: Gray media," *Polymer Engineering and Science*, vol. 34, no. 2, pp. 116-121, Jan. 1994.

16. C. Schietinger, "Wafer temperature measurement in RTP," *Advances in Rapid Thermal and Integrated Processing*, edited by F. Roozeboom, Kluwer Academic Publishers, Dortdrecht, The Netherlands, pp. 3.1-3.20, July 1995.

17. T.J. Quinn, Temperature, *Academic Press*, NewYork, 1983.

18. W.L. Wolfe and G. J. Zissis, *Infrared Handbook*, Environmental Research Institute of Michigan, Ann Arbor, MI, 1989.

19. C. Schietinger, B. Adams, and C. Yarling, "Temperature measurement and control," *Mat. Res. Soc. Symp.* vol. 224, pp. 23-31, 1996.

20. D.P. Dewitt, Gene D. Nutter, *Theory and Practice of Radiation Thermometry*, John Wiley & Sons, PA, 1988.

21. J. Bedrossian, "Industrial applications of fiber optics in infrared thermal monitoring," Thermosense IX, *Proc. of SPIE*, vol.780, pp. 90-96, 1987.

22. J.B. Bates, "Fourier transform infrared spectroscopy," *Science*, vol.191, no. 4222, pp. 31-37, Jan. 1976.

23. J.R. Markham, K. Kinsella, R.M. Carangelo, C.B Brouillitte and P.R. Solomon, "A bench top FT-IR based instrument for simultaneously measuring surface spectral emittance and temperature," *Rev. Sci. Instrum.*, vol.64, no. 9, pp. 2515-2522, Sept. 1993.

24. N.M. Ravindra, W. Chen, A. Nanda and F.M. Tong, "Emissivity measurement and modeling – An overview," *Transient Thermal Processing Techniques in Electronic Materials*, Ed. N.M. Ravindra and R.K. Singh, TMS, pp.159-164, 1996.

25. P.Vandenabeele, K.Maex, "Emissivity of silicon wafers during rapid thermal processing," *Proc. of SPIE*, vol. 1393, pp.316-336, 1990.

REFERENCE
(continued)

26. P.J. Timans, "Emissivity of silicon at elevated temperatures," *Journal of Appl. Phys.*, vol.74, p.6353-6364, 1993.

27. H. Xu and Strum, J.C, "Effects of reflective surfaces on silicon emissivity and temperature measurement," *Mat. Res. Soc. Symp. Proc.*, vol.429, pp.297-302,1996.

28. J.L. crowley, J. Liao and J. Gelpey, "Effect of silicon emissivity on temperature measurement and control in rapid thermal processing," *Proc. of SPIE*, vol. 1189, p. 64, Oct. 1989.

29. H.H. Li, "Refractive index of silicon and its wavelength and temperature dependencies," *Journal Phys. and Chem. Ref. Data*, vol. 9, pp. 561-658, 1980.

30. D.F. Edwards, *Handbook of Optical Constants of Solids*, Ed. E. Palik, Academic, NewYork, 1985.

31. G.E. Jellison , Jr. and F.A. Modine, "Optical functions of silicon at elevated temperatures," *Journal of Appl. Phys.*, vol. 76, pp. 3758-3761, 1994.

32. H.W. Icenogle, B.C. Platt, and W.L. Wolfe, "Refractive index of silicon," *Appl. Opt.*, vol. 15, p. 2398, 1976.

33. N.M. Ravindra et al., "Temperature dependent emissivity measurements of Si, Sio_2/Si and HgCdTe," *Proc. of Mat. Res. Soc.*, vol. 342, pp. 431-436, 1994.

34. N.M. Ravindra et al., "Development of emissivity models and induced transmission filters for multi-wavelength imaging pyrometry," *Proc. of SPIE*, vol. 2245, pp. 304-318, 1994.

35. H.Y. Fan and Spitzer, W, "Infrared absorption in n-type silicon," *Phys. Rev.*, vol. 108, pp. 268-271, 1957.

36. W.R. Runyan, *Silicon Semiconductor Technology*, McGraw-Hill Book Company, NewYork, 1976.

37. P. Vanenabeele and K. Maex, "Influence of temperature and back-side roughness on the emissivity of Si wafers during rapid thermal processing," *Journal of Appl. Phys.*, vol.72, pp.5867, 1992.

38. P.E. Schmid, "Optical absorption in heavily doped silicon", *Phys. Rev. B*, vol. 23, no. 10, pp.5531-5536.