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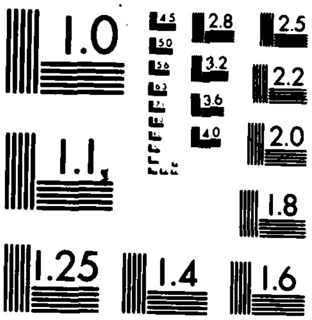

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REFRACTIVE INDEX OF SILICON AND GERMANIUM AND ITS WAVELENGTH AND TEMPERATURE DERIVATIVES

By

H. H. Li

CINDAS REPORT 53

March 1979

Prepared for

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Key Words: refractive index, temperature coefficient of refractive index, optical constants, silicon, germanium.

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LIST OF SYMBOLS

a	Adjustable constant; lattice constant
A, A_0, A_1, A_2	Adjustable constants
b	Adjustable constant
B	Adjustable constant
c	Adjustable constant
C	Adjustable constant
D	Adjustable constant
E	Adjustable constant
E_g	Energy gap
L_{293}	Length at 293 K
n	Refractive index
N	Complex refractive index; density of harmonic oscillator
T	Absolute temperature
V	Volume

Greek
<u>Symbols</u>

α	Linear thermal expansion coefficient
γ	Damping factor
ε	Complex dielectric constant, value of dielectric constant
ε_1	Real part of ε
ε_2	Imaginary part of ε
ε_0	Static dielectric constant
ε_∞	High-frequency dielectric constant
κ	Extinction coefficient; oscillator strength
λ	Wavelength of light
λ_i	Wavelength of the ith absorption band
Δ	Change in a quantity
ν	Wavenumber
ν_i	Resonant frequency; wavenumber of the ith absorption band

1. INTRODUCTION

SCOPE OF PRESENT INVESTIGATION

The refractive index of a material is one of its fundamental and useful optical properties. Accurate knowledge of the refractive index over a wide range of wavelength is indispensable for many applications. Although this property continues to receive attention for both industrial as well as purely scientific applications, the current state of the available data is less than adequate. While experimental results for the refractive index of pure silicon and germanium are reported by several groups of investigators claiming high internal accuracy and agreement, the data as a whole are in disagreement.

In this study, an attempt is made to consolidate all of the published refractive index data on silicon and germanium and to critically evaluate the raw experimental data and techniques of observation. A modified Sellmeier type dispersion relation is utilized to describe the available body of data. The resultant equations were used to generate the most probable values which agree with the selected experimental data to within $\pm 2.0 \times 10^{-3}$ over the wavelength range 1.2 to 14.0 μm for silicon and 1.9 to 18.0 μm for germanium.

GENERAL CHARACTERISTICS OF SILICON AND GERMANIUM

Silicon makes up nearly 26%, by weight, of the earth's crust and is the second most abundant element. It is not found free in nature but occurs chiefly as oxides and silicates. Rock, sand, quartz, agate, flint, jasper, and opal are a few forms of silicon oxides. Granite, asbestos, feldspar, mica, clay, etc. are silicate minerals. Although Gay Lussac and Thenard probably were the first to prepare impure, amorphous silicon in 1811 by heating potassium with silicon tetrafluoride, Berzelius is generally credited with the discovery in 1824. He succeeded in preparing amorphous silicon by the same general method used earlier, but he purified the product by removing the fluorosilicates by repeated washings. Crystalline silicon was first prepared by Deville in 1854.

In commercial scale, silicon is recovered from its oxide by reduction with carbon. Purification is made by distillation of silicon tetrachloride with subsequent reduction of the tetrachlor[illegible]ith [illegible]nc. Hyper-pure single crystal silicon is produced by the thermal decomposition of ultrapure trichlorosilane in a hydrogen atmosphere and by a vacuum float zone process. Highly purified silicon has a resistivity of approximately 2.5×10^5 ohm-cm. Pure silicon crystal transmits more than 95% of incident radiation in the spectral range from 1.3 to 6.7 µm. Thus, it is found to be useful in fabricating optical components used in infrared instruments.

Silicon is a chemically inert element which is attacked only by halogens, dilute alkali, and hydrofluoric acid. In its pure form or doped, respectively, with arsenic, boron, gallium, and phosphorus, silicon is a superb semiconductor that has found a wide variety of applications in infrared optics, electronics, solar energy conversion, and even as an industrial alloying agent and silicone products.

Germanium was first discovered in 1871 by Mendeleef as the 32nd element, and he named it ekasilicon, meaning "like silicon". Unfortunately, this label turned out to be somewhat of a misnomer and, although Clemens Winkler is credited with the discovery of the element in 1886, germanium has become an element of interest in its own right only since the early 1950's. Naturally occurring germanium has a tendency to crystallize with other elements rather than forming a binary mineral compound of its own. It is readily found in the ores of zinc, copper, silver, arsenic, and iron. While this property hindered early attempts at its isolation and purification, it has become the most prominent single asset of germanium for many varied applications in the electronics industry. Its extensive presence in nature allows for easy extraction and refinement with existing technology and underlies the present importance of germanium as a semiconducting material.

Germanium occurs naturally in agyrodite, a sulfide of germanium and silver, in germanite which is composed of approximately 8% pure germanium, in zinc ores, coal, and numerous other combinations. Commercially, germanium is most frequently extracted from the flue dusts of zinc ore smelting processes as well as from combustion by-products of several types of coal. This second source should assure an abundant supply of germanium for the immediate future. Subsequent purification of the raw element, most commonly by zone-refining techniques, permits the production of ultra-high purity samples in commercial quantities. Crystalline germanium, having an impurity content of less than one part in 10^{10} has been produced in this manner. Highly purified germanium has a resistivity of 50 ohm-cm or higher.

Germanium has rapidly become one of the most important semiconducting materials, second only to silicon in overall applications. Through existing techniques, germanium is readily doped with many elements in precisely determined quantities and thereby finds its important applications in solid state electronics. However, germanium is also finding many other applications ranging from an industrial alloying agent to a chemotherapeutic agent in bacteriological studies. Germanium, and germanium oxide, are both transparent in the infrared region of the spectrum and are extremely important optical materials for both lenses and lens coatings used in infrared detection equipment.

Both of these silvery-grey metals, silicon and germanium, are useful optical materials in both their single crystal and polycrystalline forms. They occur naturally in the diamond lattice wirtzite and zinc-blende structures. Most commonly it is seen as two interpenetrating face centered cubic structures displaced by about 1/4 of the distance along the main body diagonal. This creates a structure in which each atom has four nearest neighbors located at the corners of a regular tetrahedron. Thus, the distance between nearest neighbors is $\sqrt{3}\ a/4$, where a is the lattice constant. Silicon and germanium occur as Group IV elements having four outer electrons and bonding orbitals of the sp^3 hybrid type. The four orbitals define a regular tetrahedron and may accommodate two electrons, thus bonds are completely covalent in nature, an exact analogy to the diamond structure. Although hard and brittle at room temperatures, large crystals of high purity silicon and germanium have been grown and many difficult shapes have been fabricated including optical quality domes.

Some of the physical properties of silicon and germanium are given in Tables 1 and 2, respectively.

TABLE 1. SOME PHYSICAL PROPERTIES OF SILICON

Property	Value	Reference
Atomic number	14	
Atomic weight	28.086	
Density, g cm^{-3}	2.32902	[1]
Melting point, K	1685	[2]
Energy gap at 300 K, eV	1.120	[3]
Lattice constant, Å	5.430951	[4]
Solubility in water at 298 K, $g \cdot 10^{-2} cm^{-3}$	<0.005	[5]
Linear expansion coefficient at 293 K, $10^{-6} K^{-1}$	2.6	[6]
Thermal conductivity at 300 K, W $cm^{-1} K^{-1}$	1.48	[7]
Specific heat at 298 K, cal $g^{-1} K^{-1}$	0.170	[8]
Transmission region, μm	1.2-15	
Young's modulus, 10^6 psi	19.0	[5]
Hardness, Knoop no.	1100-1400	[5]

TABLE 2. SOME PHYSICAL PROPERTIES OF GERMANIUM

Property	Value	Reference
Atomic number	32	
Atomic weight	72.593	
Density, g cm^{-3}	5.32674	[1]
Melting point, K	1210	[9]
Energy gap at 300 K, eV	0.663	[3]
Lattice constant, Å	5.646133	[11]
Solubility in water at 298 K, $g \cdot 10^{-2} cm^{-3}$	<0.005	[5]
Linear expansion coefficient at 293 K, $10^{-6} K^{-1}$	5.7	[10]
Thermal conductivity at 300 K, W $cm^{-1}K^{-1}$	0.599	[7]
Specific heat at 298 K, cal $g^{-1}K^{-1}$	0.0769	[8]
Transmission region, μm	1.8-23	[8]
Young's modulus, 10^6 psi	14.9	[5]
Hardness, Knoop no.	700-880	[5]

2. THEORETICAL BACKGROUND ON REFRACTIVE DISPERSION IN CRYSTALS

Dispersion relations are of fundamental importance to the description of the optical properties of materials. They relate both the absorptive and dispersive properties into one relatively concise statement describing a general linear relationship between fundamental amplitudes. The only two major restrictions are boundedness and causality, thus these relations are useful in many fields and applications in both physics and engineering.

The dispersion of radiation in an optical material is intimately related to the microscopic structure of the material itself. In the most general terms, long wavelength transmission is limited by molecular vibrations and rotations while short wavelength transmission is limited by the electronic excitations of individual atoms. Practically, this implies that the fundamental transparent spectral range may be determined by knowledge of the absorption spectra of a material. The energy necessary for electronic excitations is generally noted by the location of the energy gaps while the molecular excitation is represented by the fundamental phonon frequency. Experimentally, both of these parameters may be altered by various techniques including doping, stress, strain, and temperature variations. One other area of primary importance is that of point defects. The varied effects of point defects in semiconducting materials plays an important role in both the electrical and optical properties, however a detailed analysis of these effects is beyond the scope of this work. A more complete analysis of these effects is given by Crawford and Slifkin [11].

In general, the absorption and transmission of a material is not well known except for a small wavelength range. Thus, on theoretical grounds, it is convenient to consider dispersion as arising from two major sources separately; namely, the bound and free electrons. In non-conducting dielectric materials, the bound electron, or molecular, interactions tend to predominate, while free electron interactions are most common in metals. In semiconducting materials, both of these contributions may be important. In fact, most semiconductors show an optical absorption and an anomalous dispersion in the far-infrared region. This effect is rather small in covalent semiconductors like Si and Ge, it increases, however, with increasing polarity. Both the radio-frequency measurement and infrared observation indicate that the effect of free carriers on Si and Ge are negligibly small. Furthermore, in the elemental Si and Ge, the lattice has no permanent dipole moment and c[illegible] the lattice absorption is small.

For pure dielectrics, the wavelength or frequency dependence of the optical constants may be described by the classical treatment of Lorentz. The theory assumes the solid to be composed of a series of independent oscillators, which are set into forced vibrations by the incident radiation. The Lorentz theory of absorption and dispersion for both insulating and semiconducting materials leads to the two familiar relations,

$$n^2 - \kappa^2 = 1 + \sum_i \frac{N_i(\nu_i{}^2-\nu^2)}{(\nu_i{}^2-\nu^2)^2 + \gamma_i{}^2\nu^2} \tag{1}$$

and

$$2n\,\kappa = \frac{1}{\nu} \sum_i \frac{N_i\gamma^2\nu^2}{(\nu_i{}^2-\nu^2)^2 + \gamma_i{}^2\nu^2} \tag{2}$$

where n is the refractive index, κ the absorption index, N_i the parameter associated with the oscillator strength of the i-th oscillator, ν_i the resonant frequency of the i-th oscillator and γ_i the damping constant of the i-th oscillator. In the transparent wavelength region, eq. (1) can be reduced to a Sellmeier type equation by neglecting the line width of the oscillators, thus reducing to:

$$n^2 = 1 + \sum_i \frac{a_i\lambda^2}{\lambda^2 - \lambda_i{}^2} + \sum_j \frac{b_j\lambda^2}{\lambda^2 - \lambda_j{}^2} \tag{3}$$

Terms in the first summation are contributions from the ultraviolet absorption bands and those in the second from the infrared absorption bands. From eq. (3), the dielectric constants, ε_∞ and ε_0, of the material under consideration are defined as:

$$\varepsilon_\infty = 1 + \sum_i a_i,$$

and (4)

$$\varepsilon_0 = 1 + \sum_i a_i + \sum_j b_j$$

As noted before, the effects of free carries and lattice absorption are found to be negligibly small in elemental Si and Ge, thus the contributions from infrared absorption bands can be dropped and eqs. (3) and (4) are simplified to:

$$n^2 = 1 + \sum_i \frac{a_i \lambda^2}{\lambda^2 - \lambda_i^{\,2}} \tag{5}$$

and

$$\varepsilon = \varepsilon_0 = \varepsilon_\infty = 1 + \sum_i a_i \tag{6}$$

In an ideal application of eq. (5), one would need to know the wavelengths of all of the absorption peaks in the short wavelength region. This is very difficult in practice because of the large number of absorption peaks. In fact, only a few absorption peaks are accessible for experimental observation. It is also observed that among the absorption peaks, only the one that is located closest to the transparent region has noticeable effect on the refractive index in the transparent region. In order to simplify the calculations of the effect due to unobserved absorption bands and those other than the one affecting most the refractive index in the transparent region, the following considerations were taken. Each term, except the predominating one, in the summation of eq. (5) is expanded as:

$$\frac{a_i \lambda^2}{\lambda^2 - \lambda_i^{\,2}} = a_i \left(1 + \frac{\lambda_i^{\,2}}{\lambda^2} + \frac{\lambda_i^{\,4}}{\lambda^4} + \ldots . \right) \tag{7}$$

Since λ_i's are usually considerably smaller than λ's in the transparent region, a good approximation of eq. (5) is

$$n^2 = 1 + \sum_{i=2}^{N} a_i \left(1 + \frac{\lambda_i^{\,2}}{\lambda^2} \right) + \frac{a_1 \lambda^2}{\lambda^2 - \lambda^{\ 2}} \tag{8}$$

or

$$n^2 = 1 + \sum_i a_i + \frac{1}{\lambda^2} \sum_{i=2}^{N} a_i \lambda_i^{\,2} + \frac{a_1 \lambda_1^{\,2}}{\lambda^2 - \lambda_1^{\,2}} \tag{9}$$

with a_1 and λ_1 associated with the term that has the greatest effect on the refractive index in the transparent region. Therefore, we have the simplified dispersion equation as:

$$n^2 = \varepsilon + \frac{A}{\lambda^2} + \frac{B \lambda_1^{\,2}}{\lambda^2 - \lambda_1^{\,2}} \tag{10}$$

where A and B are adjustable parameters, $\lambda_1 = 1.1071$ μm for Si and $\lambda_1 = 1.8703$ μm for Ge [3]. Equation (10) can be generalized to include temperature as an independent variable. In this case, the parameters ε, A, B, and λ_1 are functions of temperature.

At long wavelengths, the dielectric constant, ε, is numerically equal to the square of refractive index, i.e., $\varepsilon(T) = n^2(T)$ at long wavelength. Therefore,

$$\frac{1}{\varepsilon(T)}\frac{d\varepsilon(T)}{dT} = 2\,\frac{1}{n(T)}\frac{dn(T)}{dT} \tag{11}$$

Cardona, Paul, and Brooks [12] found the long-wavelength (1/n)(dn/dT) to be $(3.9 \pm 0.4) \times 10^{-5}K^{-1}$ for Si and $(6.9 \pm 0.4) \times 10^{-5}K^{-1}$ for Ge, between 77 and 400 K. Higher values of (1/n)(dn/T) were observed by other workers: $(4.8 \pm 0.2) \times 10^{-5}K^{-1}$ for silicon [13] and $9.7 \times 10^{-5}K^{-1}$ for germanium [14]. However, these constant values of (1/n)(dn/dT) only hold at high temperatures. Deviation from linearity at low temperatures requires that a non-linear relation between ε and T be established. The values of the dielectric constant which appear in the literature are inaccurate. In the survey work of Young and Frederikse [17], the value for Si varies from 11.7 to 12.1 and that of Ge from 13.6 to 16.6. As a consequence, the reported values of ε are not suitable for eq. (10) and $\varepsilon(T)$ can only be obtained by fitting selected room-temperature refractive index data to eq. (10). The temperature dependence of λ_1 was investigated by Macfarlane et al. [15,16], their results are $d\lambda_1/dT = 0.000267$ μm K^{-1} for Si and 0.001016 μm K^{-1} for Ge at temperatures higher than 200 K. Non-linearity predominates at low temperatures.

The parameters, A and B, in eq. (10) can be expressed in terms of temperature based on the considerations given below. Since

$$A = \sum_{i=2}^{N} a_i\lambda_i^2 \quad \text{and} \quad B = a_1 \tag{12}$$

and the a's are respectively proportional to the density of the corresponding oscillator, the temperature dependence of a_i is given by the relation

$$\frac{1}{a_i}\frac{da_i}{dT} = -\frac{1}{V}\frac{dV}{dT} = -3\alpha \tag{13}$$

where V and α are respectively the volume and the thermal expansion coefficient of the material. Hence

$$a_i = a_{i0} e^{-3\int_{293}^{T} \alpha dT} = a_{i0} e^{-3\Delta L(T)/L_{293}} \quad (14)$$

with a_{0i} being the value of a_i at 293 K. Furthermore, each of the λ_i^2's in the summation can be considered as a quadratic function of temperature because it is an experimentally observed fact that λ_i is approximately a linear function of T [18] in the temperature region of interest. Therefore

$$A(T) = e^{-3\Delta L(T)/L_{293}}(A_0 + A_1 T + A_2 T^2) \quad (15)$$

and

$$B = B_0 e^{-3\Delta L(T)/L_{293}} \quad (16)$$

where A_0, A_1, A_2, and B_0 are adjustable coefficients. Incorporating these considerations into eq. (10), the latter can be written in the general form as

$$n^2 = f(\lambda, T) \quad (17)$$

In the actual cases, however, one finds negligibly small values for B_0's through data fitting procedures. As a result, the following dispersion equation is adopted to calculate the refractive index of Si and Ge:

$$n^2(\lambda, T) = \varepsilon(T) + \frac{A(T)}{\lambda^2} \quad (18)$$

With ε and the parameters A_0, A_1, and A_2 appropriately determined, dn/dT and dn/dλ can be easily calculated taking the first derivatives of eq. (18) with respect to T and λ.

3. PRESENTATION OF NUMERICAL DATA

Reference data are generated here through critical evaluation, analysis, and synthesis of the available experimental data. The procedure involves critical evaluation of the validity and accuracy of the available data and information, resolution, and reconciliation of disagreements in cases of conflicting data, correlation of data in terms of various controlling parameters, curve fitting with theoretical or empirical equations, and comparisons of experimental values with predictions. No attempt was made to analyze the thin-film data and the regions of strong absorption, because of the scantiness of reliable information. However, experimental data of thin films and absorption regions are also presented along with those of the transparent region in the tables reporting experimental data.

A number of figures and tables summarize the information and give data as a function of wavelength and temperature. The conventions used in this presentation, and specific comments concerning the interpretation and use of the data are given below. The subsections for Si and Ge give all the information and data for a given material and cover the following:

a. A text discussing the data, analysis, and recommendations,
b. A figure of experimental n values (for wavelength and temperature, respectively),
c. A figure of experimental $dn/dT = f(\lambda)$,
d. A figure of experimental $dn/dT = f(T)$,
e. A table of experimental data on $n = f(\lambda)$, given in Appendix
f. A table of experimental data on $n = f(T)$, given in Appendix,
g. A table of experimental data on $dn/dT = f(\lambda)$ given in Appendix,
h. A table of experimental data on $dn/dT = f(T)$ given in Appendix,
i. Figures of recommended or provisional values of n, dn/dT, and $dn/d\lambda$,
j. Tables of recommended or provisional values of n, dn/dT, and $dn/d\lambda$.

In figures containing experimental data, selected data sets are labeled by appropriate legends corresponding to those in the corresponding tables of experimental data given in Appendix, where specifications for individual data sets are also included.

There are a number of experimental methods used for the determination of refractive index, among which the following are those commonly used:

Deviation method (prism method)
Interference method
Transmission method
Reflection method
High frequency modulation method
Brewster angle method
Polarization method
Thickness determination method
Multilayer method

The methods listed above are arranged in the order of their inherent accuracy or popularity. The deviation method is the most popular means of determining the refractive indices, but the accuracy of the results depends on the conditions of the prism specimen. The highest accuracy that can be attained is in the fifth decimal place. The interference technique can be used to obtain data up to the fourth decimal place. Transmission and reflection methods yield results good to the second place, while the multilayer results are no better than two places. For a comprehensive, yet concise, review of all these methods, the reader is referred to references [19] and [20].

Dispersion equations for Si and Ge have been proposed in earlier works. Available relations are discussed in the text so as to facilitate comparison. Refractive indices for most of selected data sets are reported to the fourth decimal place. However, detailed compositions and characterizations of the specimens were usually not clearly given. Since impurities in the sample and conditions of the surface are decisive factors affecting the accuracy of the observed results, such highly precise data cannot be applied to a sample chosen at random. For this reason no attempt is made to recommend any particular set of data with the reported high accuracy, but to generate the most probable values for the pure crystals. As a result, the estimated uncertainties for the recommended values on the refractive index are higher than those for the reported data obtained even by high-precision measurements. The accuracy of the recommended refractive index values in this work is estimated to be 1 to 2×10^{-3}.

3.1. Silicon, Si

There are 55 sets of experimental data available for the refractive index (wavelength dependence and temperature dependence) of silicon as tabulated in tables A-1 and A-2 and plotted in figures 1 and 2. It should be pointed out that a few of the data sets are from observations for thin films and are reported here for purposes of comparison. After careful review and evaluation of the available information, it was found that data sets reported by Briggs [21], Salzberg and Villa [22], Cardona et al. [12], Lukes [13,23], Primk [24], and Icenogle et al. [14] are representative for the refractive index of silicon in the transparent region between 1.3 and 12 μm.

Briggs [21] probably was the first one who reported the measured refractive index of silicon. A 99.8% pure silicon wedge specimen of about 11.5° apex angle was investigated using minimum deviation method over a spectral range from 1.05 to 2.60 μm. He stated that the accuracy of his measurements was good to the second decimal place.

Since this first measurement, a number of other investigations have been made. Refractive index determination from 1.35 to 11.04 μm was made by Salzberg and Villa [22] for a wedge specimen of about 16° apex angle. The sample, of unknown purity, was obtained from the Texas Instrument Company. The autocollimation minimum deviation method was used to determine the refractive index. Their results were lower than those of Briggs by about 5 parts in the third decimal place. They claimed an accuracy of ±2 parts in the fourth decimal place.

Cardona et al. [23] measured the refractive index of a thin silicon wedge of 5° in the wavelength range from 1 to 5 μm and at temperatures 100, 194, and 297 K. Their results were about 4 parts in the third decimal place lower than the corresponding ones of Briggs.

Lukes [13,23] measured the refractive index at five wavelengths, 1.259, 1.407, 1.564, 2.409, and 5.156 μm, over a wide temperature region between 109 and 750 K by the conventional method of minimum deviation. The silicon wedge of ∿18° angle was prepared from a p-type single crystal with a resistivity of ∿380 ohm-cm. The reported error was ±∿0.0004, but his values of refractive index were systematically lower than those of Salzberg and Villa by 0.0015.

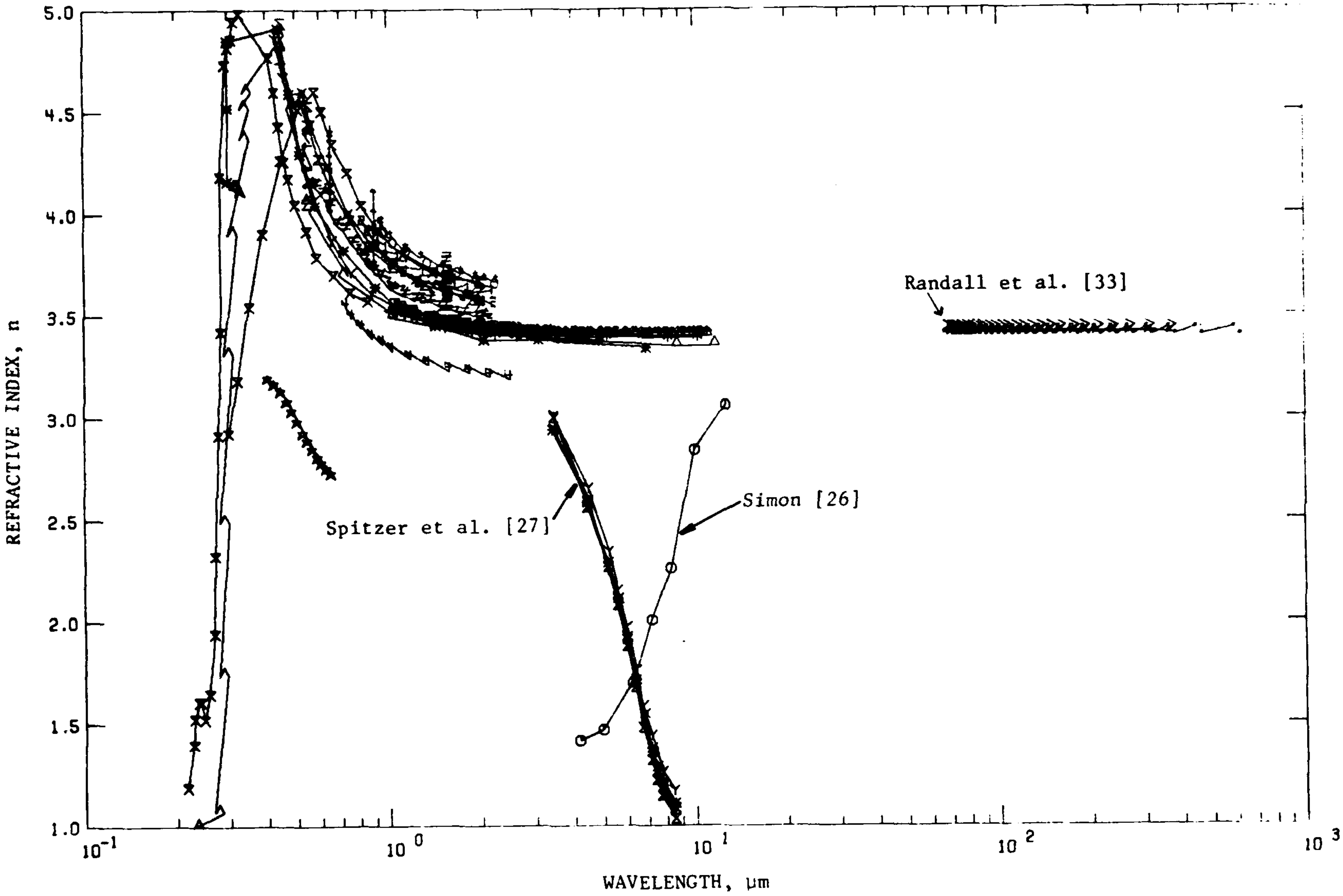

FIGURE 1. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF SILICON (Wavelength Dependence)

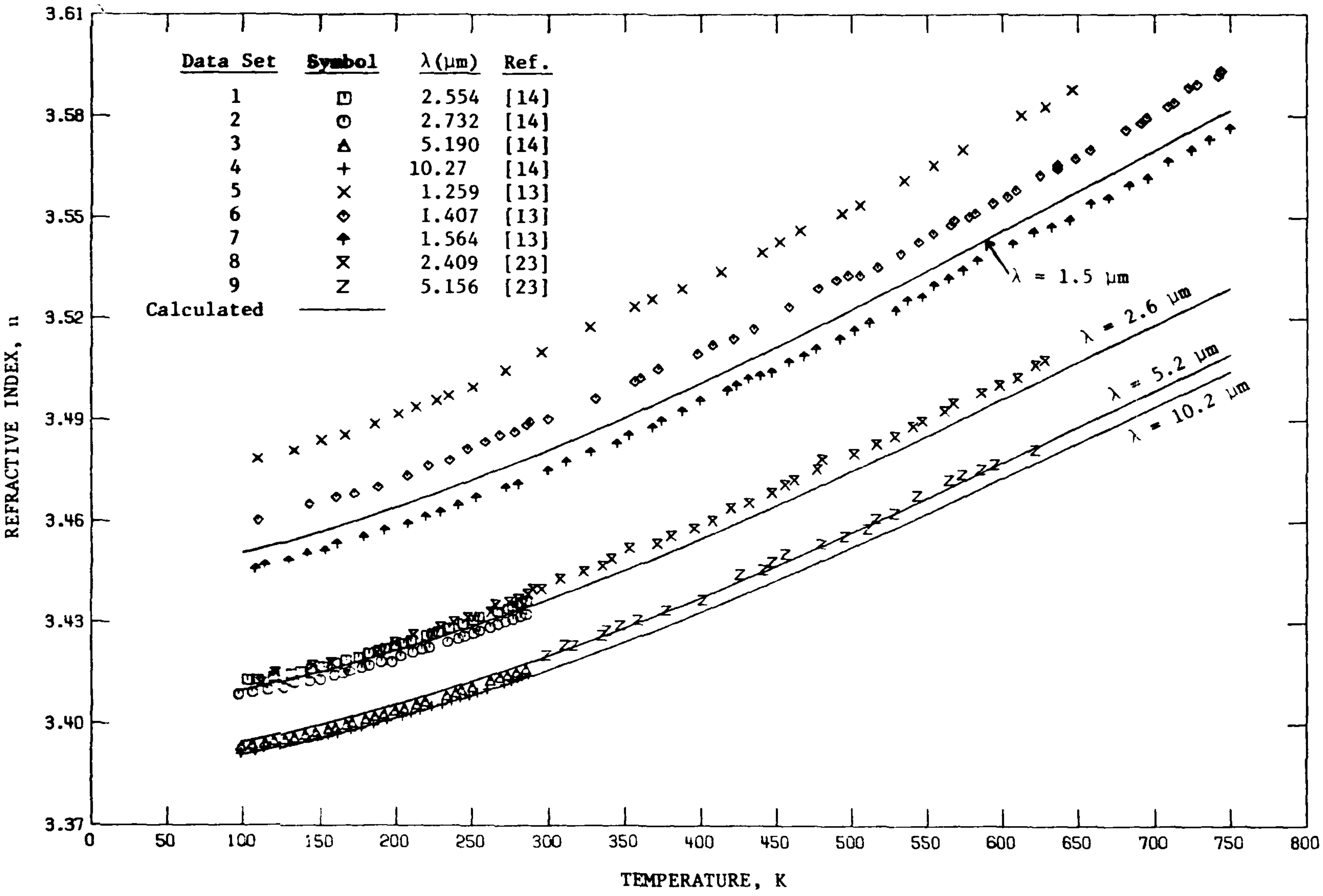

FIGURE 2. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF SILICON (Temperature Dependence)

Primak [24] went to great lengths in the determination of the refractive index of silicon from 1.12 to 2.16 µm. His results corresponded closely to those reported by Lukes. As he took into account all of the influencing factors in arriving at the final values, he believed that his values were reliable within an uncertainty of 1 or 2 parts in the third decimal place.

Icenogle et al. [14] made a thorough investigation on the refractive index for silicon over the temperature and wavelength ranges of 99-296 K and 2.554-10.27 µm, respectively. The samples were obtained from the Exotic Materials, Inc. and were characterized as "good optical grade" without further details of purity of the material. The results are in fair agreement with other data sets. The claimed errors were $\pm 3 \times 10^{-4}$.

For the purpose of ease of comparison, the above mentioned data sets are replotted in figure 3. It is obvious that the disagreement among the values reported by different researchers is greater than the accuracy claimed by them. Although internal consistency was observed in each investigation, unaccounted sources of errors are responsible for these discrepancies.

Primak [24] devoted considerable space to the discussion of both systematic and random errors with the conclusion that the systematic errors played the key role in data discord. The possible sources of error were attributed to:

i. Inadequate care in checking the pyramidal error. If the wedge angle was not perpendicular to the circle and parallel to the telescope, the effective angle would be greater than the true wedge angle with the consequence of a larger deviation angle which would lead to a larger value of refractive index.

ii. Small wedge angle of the samples. For a highly refracting material such as silicon, a small wedge angle is required to measure the refractive index. As a result, large errors in angle measurement can be introduced and hence in the observed refractive index.

iii. Broad detector used. Observation in the infrared requires a detector in the determination of deviation angle. The detectors that have been used are in general many times broader than the width of the spectral line, thus decreasing the accuracy in reading the angles. Significant errors are, therefore, inevitably introduced.

iv. Optical inhomogeneity of the sample. Optical inhomogeneity of the material causes image distortion and thus the error in the angle setting.

Among the above sources, the smallness of the wedge angle is the major factor that contributes to the error. A combination of these contributions limits the accuracy of the measurement of the refractive index by the minimum

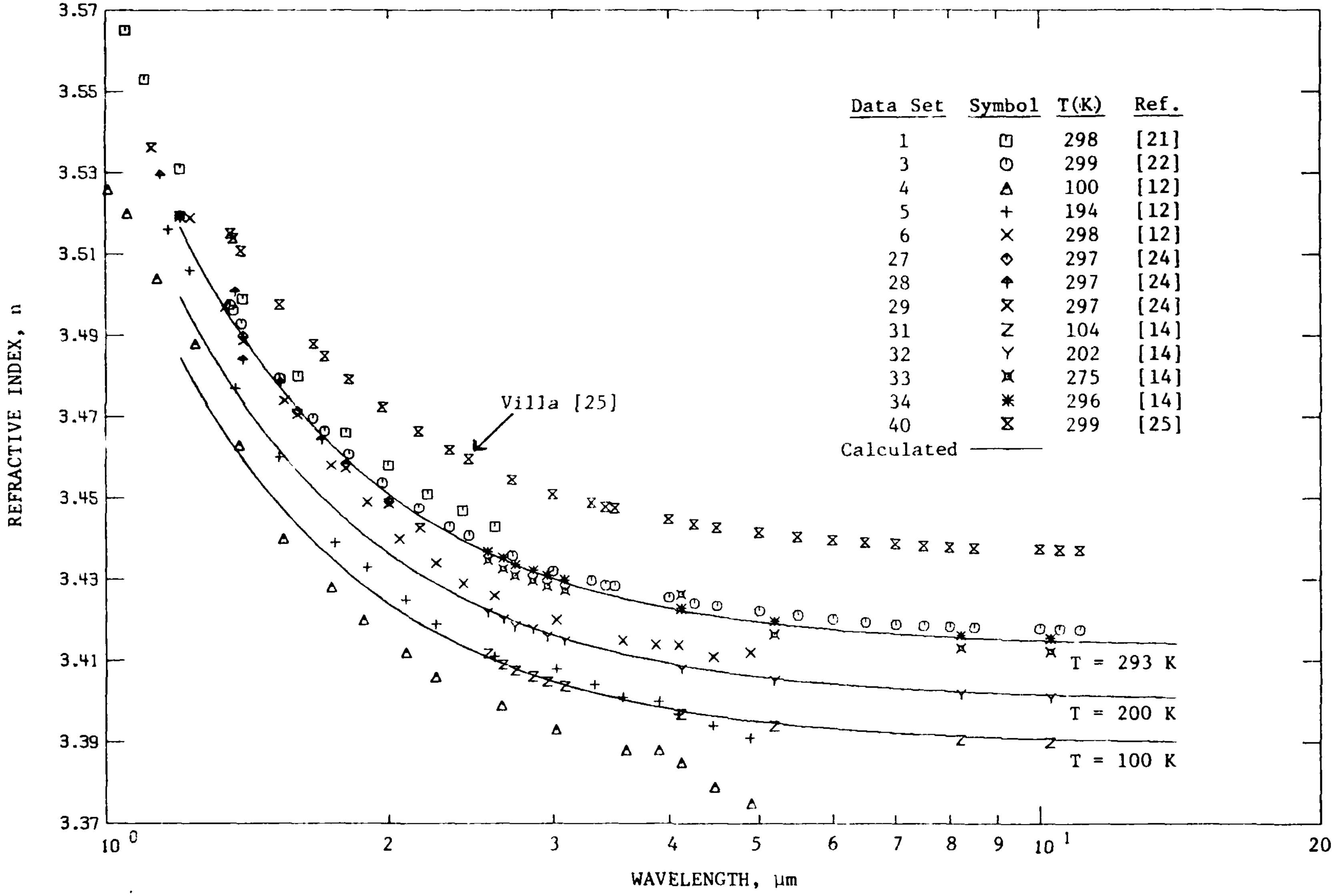

FIGURE 3. SELECTED EXPERIMENTAL REFRACTIVE INDEX OF SILICON (Wavelength Dependence)

deviation method to 1 or 2 units in the third decimal place, a few times higher than that claimed by most investigators.

The effect of impurities on the refractive index is considerable. In some cases, observations made on samples of questionable origin and undefined purity may yield radically different results. Villa [25] reported his grossly divergent values (shown in figure 3) to show that sample differences can be very significant. In figure 1 one can see Simon's [26] radically different results obtained for a silicon sample of high impurity content. The data of Spitzer et al. [27], obtained on heavily doped silicon, are significantly divergent from those of pure samples. Thus, when the effects of impurities are taken into consideration, discrepancies from pure samples may be much larger than 2 parts in the third decimal place.

Although the factors discussed above are well known, unfortunately they are generally not cited in literature, but must be deduced from the assigned accuracies. In the present work it is assumed that data sets that are discordant only in the third decimal place are in reasonable agreement. This assumption can be supported by a careful comparison of the observations by Icenogle et al. [14] in which the values of the refractive index at a given wavelength and temperature, obtained from wavelength-dependence observation and from temperature-dependence observation, can be different in many cases by more than 1 part in the third decimal, few times higher than the claimed precision of $\pm 3 \times 10^{-4}$.

More data can be found in references [28-39] and are given in tables A-1 and A-2, in which one can find also data sets obtained on thin films. No attempt was made to analyze the thin film data. However, it has been observed that the refractive indices of pure silicon thin films tend to agree with those of bulk crystal if the films are deposited on substrates maintained at elevated temperatures during deposition or appropriately annealed after deposition. Surface contamination appears to be the most serious problem. However, data for thin films reported by those who exercise appropriate precautions in the sample preparation are usually in agreement with those of bulk material.

Literature data on the temperature coefficient of the refractive index is rather scarce. Data reported in tables A-3 and A-4 and plotted in figures 4 and 5 are those of Lukes [13,23]. His values were evaluated from his measurements given in table A-2 and in figure 2.

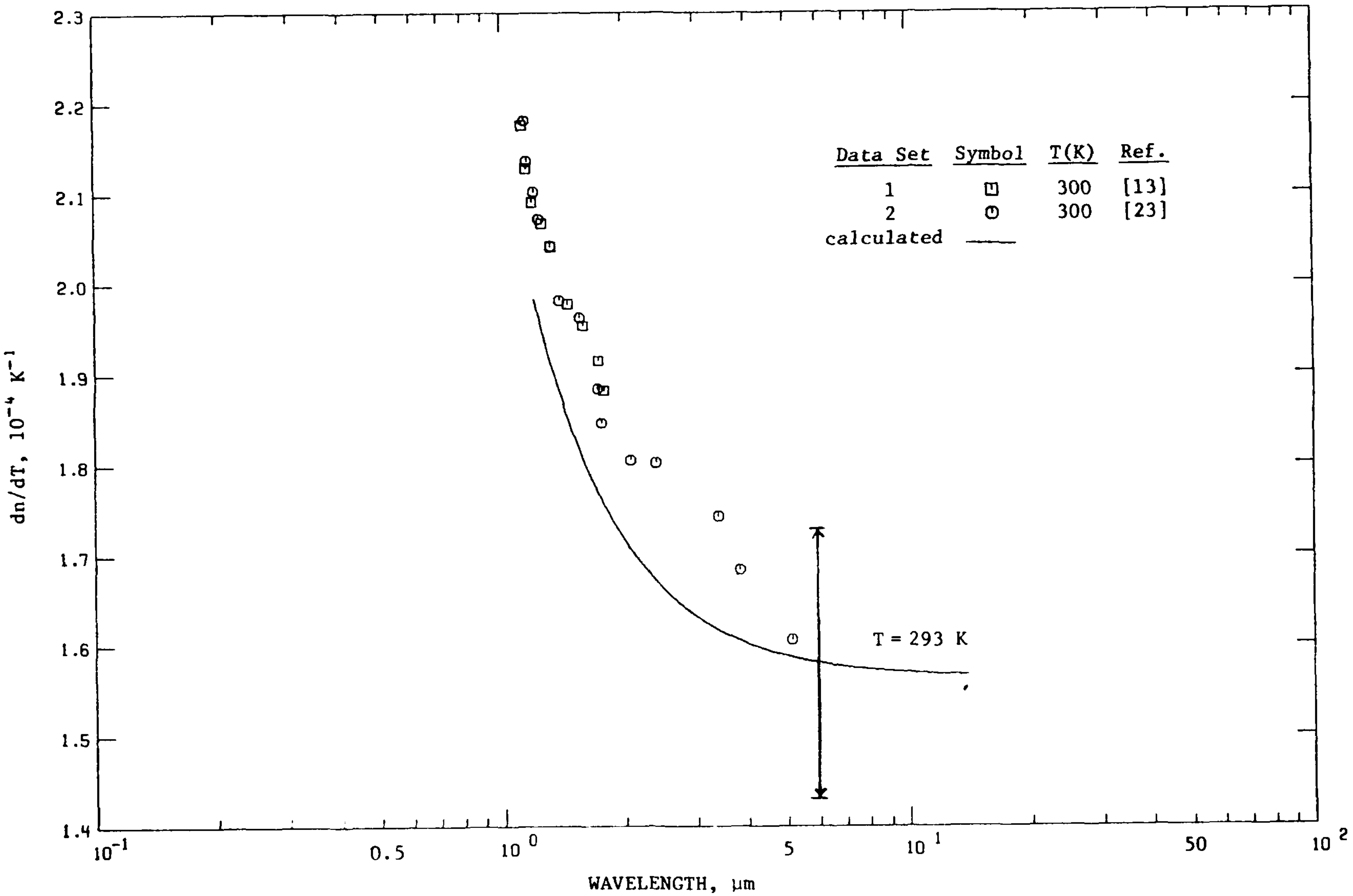

FIGURE 4. AVAILABLE EXPERIMENTAL dn/dT OF SILICON (Wavelength Dependence)

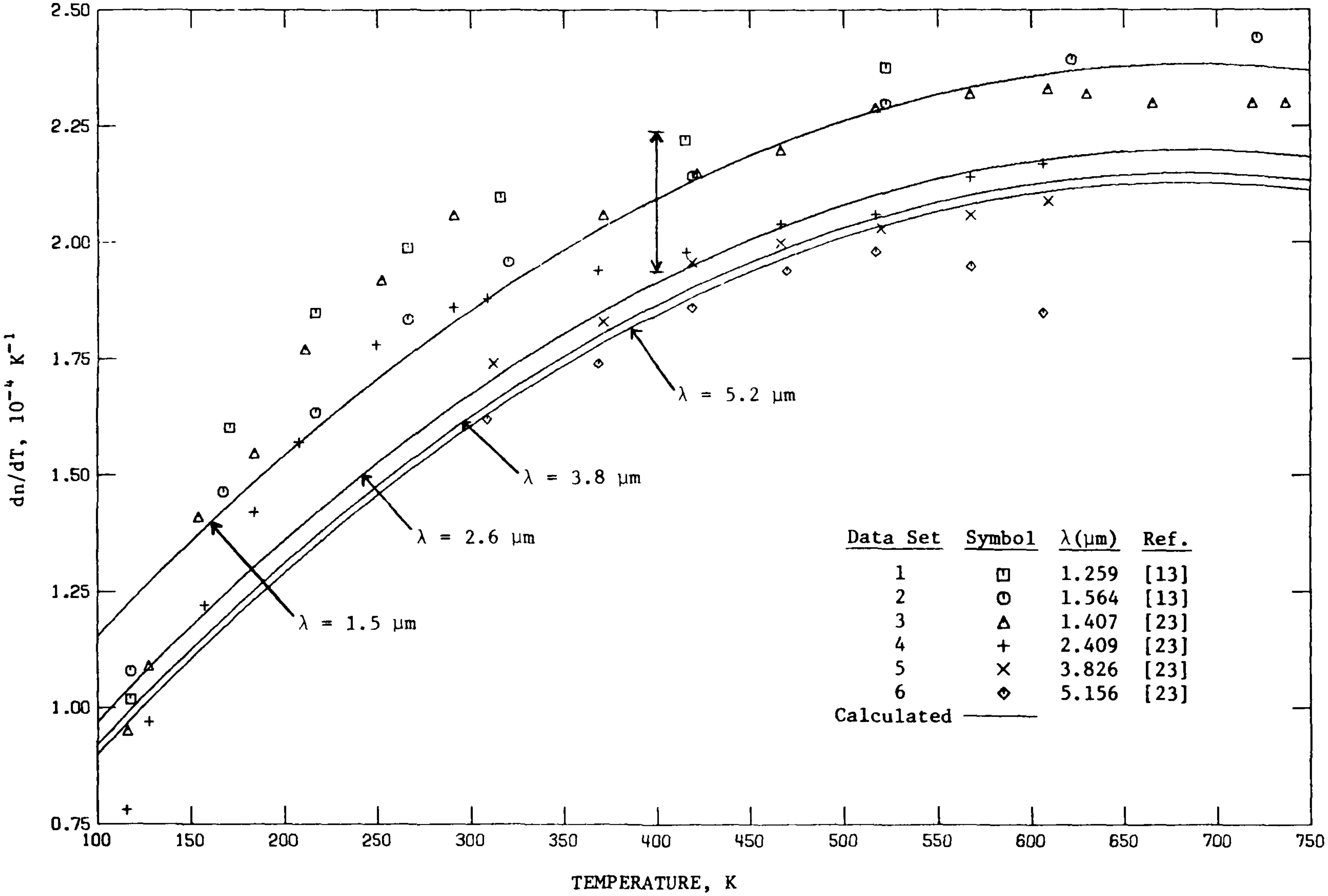

FIGURE 5. AVAILABLE EXPERIMENTAL dn/dT OF SILICON (Temperature Dependence)

Although a significant body of data on the refractive index of silicon are available, an attempt to data analysis has been rare. In the literature, only one quantitative study has been proposed. Hertzberger and Salzberg [40] proposed a dispersion equation for silicon which was derived in conjunction with 13 other materials. They noted that a comparison of the data from 14 materials indicated that all had refractive index values varying asymptotically with λ^2. Furthermore, the mean asymptote was found to be at $\lambda_0 = 0.168$ µm. The dispersion relation was based upon a Taylor expansion in λ^2 which retains only the linear terms. The equation is

$$n = A + BL + CL^2 + D\lambda^2 + E\lambda^4 \tag{19}$$

where λ is in units of µm, $L = 1/(\lambda^2 - \lambda_0{}^2)$, and the coefficients for silicon in the region 1.3 to 11.0 µm are

$A = 3.41696$
$B = 0.138497$
$C = 0.013924$
$D = -0.0000209$
$E = 0.000000148$

The determination of the coefficients in this equation was based on a single data set by Salzberg and Villa [22] and the fit is excellent.

In the present work, eq. (10) is used to represent the refractive index for silicon. The main task was the selection of the appropriate parameters ε and λ_1, and the determination of the coefficients A and B. But the most important of all was the selection of reliable data sets used as input information to eq. (10). The selected data were limited to the works of Salzberg and Villa, Primak, and Icenogle et al. Data from Cardona et al. and Lukes were not used on the basis that their values had to be read off from the graphs in their reports. Deviations between the graph readings and the true values can occur in the second decimal place of the data. The data of Briggs were not chosen as his values disagree in the second decimal place with the corresponding values of Primak who exercised great care in the experiment for high purity silicon specimens. The remaining data sets from Primak, Salzberg and Villa, and Icenogle et al. constitute the basis of our recommendations. Their results are in agreement in the third decimal as expected. Fortunately, Icenogle's work covered a sizable temperature range, thus permitting the prediction of the refraction index at temperatures other than room temperature.

Selection of ε and λ_1 in eq. (10) was rather difficult. Figure 6 shows the results of Cardona et al. [12] who observed the relative changes of refractive index, $\Delta n/n$, at a wavelength of 3 μm as temperature varied between 77 to 400 K. The average slope, $(1/n)(dn/dT)$, of this curve is $(3.9 \pm 0.4) \times 10^{-5} K^{-1}$. Lukes [13,23] obtained a higher value of $4.8 \pm 0.2 \times 10^{-5} K^{-1}$ for $(1/n)(dn/dT)$ by extrapolating his results to longer wavelengths. It appeared that at long wavelengths, ε in eq. (10) could be determined from the relation $(1/\varepsilon)(d\varepsilon/dT) = (2/n)(dn/dT)$ using one of the above mentioned $(1/n)(dn/dT)$ values. The result should be an exponential relation of the form $\varepsilon = \varepsilon_0 e^{cT}$. However, as the constancy of $(1/n)(dn/dT)$ does not hold for the wide temperature range of our interest, an empirical relation between ε and T had to be found based on the experimental data of n.

It is shown in figure 2 that curves of temperature dependence of refractive index at various wavelengths are essentially parallel to each other and that each of them smoothly and monotonically increases with temperature. This provides the possibility to find relations between ε and T. Since ε is nearly equal to n^2 at long wavelengths, the best choice in the present case seemed to be the refractive indices at 10.27 μm by Icenogle et al. [14]. As the available data of n(T) at 10.27 μm cover only the limited temperature range from 100 to 298 K, a wider temperature range coverage is needed to establish the relation between ε and T that is valid over the temperature range 100-750 K. As shown in figure 2, the 5.156 μm curve by Lukes [23] is slightly above, but parallel to, the extension made from the 10.27 μm curve. The required 10.27 μm data in the high temperature region can be estimated by an appropriate extrapolation of Icenogle's data within that region. In this way, the following polynomial expression is found to be valid at 10.27 μm and over 100-750 K temperature range,

$$n^2(10.27\ \mu m, T) = 11.4552 + 2.7765 \times 10^{-4} T + 1.7066 \times 10^{-6} T^2 - 8.1423 \times 10^{-10} T^3 \qquad (20)$$

Since at long wavelengths the dielectric constant closely approaches n , it is acceptable to consider the above quantity as a proportional factor and thus express the dielectric constant by the relation

$$\varepsilon(T) = E\, n^2(10.27\ \mu m,\ T) \qquad (21)$$

where E is the proportional constant.

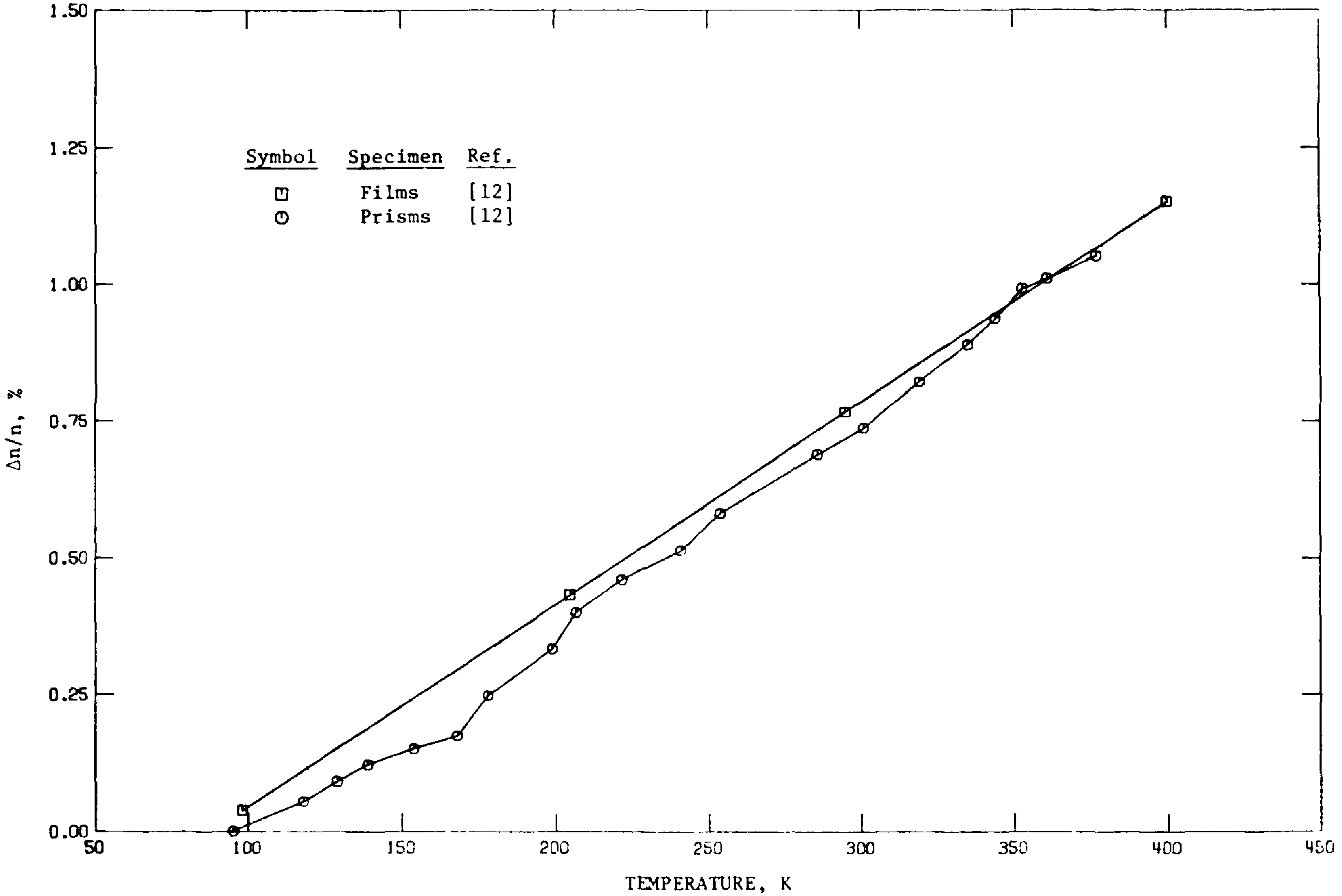

FIGURE 6. VARIATION OF REFRACTIVE INDEX OF SILICON WITH TEMPERATURE AT WAVELENGTH 3 μm [12]

The spectral positions of resonant absorption peaks have been observed by a number of investigators. Moss [41] made an attempt to calculate the refractive indices in the transparent region from the absorption data based on the general principle of oscillatory system. The spectral position of the natural frequency in his single oscillator model was determined at 3.4 eV or $\lambda = 0.365$ µm. McLean [3] investigated the absorption edge spectrum of silicon and found the optical energy gap at 300 K to be $E_g = 1.12$ eV or $\lambda_1 = 1.1071$ µm. Macfarlane et al. [15] further studied the absorption edge spectrum and found that the temperature variation of the optical energy gap is essentially linear in the temperature region 250-480 K, but nonlinearity progressively predominates at lower temperatures, as seen from figure 7. Lukes and Schmidt [18] studied the reflectivity spectrum of silicon and found two additional absorption peaks at about 0.36 and 0.27 µm. The first one is in line with the Moss' [41] result, while the second corresponds to the prediction of Yu and Cardona [42]. A summary of these findings results in three absorption peaks; namely: $\lambda_1 = 1.1071$ µm, $\lambda_2 = 0.365$ µm, and $\lambda_3 = 0.27$ µm, that supposedly have significant effects on the refractive index in the transparent region from 1.2 to 14 µm.

An attempt was made to fit the selected data to an equation similar to eq. (10) by including extra terms due to λ_2 and λ_3. It was found, however, that the introduction of the λ_2 and λ_3 terms did not improve the agreement obtained when only the λ_1 term was included. Furthermore, the coefficients of the λ_2 and λ_3 terms could not be uniquely defined because there were no reliable data in the regions bounded by and near the three peak wavelengths. Also, the value of B was found to be negligibly small, thus making the contribution of the last term in eq. (10) insignificant. As a consequence, eq. (18) was adopted and the least squares fitting of selected data to this equation yielded the following expression for the refractive index of silicon in the ranges 1.2 to 14 µm and 100-750 K:

$$n^2(\lambda,T) = \varepsilon(T) + \frac{L(T)}{\lambda^2}\,(A_0 + A_1T + A_2T^2) \qquad (22)$$

where

$\varepsilon(T) = 11.4445 + 2.7739 \times 10^{-4}T + 1.7050 \times 10^{-6}T^2 - 8.1347 \times 10^{-10}T^3$,

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

λ = wavelength in units of µm,

T = temperature in units of K,

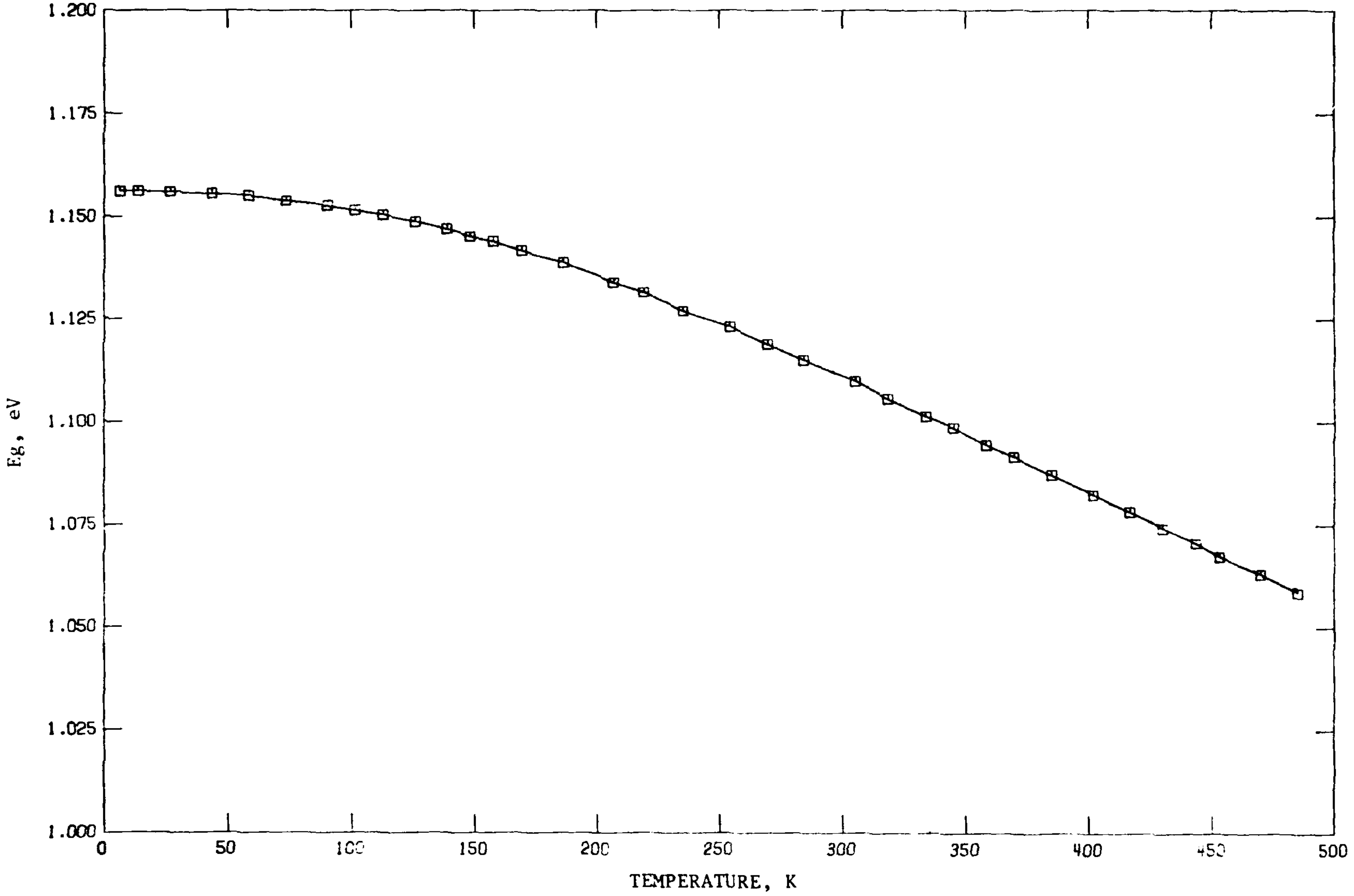

FIGURE 7. TEMPERATURE DEPENDENCE OF THE OPTICAL ENERGY GAP OF SILICON [15]

$A_0 = 0.8948,$
$A_1 = 4.3977 \times 10^{-4},$
$A_2 = 7.3835 \times 10^{-8},$

and from reference [6]

$$\frac{\Delta L(T)}{L_{293}} = \begin{cases} -0.021 - 4.149 \times 10^{-7} T - 4.620 \times 10^{-10} T^2 + 1.482 \times 10^{-11} T^3 & (20\text{-}293\ \mathrm{K}), \\ -0.071 + 1.887 \times 10^{-6} T + 1.934 \times 10^{-9}\, T^2 - 4.544 \times 10^{-13} T^3 & (293\text{-}1600\ \mathrm{K}). \end{cases}$$

It should be pointed out that the room-temperature dielectric constant for silicon can be calculated from the expression for ε in eq. (22). The result is 11.66 which agrees well with the commonly accepted value of 11.7.

Equation (22) was used to calculate the recommended values of the refractive index of silicon with uncertainties of $\pm 2 \times 10^{-3}$. The recommended values are given in table 3 and plotted in figure 8. To provide visual comparison of calculated values with the experimental data, calculated values at a few specified temperatures and wavelengths are plotted in figures 2 and 3 where excellent agreement is revealed. Tables 4 and 5, respectively, give the calculated dn/dT and $dn/d\lambda$ values based on the first derivatives of eq. (22) with respect to T and λ. The corresponding plots are shown in figures 9 and 10.

Uncertainties in the calculated dn/dT are estimated based on Icenogle's [14] results which were the essential data on which eq. (22) is based. Icenogle et al. evaluated $\Delta n/\Delta T$ values using their own measurements of n and found the average accuracy in $\Delta n/\Delta T$ to be about $\pm 0.15 \times 10^{-4} K^{-1}$. Error bars corresponding to this amount are drawn on the calculated curves in figures 4 and 5 where calculations are compared with the experimental data. Although accuracies of experimental dn/dT are not given in Lukes' work [13,23], it is reasonable to adopt the same experimental error bar since the n versus T curves in figure 2 are closely parallel.

Uncertainties of the calculated $dn/d\lambda$ are estimated in the following manner. Taking the first derivative of eq. (22) with respect to λ, we have

$$-dn/d\lambda = (1/n)\ A(T)/\lambda^3 = (1/n\lambda)\ (n^2 - \varepsilon) \tag{23}$$

which leads to

$$\delta(dn/d\lambda) \simeq \pm\ 2\ \delta n/\lambda \tag{24}$$

Based on the fact that the spectral dependence of the refractive index from various investigators are essentially parallel, it should be permissible to

TABLE 3. RECOMMENDED VALUES ON THE REFRACTIVE INDEX OF SILICON*

λ, μm	TEMPERATURE, K													
	100	150	200	250	293	350	400	450	500	550	600	650	700	750
1.20	3.4845	3.4915	3.4995	3.5084	3.5167	3.5284	3.5393	3.5508	3.5627	3.5749	3.5873	3.5999	3.6126	3.6252
1.22	3.4814	3.4884	3.4963	3.5051	3.5133	3.5250	3.5359	3.5473	3.5591	3.5712	3.5836	3.5961	3.6087	3.6213
1.24	3.4785	3.4854	3.4933	3.5020	3.5102	3.5218	3.5326	3.5439	3.5557	3.5678	3.5801	3.5925	3.6051	3.6176
1.26	3.4757	3.4826	3.4904	3.4991	3.5072	3.5187	3.5295	3.5407	3.5524	3.5644	3.5767	3.5891	3.6016	3.6140
1.28	3.4731	3.4799	3.4876	3.4963	3.5043	3.5158	3.5265	3.5377	3.5493	3.5613	3.5735	3.5858	3.5982	3.6106
1.30	3.4706	3.4773	3.4850	3.4936	3.5016	3.5130	3.5236	3.5348	3.5463	3.5582	3.5704	3.5827	3.5950	3.6074
1.32	3.4682	3.4748	3.4825	3.4910	3.4990	3.5103	3.5209	3.5320	3.5435	3.5554	3.5674	3.5797	3.5920	3.6043
1.34	3.4658	3.4725	3.4801	3.4885	3.4965	3.5077	3.5183	3.5293	3.5408	3.5526	3.5646	3.5768	3.5891	3.6013
1.36	3.4636	3.4702	3.4778	3.4862	3.4941	3.5053	3.5158	3.5268	3.5382	3.5500	3.5619	3.5741	3.5863	3.5985
1.38	3.4615	3.4681	3.4756	3.4839	3.4918	3.5029	3.5134	3.5243	3.5357	3.5474	3.5594	3.5715	3.5836	3.5957
1.40	3.4595	3.4660	3.4735	3.4818	3.4896	3.5007	3.5111	3.5220	3.5333	3.5450	3.5569	3.5689	3.5810	3.5931
1.45	3.4548	3.4612	3.4685	3.4768	3.4845	3.4955	3.5058	3.5166	3.5278	3.5394	3.5511	3.5631	3.5751	3.5871
1.50	3.4506	3.4568	3.4641	3.4722	3.4799	3.4908	3.5010	3.5117	3.5228	3.5343	3.5460	3.5578	3.5697	3.5816
1.55	3.4467	3.4529	3.4601	3.4681	3.4757	3.4865	3.4966	3.5072	3.5183	3.5297	3.5413	3.5530	3.5648	3.5766
1.60	3.4432	3.4493	3.4564	3.4644	3.4719	3.4826	3.4926	3.5032	3.5142	3.5255	3.5370	3.5487	3.5604	3.5721
1.65	3.4400	3.4461	3.4531	3.4610	3.4684	3.4791	3.4890	3.4995	3.5104	3.5216	3.5331	3.5447	3.5564	3.5680
1.70	3.4371	3.4431	3.4501	3.4579	3.4653	3.4758	3.4857	3.4961	3.5070	3.5181	3.5295	3.5411	3.5527	3.5643
1.80	3.4320	3.4379	3.4447	3.4524	3.4597	3.4701	3.4799	3.4902	3.5010	3.5120	3.5233	3.5347	3.5462	3.5577
1.90	3.4277	3.4334	3.4402	3.4478	3.4550	3.4653	3.4750	3.4852	3.4958	3.5068	3.5180	3.5293	3.5407	3.5521
2.00	3.4240	3.4297	3.4363	3.4439	3.4510	3.4612	3.4708	3.4809	3.4915	3.5023	3.5135	3.5247	3.5360	3.5473
2.25	3.4168	3.4223	3.4288	3.4362	3.4431	3.4532	3.4626	3.4726	3.4830	3.4937	3.5046	3.5157	3.5269	3.5380
2.50	3.4116	3.4170	3.4234	3.4306	3.4375	3.4474	3.4568	3.4666	3.4769	3.4875	3.4983	3.5093	3.5203	3.5313
2.75	3.4078	3.4131	3.4194	3.4266	3.4334	3.4432	3.4524	3.4622	3.4724	3.4829	3.4936	3.5045	3.5154	3.5264
3.00	3.4048	3.4101	3.4163	3.4234	3.4302	3.4399	3.4491	3.4588	3.4689	3.4794	3.4900	3.5009	3.5117	3.5226
4.00	3.3981	3.4032	3.4093	3.4163	3.4229	3.4325	3.4415	3.4510	3.4610	3.4713	3.4818	3.4925	3.5032	3.5139
5.00	3.3950	3.4000	3.4060	3.4129	3.4195	3.4290	3.4380	3.4474	3.4573	3.4675	3.4780	3.4886	3.4992	3.5099
6.00	3.3933	3.3983	3.4043	3.4111	3.4177	3.4271	3.4360	3.4455	3.4553	3.4655	3.4759	3.4865	3.4971	3.5077
7.00	3.3923	3.3973	3.4032	3.4100	3.4165	3.4260	3.4349	3.4443	3.4541	3.4643	3.4747	3.4852	3.4958	3.5063
8.00	3.3916	3.3966	3.4025	3.4093	3.4158	3.4252	3.4341	3.4435	3.4533	3.4635	3.4739	3.4844	3.4950	3.5055
9.00	3.3912	3.3961	3.4020	3.4088	3.4153	3.4247	3.4336	3.4430	3.4528	3.4629	3.4733	3.4838	3.4944	3.5049
10.00	3.3909	3.3958	3.4017	3.4085	3.4150	3.4244	3.4332	3.4426	3.4524	3.4625	3.4729	3.4834	3.4940	3.5045
11.00	3.3906	3.3955	3.4015	3.4082	3.4147	3.4241	3.4330	3.4423	3.4521	3.4623	3.4726	3.4831	3.4937	3.5042
12.00	3.3904	3.3954	3.4013	3.4080	3.4145	3.4239	3.4328	3.4421	3.4519	3.4620	3.4724	3.4829	3.4934	3.5039
13.00	3.3903	3.3952	3.4011	3.4079	3.4144	3.4237	3.4326	3.4420	3.4518	3.4619	3.4722	3.4827	3.4932	3.5037
14.00	3.3902	3.3951	3.4010	3.4078	3.4142	3.4236	3.4325	3.4418	3.4516	3.4617	3.4721	3.4826	3.4931	3.5036

* IN THIS TABLE MORE DECIMAL PLACES ARE REPORTED THAN WARRANTED MERELY FOR THE PURPOSE OF TABULAR SMOOTHNESS AND INTERNAL COMPARISON. THE NUMBER OF DIGITS WITH AN OVERSTRIKE ARE NOT RELEVANT TO ACCURACY OF THE DATA.

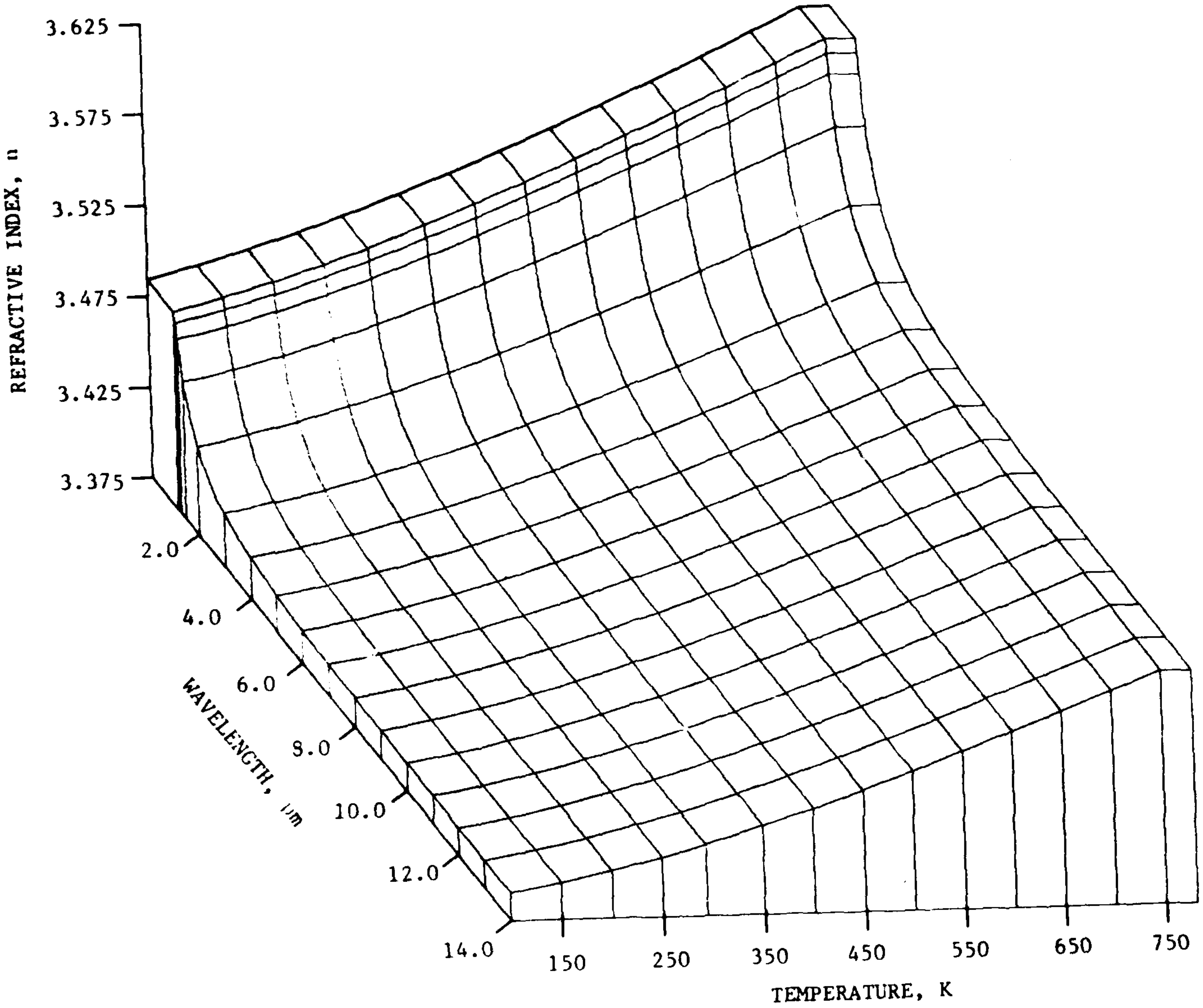

FIGURE 8. RECOMMENDED n-λ-T DIAGRAM OF SILICON

TABLE 4. RECOMMENDED VALUES ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF SILICON*

λ, μm	TEMPERATURE, K													
	100	150	200	250	293	350	400	450	500	550	600	650	700	750
1.20	1.305	1.509	1.693	1.857	1.983	2.132	2.244	2.336	2.411	2.468	2.508	2.530	2.535	2.523
1.22	1.292	1.495	1.679	1.844	1.970	2.119	2.230	2.323	2.398	2.455	2.494	2.516	2.521	2.509
1.24	1.279	1.482	1.666	1.831	1.957	2.107	2.218	2.310	2.385	2.442	2.481	2.503	2.508	2.496
1.26	1.266	1.470	1.654	1.819	1.945	2.094	2.205	2.298	2.373	2.430	2.469	2.491	2.496	2.484
1.28	1.254	1.458	1.642	1.807	1.934	2.083	2.194	2.287	2.361	2.418	2.457	2.479	2.484	2.472
1.30	1.243	1.447	1.631	1.796	1.923	2.072	2.183	2.276	2.350	2.407	2.446	2.468	2.473	2.460
1.32	1.232	1.436	1.620	1.785	1.912	2.061	2.172	2.265	2.340	2.396	2.436	2.457	2.462	2.449
1.34	1.222	1.426	1.610	1.775	1.902	2.051	2.162	2.255	2.330	2.386	2.425	2.447	2.451	2.439
1.36	1.212	1.416	1.600	1.765	1.892	2.042	2.153	2.245	2.320	2.377	2.416	2.437	2.442	2.429
1.38	1.203	1.407	1.591	1.756	1.883	2.032	2.143	2.236	2.311	2.367	2.406	2.428	2.432	2.419
1.40	1.194	1.398	1.582	1.747	1.874	2.023	2.134	2.227	2.302	2.358	2.397	2.419	2.423	2.410
1.45	1.173	1.376	1.561	1.726	1.854	2.003	2.114	2.206	2.281	2.337	2.376	2.398	2.402	2.389
1.50	1.153	1.357	1.542	1.708	1.835	1.984	2.095	2.188	2.262	2.319	2.357	2.379	2.383	2.370
1.55	1.136	1.340	1.525	1.691	1.818	1.967	2.078	2.171	2.245	2.302	2.340	2.361	2.365	2.352
1.60	1.120	1.325	1.509	1.675	1.803	1.952	2.063	2.155	2.230	2.286	2.325	2.346	2.350	2.336
1.65	1.106	1.310	1.495	1.661	1.789	1.938	2.049	2.141	2.215	2.272	2.310	2.331	2.335	2.322
1.70	1.093	1.297	1.482	1.648	1.776	1.925	2.036	2.128	2.203	2.259	2.297	2.318	2.322	2.308
1.80	1.070	1.274	1.459	1.625	1.753	1.902	2.013	2.106	2.180	2.236	2.274	2.295	2.299	2.285
1.90	1.050	1.255	1.440	1.606	1.734	1.883	1.994	2.086	2.161	2.217	2.255	2.276	2.279	2.265
2.00	1.033	1.238	1.423	1.589	1.717	1.866	1.977	2.070	2.144	2.200	2.238	2.259	2.262	2.248
2.25	1.001	1.205	1.391	1.557	1.685	1.834	1.945	2.038	2.112	2.168	2.206	2.226	2.229	2.215
2.50	.977	1.182	1.368	1.534	1.662	1.811	1.922	2.015	2.089	2.145	2.183	2.203	2.206	2.191
2.75	.960	1.165	1.350	1.517	1.645	1.794	1.905	1.998	2.072	2.127	2.165	2.185	2.188	2.173
3.00	.947	1.151	1.337	1.504	1.632	1.781	1.892	1.985	2.058	2.114	2.152	2.172	2.175	2.160
4.00	.916	1.121	1.307	1.474	1.602	1.751	1.862	1.954	2.028	2.084	2.122	2.142	2.144	2.129
5.00	.902	1.107	1.293	1.460	1.588	1.737	1.848	1.940	2.014	2.070	2.108	2.127	2.130	2.114
6.00	.894	1.099	1.285	1.452	1.581	1.730	1.841	1.933	2.007	2.062	2.100	2.120	2.122	2.107
7.00	.889	1.094	1.280	1.448	1.576	1.725	1.836	1.928	2.002	2.058	2.095	2.115	2.117	2.102
8.00	.886	1.091	1.277	1.445	1.573	1.722	1.833	1.925	1.999	2.055	2.092	2.112	2.114	2.099
9.00	.884	1.089	1.275	1.442	1.571	1.720	1.831	1.923	1.997	2.053	2.090	2.110	2.112	2.097
10.00	.883	1.088	1.274	1.441	1.570	1.719	1.830	1.922	1.996	2.051	2.089	2.108	2.110	2.095
11.00	.882	1.087	1.273	1.440	1.569	1.718	1.828	1.921	1.994	2.050	2.088	2.107	2.109	2.094
12.00	.881	1.086	1.272	1.439	1.568	1.717	1.828	1.920	1.994	2.049	2.087	2.106	2.108	2.093
13.00	.880	1.085	1.271	1.438	1.567	1.716	1.827	1.919	1.993	2.049	2.086	2.106	2.108	2.093
14.00	.880	1.085	1.271	1.438	1.567	1.716	1.827	1.919	1.992	2.048	2.086	2.105	2.107	2.092

* IN THIS TABLE MORE DECIMAL PLACES ARE REPORTED THAN WARRANTED MERELY FOR THE PURPOSE OF TABULAR SMOOTHNESS AND INTERNAL COMPARISON. THE NUMBER OF DIGITS WITH AN OVERSTRIKE ARE NOT RELEVANT TO ACCURACY OF THE DATA.

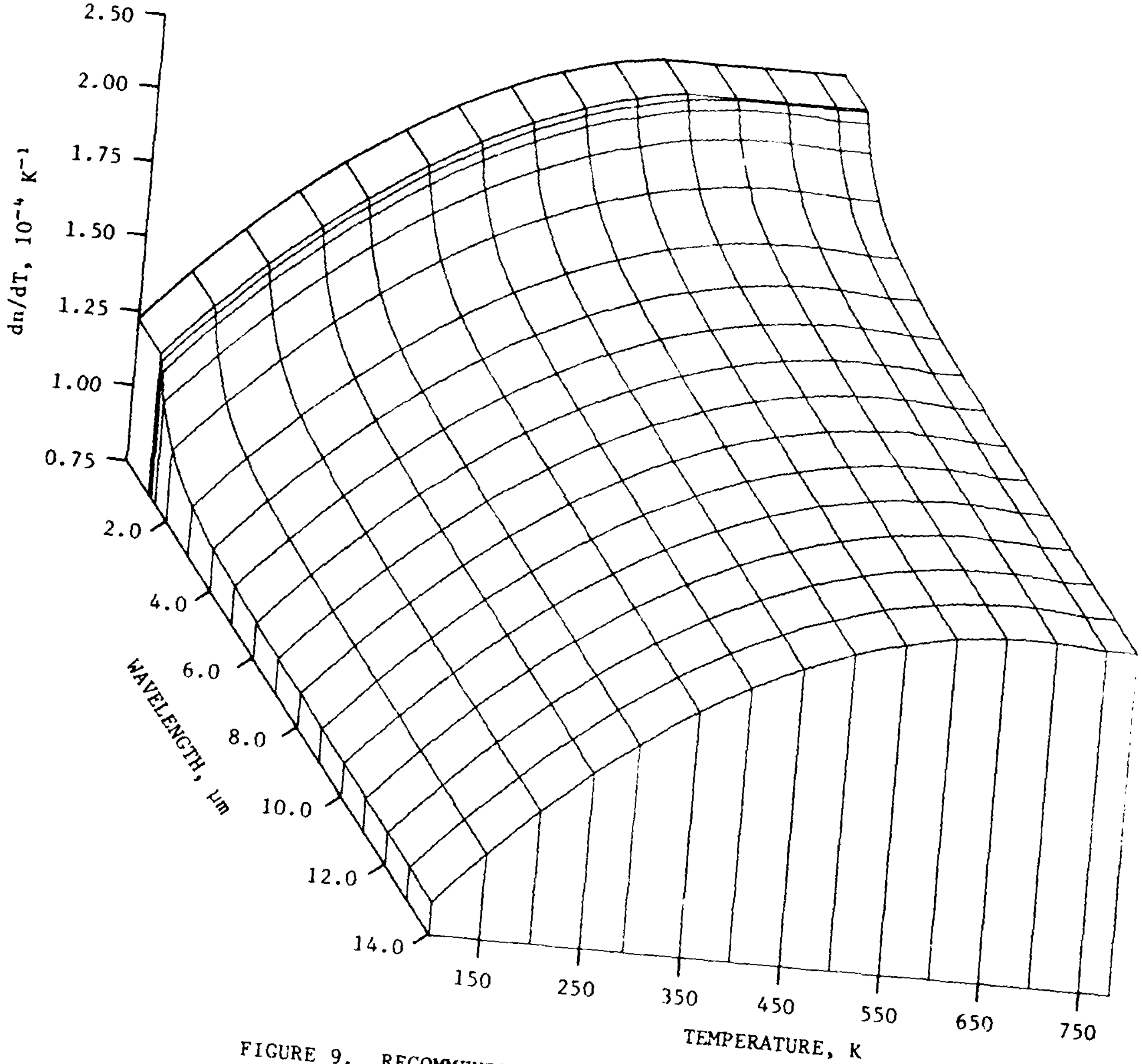

FIGURE 9. RECOMMENDED dn/dT-λ-T DIAGRAM OF SILICON

TABLE 5. CALCULATED VALUES ON THE WAVELENGTH DERIVATIVE OF REFRACTIVE INDEX OF SILICON AT 293K*

λ, μm	$-dn/d\lambda$, 10^{-4} μm^{-1}
1.20	1694.5
1.22	1614.0
1.24	1538.6
1.26	1467.7
1.28	1401.1
1.30	1338.5
1.32	1279.5
1.34	1224.0
1.36	1171.6
1.38	1122.1
1.40	1075.4
1.45	969.3
1.50	876.8
1.55	795.6
1.60	724.1
1.65	660.9
1.70	604.8
1.80	510.3
1.90	434.5
2.00	373.0
2.25	262.5
2.50	191.7
2.75	144.2
3.00	111.2
4.00	47.0
5.00	24.1
6.00	13.9
7.00	8.8
8.00	5.9
9.00	4.1
10.00	3.0
11.00	2.3
12.00	1.7
13.00	1.4
14.00	1.1

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* IN THIS TABLE MORE DECIMAL PLACES ARE REPORTED THAN WARRANTED MERELY FOR THE PURPOSE OF TABULAR SMOOTHNESS AND INTERNAL COMPARISON. THE NUMBER OF DIGITS WITH OVERSTIKE ARE NOT RELEVANT TO ACCURACY OF THE DATA.

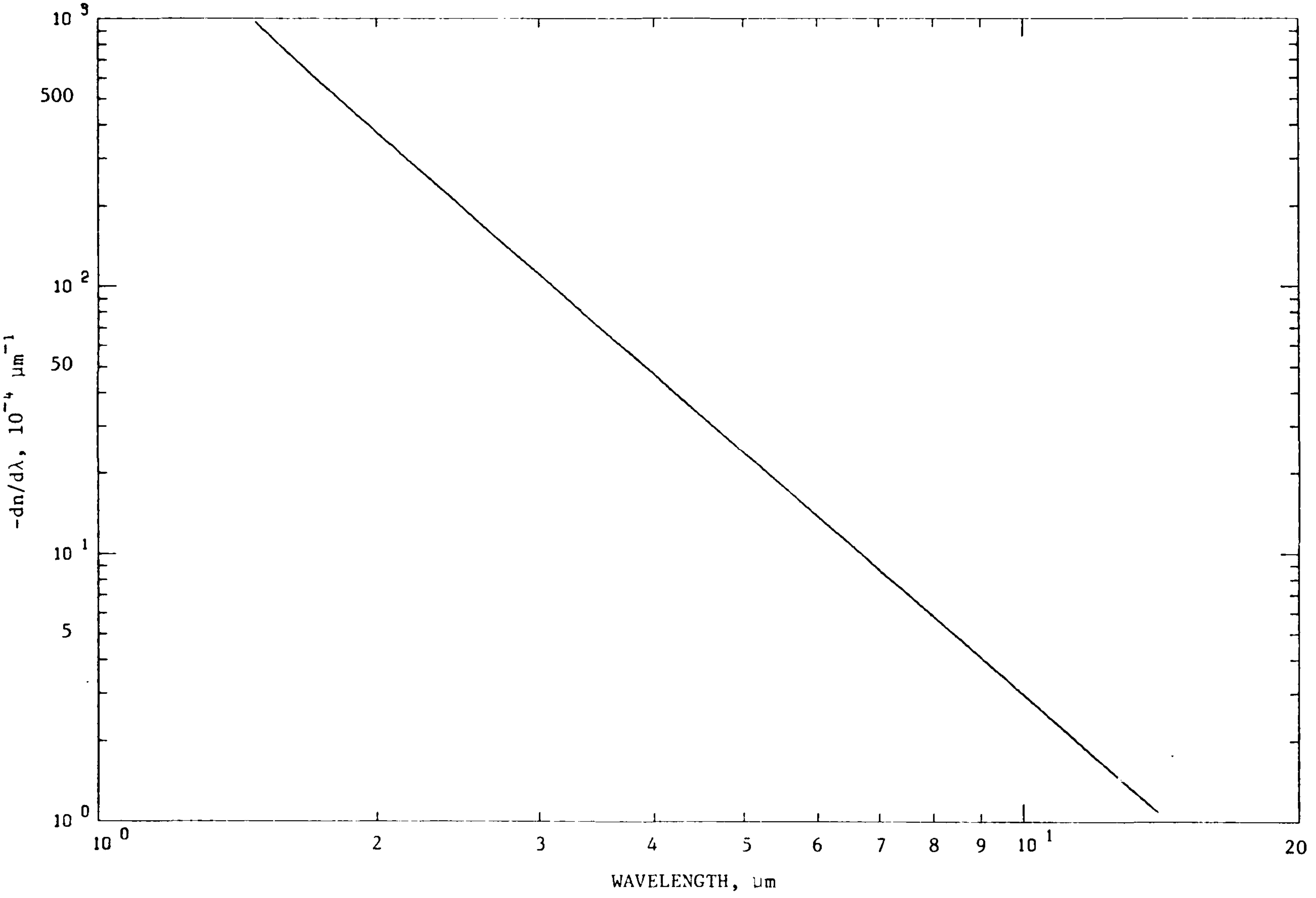

FIGURE 10. RECOMMENDED $dn/d\lambda$ CURVE OF SILICON AT 293 K

apply the uncertainties, $\delta n = \pm 3 \times 10^{-4}$, quoted in Icenogle's work to evaluate $\delta(dn/d\lambda)$ using the above relation for the wavelength region between 2.55 and 14 μm. For wavelengths < 2.55 μm, the uncertainty $\delta n = \pm 2 \times 10^{-3}$ of eq. (22) should be used. Under these conditions, uncertainties of $dn/d\lambda$ are about $\pm 20 \times 10^{-4}$ μm^{-1} at 2 μm, $\pm 2.4 \times 10^{-4}$ μm^{-1} at 2.55 μm, $\pm 0.6 \times 10^{-4}$ μm^{-1} at 10 μm, and $\pm 0.44 \times 10^{-4}$ μm^{-1} at 14 μm.

It should be noted that calculated values in tables 3, 4, and 5 are given with more decimal places than warranted merely for the purpose of tabular smoothness and internal comparison. They should not be interpreted as indicative of the accuracy of the values. Extra figures which are not indicative of the accuracy of the values are indicated with an overstrike.

3.2. Germanium, Ge

There are 88 sets of experimental data available for the refractive index (wavelength and temperature dependences) of germanium as given in tables A-5 and A-6 and plotted in figures 11 and 12. A few sets of measurements on thin films are included for the purpose of completeness and comparison. After careful review and evaluation of the available information, it was found that the data reported by Briggs [21], Salzberg and Villa [22], Cardona et al. [12], Rank et al. [43], Lukes [44,45], Icenogle et al. [14], and Edwin et al. [46] are representative for the refractive index of germanium in the transparent region between 1.8 and 16 μm.

Briggs [21] measured the refractive index of a germanium specimen of 99.99% purity over the spectral region between 1.8 and 2.6 μm. He used the minimum deviation method on a wedge of about 17° apex angle. The range of his measurements was limited on the short wavelength side by absorption in the prism, and on the long wavelength side by absorption in the glass components of the optical system used. The claimed error was a few parts in the third decimal place. He also observed a definite increase in refractive index value with increasing temperature. In other words, the temperature coefficient of refractive index of germanium is positive.

Since Briggs' observation, several other independent measurements were carried out. Salzberg and Villa [22] used the autocollimation minimum deviation method in the determination of n over a wide wavelength range from 2.0 to 16 μm for a single crystal germanium prism of 11.8° apex angle with unknown purity. The reported accuracy was estimated to be ±2 parts in the fourth decimal. Compared with the results of Briggs, their n values are systematically about 0.005 lower in the corresponding spectral region. No source was ascribed for such discrepancies. In a later work [47], a polycrystalline sample was measured and they found that there were no significant differences between the results obtained for different crystals.

Cardona et al. [12] measured the refractive index for a thin germanium wedge of 5° in the wavelength range from 1.7 to 5.6 μm and at temperatures 87, 190, and 297 K. Their n values were also about 0.005 lower than those of Briggs in the corresponding wavelength region. Their results clearly indicate that dn/dt of germanium is positive over the transparent wavelength

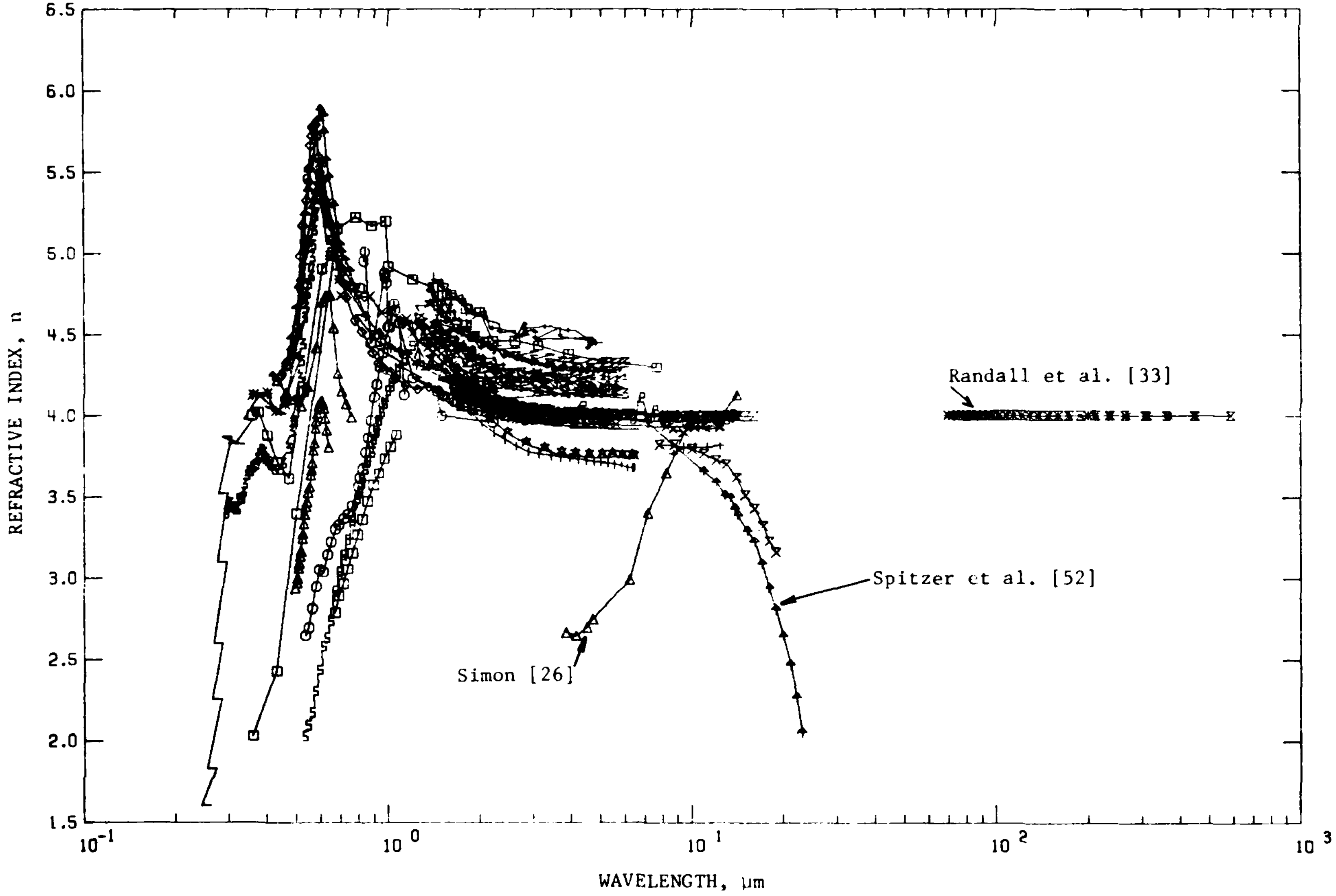

FIGURE 11. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)

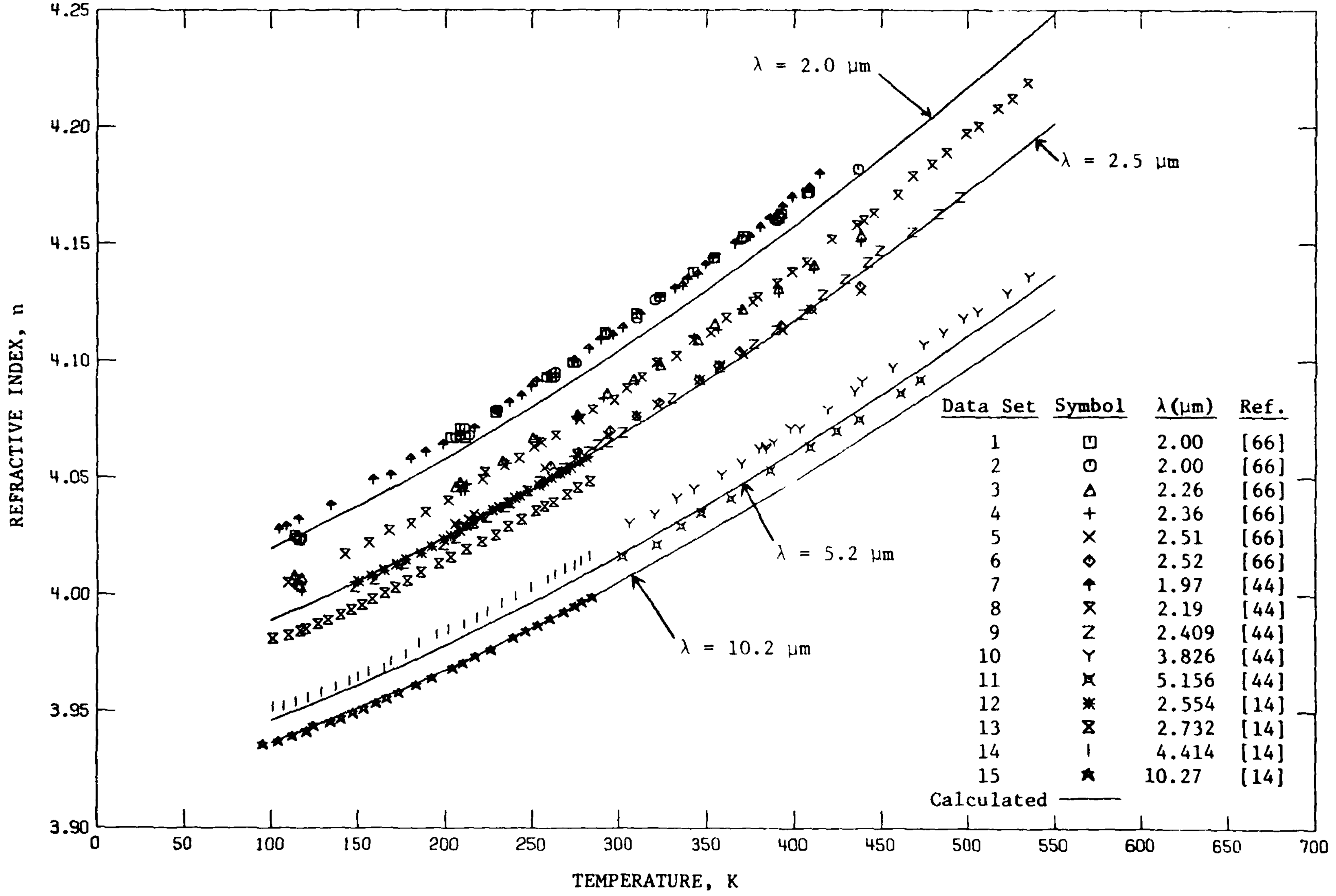

FIGURE 12. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence)

region. At a fixed long wavelength, 3 μm, they measure the relative changes of n, Δn/n, as a function of temperature. A linear relation between Δn/n and T was observed over the temperature range between 77 and 400 K. The result, $(1/n)(dn/dT) = (6.9 \pm 0.4) \times 10^{-5}K^{-1}$, agrees well with those for the dielectric constant measurement at 10 mc/s [48] at low temperatures, but discrepancies occurred at high temperatures where values obtained in reference [48] are higher. Such discrepancies were attributed to the inhomogeneities and impurities in the samples which effectively reduced the thickness of the capacitors and thus resulted in an apparent increase in the dielectric constant.

Rank et al. [43] measured the refractive index over a wavelength region between 2.0 and 2.4 μm by an interferometric method. A single crystal germanium of unspecified purity was used and the resulting n's were about 0.01 higher than the corresponding values of Briggs. The temperature variation of the refractive index was observed to have a positive coefficient and the absorption edge moved to longer wavelengths as temperature increased.

Lukes [44,45] measured the refractive index for several germanium prism samples cut from single crystals of varying impurity. His measurements were carried out over a wavelength range of 1.8-5.5 μm and the temperature range 100-530 K. The results obtained for the purest sample were in agreement with those of Salzberg and Villa, while the results for the impure samples showed discrepancies at the long wavelengths, the higher the impurity, the lower the n. In the shorter wavelength region, <4 μm, the refractive index appeared practically independent on the impurity content.

Icenogle et al. [14] made a thorough investigation on the refractive index for germanium over the 95-297 K and 2.554-12.360 μm regions. The samples were obtained from the Exotic Material, Inc. and were characterized as "good optical grade" without further details of purity of the material. The claimed error in the measurement of n was $\pm 6 \times 10^{-4}$. The results disagree with those of other workers by several parts in the third decimal. At room temperature and in the wavelength region where $\lambda > 3$ μm, Icenogle's values are higher than the earlier works. The sources for such discrepancies can possibly be ascribed to differences in the impurity content of the samples.

Edwin et al. [46] made careful measurements of n for well characterized germanium specimens in the spectral region 8-14 μm. Their results are in agreement with Icenogle's values when account is taken of both of their claimed uncertainties. Edwin et al. took into account the main sources of uncertainty in arriving at their reported values, including probable errors from temperature readings, angle determinations, wavelength identification, curvature of slit image, and random errors. The claimed uncertainty of their results is ±0.0003. According to their sample description, the specimens had a resistivity about 45 to 53 ohm-cm which indicated that they used purer samples than others.

For ease of comparison, the above mentioned data sets are replotted on an enlarged scale in figure 13. It is obvious that the disagreement among the data sets is greater than the individually claimed accuracies. True internal consistency was observed in each measurement, unaccounted sources or errors were responsible for the discrepancies.

Primak [24] devoted considerable space to discussions of both systematic and random errors for the case of silicon (see subsection 3.1). The conclusions are generally valid for other materials. Among the possible sources, the smallness of the prism angle is the major factor that contributes to the error. Combined with the errors from other sources, the limit of accuracy in the measurement of n by the minimum deviation method is 1 to 2 parts in the third decimal place, a few times higher than that claimed by many workers.

The effect of impurities on the refractive index is considerable. In some cases, observations made on samples of questionable origin and undefined purity may yield radically different results. Simon [26] reported his radically different results (shown in figure 11) obtained for a germanium sample of high impurity content. Spitzer et al. [52] investigated the optical constants of heavily doped germanium with results greatly different from those of pure samples shown in figure 11. Thus, when the effects of impurities are taken into consideration, discrepancies from pure samples may be much higher than 2 parts in the third decimal place.

Although the error causing factors given above are well known, unfortunately they are not generally given in the literature and authors advance independent claims of their own precisions. In the present work it is assumed that data sets are concordant if they are not identical in the third decimal place.

More data can be found in references [49-66] and are given in tables A-5 and A-6, in which one can also find data sets obtained for thin films. No attempt was made to analyze the thin film data. However, it has been observed

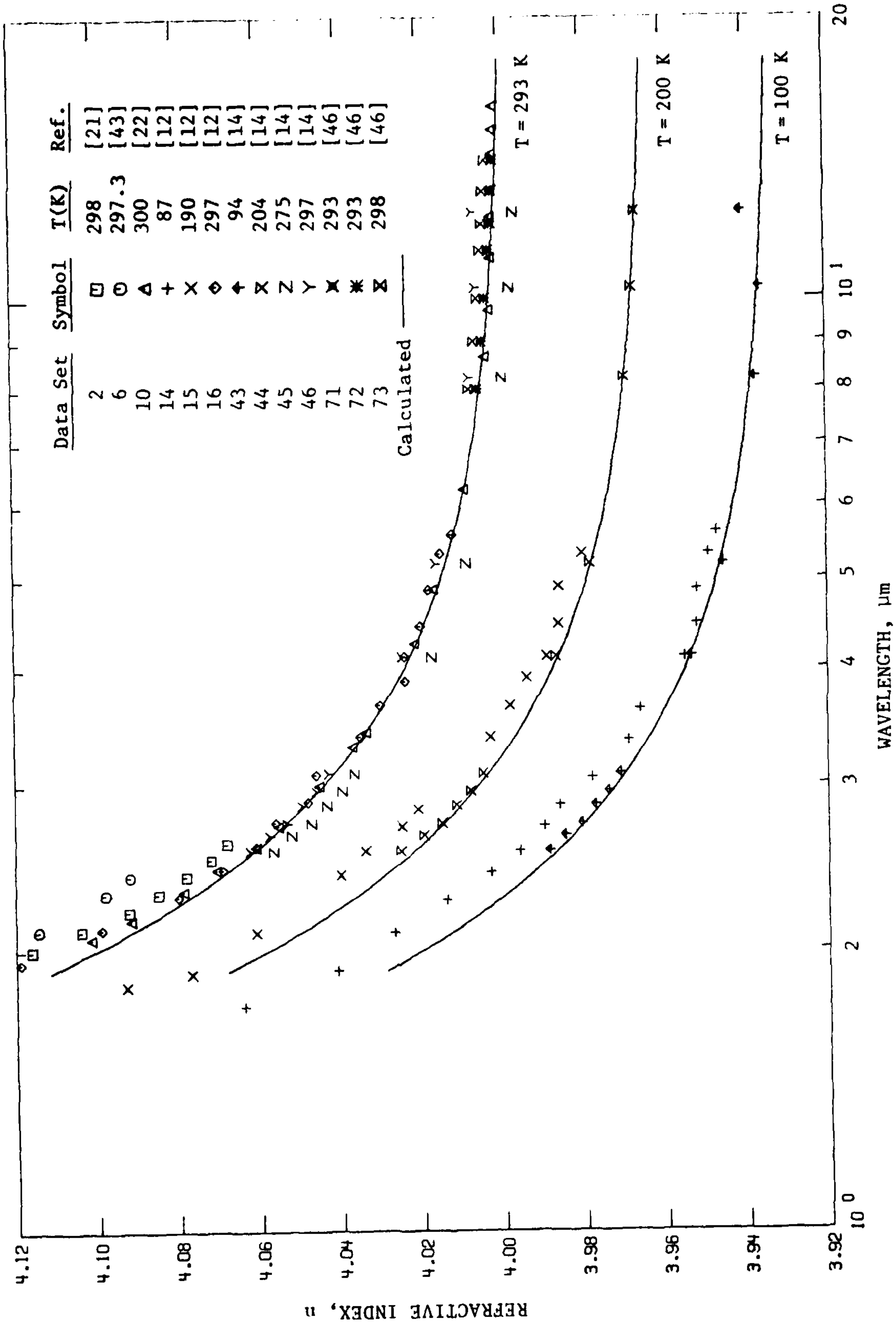

FIGURE 13. SELECTED EXPERIMENTAL REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)

that the refractive indices of pure germanium thin films tend to agree with those of bulk crystal if the films are deposited on substrates maintained at elevated temperatures during the course of deposition or appropriately annealed after deposition. Surface contamination appears to be the most serious problem. However, data for thin films reported by those who exercised precaution in sample preparation are usually in agreement with those for bulk material.

Literature data on the temperature derivative of the refractive index of germanium is rather scarce. The data tabulated in tables A-7 and A-8 and plotted in figures 14 and 15 are mainly those of Lukes [44,66,67]. His dn/dT values were evaluated from his measurements of n given in table A-6 and figure 12.

Although considerable amount of experimental data on the refractive index of germanium are available, they have received little analysis. The earliest quantitative results for germanium are generally attributed to Brattain and Briggs [49]. While they presented no dispersion relations in their work, they noted that their results were extremely sensitive to specimen preparation and that large discrepancies arose between samples.

The first qualitacive attempt was made by Rank et al. [43], who fitted a Cauchy type dispersion relation of the form

$$n = n_o + \frac{a}{\lambda^2} + \frac{b}{\lambda^4} \tag{25}$$

where λ is in units of μm. They presented results for fits on both their own data and for the Brattain and Briggs data with the following constants:

Data	n_o	a	b
RBC [43]	4.0385	0.21345	0.5363
BB [49]	3.9992	0.44647	0.6882

While this relation represented well each of the data sets, the authors found discrepancy between the two data sets as indicated by the coefficients.

The next dispersion relation was advanced by Hertzberger and Salzberg [40] which they developed using data for 13 materials in addition to germanium. They noted that comparisons of the data for 14 different materials indicated that all had refractive indices varying asymptotically with λ^2. They found the mean asymptote of all the materials in the UV region to be at $\lambda_o = 0.168$ μm.

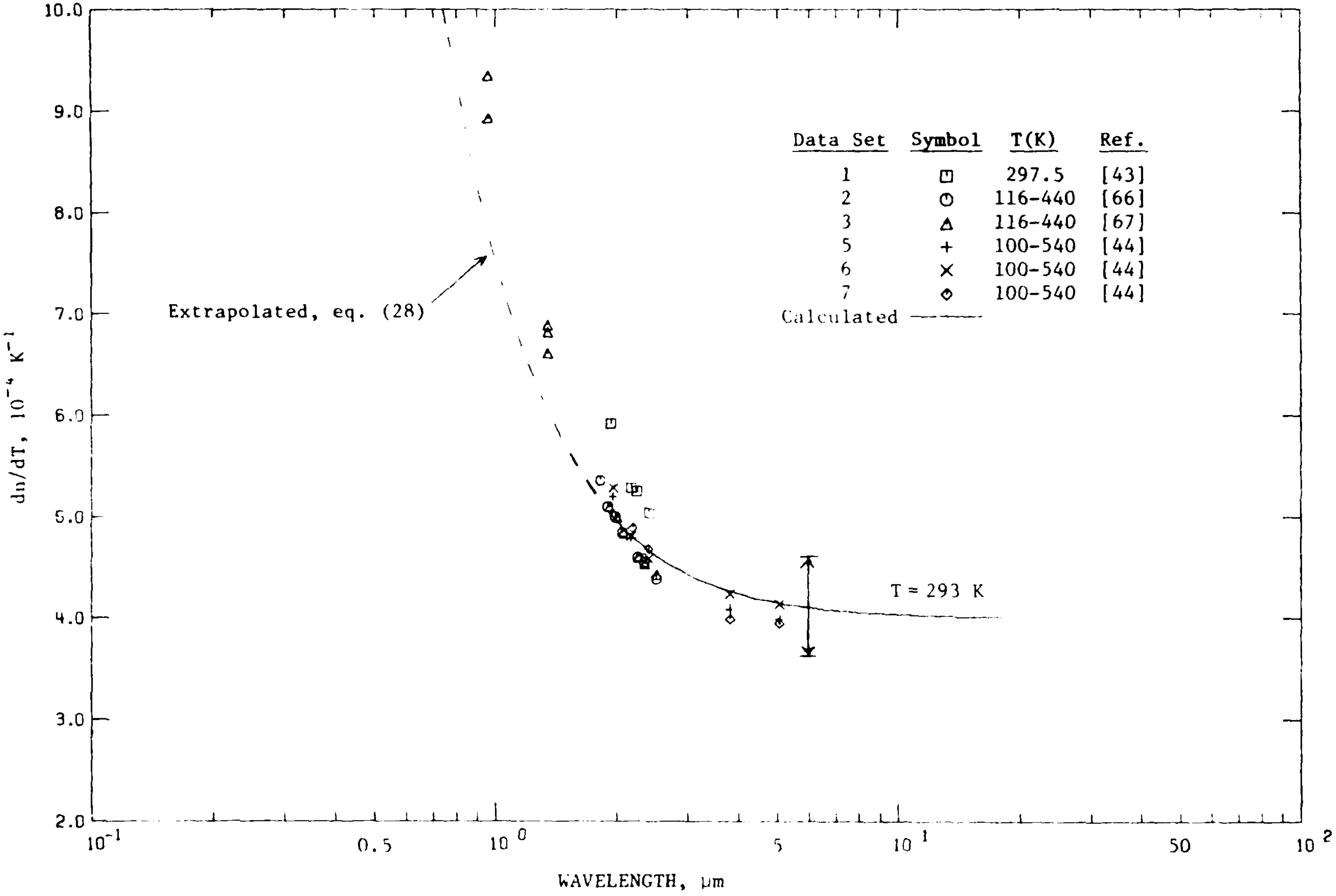

FIGURE 14. AVAILABLE EXPERIMENTAL dn/dT OF GERMANIUM (Wavelength Dependence)

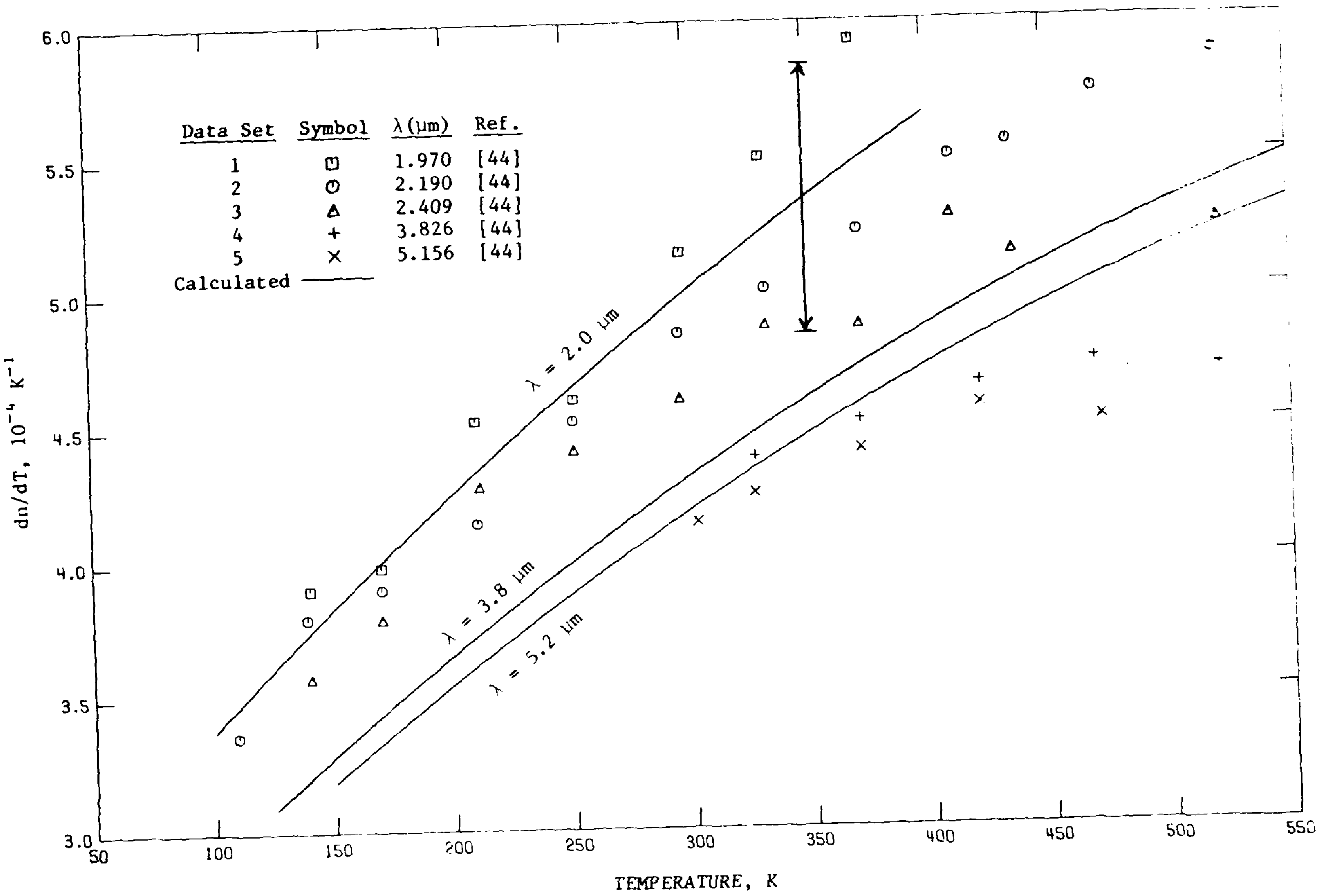

FIGURE 15. AVAILABLE EXPERIMENTAL dn/dT OF GERMANIUM (Temperature Dependence)

Their dispersion relation is based upon a Taylor expansion in λ^2 which retains only the linear terms. The form is

$$n = A + BL + CL^2 + D\lambda^2 + E\lambda^4 \tag{26}$$

where λ is in units of μm, $L = 1/(\lambda^2 - \lambda_0^2)$, and the coefficients for the region 2.0 to 13.5 μm are:

$A = 3.99931$
$B = 0.391707$
$C = 0.163492$
$D = -0.0000060$
$E = 0.000000053$

These results agree very well with the data from which they are derived.

In the present work, eq. (10) was used to represent the refractive index of germanium. The main task was the selection of the reliable data sets, the appropriate parameters ϵ and λ_1, and the determination of the coefficients A and B. The data reported by Cardona et al. and Lukes were not used on the grounds that their values in our collection were read from the graphs in their papers. We have found that deviations between the graph readings and the true values were quite large, estimated at 1 to 2 percent. Values reported by Rank et al. (after correcting from vacuum values to air values) appear to be relatively too high compared with those of Briggs and Salzberg and Villa in the corresponding wavelength region, 2.0-2.4 μm.

Although germanium has long been an important infrared material, its refractive index in the long wavelength region has not been well defined. Results from different workers often differ by as much as 0.003. Such a large discrepancy cannot be accounted for by merely experimental errors. Unknown impurities in some of the samples are probably responsible for the differences. However, this very important information is generally missing from the papers. As a result, the current knowledge of the refractive index of germanium still remains uncertain. Results of Edwin et al. [46] and Icenogle et al. [14] are uniformly higher than those of Salzberg and Villa [22] in the long wavelength region. Spitzer and Fan [52] observed that the refractive index of an impure sample in the long wavelength region is lower than that of a purer specimen. According to this, it would seem that Salzberg and Villa had more impurities in their specimen than did Edwin and Icenogle. This is not the case, however, as the above mentioned data sets are essentially parallel in the long wavelength region while Spitzer and Fan's results indicate a progressively decreasing n with increasing wavelength (see figures 1 and 11). Based on this consideration, the selected data sets were given equal weight. Fortunately, data by Icenogle et al. cover a sizable temperature range, permitting the prediction of n at temperatures other than room temperature.

Selection of ε and λ_1 presented some difficulties. Cardona et al. [12] observed the relative changes of refractive index, $\Delta n/n$, at a wavelength of 3 µm as temperature varied from 77 to 400 K with results plotted in figure 16. The average slope, $(1/n)(dn/dT)$, of this plot is $(6.9 \pm 0.4) \times 10^{-5} K^{-1}$. Icenogle et al. obtained a higher value of $9.9 \times 10^{-5} K^{-1}$ for $(1/n)(dn/dT)$ in the wavelength range 2.554 to 12.1 µm. It appeared that ε in eq. (10) could be determined from the relation $(1/\varepsilon)(d\varepsilon/dT) = (2/n)(dn/dT)$ using the value of $(1/n)(dn/dT)$ at long wavelengths. The result would be an exponential relation of the form $\varepsilon = \varepsilon_0 e^{cT}$. However, the constancy of $(1/n)(dn/dT)$ does not hold for a wide temperature range. Hence, an empirical relation between ε and T should be found based on available data of n.

It is shown in figure 12 that curves of temperature dependence of refractive index at various wavelengths are essentially parallel to each other and that each of them smoothly and monotonically increases with temperature. This provides a possibility to find a relation between ε and T. As ε closely equals n^2 at long wavelengths, the best choice in the present case is the refractive indices at 10.27 µm by Icenogle et al. [14]. However, their results cover only a temperature range from 100 to 298 K. A wider temperature coverage is required to establish a relation between ε and T that is reliable over the temperature region 100-550 K of general interest. As shown in figure 12, the 5.156 µm curve of Lukes [44] is slightly above and parallel to the extension made from the 10.27 µm curve. The needed refractive indices at 10.27 µm in the higher temperature region was therefore obtained by appropriate extrapolation of Icenogle's data in that region. In this way, the following polynomial equation is found to be valid at 10.27 µm and over 100-550 K:

$$n^2(10.27\ \mu m, T) = 15.3122 + 1.4571 \times 10^{-3} T + 3.5131 \times 10^{-6} T^2 - 1.2089 \times 10^{-9} T^3 \qquad (27)$$

Since at long wavelengths the dielectric constant closely approaches but does not exactly equal n^2, it is therefore appropriate to consider the above quantity as a proportional factor and the dielectric constant is expressed as:

$$\varepsilon(T) = E\, n^2\ (10.27\ \mu m, T)$$

where E is the proportional constant.

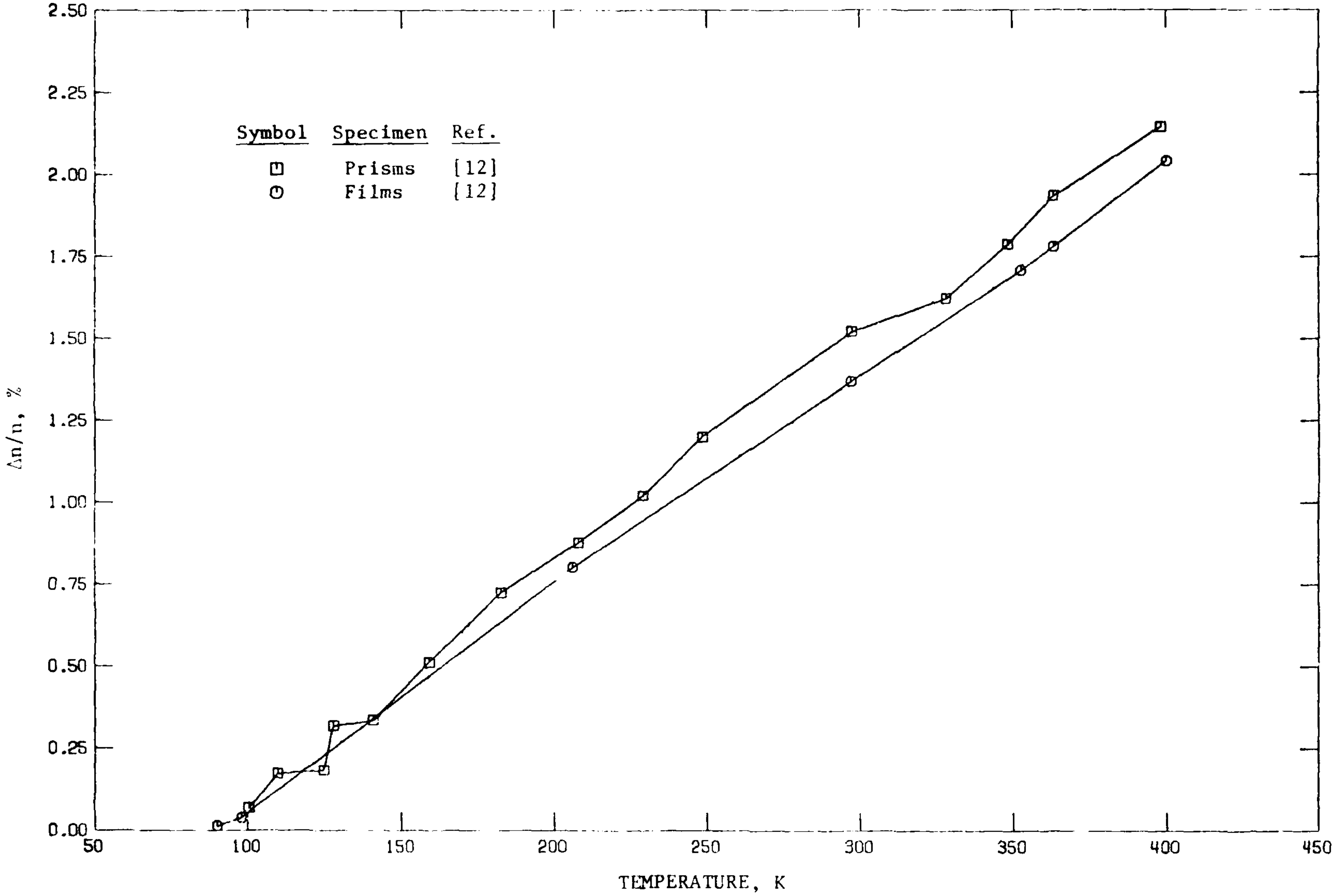

FIGURE 16. VARIATION OF REFRACTIVE INDEX OF GERMANIUM WITH TEMPERATURE AT WAVELENGTH 3 μm [12]

Spectral positions of natural absorption peaks in germanium have been studied by a number of investigators. McLean [3] investigated the absorption edge spectrum of germanium and found the optical energy gap at 300 K to be $E_g = 0.663$ eV or $\lambda_1 = 1.8703$ μm. Macfarlane et al. [16] further studied the absorption edge spectrum and found the temperature variation of the optical energy gap is essentially linear in the temperature range 200-300 K, but nonlinearity progressively predominates at lower temperatures as shown in figure 17. Lukes and Schmidt [18] studied the reflectivity spectrum of germanium and found two additional absorption peaks at $\lambda_2 \sim 0.589$ μm and $\lambda_3 \sim 0.282$ μm. The latter corresponds to that predicted by Yu and Cardona [42]. As a summary of these findings, one now has three absorption peaks; namely: $\lambda_1 = 1.8703$ μm, $\lambda_2 \sim 0.589$ μm, and $\lambda_3 \sim 0.282$ μm that are supposed to have significant effects on the refractive index in the transparent region, 1.9-16 μm.

In this work, the selected data were fitted to an equation similar to eq. (10) by including extra terms due to λ_2 and λ_3. It was found, however, that introduction of the λ_2 and λ_3 terms did not improve the agreement obtained when only the λ_1 term was included. Furthermore, the coefficients of the λ_2 and λ_3 terms could not be uniquely defined because there were no reliable data in the regions bounded by and near the three peak wavelengths. Also, the value of B was found to be negligibly low and hence the contribution of the last term in eq. (10) was insignificant. As a consequence, eq. (18) was adopted and the least squares fitting of selected data to this equation yielded the following expression for the refractive index of germanium in the ranges of 1.9 to 18 μm and 100-550 K:

$$n^2(\lambda,T) = \varepsilon(T) + \frac{L(T)}{\lambda^2}(A_0 + A_1T + A_2T^2) \tag{28}$$

where

$\varepsilon(T) = 15.2892 + 1.4549 \times 10^{-3}T + 3.5078 \times 10^{-6}T^2 - 1.2071 \times 10^{-9}T^3$

$L(T) = e^{-3\Delta L(T)/L_{293}}$

λ = wavelength in units of μm,

T = temperature in units of K,

$A_0 = 2.5381$,

$A_1 = 1.8260 \times 10^{-3}$,

$A_3 = 2.8888 \times 10^{-6}$,

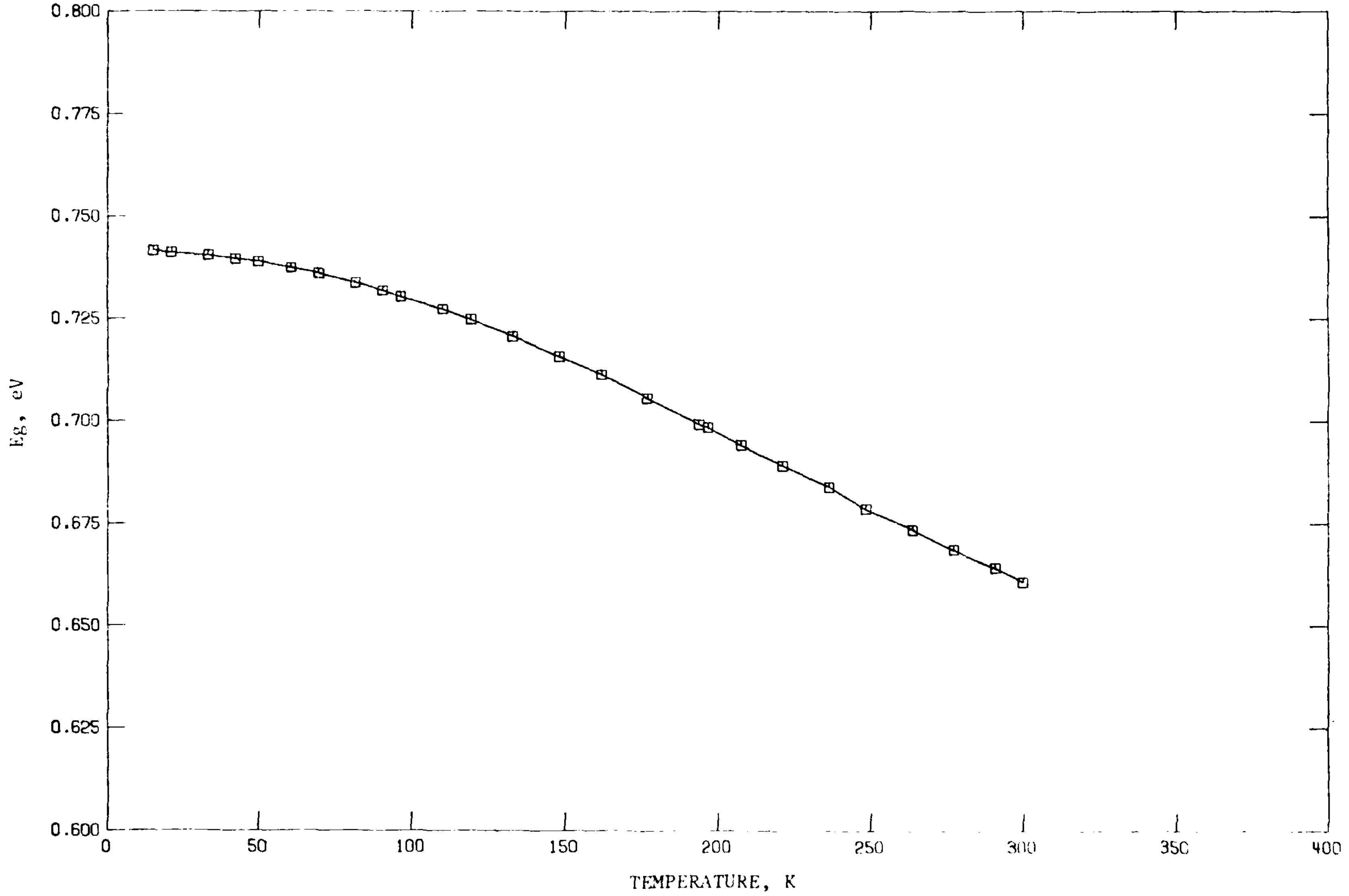

FIGURE 17. TEMPERATURE DEPENDENCE OF THE OPTICAL ENERGY GAP OF GERMANIUM [16]

and from reference [18]

$$\frac{\Delta L(T)}{L_{293}} = \begin{cases} -0.089 + 2.626 \times 10^{-6}(T-100) + 1.463 \times 10^{-8}(T-100)^2 - \\ \quad 2.221 \times 10^{-11}(T-100)^3 & (100 < T < 293) \\ 5.790 \times 10^{-6}(T-293) + 1.768 \times 10^{-9}(T-293)^2 - \\ \quad 4.562 \times 10^{-13}(T-293)^3 & (293 < T < 1200). \end{cases}$$

It is interesting to point out that the room temperature dielectric constant for germanium can now be calculated from the expression of ε in eq. (28). The result is 16.009 which is in good agreement with the commonly accepted value of 16.0.

Equation (28) was used to calculate the recommended values of the refractive index of germanium with uncertainties of $\pm 2 \times 10^{-3}$. The recommended values are given in table 6 and plotted in figure 18. To provide a visual comparison of the calculated values with experimental data, calculated values at a few specified temperatures and wavelengths are plotted in figures 12 and 13 where close agreement is revealed. Tables 7 and 8, respectively, give the calculated dn/dT and $dn/d\lambda$ values based on the first derivatives of eq. (28) with respect to T and λ. The corresponding plots are shown in figures 19 and 20.

Uncertainties in the calculated dn/dT values are estimated based on Icenogle's data [14] which are essentially the basis for eq. (28). Icenogle et al. evaluated $\Delta n/\Delta T$ values using their own measurements of n and found the average uncertainty in $\Delta n/\Delta T$ to be about $\pm 0.5 \times 10^{-4} K^{-1}$. Error bars corresponding to this amount are drawn on the calculated curves in figures 14 and 15 where calculated results are compared with experimental data. Although accuracies of experimental dn/dT are not available in Lukes' work [44,46,67], it is reasonable to use the same error bar as the experimental errors because the n versus T curves in figure 12 are closely parallel.

Uncertainties in the calculated $dn/d\lambda$ are estimated from the expression:

$$\delta(dn/d\lambda) \simeq \pm 2\,\delta n/\lambda$$

as discussed in subsection 3.1. Similar to the case of silicon, the uncertainties in $dn/d\lambda$ of germanium are about $\pm 5 \times 10^{-4}\ \mu m^{-1}$ at 2.55 μm, $1.2 \times 10^{-4}\ \mu m^{-1}$ at 10 μm, and $0.7 \times 10^{-4}\ \mu m^{-1}$ at 18 μm.

It should be noted that calculated values in tables 6, 7, and 8 are given with more decimal places than warranted for the purpose of tabular smoothness

TABLE 6. RECOMMENDED VALUES ON THE REFRACTIVE INDEX OF GERMANIUM*

λ, µm	TEMPERATURE, K									
	100	150	200	250	293	350	400	450	500	550
1.90	4.0290	4.0474	4.0680	4.0907	4.1117	4.1417	4.1697	4.1993	4.2302	4.2623
1.92	4.0270	4.0453	4.0659	4.0885	4.1094	4.1393	4.1672	4.1966	4.2274	4.2593
1.94	4.0251	4.0433	4.0638	4.0863	4.1072	4.1369	4.1647	4.1940	4.2246	4.2565
1.96	4.0232	4.0414	4.0618	4.0842	4.1050	4.1346	4.1623	4.1915	4.2220	4.2537
1.98	4.0214	4.0395	4.0598	4.0822	4.1029	4.1324	4.1599	4.1890	4.2194	4.2510
2.00	4.0197	4.0377	4.0579	4.0802	4.1008	4.1302	4.1577	4.1866	4.2169	4.2484
2.05	4.0156	4.0334	4.0534	4.0755	4.0959	4.1250	4.1523	4.1810	4.2110	4.2421
2.10	4.0117	4.0294	4.0493	4.0711	4.0914	4.1202	4.1472	4.1757	4.2054	4.2363
2.15	4.0081	4.0257	4.0454	4.0670	4.0872	4.1158	4.1426	4.1708	4.2003	4.2309
2.20	4.0048	4.0222	4.0417	4.0632	4.0832	4.1116	4.1382	4.1662	4.1954	4.2259
2.25	4.0017	4.0190	4.0383	4.0597	4.0795	4.1077	4.1341	4.1619	4.1909	4.2211
2.30	3.9987	4.0159	4.0352	4.0564	4.0761	4.1041	4.1303	4.1579	4.1867	4.2167
2.40	3.9934	4.0104	4.0294	4.0503	4.0698	4.0974	4.1233	4.1506	4.1791	4.2087
2.50	3.9887	4.0055	4.0243	4.0450	4.0642	4.0916	4.1172	4.1441	4.1723	4.2015
2.60	3.9845	4.0011	4.0197	4.0402	4.0593	4.0864	4.1117	4.1384	4.1663	4.1952
2.70	3.9808	3.9972	4.0157	4.0360	4.0549	4.0817	4.1068	4.1333	4.1609	4.1896
2.80	3.9775	3.9938	4.0121	4.0322	4.0509	4.0776	4.1025	4.1287	4.1561	4.1845
2.90	3.9745	3.9907	4.0088	4.0288	4.0474	4.0738	4.0985	4.1246	4.1518	4.1800
3.00	3.9718	3.9878	4.0059	4.0257	4.0442	4.0704	4.0950	4.1209	4.1479	4.1759
3.20	3.9671	3.9830	4.0008	4.0204	4.0387	4.0646	4.0889	4.1144	4.1411	4.1688
3.40	3.9632	3.9789	3.9966	4.0160	4.0341	4.0598	4.0838	4.1091	4.1355	4.1629
3.60	3.9600	3.9755	3.9930	4.0123	4.0302	4.0557	4.0795	4.1046	4.1308	4.1580
3.80	3.9572	3.9727	3.9900	4.0092	4.0270	4.0523	4.0759	4.1008	4.1268	4.1538
4.00	3.9549	3.9702	3.9875	4.0065	4.0242	4.0493	4.0728	4.0976	4.1234	4.1502
4.25	3.9524	3.9676	3.9848	4.0037	4.0212	4.0462	4.0696	4.0942	4.1198	4.1464
4.50	3.9503	3.9655	3.9825	4.0013	4.0188	4.0436	4.0668	4.0913	4.1168	4.1433
4.75	3.9485	3.9636	3.9806	3.9993	4.0167	4.0414	4.0645	4.0888	4.1142	4.1406
5.00	3.9470	3.9620	3.9789	3.9976	4.0149	4.0395	4.0625	4.0868	4.1121	4.1383
5.50	3.9446	3.9595	3.9763	3.9948	4.0120	4.0365	4.0594	4.0834	4.1086	4.1346
6.00	3.9428	3.9576	3.9743	3.9927	4.0098	4.0342	4.0569	4.0809	4.1059	4.1318
6.50	3.9413	3.9561	3.9727	3.9911	4.0081	4.0324	4.0550	4.0789	4.1038	4.1296
7.00	3.9402	3.9549	3.9715	3.9898	4.0068	4.0309	4.0536	4.0773	4.1021	4.1279
8.00	3.9385	3.9532	3.9697	3.9879	4.0048	4.0289	4.0514	4.0750	4.0997	4.1253
9.00	3.9374	3.9520	3.9684	3.9866	4.0034	4.0274	4.0498	4.0734	4.0981	4.1236
10.00	3.9365	3.9511	3.9675	3.9856	4.0025	4.0264	4.0488	4.0723	4.0969	4.1223
11.00	3.9359	3.9505	3.9669	3.9849	4.0017	4.0256	4.0480	4.0715	4.0960	4.1214
12.00	3.9355	3.9500	3.9664	3.9844	4.0012	4.0250	4.0474	4.0708	4.0953	4.1207
13.00	3.9351	3.9496	3.9660	3.9840	4.0008	4.0246	4.0469	4.0703	4.0948	4.1202
14.00	3.9348	3.9493	3.9657	3.9837	4.0004	4.0242	4.0465	4.0699	4.0944	4.1197
15.00	3.9346	3.9491	3.9654	3.9834	4.0001	4.0240	4.0462	4.0696	4.0941	4.1194
16.00	3.9344	3.9489	3.9652	3.9832	3.9999	4.0237	4.0460	4.0694	4.0938	4.1191
17.00	3.9342	3.9487	3.9650	3.9830	3.9997	4.0235	4.0458	4.0691	4.0936	4.1188
18.00	3.9341	3.9486	3.9649	3.9829	3.9996	4.0234	4.0456	4.0690	4.0934	4.1186

* IN THIS TABLE MORE DECIMAL PLACES ARE REPORTED THAN WARRANTED MERELY FOR THE PURPOSE OF TABULAR SMOOTHNESS AND INTERNAL COMPARISON. THE NUMBER OF DIGITS WITH AN OVERSTRIKE ARE NOT RELEVANT TO ACCURACY OF THE DATA.

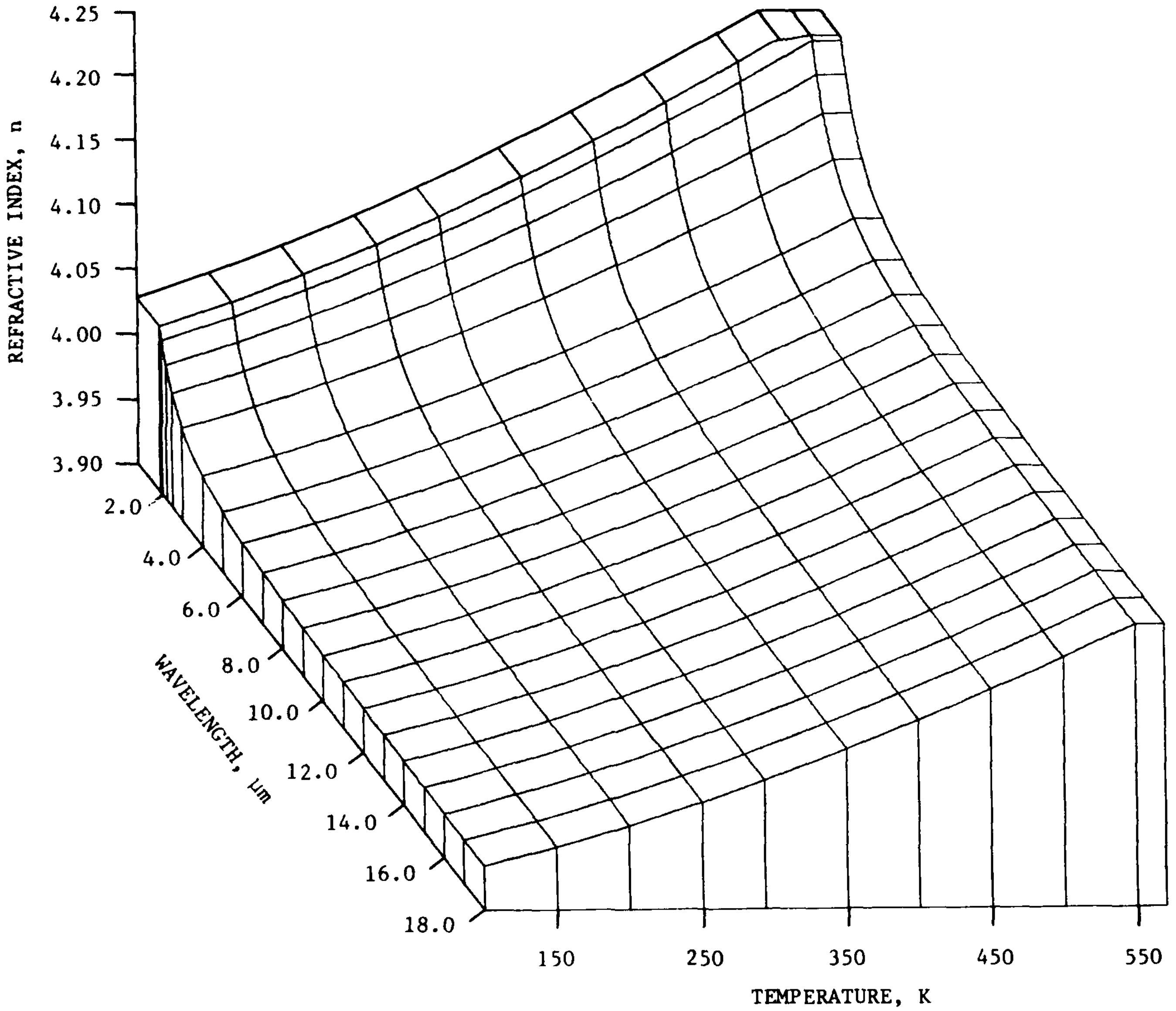

FIGURE 18. RECOMMENDED n-λ-T DIAGRAM OF GERMANIUM

TABLE 7. RECOMMENDED VALUES ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF GERMANIUM*

λ, µm	TEMPERATURE, K									
	100	150	200	250	293	350	400	450	500	550
1.90	3.452	3.909	4.337	4.736	5.057	5.450	5.764	6.050	6.307	6.538
1.92	3.437	3.892	4.318	4.716	5.036	5.427	5.739	6.024	6.280	6.510
1.94	3.422	3.875	4.300	4.696	5.015	5.404	5.716	5.999	6.254	6.482
1.96	3.408	3.859	4.283	4.678	4.995	5.383	5.693	5.974	6.228	6.455
1.98	3.394	3.844	4.266	4.659	4.975	5.362	5.670	5.951	6.204	6.429
2.00	3.380	3.829	4.249	4.642	4.956	5.341	5.649	5.928	6.179	6.404
2.05	3.348	3.793	4.210	4.599	4.911	5.293	5.597	5.873	6.122	6.344
2.10	3.318	3.760	4.174	4.560	4.869	5.248	5.549	5.823	6.069	6.288
2.15	3.290	3.729	4.140	4.523	4.830	5.205	5.504	5.775	6.019	6.236
2.20	3.263	3.700	4.108	4.489	4.794	5.166	5.462	5.731	5.972	6.187
2.25	3.239	3.673	4.079	4.457	4.760	5.129	5.423	5.689	5.929	6.141
2.30	3.216	3.647	4.051	4.427	4.728	5.094	5.386	5.651	5.888	6.098
2.40	3.174	3.601	4.001	4.372	4.669	5.032	5.319	5.580	5.813	6.020
2.50	3.137	3.560	3.956	4.324	4.618	4.976	5.260	5.517	5.748	5.951
2.60	3.104	3.524	3.916	4.281	4.572	4.926	5.208	5.462	5.689	5.890
2.70	3.075	3.492	3.881	4.242	4.531	4.882	5.161	5.412	5.637	5.835
2.80	3.048	3.462	3.849	4.208	4.494	4.842	5.119	5.367	5.590	5.786
2.90	3.025	3.436	3.820	4.177	4.461	4.807	5.081	5.327	5.547	5.741
3.00	3.003	3.413	3.795	4.149	4.431	4.775	5.046	5.291	5.509	5.701
3.20	2.966	3.372	3.750	4.100	4.380	4.719	4.987	5.228	5.443	5.632
3.40	2.936	3.338	3.713	4.060	4.337	4.673	4.938	5.176	5.388	5.575
3.60	2.910	3.309	3.682	4.026	4.301	4.634	4.896	5.133	5.342	5.526
3.80	2.888	3.285	3.655	3.998	4.270	4.601	4.861	5.095	5.303	5.485
4.00	2.869	3.265	3.633	3.973	4.244	4.572	4.831	5.064	5.270	5.450
4.25	2.850	3.243	3.609	3.947	4.217	4.543	4.800	5.030	5.234	5.413
4.50	2.833	3.225	3.589	3.926	4.193	4.518	4.773	5.002	5.205	5.382
4.75	2.819	3.209	3.572	3.907	4.174	4.496	4.750	4.978	5.179	5.355
5.00	2.807	3.196	3.557	3.891	4.157	4.478	4.731	4.958	5.158	5.333
5.50	2.788	3.174	3.534	3.866	4.130	4.449	4.700	4.925	5.123	5.296
6.00	2.773	3.158	3.516	3.847	4.110	4.427	4.677	4.900	5.097	5.269
6.50	2.762	3.146	3.502	3.832	4.094	4.410	4.658	4.880	5.076	5.247
7.00	2.752	3.136	3.491	3.820	4.081	4.396	4.644	4.865	5.060	5.230
8.00	2.739	3.121	3.475	3.803	4.062	4.376	4.622	4.842	5.036	5.205
9.00	2.730	3.111	3.464	3.791	4.049	4.362	4.607	4.827	5.020	5.188
10.00	2.723	3.103	3.456	3.782	4.040	4.352	4.597	4.815	5.008	5.175
11.00	2.719	3.098	3.450	3.776	4.033	4.345	4.589	4.807	4.999	5.166
12.00	2.715	3.094	3.446	3.771	4.028	4.339	4.583	4.801	4.993	5.159
13.00	2.712	3.091	3.443	3.767	4.024	4.335	4.578	4.796	4.988	5.154
14.00	2.710	3.088	3.440	3.764	4.021	4.331	4.575	4.792	4.983	5.150
15.00	2.708	3.086	3.438	3.762	4.019	4.328	4.572	4.789	4.980	5.146
16.00	2.706	3.085	3.436	3.760	4.016	4.326	4.569	4.786	4.977	5.143
17.00	2.705	3.083	3.434	3.758	4.015	4.324	4.567	4.784	4.975	5.141
18.00	2.704	3.082	3.433	3.757	4.013	4.323	4.566	4.782	4.973	5.139

* IN THIS TABLE MORE DECIMAL PLACES ARE REPORTED THAN WARRANTED MERELY FOR THE PURPOSE OF TABULAR SMOOTHNESS AND INTERNAL COMPARISON. THE NUMBER OF DIGITS WITH AN OVERSTRIKE ARE NOT RELEVANT TO ACCURACY OF THE DATA.

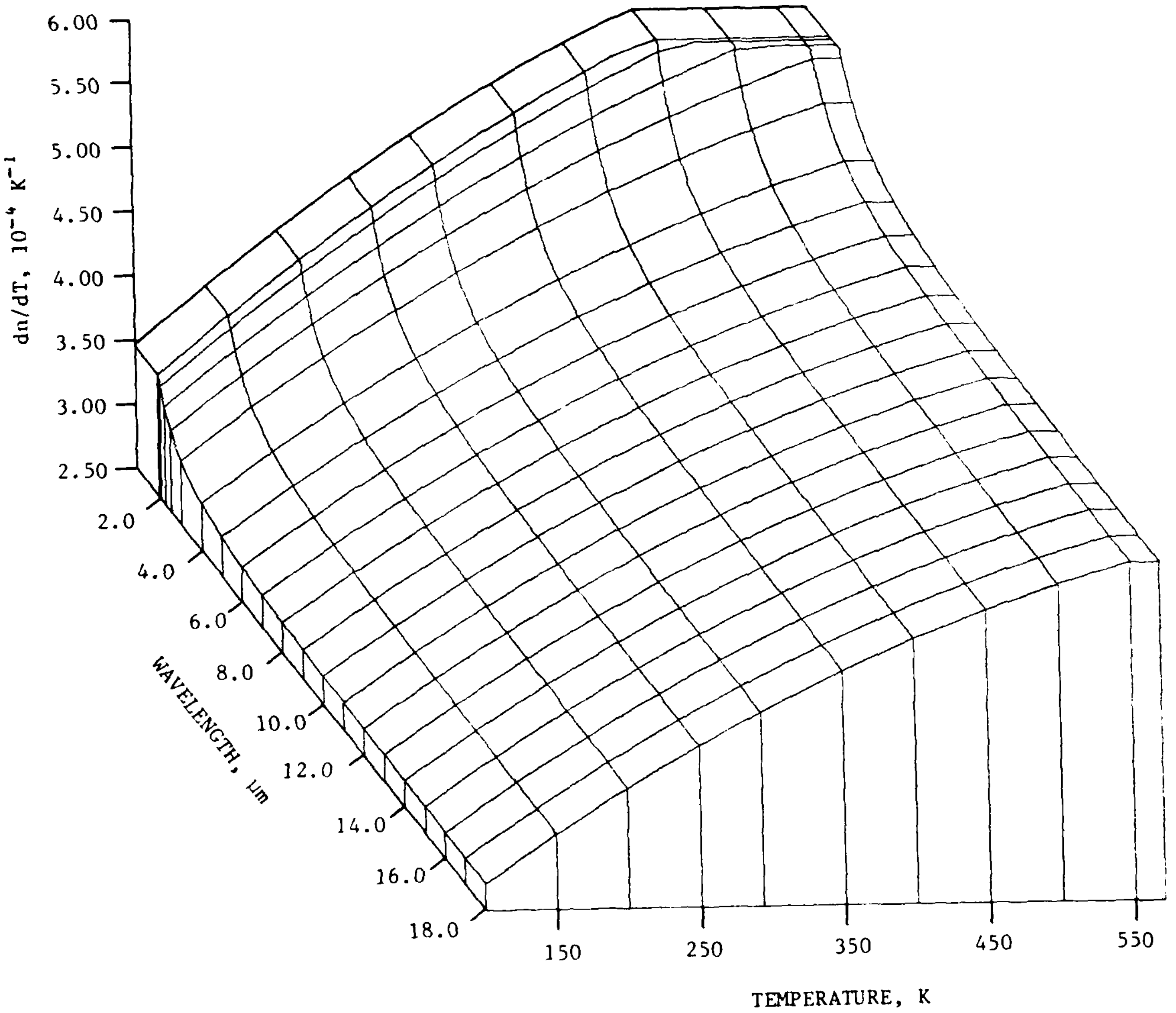

FIGURE 19. RECOMMENDED dn/dT-λ-T DIAGRAM OF GERMANIUM

TABLE 8. CALCULATED VALUES ON THE WAVELENGTH DERIVATIVE OF REFRACTIVE INDEX OF GERMANIUM AT 293K *

λ, μm	$-dn/d\lambda$, 10^{-4} μm^{-1}
1.90	117$\overline{7.6}$
1.92	114$\overline{1.8}$
1.94	110$\overline{7.5}$
1.96	107$\overline{4.5}$
1.98	104$\overline{2.8}$
2.00	101$\overline{2.3}$
2.05	94$\overline{1.2}$
2.10	87$\overline{6.5}$
2.15	81$\overline{7.6}$
2.20	76$\overline{3.9}$
2.25	71$\overline{4.7}$
2.30	66$\overline{9.7}$
2.40	590.$\overline{3}$
2.50	523.$\overline{0}$
2.60	465.$\overline{5}$
2.70	416.$\overline{1}$
2.80	373.$\overline{5}$
2.90	336.$\overline{5}$
3.00	304.$\overline{2}$
3.20	251.$\overline{0}$
3.40	209.$\overline{5}$
3.60	176.$\overline{6}$
3.80	150.$\overline{3}$
4.00	129.$\overline{0}$
4.25	107.$\overline{6}$
4.50	90.$\overline{7}$
4.75	77.$\overline{2}$
5.00	66.2
5.50	49.8
6.00	38.3
6.50	30.2
7.00	24.2
8.00	16.2
9.00	11.4
10.00	8.3
11.00	6.2
12.00	4.8
13.00	3.8
14.00	3.0
15.00	2.5
16.00	2.0
17.00	1.7
18.00	1.4

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* IN THIS TABLE MORE DECIMAL PLACES ARE REPORTED THAN WARRANTED MERELY FOR THE PURPOSE OF TABULAR SMOOTHNESS AND INTERNAL COMPARISON. THE NUMBER OF DIGITS WITH OVERSTIKE ARE NOT RELEVANT TO ACCURACY OF THE DATA.

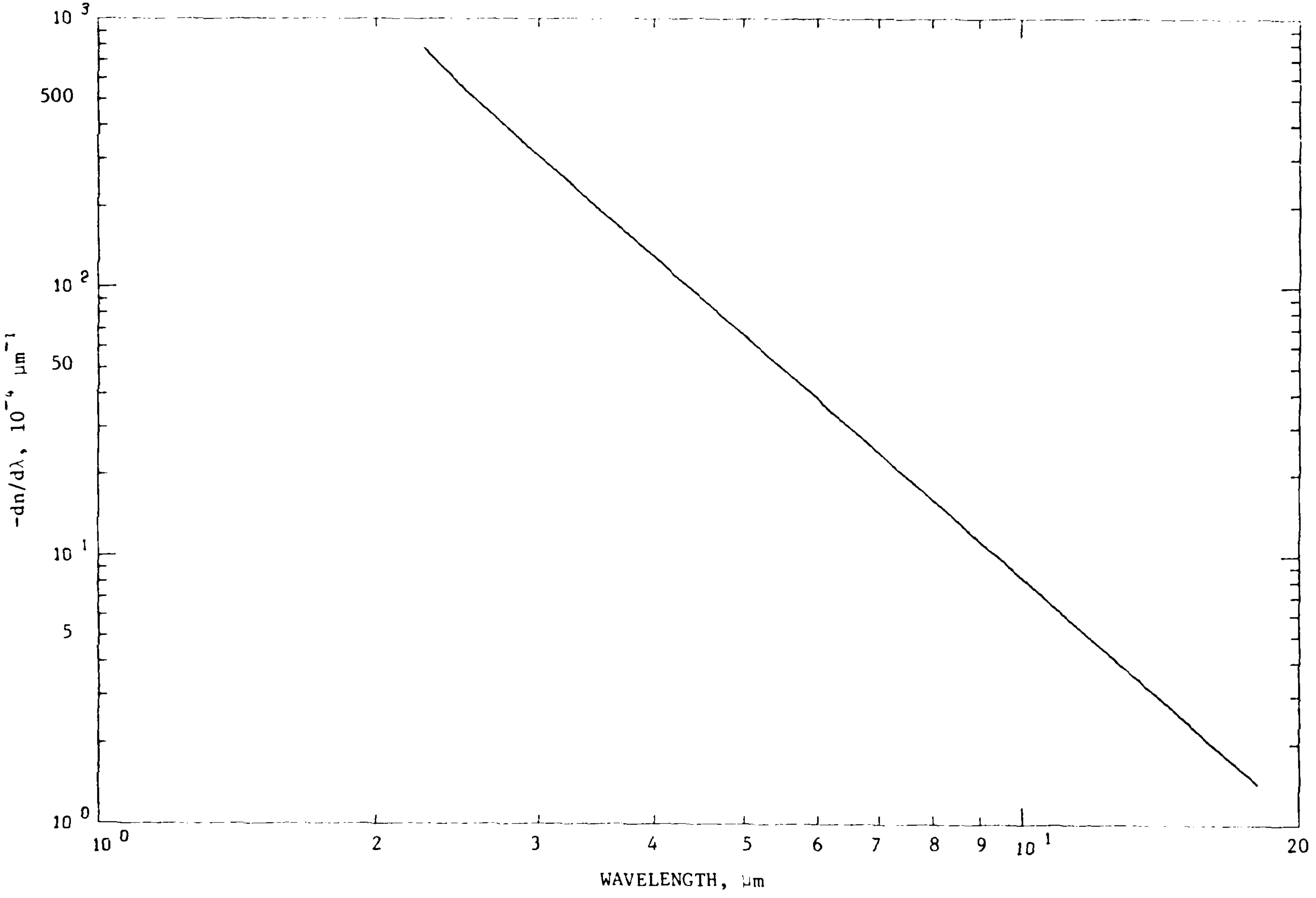

FIGURE 20. RECOMMENDED dn/dλ CURVE OF GERMANIUM AT 293 K

and internal comparison. They should not be considered as an indication of the accuracy of the values. To identify the unwarranted significant figures in the values, an overstrike is used.

4. CONCLUSIONS AND RECOMMENDATIONS

Experimental data on the refractive index of crystalline silicon and germanium and its temperature derivative were exhaustively surveyed and reviewed. Values of physical properties which are related to the dispersion equation were selected from the open literature. In addition, a number of thin film data sets were also compiled.

The purpose of the present work was to survey and compile the available data and to generate recommended values of the refractive index and its temperature derivative for crystalline silicon and germanium. Recommended values for these materials were generated based on currently available data. Since the state of the refractive index of either of the crystals have not been well defined, our recommendations should be considered at best representing average values of the selected data sets. Many factors are known to influence the accuracy of the refractive index of a crystal. Although the minimum deviation method is known to be the most accurate way to determine the refractive index, this is not true in the case of silicon and germanium. Being highly refractive, the prism specimens used must be thin, usually about 15° apex angle or sometimes lower, thus giving rise to relatively higher uncertainties. Other possible sources of experimental errors were discussed by Primak [24]. However, the most important factor which contributes to the total error is the impurity content of the specimen. Although this is a well known source of error, unfortunately, this very important piece of information is usually not reported. As a consequence, discrepancies among the currently available data cannot be reasonably resolved.

Unless one is satisfied with the existing data having uncertainties of a few parts in the third decimal place, serious considerations should be given to obtaining data reliable in the fourth or fifth decimal place. A systematic measurement program on the refractive index should be carried out with the following considerations:

1. Experimental method. Because the minimum deviation method does not yield high accuracy in the case of Si and Ge, it is strongly felt that the interference method should be used. In this method, the determination of interference order plays the decisive role in the accuracy of the results. In order to obtain high accuracy, thick plate specimens should be used.

2. Sample characterization. As the impurity content of the sample strongly affect the refractive index, the impurities in the sample should be ascertained and reported. Merely reporting the electrical resistivity of the sample is not adequate. The nature and amount of impurities should specifically be reported. In order to see the effects of impurities on the refractive index, measurement should be carried out for a group of specimens with systematically controlled impurities.

3. Environmental control. Since both silicon and germanium have high temperature coefficients of refractive index (in the order of $10^{-4}K^{-1}$), the temperature of the sample has to be carefully controlled in order to achieve the required accuracy. Pressure has little effect on the refractive index under ordinary conditions. The pressure coefficient of the refractive index of Ge at 297 K is $(1/n)(dn/dP) = -7 \pm 2 \times 10^{-7} kg^{-1} cm^2$ [12]. That of Si is $-3 \pm 2 \times 10^{-7} kg^{-1} cm^2$ [12].

In conclusion, it should be emphasized that the present work does not resolve the discrepancies between the available data sets, it simply recommends the most probable values of the refractive index that a pure crystal of Si and Ge may have with the quoted uncertainties. Also, it should be noted that, as in any statistical study of this type, the dispersion equations, eqs. (22) and (28), are valid to the reported accuracy only within the region of experimental data. In general, extrapolation of these equations for use outside of this region is invalid for quantitative results. Finally, the type of analysis presented here assumes the data to be an absolutely correct representation of the model at hand, which is not generally true since the model is an oversimplification of the true dispersion relation. However, for predictive purposes, based upon the experimental data from several authors, and within the usable region of the data, we believe that these equations are valid for calculation of the refractive index in the given wavelength and temperature regions.

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APPENDIX

The tables included in the Appendix are available experimental data compiled during the course of present work. The collected information covers the reported works in the last three decades from 1949 to 1978.

The tables give for each set of data the following information: the reference number, author's name (or names), year of publication, wavelength range, temperature range, the description and characterization of the specimen, and information on measurement conditions contained in the original paper.

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence)

[Temperature, T, K; Wavelength, λ, μm; Refractive Index, n]

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
1	(T=298 K)		Sample from a commercial Electromet melt with a purity of 99.8%; prismatic specimen of 11°24'11" angle; index of refraction measured by method of minimum deviation; data extracted from a table.	Briggs, H.B., 1949
[21]	1.05	3.565		
	1.10	3.553		
	1.20	3.531		
	1.40	3.499		
	1.60	3.480		
	1.80	3.466		
	2.00	3.458		
	2.20	3.451		
	2.40	3.447		
	2.60	3.443		
2	(T=298 K)		Polycyrstalline; $\rho \sim 0.7$ Ω-cm; impurities: 0.70% Fe, 0.55% Al, 0.32% Ca, 0.06% Ti, 0.05% Mn, 0.04% C, 0.04% Cr, 0.01% P, and traces of Cu, Ni and S; reflectances at 20 and 70 degree incidence angles obtained; refractive indices obtained by a graphical analysis; data taken from a figure.	Simon, I., 1951
[26]	4.145	1.416		
	4.952	1.467		
	6.203	1.700		
	7.193	2.007		
	8.305	2.260		
	9.967	2.840		
	12.565	3.056		
3	(T=299 K)		Single crystal; purity unknown; supplied by Texas Instruments, Inc., Dallas, TX; prism cut with faces 30 x 30 cm and refracting angle of 15.8°; index of refraction measured by autocollimation method; data with uncertainty ±2 in fourth decimal place taken from a table.	Salzberg, C.D. and Villa, J.J., 1957
[22]	1.3570	3.4975		
	1.3673	3.4962		
	1.3951	3.4929		
	1.5295	3.4795		
	1.6605	3.4696		
	1.7092	3.4664		
	1.8131	3.4608		
	1.9701	3.4537		
	2.1526	3.4476		
	2.3254	3.4430		
	2.4373	3.4408		
	2.7144	3.4356		
	3.00	3.4320		
	3.3033	3.4297		
	3.4188	3.4286		
	3.50	3.4284		
	4.00	3.4255		
	4.258	3.4242		
	4.50	3.4236		
	5.00	3.4223		
	5.50	3.4213		
	6.00	3.4202		
	6.50	3.4195		
	7.00	3.4189		
	7.50	3.4186		
	8.00	3.4184		
	8.50	3.4182		
	10.00	3.4179		
	10.50	3.4178		
	11.04	3.4176		
4	(T=100 K)		5° silicon prism mounted against a plane mirror; Abbe autocollimation method applied to measure the	Cardona, M., Paul, W., and Brooks, H., 1959
[12]	1.007	3.526		
	1.055	3.520		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
4(cont.)	1.134	3.504	deviation angle to within ±1'; data extracted from a figure.	Cardona, M., Paul, W., and Brooks, H., 1959
[12]	1.244	3.488		
	1.387	3.463		
	1.545	3.440		
	1.736	3.428		
	1.879	3.420		
	2.086	3.412		
	2.245	3.406		
	2.643	3.399		
	3.025	3.393		
	3.599	3.388		
	3.902	3.388		
	4.125	3.385		
	4.475	3.379		
	4.905	3.375		
5	(T=194 K)		5° silicon prism mounted against a plane mirror; Abbe autocollimation method applied to measure the deviation angle to within ±1'; data extracted from a figure.	Cardona, M., et al. 1959
[12]	1.166	3.516		
	1.229	3.506		
	1.372	3.477		
	1.530	3.460		
	1.752	3.439		
	1.896	3.433		
	2.086	3.425		
	2.246	3.419		
	2.596	3.411		
	3.026	3.408		
	3.329	3.404		
	3.567	3.401		
	3.902	3.400		
	4.093	3.397		
	4.460	3.394		
	4.890	3.391		
6	(T=298 K)		5° silicon prism mounted against a plane mirror; Abbe autocollimation method applied to measure the deviation angle to within ±1'; data extracted from a figure.	Cardona, M., et al. 1959.
[12]	1.230	3.519		
	1.340	3.497		
	1.547	3.474		
	1.737	3.458		
	1.896	3.449		
	2.055	3.440		
	2.246	3.434		
	2.405	3.429		
	2.596	3.426		
	3.026	3.420		
	3.568	3.415		
	3.871	3.414		
	4.094	3.414		
	4.460	3.411		
	4.891	3.412		
7	(T=298 K)		Crystal specimens; no details of source, sample preparation and measurement given; data read from a figure; temperature not given, 298 K assumed.	Runyan, W.R., 1960
[27]	1.375	3.497		
	1.437	3.492		
	1.449	3.487		
	1.487	3.483		
	1.512	3.479		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
7(cont.)	1.562	3.475		Runyan, W.R., 1960
[27]	1.612	3.471		
	1.687	3.467		
	1.737	3.464		
	1.787	3.461		
	1.850	3.458		
	1.912	3.455		
	2.000	3.451		
	2.088	3.448		
	2.214	3.445		
	2.352	3.441		
	2.477	3.439		
	2.628	3.437		
	2.792	3.435		
	2.943	3.433		
	3.081	3.432		
	3.257	3.430		
	3.408	3.429		
	3.622	3.427		
	3.811	3.426		
	4.088	3.425		
	4.340	3.424		
	4.617	3.423		
	4.957	3.422		
	5.309	3.421		
	5.624	3.421		
	5.977	3.420		
	6.342	3.420		
	6.795	3.419		
	7.186	3.419		
	7.715	3.418		
	8.143	3.418		
	8.508	3.418		
	8.848	3.418		
	9.113	3.418		
	9.339	3.418		
	9.679	3.418		
	10.032	3.418		
	10.347	3.418		
	10.574	3.418		
	10.989	3.418		
	11.040	3.418		
8	(T=300 K)		Single crystal; etched surfaces; near normal reflectance spectrum between 0.11 and 1.24 μm observed; phase angle computed using the Kramers-Kronig relation; optical constants determined from the Fresnel formulae; data taken from a figure.	Philipp, H.R. and Taft, E.A., 1960
[28]	0.124	0.332		
	0.128	0.414		
	0.138	0.409		
	0.150	0.488		
	0.165	0.524		
	0.174	0.564		
	0.187	0.687		
	0.207	0.978		
	0.217	1.187		
	0.227	1.397		
	0.229	1.524		
	0.237	1.607		
	0.240	1.606		
	0.247	1.521		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
8(cont.) [28]	0.257	1.646		Philipp, H.R. and Taft, E.A., 1960
	0.267	1.941		
	0.269	2.322		
	0.277	2.913		
	0.283	3.421		
	0.283	4.182		
	0.295	4.731		
	0.301	4.815		
	0.307	4.857		
	0.314	4.941		
	0.328	4.982		
	0.335	5.108		
	0.335	5.235		
	0.343	5.573		
	0.343	5.954		
	0.344	6.420		
	0.352	6.800		
	0.357	6.884		
	0.370	6.291		
	0.388	5.443		
	0.398	5.019		
	0.409	4.765		
	0.427	4.594		
	0.439	4.424		
	0.460	4.254		
	0.474	4.169		
	0.498	4.041		
	0.544	3.912		
	0.587	3.784		
	0.666	3.697		
	0.750	3.611		
	0.859	3.567		
9 [29]	(T=298 K)		Single crystal; ellipsometry method used to determine refractive index; the effect of oxidized film on silicon corrected; error in refractive index about ±0.007.	Archer, R.A., 1962
	0.5461	4.050		
10 [30]	(T=298 K)		n-type, phosphorus doped silicon samples; carrier concentration N = 7.5 x 10^{19} cm^{-3}; polished; refractive index derived from reflectivity measurements; data taken from a figure.	Spitzer, W.G., Gobeli, G.W., and Trumbore, F.A., 1964
	3.456	3.007		
	4.458	2.654		
	5.210	2.345		
	5.555	2.155		
	5.963	1.973		
	6.370	1.764		
	6.715	1.588		
	7.153	1.443		
	7.748	1.266		
	8.436	1.172		
11 [30]	(T=298 K)		n-type, phosphorus doped silicon silicon samples; carrier concentration N = 7.5 x 10^{19} cm^{-3}; polished; specimen heated at 1310 K for 30 sec in a vacuum of ≤1 x 10^{-7} torr; refractive index derived from reflectivity	Spitzer, W.G., et al., 1964
	3.456	2.943		
	4.459	2.584		
	5.179	2.288		
	5.618	2.111		
	5.963	1.922		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
11(cont.) [30]	6.371	1.701	measurements; data taken from a figure.	Spitzer, W.G., Gobeli, G.W., and Trumbore, F.A., 1964
	6.778	1.550		
	7.154	1.361		
	7.436	1.265		
	7.749	1.191		
	8.468	1.084		
12 [30]	(T=298 K)		n-type, phosphorus doped silicon samples; carrier concentration N = 7.5×10^{19} cm^{-3}; polished; specimen heated at 1310 K for 60 sec in a vacuum of $\leq 1 \times 10^{-7}$ Torr; refractive index derived from reflectivity measurements; data taken from a figure.	Spitzer, W.G., et al., 1964
	3.425	2.937		
	4.459	2.590		
	5.179	2.288		
	5.587	2.111		
	5.963	1.909		
	6.370	1.714		
	7.123	1.380		
	7.436	1.291		
	7.749	1.216		
	8.499	1.109		
13 [30]	(T=298 K)		n-type, phosphorus doped silicon samples: carrier concentration N = 7.5×10^{19} cm^{-3}; polished; specimen heated at 1310 K for 90 sec in a vacuum of $\leq 1 \times 10^{-7}$ Torr; refractive index derived from reflectivity measurements; data taken from a figure.	Spitzer, W.G., et al., 1964
	3.456	3.000		
	4.459	2.559		
	5.179	2.269		
	5.587	2.080		
	5.963	1.878		
	6.371	1.676		
	6.716	1.481		
	7.154	1.323		
	7.436	1.222		
	7.718	1.146		
	8.469	1.033		
14 [30]	(T=298 K)		n-type, phosphorus doped silicon samples; carrier concentration N = 7.5×10^{19} cm^{-3}; polished; specimen heated at 1310 K for 120-210 sec in a vacuum of $\leq 1 \times 10^{-7}$ Torr; refractive index derived from reflectivity measurements; data taken from a figure.	Spitzer, W.G., et al., 1964
	3.487	2.981		
	4.521	2.572		
	5.180	2.250		
	5.587	2.092		
	6.339	1.695		
	6.778	1.500		
	7.185	1.336		
	7.436	1.247		
	7.749	1.172		
	8.437	1.058		
15 [30]	(T=298 K)		Thin film specimen of 0.0346 μm thick; no details of sample preparation given; reflectance and transmittance measured and reduced to refractive indices using iterative curve fitting technique; data taken from a figure.	Bennett, J.M. and Booty, M.J., 1966
	0.400	3.191		
	0.420	3.162		
	0.441	3.128		
	0.462	3.077		
	0.481	3.030		
	0.502	2.979		
	0.522	2.923		
	0.541	2.885		
	0.560	2.843		
	0.582	2.804		
	0.600	2.775		
	0.621	2.749		
	0.643	2.724		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
16	(T=300 K)		Single crystal; specimens with surface either chemically etched or cleaved; refractive index determined using ellipsometric method; effects of the SiO_2 thin film on the surface due to aging, annealing, chemical treatment, etc. were corrected and the true value of refractive index obtained; data taken from a table.	Vedam, K., Knausenberger, W., and Lukes, F., 1969
[32]	0.5461	4.140		
17	(T=300 K)		Single crystal; obtained from Exotic Materials, Costa Mesa, CA; $\rho > 10$ Ω-cm; plate specimen of 1.94067 ± 2.3 x 10^{-4} mm thick; refractive indices measured using interference method; data taken from a figure.	Randall, C.M. and Rawcliffe, R.D., 1967
[33]	70.392	3.4191		
	72.951	3.4186		
	75.697	3.4193		
	78.662	3.4193		
	81.872	3.4188		
	84.992	3.4186		
	89.138	3.4190		
	93.279	3.4189		
	97.822	3.4189		
	102.83	3.4187		
	108.97	3.4184		
	113.92	3.4184		
	120.77	3.4184		
	128.49	3.4184		
	138.22	3.4184		
	148.44	3.4183		
	160.29	3.4183		
	177.27	3.4181		
	192.57	3.4181		
	210.76	3.4182		
	238.27	3.4180		
	270.35	3.4180		
	312.38	3.4182		
	370.01	3.4175		
	453.08	3.4200		
	604.44	3.4150		
18	(T=300 K)		Single crystal; obtained from Exotic Materials, Costa Mesa, CA; $\rho > 10$ Ω-cm; plate specimen of 6.41495 ± 5 x 10^{-4} mm thick; refractive indices measured using interference method; data taken from a figure.	Randall, C.M. and Rawcliffe, R.D., 1967
[33]	68.242	3.4186		
	70.395	.4185		
	72.689	3.4183		
	75.704	3.4182		
	78.669	3.4182		
	81.875	3.4184		
	85.354	3.4184		
	88.749	3.4184		
	93.282	3.4182		
	97.354	3.4183		
	102.83	3.4181		
	107.80	3.4181		
	113.92	3.4181		
	120.77	3.4180		
	128.50	3.4180		
	138.23	3.4178		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
18(cont.) [33]	148.45	3.4179		Randall, C.M. and Rawcliffe, R.D., 1967
	160.30	3.4178		
	175.73	3.4177		
	190.76	3.4175		
	213.02	3.4175		
	235.51	3.4174		
	270.42	3.4170		
	312.53	3.4166		
	370.27	3.4156		
19 [34]	(T=298 K)		Bulk silicon; no details of sample preparation and experiment given; refractive indices deduced from normal reflectance measurement using classical oscillator fitting technique; data taken from a figure.	Verleur, H.W., 1968
	0.124	0.35		
	0.133	0.39		
	0.151	0.43		
	0.176	0.47		
	0.196	0.54		
	0.216	0.70		
	0.225	0.74		
	0.230	0.94		
	0.233	1.02		
	0.239	0.90		
	0.242	0.74		
	0.264	0.78		
	0.274	1.09		
	0.286	1.76		
	0.290	2.51		
	0.300	3.33		
	0.311	3.92		
	0.316	4.15		
	0.322	4.15		
	0.331	4.11		
	0.341	4.39		
	0.341	4.54		
	0.348	4.62		
	0.366	5.45		
	0.374	6.07		
	0.378	6.47		
	0.382	6.54		
	0.390	6.39		
	0.399	5.84		
	0.418	5.37		
	0.445	4.90		
	0.488	4.54		
	0.576	4.03		
	0.717	3.72		
	1.033	3.52		
	1.033	3.52		
	1.598	3.45		
	3.196	3.41		
	8.794	3.37		
	11.698	3.37		
20 [35]	(T=298 K)		Amorphous silicon film; deposited on polished silica glass slides by vacuum ($\leq 1 \times 10^{-5}$ mm Hg) evaporation of pure silicon crystals ($\rho \sim 10$ Ω-cm) heated by electron bombardment;	Grigorovici, R. and Vancu, A., 1968
	0.565	4.165		
	0.591	4.157		
	0.622	4.119		
	0.654	4.059		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
20(cont.) [35]	0.692	3.968	refractive indices determined based on transmissivity, reflectivity and thickness measurements; data read from a figure.	Grigorovici, R. and Vancu, A., 1968
	0.732	3.936		
	0.780	3.877		
	0.836	3.817		
	0.890	3.756		
	0.963	3.711		
	1.041	3.650		
	1.143	3.620		
	1.246	3.597		
	1.381	3.589		
	1.550	3.559		
	1.784	3.529		
	2.050	3.513		
21 [36]	(T=298 K)		Thin films on substrates of single crystal sapphire disk; deposited by rf sputtering of a 6 inch diameter intrinsic silicon cathode; substrates held at or below room temperature and in an argon atmosphere of 0.01 Torr during deposition; specimen thickness 0.3 to 10 μm determined to within ±10%; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.	Brodsky, M.H., Title, R.S., Weiser, K., and Pettit, G.D., 1970
	0.95	3.97		
	1.02	3.90		
	1.14	3.84		
	1.29	3.80		
	1.52	3.75		
	1.74	3.72		
	1.94	3.70		
	2.07	3.69		
	2.25	3.68		
22 [36]	(T=298 K)		Thin films on substrates of single crystal sapphire disk; deposited by rf sputtering of a 6 inch diameter intrinsic silicon cathode; substrates held at or below room temperature and in an argon atmosphere of 0.01 Torr during deposition; specimen thickness 0.3 to 10 μm determined to within ±10%; specimens annealed at 365 K for 2 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.	Brodsky, M.H., et al., 1970
	0.93	3.95		
	0.98	3.91		
	1.05	3.86		
	1.16	3.82		
	1.36	3.76		
	1.50	3.73		
	1.70	3.71		
	1.96	3.68		
	2.25	3.66		
23 [36]	(T=298 K)		Thin films on substrates of single crystal sapphire disk; deposited by rf sputtering of a 6 inch diameter intrinsic silicon cathode; substrates held at or below room temperature and in an argon atmosphere of 0.01 Torr during deposition; specimen thickness 0.3 to 10 μm determined to within ±10%; specimens annealed at 496 K for 2 hours; refractive indices determined from the transmission interference fringes and thickness of the specimens; data taken from a figure.	Brodsky, M.H., et al., 1970
	0.91	3.93		
	0.93	3.89		
	0.99	3.84		
	1.08	3.80		
	1.15	3.76		
	1.30	3.72		
	1.44	3.69		
	1.66	3.66		
	1.82	3.64		
	2.18	3.61		
24 [36]	(T=298 K)		Thin films on substrates of single crystal sapphire disk; deposited by	Brodsky, M.H., et al., 1970
	0.82	3.97		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
24(cont.) [36]	0.86	3.92	rf sputtering of a 6 inch diameter intrinsic silicon cathode; substrates held at or below room temperature and in an argon atmosphere of 0.01 Torr during deposition; specimen thickness 0.3 to 10 μm determined to within ±10%; specimens annealed at 669 K for 2 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.	Brodsky, M.H., Title, R.S., Weiser, K., and Pettit, G.D., 1970
	0.92	3.85		
	0.98	3.80		
	1.03	3.76		
	1.13	3.72		
	1.26	3.67		
	1.40	3.64		
	1.58	3.62		
	1.76	3.60		
	1.96	3.58		
	2.21	3.57		
25 [36]	(T=298 K)		Thin films on substrates of single crystal sapphire disk; deposited by rf sputtering of a 6 inch diameter intrinsic silicon cathode; substrates held at or below room temperature and in an argon atmosphere of 0.01 Torr during deposition; specimen thickness 0.3 to 10 μm determined to within ±10%; specimens annealed at 773 K for 2 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.	Brodsky, M.H., et al., 1970
	0.81	3.83		
	0.86	3.78		
	0.92	3.73		
	1.01	3.67		
	1.12	3.63		
	1.30	3.59		
	1.48	3.55		
	1.68	3.52		
	1.95	3.50		
	2.14	3.49		
26 [36]	(T=298 K)		Thin films on substrates of single crystal sapphire disk; deposited by rf sputtering of a 6 inch diameter intrinsic silicon cathode; substrate held at or below room temperature and in an argon atmosphere of 0.01 Torr during deposition; specimen thickness 0.3 to 10 μm determined to within ±10%; specimen annealed at 1222 K for 2 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.	Brodsky, M.H., et al., 1970
	0.718	3.56		
	0.746	3.51		
	0.808	3.46		
	0.873	3.41		
	0.947	3.38		
	1.016	3.35		
	1.161	3.31		
	1.319	3.28		
	1.558	3.25		
	1.816	3.24		
	2.112	3.22		
	2.451	3.21		
27 [24]	(T=297 K)		Silicon wedge specimen; cut from a single crystal rod obtained from Merck and Co.; ultra-high purity p-type; ρ = 1250 Ω-cm; orientation <111> along the rod axis and perpendicular to one face of the wedge; wedge angle 11°40'35"; wedge faces 22 mm long by 12.7 mm high; refractive indices determined by autocollimation method; data taken from a table.	Primak, W., 1971
	1.2	3.5196		
	1.4	[illegible]		
	1.6	3.4715		
	1.8	3.4585		
	2.0	[illegible]		
28 [24]	(T=297 K)		Silicon wedge specimen; cut from a single crystal rod obtained from Merck and Co.; ultra-high purity p-type; ρ = [illegible]; orientation <111> along the rod axis and perpendicular to one face of the wedge; wedge angle 11°40'35";	Primak, W., 1971
	1.144	3.5295		
	1.2	3.5187		
	1.372	3.5007		
	1.4	3.4841		
	1.532	3.4784		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
28(cont.) [24]	1.696	3.4644	wedge faces 22 mm long by 12.7 mm high; refractive indices determined by auto-collimation method; data taken from a table.	Primak, W., 1971
29	(T=297 K)		Silicon wedge specimen; cut from a single crystal rod obtained from Merck and Co.; ultra-high purity p-type; ρ = 1200 Ω-cm; orientation <111> along the rod axis and perpendicular to one face of the wedge; wedge angle 11°40'35"; wedge faces 22 mm long by 12.7 mm high; refractive indices determined by auto-collimation method; data taken from a table.	Primak, W., 1971
[24]	1.12	3.5361		
	1.2	3.5193		
	1.4	3.4886		
	1.6	3.4706		
	1.8	3.4573		
	2.0	3.4487		
	2.16	3.4427		
30	(T=298 K)		Single crystal; surface polished with diamond dust; refractive index determined by the method of ellipsometry.	Shevchenko, G.K., Rachkovskii, R.R., Kol'tsov, S.I., and Aleskovskii, V.B., 1972.
[37]	0.5461	4.05		
31	(T=104 K)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.C., 1976
[14]	2.554	3.41172		
	2.652	3.40896		
	2.732	3.40754		
	2.856	3.40611		
	2.958	3.40475		
	3.090	3.40365		
	4.120	3.39695		
	5.190	3.39388		
	8.230	3.39064		
	10.270	3.38989		
32	(T=202 K)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a figure.	Icenogle, H.W., et al., 1976
[14]	2.554	3.42184		
	2.652	3.42006		
	2.732	3.41843		
	2.856	3.41776		
	2.958	3.41587		
	3.090	3.41483		
	4.120	3.40800		
	5.190	3.40496		
	8.230	3.40169		
	10.270	3.40084		
	(T=275 K)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
	[illegible]	3.43472		
	[illegible]	3.43264		
	[illegible]	3.43097		
	[illegible]	3.42971		
	[illegible]	[illegible]		
	[illegible]	[illegible]		
	[illegible]	[illegible]		
	[illegible]	[illegible]		
	[illegible]	[illegible]		
	[illegible]	[illegible]		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
34 [14]	(T=296 K)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.C., 1976
	2.554	3.43681		
	2.652	3.43529		
	2.732	3.43367		
	2.856	3.43224		
	2.958	3.43102		
	3.090	3.42987		
	4.120	3.42304		
	5.190	3.41974		
	8.230	3.41629		
	10.270	3.41551		
35 [38]	(T=298 K)		Thin films of thicknesses 0.06-0.350 μm; deposited on quartz substrate in a vacuum of 10^{-6} Torr; evaporation produced by electron beam bombardment; rate of deposition 0.0002-0.001 μm per second; substrate kept at 548 K during deposition; refractive index determined from normal incident reflectance and transmittance measurements; data taken from a figure.	Thutupalli, G.K.M. and Tomlin, S.G., 1977
	0.30	2.92		
	0.32	3.18		
	0.35	3.54		
	0.39	3.90		
	0.45	4.26		
	0.51	4.51		
	0.58	4.60		
	0.61	4.50		
	0.66	4.34		
	0.74	4.20		
	0.82	4.04		
	0.93	3.91		
	1.12	3.80		
	1.40	3.71		
	1.61	3.68		
	1.98	3.67		
36 [38]	(T=298 K)		Thin films of thicknesses 0.06-0.350 μm; deposited on quartz substrate in a vacuum of 10^{-6} Torr; evaporation produced by electron beam bombardment; rate of deposition 0.0002-0.001 μm per second; substrate kept at 873 K during deposition; refractive index determined from normal incident reflectance and transmittance measurements; data taken from a figure.	Thutupalli, G.K.M. and Tomlin, S.G., 1977
	0.52	4.57		
	0.55	4.44		
	0.60	4.27		
	0.65	4.13		
	0.75	3.97		
	0.86	3.84		
	1.04	3.74		
	1.32	3.65		
	1.56	3.62		
	1.89	3.58		
37 [38]	(T=298 K)		Thin films of thicknesses 0.06-0.350 μm; deposited on quartz substrate in a vacuum of 10^{-6} Torr; evaporation produced by electron beam bombardment; rate of deposition 0.0002-0.001 μm per second; substrate kept at 1048 K during deposition; refractive index determined from normal incident reflectance and transmittance measurements; data taken from a figure.	Thutupalli, G.K.M. and Tomlin, S.G., 1977
	0.43	4.86		
	0.46	4.67		
	0.52	4.31		
	0.58	4.07		
	0.66	3.87		
	0.76	3.71		
	0.88	3.61		
	1.10	3.54		
	1.36	3.50		
	1.67	3.48		
	1.89	3.47		
38 [38]	(T=298 K)		Thin films of thicknesses 0.06-0.350 μm; deposited on quartz substrate in	Thutupalli, G.K.M. and Tomlin, S.G., 1977
	0.53	4.60		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
38(cont.) [38]	0.56	4.44	a vacuum of 10^{-6} Torr; evaporation produced by electron beam bombardment; rate of deposition 0.0002-0.001 μm per second; substrate kept at 548 K during deposition and then annealed at 873 K for 3 hours; refractive index determined from normal incident reflectance and transmittance measurements; data taken from a figure.	Thutupalli, G.K.M. and Tomlin, S.G., 1977
	0.64	4.23		
	0.74	4.00		
	0.90	3.84		
	1.04	3.77		
	1.24	3.68		
	1.50	3.65		
	1.85	3.61		
39 [38]	(T=298 K)		Single crystal; cut at <111> face and polished with successively finer grades of diamond abrasives and finally with an Al_2O_3 polishing powder on a beeswax lap; refractive index determined from normal incident reflectance and transmittance measurements; data taken from a figure.	Thutupalli, G.K.M. and Tomlin, S.G., 1977
	0.30	4.16		
	0.30	4.52		
	0.30	4.85		
	0.31	5.21		
	0.32	5.43		
	0.33	5.65		
	0.34	5.94		
	0.35	6.30		
	0.36	6.55		
	0.37	6.70		
	0.38	6.52		
	0.39	6.08		
	0.40	5.68		
	0.41	5.32		
	0.44	4.91		
	0.48	4.59		
	0.52	4.29		
	0.58	4.04		
	0.72	3.82		
	0.91	3.64		
	1.10	3.53		
	1.43	3.45		
	2.06	3.38		
	3.10	3.38		
	6.96	3.34		
40 [25]	(T=299 K)		Single crystal; obtained from the Raytheon Co.; prism specimen of 15°38' 29" apex angle; refractive index determined by minimum deviation method; reported uncertainty 2 x 10^{-4}; the values in this set are much higher than the author's previous measure (data set 3) for a sample obtained from Texas Instrument Co.; impurities in Raytheon sample may be responsible to such discrepancies; data extracted from a table.	Villa, J.L., 1972
	1.3570	3.5151		
	1.3673	3.5139		
	1.3951	3.5107		
	1.5295	3.4976		
	1.6606	3.4879		
	1.7092	3.4849		
	1.8131	3.4792		
	1.9701	3.4724		
	2.1526	3.4664		
	2.3254	3.4618		
	2.4374	3.4596		
	2.7144	3.4545		
	3.00	3.4509		
	3.3033	3.4488		
	3.4188	3.4478		
	3.50	3.4475		
	4.00	3.4448		
	4.258	3.4436		
	4.50	3.4428		

TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
40(cont.) [25]	5.00	3.4415		Villa, J.L., 1972
	5.50	3.4405		
	6.00	3.4397		
	6.50	3.4391		
	7.00	3.4387		
	7.50	3.4383		
	8.00	3.4380		
	8.50	3.4377		
	10.00	3.4375		
	10.50	3.4373		
	11.04	3.4371		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Temperature Dependence)

[Temperature, T, K; Wavelength, λ, μm; Refractive Index, n]

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
1	(λ=2.554 μm)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
[14]	103	3.41279		
	110	3.41302		
	120	3.41374		
	131	3.41471		
	137	3.41534		
	144	3.41616		
	152	3.41695		
	160	3.41789		
	167	3.41868		
	175	3.41967		
	182	3.42074		
	189	3.42158		
	193	3.42216		
	200	3.42303		
	205	3.42375		
	210	3.42448		
	220	3.42603		
	224	3.42668		
	228	3.42730		
	235	3.42836		
	244	3.42961		
	251	3.43081		
	255	3.43181		
	261	3.41889		
	267	3.43331		
	274	3.43430		
	277	3.43492		
	282	3.43576		
	286	3.43633		
2	(λ=2.732 μm)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
[14]	97	3.40857		
	106	3.40923		
	116	3.40999		
	126	3.41084		
	133	3.41234		
	143	3.41256		
	150	3.41317		
	159	3.41429		
	165	3.41502		
	169	3.41551		
	177	3.41656		
	182	3.41723		
	190	3.41833		
	197	3.41825		
	203	3.42006		
	211	3.42118		
	217	3.42197		
	222	3.42265		
	234	3.42422		
	241	3.42523		
	245	3.42600		
	251	3.42682		
	255	3.42762		
	262	3.42863		
	267	3.42949		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
2(cont.) [14]	272	3.43037		Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
	277	3.43112		
	282	3.43182		
	286	3.43251		
3 [14]	(λ=5.190 μm)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
	99	3.39330		
	106	3.39388		
	114	3.39441		
	120	3.39497		
	127	3.39554		
	133	3.39608		
	140	3.39679		
	147	3.39757		
	155	3.39838		
	160	3.39898		
	167	3.39981		
	171	3.40037		
	180	3.40144		
	186	3.40213		
	192	3.40288		
	199	3.40382		
	205	3.40455		
	213	3.40574		
	219	3.40657		
	227	3.40760		
	233	3.40843		
	239	3.40931		
	243	3.41013		
	250	3.41104		
	262	3.41280		
	268	3.41380		
	273	3.41449		
	279	3.41529		
	285	3.41621		
4 [14]	(λ=10.27 μm)		Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
	99	3.39109		
	108	3.39185		
	114	3.39273		
	124	3.39313		
	131	3.39374		
	142	3.39484		
	148	3.39555		
	155	3.39629		
	161	3.39693		
	170	3.39796		
	177	3.39884		
	185	3.39973		
	194	3.40099		
	204	3.40229		
	210	3.40307		
	216	3.40389		
	223	3.40516		
	230	3.40572		
	236	3.40667		
	242	3.40752		

TABLE A-2. *EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON*
(Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
4(cont.) [14]	248	3.40838		Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
	253	3.40905		
	260	3.41021		
	281	3.41088		
	271	3.41186		
	276	3.41270		
	280	3.41337		
	283	3.41380		
	287	3.41427		
5 [13]	(λ=1.259 μm)		Single crystal; p-type; ρ = 380 ohm-cm; prism specimen of 17°51.4' apex angle; refractive indices for the spectral line λ = 1.259 μm at various temperatures determined by the minimum deviation method; reported error in n ∿ 0.0004; data read from a figure.	Lukes, F., 1959
	109.6	3.478		
	133.1	3.481		
	150.8	3.484		
	166.4	3.485		
	186.0	3.488		
	201.7	3.491		
	213.5	3.493		
	227.2	3.495		
	235.0	3.497		
	250.7	3.499		
	272.2	3.504		
	295.7	3.510		
	327.1	3.517		
	356.5	3.523		
	368.2	3.526		
	387.8	3.529		
	413.3	3.533		
	440.7	3.539		
	452.4	3.542		
	466.1	3.546		
	493.6	3.551		
	505.3	3.553		
	534.7	3.561		
	554.3	3.565		
	573.9	3.570		
	613.0	3.580		
	628.7	3.582		
	646.3	3.587		
6 [13]	(λ=1.407 μm)		Single crystal; p-type; ρ = 380 ohm-cm; prism specimen of 17°51.4" apex angle; refractive indices for the wavelength λ = 1.407 μm at various temperatures determined by the minimum deviation method; reported error in n ∿ 0.0004; data read from a figure.	Lukes, F., 1959
	109.7	3.460		
	143.0	3.465		
	160.6	3.467		
	172.4	3.468		
	188.1	3.470		
	207.7	3.473		
	221.4	3.476		
	235.1	3.478		
	246.9	3.481		
	258.6	3.483		
	268.4	3.485		
	278.2	3.486		
	286.0	3.488		
	288.0	3.489		
	299.8	3.490		
	331.1	3.496		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
6(cont.) [13]	356.6	3.501		Lukes, F., 1959
	360.5	3.502		
	372.2	3.505		
	397.7	3.509		
	407.5	3.512		
	421.2	3.514		
	434.9	3.517		
	458.4	3.523		
	478.0	3.529		
	489.7	3.531		
	497.6	3.532		
	505.4	3.532		
	517.2	3.535		
	532.8	3.539		
	544.6	3.542		
	554.4	3.545		
	566.1	3.547		
	568.1	3.549		
	577.0	3.550		
	581.8	3.551		
	593.6	3.554		
	603.4	3.556		
	609.2	3.558		
	624.9	3.562		
	636.6	3.564		
	636.6	3.565		
	648.4	3.567		
	655.2	3.570		
	661.7	3.575		
	691.5	3.577		
	698.4	3.579		
	704.1	3.582		
	713.0	3.583		
	722.8	3.588		
	728.7	3.589		
	742.4	3.591		
	744.3	3.593		
7 [13]	(λ=1.564 μm)		Single crystal; p-type; ρ = 380 ohm-cm; prism specimen of 17°51.4' apex angle; refractive indices for the wavelength λ = 1.564 μm at various temperatures determined by the minimum deviation method; reported error in n ∿ 0.0004; data read from a figure.	Lukes, F., 1959
	107.8	3.446		
	113.7	3.447		
	129.4	3.448		
	141.1	3.450		
	152.9	3.451		
	160.7	3.453		
	178.4	3.455		
	192.1	3.457		
	207.7	3.459		
	219.5	3.461		
	229.3	3.462		
	241.1	3.464		
	252.8	3.467		
	272.4	3.470		
	280.2	3.471		
	299.8	3.475		
	311.6	3.477		
	327.3	3.480		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
7(cont.)	344.9	3.483		Lukes, F., 1959
[13]	352.7	3.485		
	368.4	3.488		
	374.3	3.490		
	388.0	3.492		
	399.7	3.495		
	417.4	3.498		
	423.2	3.500		
	431.1	3.502		
	438.9	3.503		
	446.7	3.504		
	458.5	3.507		
	468.3	3.509		
	475.1	3.511		
	491.8	3.514		
	501.6	3.516		
	511.4	3.519		
	529.0	3.522		
	536.8	3.525		
	546.6	3.526		
	554.5	3.530		
	564.3	3.532		
	574.0	3.534		
	583.8	3.537		
	607.3	3.542		
	621.0	3.545		
	632.8	3.547		
	644.6	3.549		
	658.3	3.554		
	670.0	3.555		
	683.7	3.559		
	695.5	3.561		
	709.2	3.566		
	724.9	3.570		
	736.6	3.573		
	750.3	3.576		
8	(λ=2.409 μm)		Single crystal; p-type; ρ = 380 ohm-cm; prism specimen of 17°51.4' apex angle; refractive indices for the spectral line λ = 2.409 μm at various temperatures determined by the minimum deviation method; reported error in n ∿ 0.0004; data read from a figure.	Lukes, F., 1960
[23]	111.6	3.412		
	120.7	3.415		
	144.8	3.417		
	156.9	3.418		
	187.1	3.421		
	199.2	3.424		
	211.3	3.426		
	229.4	3.428		
	238.4	3.430		
	247.5	3.431		
	262.6	3.433		
	265.6	3.435		
	274.7	3.436		
	280.7	3.437		
	286.8	3.438		
	289.8	3.440		
	295.8	3.440		
	307.9	3.443		
	323.0	3.445		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
8(cont.) [23]	335.1	3.446		Lukes, F., 1960
	341.1	3.449		
	353.2	3.452		
	371.3	3.453		
	380.4	3.455		
	395.5	3.458		
	407.6	3.460		
	419.7	3.464		
	431.8	3.465		
	446.9	3.468		
	456.0	3.470		
	462.0	3.472		
	477.1	3.475		
	480.2	3.478		
	501.3	3.480		
	516.4	3.483		
	528.5	3.485		
	540.6	3.488		
	546.6	3.489		
	561.7	3.492		
	567.8	3.495		
	585.9	3.498		
	598.0	3.500		
	610.1	3.502		
	622.2	3.506		
	628.2	3.507		
9 [23]	(λ=5.156 μm)		Single crystal; p-type; ρ = 360 ohm-cm; prism specimen of 17°51.4' apex angle; refractive indices for the spectral line λ = 5.156 μm at various temperatures determined by the minimum deviation method; reported error in n ∿ 0.0004; data read from a figure.	Lukes, F., 1960
	298.6	3.420		
	310.7	3.423		
	316.7	3.423		
	334.9	3.426		
	337.9	3.427		
	347.0	3.429		
	359.0	3.430		
	377.2	3.433		
	401.3	3.436		
	425.5	3.444		
	440.6	3.445		
	446.7	3.448		
	455.7	3.450		
	479.9	3.453		
	495.0	3.455		
	510.1	3.458		
	516.2	3.461		
	528.2	3.462		
	543.4	3.467		
	564.5	3.472		
	573.6	3.473		
	585.7	3.475		
	594.7	3.476		
	621.9	3.481		
10 [39]	(λ=0.45 μm)		Single crystal; ρ = 15 Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the	Sato, T., 1967
	266	4.74		
	373	4.81		
	466	4.91		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
(Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
10(cont.) [39]	568	4.96	emission of the specimen and that of a V-shape cavity of graphite with the emissivity of about 0.97; refractive index determined using the expression: emissivity = $4n/(n+1)^2$; data taken from a figure.	Sato, T., 1967
	675	5.02		
	760	5.14		
	875	5.18		
	968	5.32		
11 [39]	(λ=0.55 μm)		Single crystal; ρ = 15 Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the emission of the specimen and that of a V-shape cavity of graphite with the emissivity of about 0.97; refractive index determined using the expression: emissivity = $4n/(n+1)^2$; data taken from a figure.	Sato, T., 1967
	275	4.14		
	368	4.22		
	466	4.23		
	564	4.34		
	675	4.40		
	773	4.42		
	866	4.51		
	977	4.55		
12 [39]	(λ=0.65 μm)		Single crystal; ρ = 15 Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the emission of the specimen and that of a V-shape cavity of graphite with the emissivity of about 0.97; refractive index determined using the expression: emissivity = $4n/(n+1)^2$; data taken from a figure.	Sato, T., 1967
	275	4.03		
	386	4.07		
	475	4.12		
	577	4.23		
	693	4.24		
	791	4.30		
	880	4.40		
	995	4.42		
13 [39]	(λ=0.90 μm)		Single crystal; ρ = 15 Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the emission of the specimen and that of a V-shape cavity of graphite with the emissivity of about 0.97; refractive index determined using the expression: emissivity = $4n/(n+1)^2$; data taken from a figure.	Sato, T., 1967
	271	3.75		
	368	3.83		
	475	3.83		
	568	3.92		
	675	3.91		
	768	4.00		
	871	4.00		
	973	4.10		
14 [39]	(λ=1.56 μm)		Single crystal; ρ = 15 Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the emission of the specimen and that of a V-shape cavity of graphite with the emissivity of about 0.97; refractive index determined using the expression: emissivity = $4n/(n+1)^2$; data taken from a figure.	Sato, T., 1967
	280	3.55		
	377	3.61		
	484	3.60		
	573	3.68		
	671	3.72		
	782	3.69		
	871	3.79		
	977	3.77		
15 [39]	(λ=2.00 μm)		Single crystal; ρ = 15 Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the emission of the specimen and that of a V-shape cavity of graphite with the	Sato, T., 1967
	284	3.47		
	382	3.48		
	488	3.52		
	573	3.59		
	675	3.56		

TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
(Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
15(cont.) [39]	782 871 977	3.59 3.65 3.64	emissivity of about 0.97; refractive index determined using the expression: emissivity = $4n/(n+1)^2$; data taken from a figure.	Sato, T., 1967

TABLE A-3. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF SILICON (Wavelength Dependence)

[Temperature, T, K; Wavelength, λ, μm; Temperature Derivative of Refractive Index, dn/dT, 10^{-4} K^{-1}]

Data Set [Ref.]	λ	dn/dT	Specifications and Remarks	Author(s), Year
1 [13]	(T=300 K)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices at various temperatures determined using the minimum deviation method and dn/dT at 300 K obtained; data read from a figure.	Lukes, F., 1959
	1.130	2.17		
	1.158	2.12		
	1.192	2.09		
	1.260	2.06		
	1.327	2.04		
	1.457	1.97		
	1.589	1.95		
	1.734	1.91		
	1.781	1.88		
2 [23]	(T=300 K)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices at various temperatures determined using the minimum deviation method and dn/dT at 300 K obtained; data read from a figure.	Lukes, F., 1960
	1.146	2.18		
	1.162	2.13		
	1.207	2.10		
	1.238	2.07		
	1.328	2.04		
	1.389	1.98		
	1.554	1.96		
	1.720	1.88		
	1.766	1.84		
	2.080	1.80		
	2.393	1.80		
	3.410	1.74		
	3.829	1.68		
	5.144	1.60		

TABLE A-4. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF SILICON (Temperature Dependence)

[Temperature, T, K; Wavelength, λ, μm; Temperature Derivative of Refractive Index, dn/dT, 10^{-4} K^{-1}]

Data Set (Ref.)	T	dn/dT	Specifications and Remarks	Author(s), Year
1 [13]	(λ=1.259 μm)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices for the line 1.259 μm at various temperatures determined using the minimum deviation method and dn/dT obtained; data read from a figure.	Lukes, F., 1959
	117.8	1.01		
	170.9	1.60		
	216.6	1.84		
	266.3	1.98		
	315.9	2.09		
	415.4	2.22		
	522.4	2.37		
2 [13]	(λ=1.564 μm)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices for the line λ = 1.564 μm at various temperatures determined using the minimum deviation method and dn/dT obtained; data read from a figure.	Lukes, F., 1959
	117.7	1.07		
	167.2	1.46		
	216.8	1.63		
	266.4	1.83		
	319.9	1.95		
	419.2	2.14		
	522.5	2.29		
	621.9	2.39		
	721.4	2.44		
3 [23]	(λ=1.407 μm)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices for wavelength λ = 1.407 μm at various temperatures determined using the minimum deviation method and dn/dT obtained; data read from a figure.	Lukes, F., 1960
	115.7	0.95		
	127.6	1.09		
	[illegible]	[illegible]		
	184.0	1.54		
	210.7	1.77		
	252.3	1.92		
	290.9	2.06		
	371.2	2.06		
	421.7	2.15		
	466.3	2.20		
	516.9	2.29		
	567.4	2.32		
	609.0	2.33		
	629.9	2.32		
	665.5	2.30		
	719.1	2.30		
	736.9	2.30		
4 [23]	(λ=2.409 μm)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices for the line λ = 2.409 μm at various temperatures determined using the minimum deviation method and dn/dT obtained; data read from a figure.	Lukes, F., 1960
	115.7	0.78		
	127.6	0.97		
	157.3	1.22		
	184.0	1.42		
	207.7	1.57		
	249.3	1.78		
	290.9	1.86		
	308.8	1.88		
	368.2	1.94		
	415.8	1.98		
	466.4	2.04		
	516.9	2.06		
	567.4	2.14		
	606.1	2.17		

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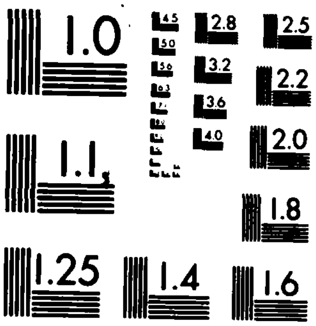

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TABLE A-4. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF SILICON (Temperature Dependence) (continued)

Data Set [Ref.]	T	dn/dT	Specifications and Remarks	Author(s), Year
5	(λ=3.826 μm)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices at various temperatures determined using the minimum deviation method and dn/dT obtained; data read from a figure.	Lukes, F., 1960
[23]	311.8	1.74		
	371.2	1.83		
	418.8	1.95		
	466.4	2.00		
	519.9	2.03		
	567.5	2.06		
	609.1	2.09		
6	(λ=5.156 μm)		Single crystal; p-type; ρ = 380 Ω-cm; prism specimen of 17°51.4' apex angle; refractive indices at various temperatures determined using the minimum deviation method and dn/dT obtained; data read from a figure.	Lukes, F., 1960
[23]	308.8	1.62		
	368.3	1.74		
	418.8	1.86		
	469.4	1.94		
	516.9	1.98		
	567.5	1.95		
	606.2	1.85		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)

[Temperature, T, K; Wavelength, λ, μm; Refractive Index, n]

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
1 [49]	(T=298 K)		Thin film specimens of thickness ranged from 0.04 to 1.0 μm; refractive index determined from the interference fringe order of the transmitted radiation and the thickness of the specimen; data extracted from a figure.	Brattain, W.H., and Briggs, H.B., 1949
	0.36	2.03		
	0.43	2.43		
	0.50	3.40		
	0.68	5.15		
	0.78	5.22		
	0.88	5.17		
	0.98	5.20		
	1.0	4.92		
	1.2	4.84		
	1.4	4.79		
	1.5	4.61		
	1.5	4.74		
	1.6	4.61		
	1.6	4.74		
	1.8	4.66		
	1.8	4.56		
	2.0	4.64		
	2.2	4.46		
	2.6	4.46		
	3.1	4.43		
	3.9	4.38		
	5.2	4.33		
	7.6	4.30		
2 [21]	(T=298 K)		Sample from a standard high back-voltage melt with impurity content estimated at less than 0.01%; prismatic specimen of 17°6'30" angle; index of refraction measured by method of minimum deviation; data extracted from a table.	Briggs, H.B., 1949
	1.80	4.143		
	1.85	4.135		
	1.90	4.129		
	2.00	4.116		
	2.10	4.104		
	2.20	4.092		
	2.30	4.085		
	2.40	4.078		
	2.50	4.072		
	2.60	4.068		
3 [26]	(T=300 K)		Crystal; obtained from RCA Laboratories; $\rho \sim 1$ Ω-cm; polished specimen of 0.89 mm thick; reflectances at 20 and 70 degree incidence angles obtained; refractive indices obtained by a graphical analysis; data taken from a figure.	Simon, I., 1951.
	3.842	2.669		
	4.147	2.648		
	4.518	2.698		
	4.715	2.750		
	6.209	2.993		
	7.158	3.403		
	8.202	3.652		
	9.735	3.954		
	12.168	3.968		
	13.983	4.128		
4 [50]	(T=77 K)		Pure crystal; thin plate specimen of 227 μm thick; interference fringe of transmitted radiation observed and refractive index determined; data extracted from a table.	Collins, R.J., 1953
	8.66	3.77		
	9.4	3.81		
	10.2	3.81		
	11.22	3.81		
	12.35	3.82		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
5 [50]	(T=300 K)		Pure crystal; thin plate specimen of 227 μm thick; interference fringe of transmitted radiation observed and refractive index determined; data extracted from a table.	Collins, R.J., 1953
	8.66	3.92		
	9.4	3.90		
	10.2	3.93		
	11.22	3.92		
	12.35	3.93		
6 [43]	(T=297.3 K)		Germanium crystal; grown at the General Electric Co., Electronic Lab., Electronic Park, Syracuse, NY; plane parallel plate specimen of 3.0575 mm thick and 28 mm clear aperature; interference fringe order observed and vacuum refractive index of the plate determined; data taken from a table.	Rank, D.H., Bennett, H.E., and Cronemeyer, D.C., 1954
	2.00	4.1254		
	2.10	4.1145		
	2.30	4.0980		
	2.40	4.0918		
7 [51]	(T=297 K)		Single crystal; ρ=56 Ω-cm; plate specimen of about 7 mm thick; refractive index deduced from reflectance and transmittance measurements; reflective index in the wavelength region between 1.8 and 15.2 μm being a constant 3.95.	Oswald, F. and Schade, R., 1954
	1.8 to 15.2	3.95		
8 [52]	(T=297 K)		Single crystals, n-type with majority carrier concentration $N = 3.9 \times 10^{19}$ cm^{-3}; refractive index derived from reflectivity and transmission measurements; data taken from a figure.	Spitzer, W.G. and Fan, H.Y., 1957
	2.811	4.027		
	3.217	4.027		
	3.623	4.027		
	4.029	4.014		
	7.139	3.959		
	10.926	3.662		
	12.008	3.595		
	12.820	3.514		
	13.361	3.500		
	13.902	3.432		
	14.172	3.392		
	15.254	3.297		
	16.066	3.230		
	17.012	3.095		
	17.959	2.946		
	18.906	2.811		
	19.988	2.649		
	21.070	2.473		
	22.152	2.270		
	22.963	2.054		
9 [52]	(T=297 K)		Single crystals, p-type with majority carrier concentration $N = 1.1 \times 10^{19}$ cm^{-3}; refractive index derived from reflectivity and transmission measurements; data taken from a figure.	Spitzer, W.G. and Fan, H.Y., 1957
	7.816	3.824		
	8.762	3.824		
	9.980	3.797		
	10.926	3.770		
	12.008	3.730		
	12.955	3.703		
	14.037	3.622		
	14.984	3.514		
	16.066	3.432		
	17.148	3.324		
	17.959	3.230		
	18.906	3.162		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
10 [22]	(T=300 K)		Single crystal of germanium from Sylvania Electronic Products Co., Woburn, MA; test prism cut with faces 4.5 x 4.0 cm and refracting angle of 11.8°; index of refraction measured by autocollimation method at 300 K; data with uncertainty ±2 in fourth decimal place taken from a table.	Salzberg, C.D. and Villa, J.J., 1957
	2.0581	4.1016		
	2.1526	4.0917		
	2.3126	4.0788		
	2.4374	4.0706		
	2.577	4.0610		
	2.7144	4.0554		
	2.998	4.0453		
	3.3033	4.0370		
	3.4188	4.0336		
	4.258	4.0217		
	4.866	4.0170		
	6.238	4.0092		
	8.66	4.0036		
	9.72	4.0026		
	11.04	4.0020		
	12.20	4.0018		
	13.02	4.0016		
	14.21	4.0015		
	15.08	4.0014		
	16.00	4.0012		
11 [47]	(T=300 K)		Remeasurement of above single crystal prism; minimum deviation method used; comparison of the single and polycrystalline results indicated no significant differences; data from a table.	Salzberg, C.D. and Villa, J.J., 1958
	2.0581	4.1016		
	2.1526	4.0919		
	2.3126	4.0786		
	2.4374	4.0708		
	2.577	4.0609		
	2.7144	4.0552		
	2.998	4.0452		
	3.3033	4.0369		
	3.4188	4.0334		
	4.258	4.0216		
	4.866	4.0170		
	6.238	4.0094		
	8.66	4.0043		
	9.72	4.0034		
	11.04	4.0026		
	12.20	4.0023		
	13.02	4.0021		
12 [47]	(T=300 K)		Polycrystalline; supplied by Sylvania Electronic Products Co., Towonda, PA; refractive index measured by minimum deviation method; data taken from a table.	Salzberg, C.D. and Villa, J.J., 1958
	2.0581	4.1018		
	2.1526	4.0919		
	2.3126	4.0785		
	2.4374	4.0709		
	2.577	4.0608		
	2.7144	4.0554		
	2.998	4.0452		
	3.3033	4.0372		
	3.4188	4.0339		
	4.258	4.0217		
	4.866	4.0167		
	6.238	4.0095		
	8.66	4.0043		
	9.72	4.0033		
	11.04	4.0025		
	12.20	4.0020		
	13.02	4.0018		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
13	(T=298 K)		Specimens of both mechanically polished and etched 6 Ω-cm germanium; optical constants obtained from ellipticity of reflected polarized light; the polished mirrors were boiled in benzene and refluxed over acetone for several hours before use; the effect of surface films were taken into account; data extracted from a figure.	Archer, R.J., 1958
[53]	0.36	4.13		
	0.40	4.14		
	0.43	4.03		
	0.46	4.07		
	0.49	4.37		
	0.52	4.74		
	0.54	5.07		
	0.58	5.37		
	0.60	5.56		
	0.63	5.31		
	0.66	5.17		
	0.69	4.84		
14	(T=87 K)		5° germanium prism mounted against a plane mirror; Abbe autocollimation method applied to measure the deviation angle to within ±1'; data extracted from a figure.	Cardona, M., Paul, W., and Brooks, H., 1959
[12]	1.743	4.064		
	1.902	4.041		
	2.089	4.027		
	2.263	4.014		
	2.422	4.003		
	2.552	3.996		
	2.711	3.990		
	2.856	3.986		
	3.059	3.978		
	3.348	3.969		
	3.623	3.966		
	4.116	3.955		
	4.463	3.952		
	4.855	3.952		
	5.318	3.949		
	5.608	3.947		
15	(T=190 K)		5° germanium prism mounted against a plane mirror; Abbe autocollimation method applied to measure the deviation angle to within ±1'; data extracted from a figure.	Cardona, M., et al., 1959
[12]	1.831	4.093		
	1.888	4.077		
	2.091	4.061		
	2.409	4.040		
	2.553	4.034		
	2.713	4.025		
	2.828	4.021		
	3.378	4.003		
	3.654	3.998		
	3.914	3.994		
	4.117	3.989		
	4.465	3.986		
	4.900	3.986		
	5.320	3.985		
16	(T=297 K)		5° germanium prism mounted against a plane mirror; Abbe autocollimation method applied to measure the deviation angle to within ±1'; data extracted from a figure.	Cardona, M., et al., 1959
[12]	1.769	4.138		
	1.854	4.127		
	1.940	4.119		
	2.111	4.099		
	2.281	4.080		
	2.439	4.069		
	2.581	4.061		
	2.739	4.056		
	2.882	4.048		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
16(cont.) [12]	3.083	4.046		Cardona, M., Paul, W., and Brooks, H., 1959
	3.383	4.035		
	3.656	4.030		
	3.885	4.024		
	4.129	4.024		
	4.445	4.020		
	4.861	4.018		
	5.320	4.015		
	5.578	4.012		
17 [54]	(T=300 K)		Single crystal; etched surfaces; near normal reflectance spectrum between 0.1 and 1.8 μm observed, above 1.77 μm reflectance calculated from available refractive indices; phase angle computed from reflectance spectrum using the Krammers-Kronig relation; optical constants determined from the Fresnel formulae; data taken from a figure.	Philipp, H.R. and Taft, E.A., 1959
	0.124	0.821		
	0.132	0.779		
	0.138	0.815		
	0.148	0.812		
	0.156	0.848		
	0.167	0.846		
	0.178	0.920		
	0.190	0.957		
	0.204	1.108		
	0.211	1.299		
	0.218	1.452		
	0.221	1.490		
	0.227	1.451		
	0.240	1.488		
	0.253	1.602		
	0.263	1.832		
	0.275	2.254		
	0.277	2.600		
	0.285	3.099		
	0.287	3.522		
	0.295	3.868		
	0.309	3.828		
	0.325	3.827		
	0.349	3.980		
	0.369	4.133		
	0.382	4.132		
	0.410	4.054		
	0.450	4.014		
	0.498	4.359		
	0.531	4.666		
	0.549	4.935		
	0.569	5.280		
	0.590	5.434		
	0.612	5.318		
	0.675	5.009		
	0.735	4.816		
	0.807	4.623		
	0.921	4.430		
	1.108	4.313		
	1.234	4.236		
	1.452	4.158		
	1.981	4.080		
	2.844	4.041		
	5.041	4.010		
	9.394	4.001		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
18 [55]	(T=297 K)		Thin film of 1.092 μm thick; deposited on rotating glass substrate at air pressure of less than 4 x 10^{-5} mmHg and rate of deposition of 30-60 Å/sec; refractive indices determined from reflection and interference observation; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	1.513	4.815		
	1.607	4.752		
	1.725	4.723		
	1.853	4.651		
	2.031	4.622		
	2.228	4.540		
	2.803	4.497		
	2.861	4.539		
	3.334	4.548		
	3.978	4.527		
	4.900	4.450		
19 [55]	(T=297 K)		Thin film of 1.010 μm thick; deposited on rotating glass substrate at air pressure of less than 4 x 10^{-5} mmHg and rate of deposition of 30-40 Å/sec; refractive indices determined from reflection and interference observation; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	1.409	4.853		
	1.502	4.812		
	1.601	4.740		
	1.743	4.721		
	1.887	4.651		
	2.087	4.620		
	2.309	4.538		
	2.617	4.497		
	2.803	4.548		
	3.029	4.498		
	3.676	4.515		
	4.525	4.438		
	4.625	4.457		
20 [55]	(T=297 K)		Thin film on rotating glass substrate deposited at air pressure of less than 4 x 10^{-5} mmHg and at rate of 30-60 Å/sec; refractive indices determined from Brewster angle measurement; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	2.803	4.497		
	2.813	4.546		
	3.041	4.498		
	4.677	4.457		
21 [55]	(T=297 K)		Thin film of 1.340 μm thick on rotating glass substrate deposited at nitrogen pressure of less than 4 x 10^{-5} mmHg and at rate of 30-60 Å/sec; refractive indices determined from reflection and interference measurements; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	1.514	4.498		
	1.602	4.460		
	1.698	4.421		
	1.809	4.381		
	1.941	4.342		
	2.105	4.299		
	2.292	4.261		
	2.523	4.239		
	2.855	4.232		
	3.022	4.239		
	3.248	4.227		
	3.766	4.211		
	4.507	4.209		
	4.583	4.148		
22 [55]	(T=297 K)		Thin film of 1.364 μm thick on rotating glass substrate deposited at nitrogen pressure of less than 4 x 10^{-5} mmHg and at rate of 30-60 Å/sec; refractive indices determined from reflection and interference measurements; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	1.542	4.513		
	1.640	4.479		
	1.737	4.438		
	1.858	4.422		
	1.998	4.366		
	2.171	4.350		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
22(cont.) [55]	2.344	4.280		Huldt, L. and Staflin, T., 1959
	2.611	4.278		
	2.935	4.268		
	3.339	4.256		
	3.570	4.254		
	3.890	4.257		
	4.581	4.187		
	4.634	4.168		
23 [55]	(T=297 K)		Thin film of 1.449 μm thick on rotating glass substrate deposited at nitrogen pressure of less than 4 x 10^{-5} mmHg and at rate of 30-60 Å/sec; refractive indices determined from reflection and interference measurements; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	1.539	4.513		
	1.615	4.441		
	1.719	4.438		
	1.950	4.371		
	2.094	4.309		
	2.267	4.289		
	2.456	4.222		
	2.732	4.232		
	3.078	4.237		
	3.555	4.266		
	4.507	4.167		
24 [55]	(T=297 K)		Thin film on rotating glass substrate deposited at nitrogen pressure of less than 4 x 10^{-5} mmHg and at rate of 30-60 Å/sec; refractive indices determined from Brewster angle measurements; data taken from a figure.	Huldt, L. and Staflin, T., 1959
	3.033	4.242		
	3.525	4.259		
	4.583	4.167		
25 [44]	(T=293 K)		Pure germanium crystal; prism angle = 19°55.8'; ρ = 40 Ω-cm; measurements made by deviation method; data taken from a figure.	Lukes, F., 1960
	1.84	4.133		
	1.88	4.126		
	1.97	4.115		
	2.05	4.104		
	2.15	4.094		
	2.18	4.090		
	2.30	4.081		
	2.36	4.077		
	2.41	4.073		
	2.47	4.068		
	3.43	4.034		
	3.82	4.027		
	4.15	4.022		
	4.54	4.020		
	5.43	4.013		
26 [44]	(T=293 K)		Pure germanium crystal; prism angle = 14°53.0'; ρ = 1.2 Ω-cm; measurements made by deviation method; data taken from a figure.	Lukes, F., 1960
	1.75	4.150		
	5.15	4.013		
	5.44	4.010		
	5.61	4.007		
27 [44]	(T=298 K)		Pure germanium crystal; prism angle = 14°59.5'; ρ = 0.016 Ω-cm; measurements made by deviation method; data taken from a figure.	Lukes, F., 1960
	1.79	4.142		
	1.88	4.128		
	2.06	4.102		
	2.15	4.092		
	2.18	4.089		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
27(cont.) [44]	2.24	4.085		Lukes, F., 1960
	2.30	4.080		
	2.36	4.076		
	2.41	4.071		
	2.97	4.047		
	3.43	4.034		
	3.82	4.027		
	4.16	4.021		
	4.52	4.018		
	4.85	4.016		
	5.43	4.007		
	5.61	4.005		
28 [56]	(T=80 K)		High purity germanium; prism cut from a single crystal; prism angle: 4°21'30"; ρ = 50 Ω-cm; index of refraction measured by deviation method; data taken from a figure.	Kornfeld, M.I., 1960
	1.494	4.133		
	1.550	4.117		
	1.602	4.105		
	1.653	4.086		
	1.698	4.079		
	1.748	4.068		
	1.804	4.060		
	1.907	4.042		
	2.000	4.031		
	2.105	4.023		
	2.210	4.013		
29 [56]	(T=222 K)		High purity germanium; prism cut from a single crystal; prism angle: 4°21'30"; ρ = 50 Ω-cm; index of refraction measured by deviation method; data taken from a figure.	Kornfeld, M.I., 1960
	1.602	4.159		
	1.653	4.143		
	1.703	4.130		
	1.748	4.123		
	1.794	4.110		
	1.907	4.097		
	1.993	4.081		
	2.105	4.071		
	2.194	4.058		
30 [56]	(T=291 K)		High purity germanium; prism cut from a single crystal; prism angle: 4°21'30"; ρ = 50 Ω-cm; index of refraction measured by deviation method; data taken from a figure.	Kornfeld, M.I., 1960
	1.648	4.171		
	1.698	4.161		
	1.744	4.148		
	1.799	4.138		
	1.907	4.120		
	2.000	4.107		
	2.098	4.094		
	2.202	4.084		
31 [56]	(T=343 K)		High purity germanium; prism cut from a single crystal; prism angle: 4°21'30"; ρ = 50 Ω-cm; index of refraction measured by deviation method; data taken from a figure.	Kornfeld, M.I., 1960
	1.698	4.199		
	1.744	4.192		
	1.794	4.174		
	1.907	4.156		
	2.000	4.138		
	2.105	4.123		
	2.218	4.112		
32 [56]	(T=401 K)		High purity germanium; prism cut from a single crystal; prism angle: 4°21'30";	Kornfeld, M.I., 1960
	1.794	4.215		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
32(cont.) [56]	1.901	4.192	$\rho = 50\ \Omega$-cm; index of refraction measured by deviation method; data taken from a figure.	Kornfeld, M.I., 1960
	2.000	4.174		
	2.098	4.159		
	2.210	4.148		
33 [56]	(T=460 K)		High purity germanium; prism cut from a single crystal; prism angle: 4°21'30"; $\rho = 50\ \Omega$-cm; index of refraction measured by deviation method; data taken from a figure.	Kornfeld, M.I., 1960
	1.901	4.230		
	1.993	4.212		
	2.098	4.197		
	2.218	4.184		
34 [45]	(T=298 K)		Thin films of germanium obtained by evaporating very pure germanium in a vacuum from molybdenum or tungsten boats on to glass plates at a pressure on the order of 10^{-5} mmHg; refractive indices determined from the measured values of the transmissivity and reflectivity; data taken from a figure.	Lukes, F., 1960
	0.358	4.001		
	0.377	4.022		
	0.402	3.880		
	0.431	3.717		
	0.471	3.616		
	0.522	4.148		
	0.604	4.905		
	0.648	4.987		
	0.656	5.008		
	0.677	4.927		
	0.802	4.787		
35 [45]	(T=298 K)		Thin films of germanium obtained by evaporating very pure germanium in a vacuum from a molybdenum or tungsten boats on to glass plates at a pressure on the order of 10^{-5} mmHg; refractive indices determined from the measured values of the transmissivity and reflectivity; data taken from a figure.	Lukes, F., 1960
	0.827	4.95		
	0.836	5.01		
	0.875	4.45		
	0.904	4.50		
	0.970	4.88		
	0.973	4.85		
	0.983	4.82		
	1.00	4.55		
	1.04	4.69		
	1.20	4.23		
	1.44	4.15		
	1.50	4.00		
	2.21	3.96		
36 [57]	(T=298 K)		Single crystal; polished specimens of 7 x 7 mm^2 surface; refractive index determined from the reflectance data from the specimen measured in air and in an immersing liquid of known refractive index; data taken from a figure.	Kiseleva, N.K. and Pribytkova, N.N., 1961
	0.43	4.22		
	0.46	4.14		
	0.49	4.10		
	0.52	4.06		
	0.54	4.18		
	0.58	4.42		
	0.60	4.70		
	0.62	4.74		
	0.64	4.74		
	0.66	4.54		
	0.68	4.26		
	0.70	4.15		
	0.73	4.07		
	0.76	3.99		
37 [40]	(T=298 K)		Calculated data based upon similarities in several materials; data taken from a given table.	Hertzberger, M. and Salzberg, C.D., 1962
	2.0	4.1083		
	2.5	4.0664		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
37(cont.)	3.0	4.0449		Hertzberger, M. and Salzberg, C.D., 1962
[40]	3.5	4.0324		
	4.0	4.0244		
	4.5	4.0190		
	5.0	4.0151		
	5.5	4.0123		
	6.0	4.0102		
	6.5	4.0085		
	7.0	4.0072		
	7.5	4.0062		
	8.0	4.0053		
	8.5	4.0046		
	9.0	4.0040		
	9.5	4.0036		
	10.0	4.0032		
	10.5	4.0029		
	11.0	4.0026		
	11.5	4.0024		
	12.0	4.0023		
	12.5	4.0022		
	13.0	4.0021		
	13.5	4.0021		
38	(T=7.5 K)		Single crystal; thin plate specimens of 0.5 to 2.0 mm thick cut perpendicular to the <111> axis; refractive index measured using interference method; refractive indices found to be constant in the region between 23 and 67 μm.	Aronson, J.R., McLinden, H.G., and Gielisse, P.J., 1964
[58]	23-40	3.98±0.02		
	45-67	3.90±0.02		
39	(T=297 K)		Single crystal; thin plate specimens of 0.5 to 2.0 mm thick cut perpendicular to the <111> axis; refractive index measured using interference method.	Aronson, J.R., et al., 1964
[58]	83-143	3.98±0.02		
40	(T=298 K)		Amorphous germanium thin film prepared by evaporation of very pure germanium in a vacuum better than 10^{-5} mmHg on a fused quartz substrate at room temperature; refractive index determined from reflection and transmission measurements; data read from a figure.	Tauc, J., Abraham, A., Pajasova, L., Grigorovici, R., and Vancu, A., 1965
[59]	0.695	4.742		
	0.743	4.792		
	0.797	4.735		
	0.865	4.736		
	0.952	4.637		
	1.147	4.597		
	1.156	4.564		
	1.202	4.506		
	1.263	4.457		
	1.305	4.515		
	1.352	4.424		
	1.403	4.392		
	1.514	4.326		
	1.647	4.260		
	1.742	4.244		
	1.742	4.211		
	1.920	4.162		
	2.105	4.146		
	2.150	4.096		
	2.195	4.096		
	2.331	4.014		
	2.[illegible]73	3.998		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
41	(T=120 K)		Intrinsic germanium; electropolished; the ratio of the reflectances of the parallel and perpendicular components of radiation, and the pseudo-Brewster angle measured; the effects of the presence of the oxide layer were corrected; optical constants were reduced based on the Fresnel relationships; data taken from a figure.	Potter, R.F., 1966
[60]	0.443	4.246		
	0.463	4.305		
	0.480	4.410		
	0.496	4.504		
	0.501	4.551		
	0.508	4.797		
	0.513	4.984		
	0.523	5.172		
	0.537	5.324		
	0.548	5.441		
	0.551	5.523		
	0.557	5.664		
	0.563	5.723		
	0.566	5.770		
	0.566	5.781		
	0.578	5.793		
	0.585	5.723		
	0.591	5.594		
	0.594	5.500		
	0.608	5.453		
	0.619	5.324		
	0.638	5.195		
	0.662	5.066		
	0.679	4.996		
	0.697	4.914		
	0.707	4.820		
	0.726	4.727		
	0.775	4.586		
	0.817	4.516		
	0.886	4.387		
	0.925	4.328		
	0.977	4.281		
	1.015	4.270		
	1.055	4.234		
	1.136	4.188		
	1.244	4.164		
	1.357	4.176		
	1.450	4.152		
	1.512	4.117		
42	(T=300 K)		Intrinsic germanium; electropolished; the ratio of the reflectances of the parallel and perpendicular components of radiation and the pseudo-Brewster angle measured; the effects of the presence of the oxide layer were corrected; optical constants were reduced based on the Fresnel relations; data taken from a figure.	Potter, R.F., 1966
[60]	0.416	4.248		
	0.446	4.259		
	0.461	4.328		
	0.480	4.478		
	0.499	4.663		
	0.516	4.835		
	0.532	5.078		
	0.534	5.239		
	0.546	5.389		
	0.548	5.504		
	0.566	5.573		
	0.579	5.700		
	0.589	5.816		
	0.598	5.885		
	0.612	5.850		
	0.616	5.746		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
42(cont.)	0.627	5.573		Potter, R.F., 1966
[60]	0.638	5.469		
	0.662	5.296		
	0.679	5.157		
	0.692	5.053		
	0.701	5.007		
	0.721	4.961		
	0.746	4.891		
	0.773	4.764		
	0.841	4.614		
	0.930	4.510		
	1.019	4.417		
	1.082	4.394		
	1.153	4.382		
	1.234	4.313		
	1.361	4.289		
	1.476	4.278		
	1.540	4.266		
	1.586	4.231		
	1.687	4.197		
	2.010	4.139		
43	(T=94 K)		Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
[14]	2.554	3.98859		
	2.652	3.98462		
	2.732	3.98052		
	2.856	3.97720		
	2.958	3.97390		
	3.090	3.97100		
	4.120	3.95334		
	5.190	3.94536		
	8.230	3.93720		
	10.270	3.93597		
	12.360	3.94026		
44	(T=204 K)		Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
[14]	2.554	4.02528		
	2.652	4.01955		
	2.732	4.01511		
	2.856	4.01139		
	2.958	4.00796		
	3.090	4.00485		
	4.120	3.98662		
	5.190	3.97820		
	8.230	3.96934		
	10.270	3.96745		
	12.360	3.96625		
45	(T=275 K)		Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
[14]	2.554	4.05659		
	2.652	4.05201		
	2.732	4.04725		
	2.856	4.04338		
	2.958	4.03957		
	3.090	4.03649		
	4.120	4.01732		
	5.190	4.00853		
	8.230	3.99933		
	10.270	3.99729		
	12.360	3.99607		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
46 [14]	(T=297 K)		Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
	2.554	4.06230		
	2.652	4.05754		
	2.732	4.05310		
	2.856	4.04947		
	2.958	4.04595		
	3.090	4.04292		
	4.120	4.02457		
	5.190	4.01617		
	8.230	4.00743		
	10.270	4.00571		
	12.360	4.00627		
47 [33]	(T=300 K)		Single crystal; obtained from Exotic Materials, Costa Mesa, CA; $\rho > 20$ Ω-cm; plate specimen of 1.93837 ± 1.3 x 10^{-4} mm thick; refractive indices measured using interference method; data taken from a figure.	Randall, C.M. and Rawcliffe, R.D., 1967
	69.793	4.0065		
	72.491	4.0058		
	75.686	4.0055		
	77.691	4.0060		
	81.374	4.0057		
	85.075	4.0058		
	88.748	4.0062		
	92.747	4.0062		
	97.584	4.0062		
	101.94	4.0066		
	108.38	4.0065		
	113.77	4.0066		
	121.13	4.0064		
	128.71	4.0066		
	137.30	4.0066		
	148.17	4.0066		
	159.65	4.0063		
	173.06	4.0061		
	199.68	4.0059		
	210.15	4.0058		
	236.70	4.0054		
	267.42	4.0051		
	311.98	4.0049		
	367.59	4.0045		
	447.46	4.0043		
48 [33]	(T=300 K)		Single crystal; obtained from Exotic Materials, Costa Mesa, CA; $\rho > 10$ Ω-cm; plate specimen of 6.22931 ± 1.3 x 10^{-4} mm thick; refractive indices measured using interference method; data taken from a figure.	Randall, C.M. and Rawcliffe, R.D., 1967
	79.470	4.0042		
	81.682	4.0045		
	85.062	4.0049		
	88.726	4.0047		
	92.729	4.0051		
	97.106	4.0052		
	102.42	4.0055		
	107.79	4.0055		
	113.75	4.0058		
	121.11	4.0059		
	128.68	4.0059		
	137.28	4.0059		
	148.14	4.0059		
	159.63	4.0059		
	173.04	4.0056		
	188.92	4.0057		
	212.29	4.0055		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
48(cont.) [33]	233.98	4.0052		Randall, C.M. and Rawcliffe, R.D., 1967
	264.01	4.0053		
	307.37	4.0052		
	361.28	4.0050		
	447.64	4.0048		
	587.95	4.0041		
49 [61]	(T=298 K)		Thin film of 1 x 10^{-3} mm thick obtained from evaporation of crystal germanium, with ρ=40 Ω-cm, from graphite boats in a vacuum of 2-5 x 10^{-5} Torr; polished plates of barium fluoride served as the substrates at temperature of 293-303 K during evaporation; optical constants determined from the transmission of the films and the order of interference; data taken from a figure.	Gisin, M.A. and Ivanov, V.A., 1967
	1.485	4.685		
	1.487	4.572		
	1.536	4.410		
	1.633	4.249		
	1.777	4.108		
	1.873	4.023		
	2.039	3.953		
	2.230	3.897		
	2.420	3.855		
	2.634	3.813		
	2.895	3.778		
	3.132	3.764		
	3.441	3.757		
	3.702	3.751		
	3.963	3.744		
	4.224	3.737		
	4.485	3.730		
	4.769	3.717		
	5.007	3.717		
	5.291	3.710		
	5.552	3.703		
	5.837	3.697		
	6.098	3.683		
	6.335	3.683		
	6.454	3.683		
50 [61]	(T=298 K)		Thin films of 1 x 10^{-3} mm thick obtained from evaporation of crystal germanium, with ρ=40 Ω-cm, from graphite boats in a vacuum of 2.5 x 10^{-5} Torr; polished plates of barium fluoride served as the substrates at temperature of 403-423 K during evaporation; optical constants determined from the transmission of the films and the order of interference; data taken from a figure.	Gisin, M.A. and Ivanov, V.A., 1967
	1.367	4.692		
	1.416	4.565		
	1.464	4.453		
	1.561	4.340		
	1.681	4.213		
	1.895	4.101		
	2.158	3.989		
	2.467	3.904		
	2.847	3.841		
	3.274	3.807		
	3.725	3.786		
	4.128	3.779		
	4.579	3.773		
	5.053	3.773		
	5.457	3.774		
	5.883	3.767		
	6.334	3.767		
	6.429	3.760		
51 [61]	(T=298 K)		Thin films of 1 x 10^{-3} mm thick obtained from evaporation of crystal germanium, with ρ=40 Ω-cm, from graphite boats in a vacuum of 2.5 x 10^{-5} Torr; polished	Gisin, M.A. and Ivanov, V.A., 1967
	1.272	4.678		
	1.273	4.593		
	1.298	4.467		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
51(cont.) [61]	1.371	4.368	plates of barium fluoride served as the substrates at temperatures of 523-573 K during evaporation; optical constants determined from the transmission of the films and the order of interference; data taken from a figure.	Gisin, M.A. and Ivanov, V.A., 1967
	1.442	4.305		
	1.538	4.234		
	1.681	4.171		
	1.848	4.115		
	2.109	4.073		
	2.371	4.024		
	2.703	3.989		
	3.130	3.961		
	3.581	3.948		
	4.032	3.934		
	4.482	3.935		
	4.909	3.928		
	5.407	3.921		
	5.977	3.915		
	6.309	3.915		
	6.498	3.915		
52 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick prepared by thermal evaporation from an electron beam heated source on to unheated substrates in a vacuum of 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference fringe order observations; averaged values read from a best fit curve.	Wales, J., Lovitt, G.J., and Hill, R.A., 1967
	1.464	4.576		
	1.640	4.527		
	1.916	4.468		
	2.167	4.428		
	2.493	4.384		
	2.843	4.344		
	3.369	4.310		
	3.919	4.296		
	4.445	4.281		
	4.870	4.276		
	5.220	4.272		
	5.445	4.267		
53 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on unheated substrates from an electron beam heated source in a vacuum of 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference fringe order observations; averaged values read from a best fit curve.	Wales, J., et al., 1967
	1.359	4.788		
	1.406	4.724		
	1.477	4.651		
	1.547	4.592		
	1.686	4.533		
	1.847	4.483		
	2.009	4.438		
	2.216	4.406		
	2.400	4.379		
	2.653	4.361		
	2.951	4.339		
	3.319	4.317		
	3.755	4.303		
	4.053	4.294		
	4.283	4.290		
	4.512	4.286		
	4.719	4.286		
54 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on unheated substrates from an electron beam heated source in an atmosphere of oxygen at 1 x 10^{-4} Torr; refractive indices determined from the sample thickness and interference order	Wales, J., et al., 1967
	1.316	4.543		
	1.410	4.493		
	1.503	4.439		
	1.644	4.381		
	1.806	4.340		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
54(cont.) [62]	1.992	4.304	observations; averaged values read from a best fit curve.	Wales, J., Lovitt, G.J., and Hill, R.A., 1967
	2.269	4.264		
	2.478	4.242		
	2.709	4.224		
	2.962	4.211		
	3.285	4.202		
	3.562	4.193		
	3.908	4.185		
	4.277	4.176		
	4.600	4.177		
	5.015	4.168		
	5.314	4.173		
	5.567	4.173		
55 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on unheated substrates from an electron beam heated source in an atmosphere of nitrogen at 1 x 10^{-6} Torr; refractive indices determined from sample thickness and interference fringe order observation; averaged values read from a best fit curve.	Wales, J., et al., 1967
	1.463	4.679		
	1.551	4.606		
	1.641	4.560		
	1.776	4.519		
	1.935	4.487		
	2.094	4.455		
	2.276	4.432		
	2.618	4.390		
	3.006	4.367		
	3.395	4.348		
	3.716	4.333		
	4.082	4.328		
	4.610	4.322		
	5.023	4.321		
	5.436	4.325		
	5.734	4.324		
	6.009	4.328		
56 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on unheated substrates from an electron beam heated source in an atmosphere of hydrogen at 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference fringe order observations; averaged values read from a best fit curve.	Wales, J., et al., 1967
	1.560	4.681		
	1.608	4.640		
	1.679	4.595		
	1.773	4.546		
	1.912	4.501		
	2.006	4.452		
	2.191	4.416		
	2.445	4.371		
	2.698	4.345		
	2.973	4.323		
	3.293	4.305		
	3.637	4.288		
	4.003	4.280		
	4.391	4.276		
	4.779	4.273		
	5.099	4.278		
	5.418	4.278		
	5.624	4.283		
57 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on cooled substrates at 273 K from a carbon boat in a vacuum of 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference	Wales, J., et al., 1967
	1.265	4.605		
	1.266	4.556		
	1.336	4.493		
	1.405	4.435		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
57(cont.) [62]	1.498	4.386	fringe order observation; averaged values read from a best fit curve.	Wales, J., Lovitt, G.J., and Hill, R.A., 1967
	1.636	4.318		
	1.728	4.292		
	1.911	4.256		
	2.140	4.216		
	2.392	4.193		
	2.643	4.176		
	3.100	4.158		
	3.420	4.149		
	3.808	4.141		
	4.219	4.141		
	4.562	4.141		
	4.859	4.141		
	5.132	4.146		
58 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on substrates at 373-473 K from a carbon boat in a vacuum of 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference fringe order observations; averaged values read from a best fit curve.	Wales, J., et al., 1967
	1.300	4.570		
	1.425	4.492		
	1.525	4.427		
	1.675	4.373		
	1.825	4.319		
	1.973	4.280		
	2.150	4.250		
	2.325	4.220		
	2.600	4.196		
	2.925	4.186		
	3.300	4.181		
	3.825	4.171		
	4.250	4.166		
	4.650	4.156		
	5.025	4.156		
	5.325	4.146		
	5.575	4.142		
	5.700	4.142		
59 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on substrates at 673 K from a carbon boat in a vacuum of 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference fringe observations; averaged values read from a best fit curve.	Wales, J., et al., 1967
	1.256	4.386		
	1.370	4.314		
	1.507	4.250		
	1.644	4.205		
	1.804	4.145		
	1.963	4.100		
	2.192	4.059		
	2.420	4.027		
	2.808	4.000		
	3.174	3.995		
	3.539	3.991		
	3.950	3.986		
	4.498	3.982		
	4.840	3.986		
	5.114	3.995		
60 [62]	(T=298 K)		Thin film samples of 0.5-5 μm thick deposited on substrate at 773-873 K from a carbon boat in a vacuum of 1 x 10^{-6} Torr; refractive indices determined from the sample thickness and interference fringe order observations;	Wales, J., et al., 1967
	1.593	4.381		
	1.662	4.286		
	1.845	4.204		
	1.983	4.150		
	2.191	4.104		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
60(cont.) [62]	2.605	4.063	averaged values read from a best fit curve.	Wales, J., Lovitt, G.J., and Hill, R.A., 1967
	2.974	4.045		
	3.388	4.031		
	3.849	4.026		
	4.264	4.022		
	4.702	4.026		
	5.001	4.026		
61 [62]	(T=298 K)		Film samples deposited from carbon boat source; refractive indices determined from the sample thickness and interference fringe order observation; averaged values read from a best fit curve.	Wales, J., et al., 1967
	1.420	4.530		
	1.512	4.482		
	1.667	4.422		
	1.821	4.385		
	2.068	4.336		
	2.377	4.298		
	2.778	4.277		
	3.148	4.266		
	3.488	4.250		
	3.858	4.239		
	4.259	4.239		
	4.691	4.234		
	5.062	4.234		
	5.278	4.223		
	5.617	4.223		
	5.988	4.234		
62 [63]	(T=298 K)		Single crystal; ρ=40 Ω-cm; n-type; specimens with <111> surfaces cleaved by the Gobeli-Allen technique; refractive index determined by ellipsometry method; the average value reported with error ±0.10.	Knausenberger, W.H. and Vedam, K., 1969
	0.5461	5.46		
63 [64]	(T=298 K)		Amorphous Ge films; vacuum deposited onto rotating substrates of fused quartz, fused silica and KCl; evaporation sources of tungsten boat, Al_2O_3-coated boat and electron beam gun; deposition rate 10-50 Å/sec; refractive indices determined from the reflectance and transmittance measurements made in a dry nitrogen atmosphere; average values of refractive indices of films of thicknesses 0.0816 μm, 0.2138 μm, 0.3576 μm and 0.5371 μm taken from a table.	Donovan, T.M., Spicer, W.E., Bennett, J.M., and Ashley, E.J., 1970
	1.0	4.67		
	1.1	4.59		
	1.2	4.55		
	1.3	4.31		
	1.4	4.34		
	1.5	4.30		
	1.6	4.24		
	1.7	4.22		
	1.8	4.24		
	1.9	4.11		
	2.0	4.09		
	2.1	4.07		
	2.2	4.06		
	2.3	4.06		
	2.4	4.06		
	2.5	4.07		
	2.6	4.05		
	2.7	4.04		
	2.8	3.97		
	2.9	4.01		
	3.0	4.00		
	3.1	3.99		
	3.2	4.00		
	3.3	3.99		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
63(cont.) [64]	3.4	4.00		Donovan, T.M., Spicer, W.E., Bennett, J.M., and Ashley, E.J., 1970
	3.5	3.99		
	3.6	4.00		
	3.7	3.99		
	3.8	4.00		
	3.9	3.995		
	4.0	4.00		
64 [64]	(T=298 K)		Amorphous Ge film of 0.5371 μm; vacuum deposited onto rotating substrate of KCl; evaporation sources of tungsten boat, Al_2O_3-coated boat and electron beam gun; deposition rate 10-50 Å/sec; refractive indices determined from the reflectance and transmittance measurements made in a dry nitrogen atmosphere; data taken from a table.	Donovan, T.M., et al., 1970
	4.0	4.02		
	4.4	4.06		
	4.8	4.01		
	5.2	4.01		
	5.6	4.01		
	6.0	4.01		
	6.4	3.98		
	6.8	4.11		
	7.2	3.99		
	7.6	4.04		
	8.0	3.98		
	8.5	3.98		
	9.0	3.99		
	9.5	3.97		
	10.0	3.98		
	11.0	3.95		
	12.0	3.98		
	13.0	3.98		
	13.5	3.99		
	13.7	4.01		
65 [65]	(T=300 K)		Single crystal polished and etched; optical constants determined by the ellipsometric method; data extracted from a figure.	Jungk, G., 1971
	0.294	3.397		
	0.298	3.437		
	0.303	3.463		
	0.307	3.437		
	0.309	3.437		
	0.313	3.437		
	0.316	3.424		
	0.321	3.424		
	0.325	3.489		
	0.330	3.489		
	0.335	3.528		
	0.339	3.580		
	0.344	3.632		
	0.349	3.659		
	0.353	3.659		
	0.360	3.685		
	0.368	3.698		
	0.374	3.737		
	0.380	3.763		
	0.385	3.789		
	0.392	3.776		
	0.397	3.737		
	0.404	3.724		
	0.413	3.698		
	0.426	3.672		
	0.442	3.672		
	0.454	3.711		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
65(cont.) [65]	0.472	3.802		Jungk, G., 1971
	0.484	3.907		
	0.489	3.972		
	0.494	3.969		
	0.506	4.088		
	0.514	4.236		
	0.519	4.341		
	0.524	4.445		
	0.530	4.608		
	0.533	4.668		
	0.540	4.757		
	0.547	4.817		
	0.555	4.861		
	0.562	4.980		
	0.566	5.055		
	0.571	5.144		
	0.573	5.233		
	0.579	5.337		
	0.583	5.397		
	0.587	5.456		
	0.589	5.486		
	0.595	5.471		
	0.600	5.426		
	0.605	5.382		
	0.609	5.337		
	0.614	5.292		
	0.621	5.247		
	0.625	5.188		
	0.638	5.083		
66 [65]	(T=300 K)		Amorphous germanium; thin film specimen of about 1 μm thick prepared by thermal evaporation of germanium from a tungsten boat on glass substrate in a vacuum of 10^{-6} Torr; substrate held at 293 K during evaporation; refractive indices determined by ellipsometric method; data taken from a figure.	Jungk, G., 1971
	0.672	2.911		
	0.691	3.024		
	0.712	3.137		
	0.738	3.242		
	0.765	3.347		
	0.794	3.500		
	0.809	3.557		
	0.824	3.605		
	0.839	3.686		
	0.860	3.750		
	0.877	3.807		
	0.895	3.871		
	0.913	3.920		
	0.932	3.984		
	0.952	4.049		
	0.972	4.089		
	0.994	4.154		
	1.021	4.202		
	1.044	4.243		
	1.073	4.299		
67 [65]	(T=300 K)		Amorphous germanium; thin film specimen of about 1 μm thick prepared by thermal evaporation of germanium from a tungsten boat on glass substrate in a vacuum of 10^{-6} Torr; substrate held at 373 K during evaporation; refractive indices	Jungk, G., 1971
	0.533	2.033		
	0.547	2.098		
	0.562	2.177		
	0.578	2.308		
	0.597	2.439		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
67(cont.) [65]	0.615	2.583	determined by ellipsometric method; data taken from a table.	Jungk, G., 1971
	0.631	2.635		
	0.651	2.740		
	0.669	2.923		
	0.692	3.041		
	0.715	3.146		
	0.738	3.238		
	0.765	3.356		
	0.810	3.526		
	0.822	3.591		
	0.843	3.670		
	0.856	3.722		
	0.884	3.775		
	0.898	3.853		
	0.913	3.906		
	0.934	3.971		
	0.955	4.023		
	0.978	4.076		
	0.995	4.154		
	1.020	4.181		
	1.046	4.233		
	1.073	4.272		
	1.132	4.351		
	1.198	4.430		
68 [65]	(T=300 K)		Amorphous germanium; thin film specimen of about 1 μm thick prepared by thermal evaporation of germanium from a tungsten boat on glass substrate in a vacuum of 10^{-6} Torr; substrate held at 473 K during evaporation; refractive indices determined by ellipsometric method; data taken from a figure.	Jungk, G., 1971
	0.670	2.791		
	0.691	2.895		
	0.713	2.968		
	0.736	3.057		
	0.763	3.154		
	0.795	3.267		
	0.824	3.364		
	0.858	3.477		
	0.895	3.574		
	0.933	3.647		
	0.973	3.736		
	1.018	3.809		
	1.066	3.882		
69 [65]	(T=300 K)		Microcrystalline germanium; thin film specimen of about 1 μm thick prepared by thermal evaporation of germanium from a tungsten boat on glass substrate in a vacuum of 10^{-6} Torr; substrate held at 573 K during evaporation; refractive indices determined by ellipsometric method; data taken from a figure.	Jungk, G., 1971
	0.535	2.647		
	0.549	2.699		
	0.564	2.817		
	0.580	2.948		
	0.594	3.053		
	0.614	3.040		
	0.633	3.145		
	0.650	3.223		
	0.672	3.302		
	0.691	3.329		
	0.715	3.368		
	0.741	3.395		
	0.765	3.447		
	0.799	3.565		
	0.806	3.617		
	0.826	3.670		
	0.843	3.774		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
69(cont.) [65]	0.861	3.866		Jungk, G., 1971
	0.879	3.971		
	0.898	4.114		
	0.913	4.193		
	0.939	4.298		
	0.961	4.389		
	0.977	4.468		
	1.007	4.546		
	1.026	4.599		
	1.052	4.651		
	1.087	4.573		
	1.125	4.129		
70 [65]	(T=300 K)		Amorphous germanium; thin film specimen of about 1 μm thick prepared by thermal evaporation of germanium from a tungsten boat on glass substrate in a vacuum of 10^{-6} Torr; substrate held at 673 K during evaporation; refractive indices determined by ellipsometric method; data taken from a figure.	Jungk, G., 1971
	0.497	2.942		
	0.501	2.972		
	0.504	3.002		
	0.508	3.063		
	0.510	3.093		
	0.515	3.138		
	0.517	3.168		
	0.522	3.244		
	0.524	3.274		
	0.528	3.334		
	0.533	3.394		
	0.537	3.440		
	0.541	3.470		
	0.546	3.530		
	0.550	3.561		
	0.556	3.636		
	0.559	3.666		
	0.563	3.712		
	0.567	3.787		
	0.572	3.932		
	0.578	3.923		
	0.581	3.968		
	0.585	4.013		
	0.592	4.058		
	0.596	4.074		
	0.600	4.089		
	0.605	4.089		
	0.610	4.074		
	0.616	4.045		
	0.621	3.985		
	0.628	3.910		
	0.638	3.806		
71 [46]	(T=293 K)		Single crystal; grown at the Royal Signals and Radar Establishment, Malvern, U.K. using the Czochraski pulling technique; ρ = 45-53 Ω-cm; prismatic specimen of 10.5 degree apex angle and 30 mm x 15 mm faces; refractive index measurements made at the Institut d'Optique, Orsay, France; data taken from a table.	Edwin, R.P., Dudermel, M.T., and Lamare, M., 1978
	8.00	4.0058		
	9.00	4.0043		
	10.00	4.0032		
	11.25	4.0022		
	12.00	4.0017		
	13.00	4.0013		
	14.00	4.0011		

TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

Data Set [Ref.]	λ	n	Specifications and Remarks	Author(s), Year
72 [46]	(T=293 K)		Single crystal; grown at the Royal Signals and Radar Establishment, Malvern, U.K. using the Czochraski pulling technique; ρ = 45-53 Ω-cm; prismatic specimen of 10.5 degree apex angle and 30 mm x 50 mm faces; refractive index measurements made at the National Physical Laboratory, U.K.; data taken from a table.	Edwin, R.P., Dudermel, M.T., and Lamare, M., 1978
	8.00	4.00551		
	9.00	4.00423		
	10.00	4.00329		
	11.25	4.00242		
	12.00	4.00204		
	13.00	4.00157		
	14.00	4.00123		
73 [46]	(T=298 K)		Single crystal; grown at the Royal Signals and Radar Establishment, Malvern, U.K. using the Czochraski pulling technique; ρ = 45-53 Ω-cm; prismatic specimen of 10.5 degree apex angle and 30 mm x 15 mm faces; refractive index measurements made at the National Physical Laboratory, U.K.; data taken from a table.	Edwin, R.P., et al., 1978
	8.00	4.00748		
	9.00	4.00620		
	10.00	4.00525		
	11.25	4.00436		
	12.00	4.00398		
	13.00	4.00352		
	14.00	4.00315		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence)

[Temperature, T, K; Wavelength, λ, μm; Refractive Index, n]

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
1 [66]	(λ=2.00 μm)		High purity single crystal; prism specimen of about 20 degree apex angle; accuracy of deviation angle measurement about 1' corresponding to an error of 0.001 in refractive index; average accuracy of temperature measurement about 0.5 K; data read from a figure.	Lukes, F., 1958
	113.593	4.025		
	116.291	4.023		
	202.919	4.067		
	208.329	4.068		
	208.338	4.071		
	211.027	4.067		
	228.630	4.078		
	258.408	4.093		
	261.111	4.093		
	273.295	4.099		
	292.254	4.112		
	309.848	4.120		
	323.383	4.127		
	342.337	4.138		
	354.522	4.144		
	370.764	4.153		
	391.061	4.161		
	392.421	4.163		
	407.312	4.172		
2 [66]	(λ=2.00 μm)		High purity single crystal; prism specimen of about 20 degree apex angle; accuracy of deviation angle measurement about 1' corresponding to an error of 0.001 in refractive index; average accuracy of temperature measurement about 0.5 K; data taken from a figure.	Lukes, F., 1958
	114.759	4.024		
	117.425	4.024		
	205.588	4.067		
	208.260	4.068		
	210.937	4.071		
	213.593	4.068		
	229.634	4.079		
	263.018	4.093		
	263.029	4.095		
	275.044	4.099		
	292.423	4.111		
	309.782	4.118		
	320.479	4.126		
	353.879	4.144		
	369.909	4.152		
	389.940	4.160		
	391.283	4.162		
	408.652	4.172		
	436.693	4.182		
3 [66]	(λ=2.26 μm)		High purity single crystal; prism specimen of about 20 degree apex angle; accuracy of deviation angle measurement about 1' corresponding to an error of 0.001 in refractive index; average accuracy of temperature measurement about 0.5 K; data read from a figure.	Lukes, F., 1958
	113.540	4.008		
	116.229	4.004		
	117.590	4.007		
	205.555	4.046		
	208.262	4.048		
	232.617	4.057		
	250.216	4.067		
	275.927	4.077		
	293.521	4.086		
	308.408	4.092		
	323.290	4.098		
	344.947	4.109		
	354.429	4.116		
	370.667	4.122		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
3(cont.) [66]	390.964	4.131		Lukes, F., 1958
	411.269	4.141		
	438.336	4.154		
4 [66]	(λ=2.36 μm)		High purity single crystal; prism specimen of about 20 degree apex angle; accuracy of deviation angle measurement about 1' corresponding to an error of 0.001 in refractive index; average accuracy of temperature measurement about 0.5 K; data taken from a figure.	Lukes, F., 1958
	113.349	4.004		
	117.338	4.001		
	117.349	4.004		
	208.168	4.044		
	210.835	4.044		
	212.178	4.047		
	234.881	4.056		
	252.250	4.066		
	274.957	4.076		
	290.988	4.084		
	309.680	4.091		
	321.705	4.098		
	343.084	4.110		
	356.428	4.113		
	369.797	4.122		
	391.156	4.129		
	411.196	4.139		
	437.909	4.151		
5 [66]	(λ=2.51 μm)		High purity single crystal; prism specimen of about 20 degree apex angle; accuracy of deviation angle measurement about 1' corresponding to an error of 0.001 in refractive index; average accuracy of temperature measurement about 0.5 K; data read from a figure.	Lukes, F., 1958
	205.502	4.030		
	213.619	4.032		
	216.326	4.034		
	256.933	4.054		
	275.869	4.060		
	293.463	4.068		
	309.706	4.076		
	321.886	4.081		
	346.245	4.092		
	357.074	4.098		
	370.605	4.103		
	393.609	4.113		
	409.856	4.122		
	438.261	4.130		
6 [66]	(λ=2.52 μm)		High purity single crystal; prism specimen of about 20 degree apex angle; accuracy of deviation angle measurement about 1' corresponding to an error of 0.001 in refractive index; average accuracy of temperature measurement about 0.5 K; data taken from a figure.	Lukes, F., 1958
	208.112	4.029		
	216.122	4.032		
	260.209	4.055		
	276.234	4.061		
	294.931	4.070		
	309.623	4.076		
	322.977	4.082		
	345.685	4.092		
	356.372	4.098		
	368.397	4.104		
	392.438	4.115		
	409.797	4.122		
	437.837	4.132		
7 [44]	(λ=1.970 μm)		Pure germanium crystal; prism angle: 14°53'; ρ=1.2 Ω-cm; minimum deviation method used; data read from a figure.	Lukes, F., 1960
	104.591	4.028		
	108.842	4.029		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
7(cont.) [44]	115.943	4.032		Lukes, F., 1960
	134.396	4.038		
	158.571	4.049		
	168.487	4.051		
	179.873	4.058		
	188.399	4.061		
	198.326	4.064		
	208.276	4.068		
	216.791	4.071		
	229.602	4.078		
	236.714	4.082		
	243.826	4.085		
	249.525	4.089		
	252.374	4.091		
	259.486	4.094		
	273.699	4.100		
	282.236	4.105		
	289.348	4.109		
	296.449	4.111		
	302.136	4.114		
	312.109	4.120		
	323.507	4.127		
	332.032	4.131		
	336.284	4.132		
	339.144	4.135		
	344.832	4.137		
	349.117	4.141		
	353.391	4.144		
	366.191	4.150		
	374.716	4.153		
	380.415	4.157		
	386.125	4.161		
	393.249	4.166		
	398.947	4.170		
	408.898	4.174		
	414.630	4.180		
8 [44]	(λ=2.190 μm)		Pure germanium crystal; prism angle: 14°53'; ρ=1.2 Ω-cm; minimum deviation method used; data read from a figure.	Lukes, F., 1960
	109.878	4.005		
	115.501	4.006		
	142.275	4.017		
	156.364	4.022		
	167.637	4.027		
	180.304	4.030		
	188.770	4.035		
	201.455	4.040		
	208.526	4.046		
	221.193	4.049		
	222.624	4.052		
	233.879	4.055		
	242.335	4.058		
	250.801	4.063		
	255.030	4.065		
	263.486	4.068		
	277.593	4.075		
	284.646	4.079		
	297.323	4.083		
	304.385	4.088		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
8(cont.)	312.860	4.093		Lukes, F., 1960
[44]	321.334	4.099		
	332.598	4.102		
	342.485	4.109		
	352.346	4.112		
	360.829	4.118		
	376.331	4.125		
	379.165	4.127		
	390.446	4.133		
	398.921	4.138		
	407.378	4.142		
	421.511	4.152		
	435.609	4.158		
	439.838	4.160		
	445.487	4.163		
	459.603	4.171		
	468.096	4.179		
	479.378	4.184		
	487.852	4.189		
	499.161	4.197		
	506.205	4.200		
	517.514	4.208		
	525.971	4.212		
	534.464	4.219		
9	(λ=2.409 μm)		Pure germanium crystal; prism angle: 14°53'; ρ=1.2 Ω-cm; minimum deviation method used; data read from a figure.	Lukes, F., 1960
[44]	147.914	4.003		
	159.202	4.006		
	176.157	4.013		
	198.746	4.021		
	205.815	4.024		
	215.721	4.030		
	224.192	4.033		
	234.078	4.037		
	236.916	4.039		
	246.808	4.044		
	253.884	4.048		
	263.771	4.052		
	268.009	4.054		
	273.670	4.057		
	282.148	4.061		
	287.802	4.064		
	293.449	4.065		
	301.927	4.069		
	330.210	4.084		
	357.065	4.097		
	376.858	4.107		
	389.581	4.113		
	405.128	4.120		
	416.449	4.128		
	429.179	4.135		
	441.909	4.142		
	448.992	4.147		
	467.356	4.155		
	482.909	4.163		
	495.639	4.170		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
10 [44]	(λ=3.826 μm)		Pure germanium crystal; prism angle: 14°53'; ρ=1.2 Ω-cm; minimum deviation method used; data read from a figure.	Lukes, F., 1960
	306.022	4.030		
	320.151	4.034		
	332.917	4.041		
	342.821	4.045		
	358.393	4.051		
	369.728	4.056		
	379.654	4.062		
	383.879	4.062		
	383.902	4.063		
	388.150	4.065		
	398.076	4.071		
	403.721	4.071		
	419.315	4.079		
	434.898	4.087		
	439.180	4.091		
	456.160	4.097		
	474.593	4.107		
	485.917	4.112		
	497.263	4.118		
	505.758	4.121		
	522.761	4.129		
	535.516	4.136		
11 [44]	(λ=5.156 μm)		Pure germanium crystal; prism angle: 14°53'; ρ=1.2 Ω-cm; minimum deviation method used; data read from a figure.	Lukes, F., 1960
	301.528	4.016		
	321.286	4.021		
	335.432	4.029		
	346.740	4.035		
	363.688	4.041		
	386.311	4.053		
	408.920	4.063		
	424.467	4.070		
	437.184	4.075		
	461.208	4.086		
	472.516	4.092		
12 [14]	(λ=2.554 μm)		Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen; measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
	150	4.00541		
	158	4.00775		
	165	4.00997		
	172	4.01248		
	177	4.01479		
	186	4.01753		
	192	4.02031		
	199	4.02305		
	203	4.02492		
	208	4.02712		
	212	4.02900		
	216	4.03039		
	221	4.03287		
	227	4.03601		
	231	4.03721		
	236	4.03893		
	240	4.04096		
	243	4.04209		
	247	4.04407		
	254	4.04641		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
12(cont.)	257	4.04832		Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
[14]	261	4.04994		
	266	4.05181		
	269	4.05284		
	272	4.05429		
	277	4.05655		
	281	4.05836		
13	(λ=2.732 μm)		Good optical grade germanium samples; supplied by Exotic Materials Inc.; prism specimen; measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
[14]	101	3.98111		
	110	3.98237		
	117	3.98419		
	120	3.98508		
	127	3.98728		
	133	3.98888		
	140	3.99107		
	146	3.99331		
	152	3.99534		
	158	3.99774		
	165	4.00026		
	171	4.00277		
	178	4.00565		
	186	4.00938		
	196	4.01293		
	203	4.01582		
	212	4.01918		
	221	4.02229		
	229	4.02516		
	236	4.02893		
	244	4.03202		
	252	4.03554		
	257	4.03767		
	262	4.03937		
	270	4.04257		
	276	4.04562		
	283	4.04833		
14	(λ=4.414 μm)		Good optical grade germanium samples; supplied by Exotic Materials Inc.; prism specimen; measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
[14]	101	3.95198		
	107	3.95220		
	114	3.95407		
	121	3.95579		
	129	3.95798		
	137	3.96026		
	145	3.96295		
	150	3.96463		
	156	3.96678		
	165	3.96806		
	169	3.97126		
	177	3.97422		
	185	3.97922		
	195	3.98276		
	202	3.98493		
	211	3.98699		
	218	3.98967		
	224	3.99240		
	232	3.99591		
	240	3.99920		

TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

Data Set [Ref.]	T	n	Specifications and Remarks	Author(s), Year
14(cont.) [14]	249	4.00305		Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1976
	259	4.00655		
	263	4.00848		
	269	4.01095		
	274	4.01236		
	278	4.01435		
	283	4.01635		
15 [14]	(λ=10.27 μm)		Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen; measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., et al., 1976
	95	3.93562		
	104	3.93692		
	112	3.93909		
	120	3.94088		
	124	3.94335		
	134	3.94501		
	140	3.94639		
	147	3.94898		
	153	3.95075		
	160	3.95295		
	166	3.95497		
	173	3.95754		
	183	3.96090		
	192	3.96390		
	204	3.96808		
	210	3.97028		
	217	3.97296		
	226	3.97587		
	234	3.86896		
	239	3.98113		
	246	3.98387		
	253	3.98633		
	260	3.98923		
	268	3.99203		
	274	3.99458		
	278	3.99634		
	284	3.9985		

TABLE A-7. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)

[Temperature, T, K; Wavelength, λ, μm; Temperature Derivative of Refractive Index, dn/dT, 10^{-4} K^{-1}]

Data Set [Ref.]	λ	dn/dT	Specifications and Remarks	Author(s), Year
1 [43]	(T=297.5 K)		Germanium crystal; grown at the General Electric Co., Electronics Laboratory, Electronic Park, Syracuse, NY; plane parallel plate specimen of 3.0575 mm thick and 28 mm clear aperture; refractive indices measured by interference method; dn/dT determined; data taken from a table.	Rank, O.H., Bennett, H.E., and Cronemeyer, D.C., 1954
	1.934	5.919		
	2.174	5.285		
	2.246	5.251		
	2.401	5.037		
2 [66]	(T=116-440 K)		Single crystal; high purity; prism specimen of about 20 degree apex angle; refractive index for several wavelengths measured in the temperature range between 116 and 440 K; it was found that the refractive index of germanium increases linearly with the temperature in the wavelength region between 1.8 and 2.5 μm; dn/dT determined; data taken from a figure.	Lukes, F., 1957
	1.82	5.36		
	1.90	5.10		
	1.98	5.00		
	2.07	4.84		
	2.25	4.60		
	2.34	4.55		
	2.51	4.39		
3 [67]	(T=116-440 K)		High purity single crystal; prism specimen of 20 degree apex angle; refractive indices determined in the temperature range from 116 to 440 K; dn/dT determined; data taken from a figure.	Lukes, F., 1958
	0.961	9.352		
	0.961	8.929		
	1.349	6.890		
	1.349	6.819		
	1.349	6.608		
	1.918	5.097		
	2.000	4.992		
	2.075	4.852		
	2.260	4.607		
	2.349	4.537		
	2.514	4.432		
4 [67]	(T=116-440 K)		High purity single crystal; prism specimen of 20 degree apex angle; refractive indices determined in the temperature range from 116 to 440 K; dn/dT determined; data taken from a figure.	Lukes, F., 1958
	0.667	-13.038		
	0.957	10.688		
5 [44]	(T=100-540 K)		Pure germanium crystal; prism angle about 20 degrees: ρ=40 Ω-cm; minimum deviation method used for refractive indices determined; dn/dT determined; data taken from a figure.	Lukes, F., 1960
	1.96	5.20		
	2.17	4.79		
	3.81	4.09		
	5.07	3.99		
6 [44]	(T=100-540 K)		Pure germanium crystal; prism angle about 15 degrees: ρ=1.2 Ω-cm; minimum deviation method used for refractive indices determination; dn/dT determined data taken from a figure.	Lukes, F., 1960
	1.96	5.29		
	2.17	4.81		
	2.39	4.59		
	3.81	4.24		
	5.06	4.14		
7 [44]	(T=100-540 K)		Pure germanium crystal; prism angle about 15 degree; ρ=0.016 Ω-cm; minimum deviation method used to determine the	Lukes, F., 1960
	2.19	4.887		
	2.40	4.685		

TABLE A-7. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

Data Set [Ref.]	λ	dn/dT	Specifications and Remarks	Author(s), Year
7(cont.) [44]	3.82 5.05	3.989 3.952	refractive index; dn/dT determined; data taken from a figure.	Lukes, F., 1960
8 [14]	(T=173-298 K) 2.554 to 12.1	3.96	Good optical grade germanium samples; supplied by Exotic Materials, Inc.; prism specimen; measured with a modified minimum deviation method; data taken from a table.	Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1967

TABLE A-8. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence)

[Temperature, T, K; Wavelength, λ, μm; Temperature Derivative of Refractive Index, dn/dT, $10^{-4}K^{-1}$]

Data Set [Ref.]	T	dn/dT	Specifications and Remarks	Author(s), Year
1 [44]	(λ=1.970 μm)		Pure germanium crystal; prism angle of 14°53.0'; ρ=1.2 Ω-cm; measurements made by minimum deviation method; data taken from a figure.	Lukes, F., 1960
	140.663	3.902		
	170.323	3.982		
	210.824	4.523		
	251.266	4.602		
	297.157	5.143		
	330.895	5.494		
	370.035	5.926		
2 [44]	(λ=2.190 μm)		Pure germanium crystal; prism angle of 14°53.0'; ρ=1.2 Ω-cm; measurements made by minimum deviation method; data taken from a figure.	Lukes, F., 1960
	109.596	3.361		
	139.302	3.794		
	170.313	3.901		
	210.775	4.143		
	251.255	4.521		
	295.771	4.844		
	332.180	5.005		
	371.292	5.220		
	410.410	5.490		
	434.676	5.543		
	471.088	5.731		
	520.970	5.864		
3 [44]	(λ=2.409 μm)		Pure germanium crystal; prism angle of 14°53.0'; ρ=1.2 Ω-cm; measurements made by minimum deviation method; data taken from a figure.	Lukes, F., 1960
	140.622	3.576		
	170.299	3.792		
	212.141	4.279		
	251.241	4.412		
	295.740	4.600		
	332.163	4.870		
	371.246	4.868		
	410.382	5.273		
	435.971	5.136		
	520.890	5.240		
4 [44]	(λ=3.826 μm)		Pure germanium crystal; prism angle of 14°53.0'; ρ=1.2 Ω-cm; measurements made by minimum deviation method; data taken from a figure.	Lukes, F., 1960
	326.709	4.381		
	371.201	4.515		
	421.083	4.648		
	469.611	4.727		
	520.821	4.697		
5 [44]	(λ=5.156 μm)		Pure germanium crystal; prism angle of 14°53.0'; ρ=1.2 Ω-cm; measurements made by minimum deviation method; data taken from a figure.	Lukes, F., 1960
	302.419	4.138		
	326.692	4.245		
	371.187	4.406		
	421.073	4.566		
	472.279	4.509		

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