Refractive index of silicon and germanium and its wavelength and temperature derivatives

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H. H. Li

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Refractive Index of Silicon and Germanium and Its Wavelength and Temperature Derivatives

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Refractive index data for silicon and germanium were searched, compiled, and analyzed. Recommended values of refractive index for the transparent spectral region were generated in the ranges 1.2 to 14 μm and 100–750 K for silicon, and 1.9 to 16 μm and 100–550 K for germanium. Generation of these values was based on a dispersion equation which best fits selected data sets covering wide temperature and wavelength ranges. Temperature derivative of refractive index was simply calculated from the first derivative of the equation with respect to temperature. The results are in concordance with the existing dn/dT data.

Key words: Germanium; optical constants; refractive index; silicon; temperature coefficient of refractive index.

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<td>$a$</td>
<td>Adjustable constant; lattice constant</td>
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Greek Symbols

<table>
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<tr>
<th>Symbol</th>
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<tr>
<td>$\alpha$</td>
<td>Linear thermal expansion coefficient</td>
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<tr>
<td>$\gamma$</td>
<td>Damping factor</td>
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<td>$\epsilon$</td>
<td>Complex dielectric constant, value of dielectric constant</td>
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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 for certain widely used materials 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 $\pm 2.0 \times 10^{-4}$ over the wavelength range 1.2 to 14.0 $\mu$m for silicon and 1.9 to 18.0 $\mu$m for germanium.

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 of a pure crystal is limited by molecular vibrations, 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 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 [1].

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 usual 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 consequently the lattice absorption is small.

Forpure 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 semi-conducting materials leads to the two familiar relations,

\[ n^2 - k^2 = 1 + \sum_i \frac{N_i(v_i^2 - v^2)}{(v_i^2 - v^2) + \gamma_i^2} \]  

and

\[ 2nk = \sum_i \frac{N_i\gamma_i^2 v_i}{(v_i^2 - v^2) + \gamma_i^2} \]  

where \( n \) is the refractive index, \( k \) the absorption index, \( N_i \) the parameter associated with the oscillator strength of the \( i \)-th oscillator, \( v_i \) the resonant frequency of the \( i \)-th oscillator and \( \gamma_i \) 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:

\[ n^2 = 1 + \sum_i \frac{a_i \lambda_i^2}{\lambda_i^2 - \lambda^2} + \sum_j \frac{b_j \lambda_j^2}{\lambda_j^2 - \lambda^2} \]  

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, \( \varepsilon_\infty \) and \( \varepsilon_0 \), of the material under consideration are defined as:

\[ \varepsilon_\infty = 1 + \sum_i a_i \]  

and

\[ \varepsilon_0 = 1 + \sum_i a_i + \sum_j b_j \]  

As noted before, the effects of free carriers 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:

\[ n^2 = 1 + \sum_i \frac{a_i \lambda_i^4}{\lambda_i^4 - \lambda^4} \]  

and

\[ \varepsilon = \varepsilon_\infty = \varepsilon_0 = 1 + \sum_i a_i \]  

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 dominating one, in the summation of eq (5) is expanded as:

\[ \frac{a_i \lambda_i^4}{\lambda_i^4 - \lambda^4} = a_i\left(1 + \frac{\lambda_i^2}{\lambda^2} + \frac{\lambda_i^4}{\lambda^4} + \cdots \right) \]  

Since \( \lambda_i \)'s are usually considerably smaller than \( \lambda \)'s in the transparent region, a good approximation of eq (5) is

\[ n^2 = 1 + \sum_i a_i\left(1 + \frac{\lambda_i^2}{\lambda^2}\right) + \frac{a_i \lambda_i^2}{\lambda_i^4 - \lambda^4} \]  

or

\[ n^2 = 1 + \sum_i a_i + \sum_{i=2}^N a_i \frac{\lambda_i^2}{\lambda_i^4 - \lambda^4} \]  

with \( a_i \) and \( \lambda_i \) 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:

\[ n^2 = \varepsilon = \frac{A}{\lambda^2} + \frac{B \lambda_i^2}{\lambda_i^4 - \lambda^4} \]  

where \( A \) and \( B \) are adjustable parameters, \( \lambda_1 = 1.1071 \) \( \mu \)m for Si and \( \lambda_1 = 1.5703 \) \( \mu \)m for Ge [2]. Equation (10) can be generalized to include temperature as an independent variable. In this case, the parameters \( \epsilon, A, B, \) and \( \lambda_1 \) are functions of temperature.

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

\[
\frac{1}{\epsilon(T)} \frac{d\epsilon(T)}{dT} = \frac{2}{n^2(T)} \frac{dn(T)}{dT}.
\]

Cardous, Paul, and Brooks [3] found the long-wavelength \((1/n)(dn/dT)\) to be \((3.9 \pm 0.4) \times 10^{-4}K^{-1}\) for Si and \((6.9 \pm 0.4) \times 10^{-4}K^{-1}\) for Ge, between 77 and 400 K. Higher values of \((1/n)(dn/dT)\) were observed by other workers: \((4.8 \pm 0.2) \times 10^{-4}K^{-1}\) for silicon [4] and \(9.7 \times 10^{-4}K^{-1}\) for germanium [5]. 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 \( \epsilon \) 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 [6], 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 \( \epsilon \) are not suitable for eq (10) and \( \epsilon(T) \) can only be obtained by fitting selected room-temperature refractive index data to eq (10). The temperature dependence of \( \lambda_1 \) was investigated by Macfarlane et al. [7, 8], their results are \( d\lambda_1/dT = 0.000267 \) \( \mu \)m K\(^{-1}\) for Si and 0.001016 \( \mu \)m 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

\[
A = \sum_{r=2}^{\infty} a_r \lambda_r^2 \quad \text{and} \quad B = a_1,
\]

and the \( a_r \)'s are respectively proportional to the density of the corresponding oscillator, the temperature dependence of \( a_r \) is given by the relation

\[
\frac{1}{a_r} \frac{da_r}{dT} = \frac{1}{V} \frac{dV}{dT} = -3 \alpha
\]

where \( V \) and \( \alpha \) are respectively the volume and the thermal expansion coefficient of the material. Hence

\[
a_r = a_{10} e^{-3 \int_{293}^{T} \alpha dT} = a_{10} e^{-3 \lambda_1(T) / 293},
\]

with \( a_{10} \) being the value of \( a_1 \) at 293 K. Furthermore, each of the \( \lambda_r^2 \)'s in the summation can be considered as a quadratic function of temperature because it is an experimentally observed fact that \( \lambda_r \) is approximately a linear function of \( T \) [9] in the temperature region of interest. Therefore

\[
A(T) = e^{-3 \lambda_1(T)/293} (A_0 + A_1 T + A_2 T^2)
\]

and

\[
B = B_0 e^{-3 \lambda_1(T)/293},
\]

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

\[
n^2 = f(\lambda, T).
\]

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:

\[
n^2(\lambda, T) = \epsilon(T) + \frac{A(T)}{\lambda^2}.
\]

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

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 sections 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 \( dn/d\lambda = f(T) \),

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 
\( n, \frac{dn}{dT}, \) and \( \frac{dn}{d\lambda}, \)

ii. Tables of recommended or provisional values of 
\( n, \frac{dn}{dT}, \) and \( \frac{dn}{d\lambda}. \)

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 [10] and [11].

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 specific 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\( \times 10^{-4}. \)

### 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 [12], Salzberg and Villa [13], Cardona et al. [3], Lukes [4,14], Primak [15], and Icenoyle et al. [5] are representative for the refractive index of silicon in the transparent region between 1.3 and 12 \( \mu \text{m}. \)

Briggs [12] 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 \( \mu \text{m}. \) 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 \( \mu \text{m} \) was made by Salzberg and Villa [13] 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 \( \pm 2 \) parts in the fourth decimal place.

Cardona et al. [14] measured the refractive index of a thin silicon wedge of 5° in the wavelength range from 1 to 5 \( \mu \text{m} \) 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 [4,14] measured the refractive index at five wavelengths, 1.256, 1.407, 1.564, 2.400, and 5.156 \( \mu \text{m}, \) over a wide temperature region between 109 and 750 K by the conventional method of minimum deviation. The silicon wedge of \( \sim 18^\circ \) angle was prepared from a p-type single crystal with a resistivity of \( \sim 380 \) ohm-cm. The reported error was \( \pm 0.0004, \) but his values of refractive index were systematically lower than those of Salzberg and Villa by 0.0015.

Primak [15] went to great lengths in the determination of the refractive index of silicon from 1.12 to 2.16 \( \mu \text{m}. \) 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.

Icenoyle et al. [15] 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 \( \mu \text{m}, \) 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 \( \pm 8 \times 10^{-4}. \)
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 [15] 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. Broad detector used. Observation in the infrared requires a detector in the determination of deviation angle. The detectors that have been used 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.

In 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 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 [16] 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 [17] radically different results obtained for a silicon sample of high impurity content. The data of Spitzer et al. [18], 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. [5] 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 [19–20] 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 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 tab es A–3 and A–4 and plotted in figures 4 and 5 are those of Lukes [4, 14]. His values were evaluated from his measurements given in table A–2 and in figure 2.

A though a significant body of data on the refractive index of silicon is available, an attempt to analyze the data has been rare. In the literature, only one quantitative study has been proposed. Hertzberger and Salzberg [31] 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 $\lambda^2$. Furthermore, the mean asymptote was found to be at $\lambda = 0.165 \mu m$. The dispersion relation was based upon a Taylor’s expansion in $\lambda^2$ which retains only the linear terms. The equation is

$$n = A + BL + CL^2 + DL^3 + EL^4,$$

(19)

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

$$A = 3.41696,$$

$$B = -0.0000209,$$

$$C = 0.138497,$$

$$D = 0.000001488.$$

The determination of the coefficients in this equation was based on a single data set by Salzberg and Villa [13] and the fit is excellent.

In the present work, eq (19) is used to represent the refractive index for silicon. The main task was the selection of the appropriate parameters $\lambda$ and $\lambda_0$ 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 $\varepsilon$ and $\lambda_i$ in eq (10) was rather difficult. Figure 6 shows the results of Cardona et al. [3] who observed the relative changes of refractive index, $\Delta n_\nu$, at a wavelength of 3 $\mu$m as temperature varied between 77 to 400 K. The average slope, $(1/\nu)(dn_\nu/dT)$, of this curve is $(3.9 \pm 0.4) \times 10^{-4}$ K$^{-1}$. Lukes [4, 14] obtained a higher value of $4.8 \pm 0.2 \times 10^{-4}$ K$^{-1}$ for $(1/\nu)(dn_\nu/dT)$ by extrapolating his results to longer wavelengths. It appeared that at long wavelengths, $\varepsilon$ in eq (10) could be determined from the relation $(1/\nu)(dn_\nu/dT) = (2/\nu)(dn/dT)$ using one of the above mentioned $(1/\nu)(dn/dT)$ values. The result should be an exponential relation of the form $\varepsilon = \varepsilon_0 e^{-\lambda T}$. However, as the constancy of $(1/\nu)(dn/dT)$ does not hold for the wide temperature range of our interest, an empirical relation between $\varepsilon$ and $T$ had to be found based on the experimental data on $n$.

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 of finding relations between $\varepsilon$ and $T$. Since $\varepsilon$ 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 $\mu$m by Icenogle et al. [5]. As the available data of $n(T)$ at 10.27 $\mu$m cover only the limited temperature range from 100 to 298 K, a wider temperature range coverage is needed to establish the relation between $\varepsilon$ and $T$ that is valid over the temperature range 100-750 K. As shown in figure 2, the 5.156 $\mu$m curve by Lukes [14] is slightly above, but parallel to, the extension made from the 10.17 $\mu$m curve. The required 10.27 $\mu$m 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 $\mu$m and over 100-750 K temperature range,

$$n^2(10.27 \mu m, T) = 11.455 + 2.7765 \times 10^{-4} T + 1.7066 \times 10^{-8} T^2 - 8.1423 \times 10^{-12} T^3. \quad (20)$$

Since at long wavelengths the dielectric constant closely approaches $n^2$, it is acceptable to consider the above quantity as a proportional factor and thus express the dielectric constant by the relation

$$\varepsilon(T) = n^2(T) \times (10.27 \mu m, T), \quad (21)$$

where $E$ is the proportional constant.

The spectral positions of resonant absorption peaks have been observed by a number of investigators. Moss [32] made an attempt to calculate the refractive indices in the transparent regions 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 $\lambda = 0.365 \mu$m. McLean [2] investigated the absorption edge spectrum of silicon and found the optical energy gap at 300 K to be $E_g = 1.12$ eV or $\lambda_1 = 1.1071 \mu$m. Macfarlane et al. [7] further studied the absorption edge spectrum and found that the temperature variation of the optical energy gap is essentially linear in the temperature range 250-480 K, but nonlinearity progressively predominates at lower temperatures, as seen from figure 7. Lukes and Schmidt [9] studied the reflectivity spectrum of silicon and found two additional absorption peaks at about 0.56 and 0.27 $\mu$m. The first one is in line with the Moss’ [32] result, while the second corresponds to the prediction of Yu and Cardona [33]. A summary of these findings results in three absorption peaks; namely: $\lambda_1 = 1.1071 \mu$m, $\lambda_2 = 0.365 \mu$m, and $\lambda_3 = 0.27 \mu$m, that supposedly have significant effects on the refractive index in the transparent region from 1.2 to 15 $\mu$m.

An attempt was made to fit the selected data to an equation similar to eq (10) by including extra terms due to $\lambda_2$ and $\lambda_3$. It was found, however, that the introduction of the $\lambda_2$ and $\lambda_3$ terms did not improve the agreement obtained when only the $\lambda_1$ term was included. Furthermore, the coefficients of the $\lambda_2$ and $\lambda_3$ 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 15 $\mu$m and 100-750 K:

$$\alpha(T) = \varepsilon(T) + \frac{L(T)}{\lambda^2} (A_o + A_1 T + A_2 T^2), \quad (22)$$

where

$$\varepsilon(T) = 11.4445 + 2.7739 \times 10^{-4} T + 1.7050 \times 10^{-8} T^2 - 8.1427 \times 10^{-12} T^3, \quad (10)$$

$$L(T) = \varepsilon^{-\lambda_2 \lambda_3 T/\nu} \lambda = \text{wavelength in units of } \mu \text{m},$$

$$T = \text{temperature in units of } K,$$

$$A_o = 0.8948,$$

$$A_1 = 4.3977 \times 10^{-4},$$

$$A_2 = 7.3853 \times 10^{-4},$$

and from reference [34]

\[
\frac{\Delta L(T)}{L_{293}} = -0.021 - 4.149 \times 10^{-7} T - 4.620 T^2 + 1.482 \times 10^{-10} T^3 \quad (20-293 \text{ K}),
\]

\[
\frac{\Delta L(T)}{L_{293}} = -0.071 + 1.887 \times 10^{-6} T + 1.934 \times 10^{-9} T^2 - 4.544 \times 10^{-13} T^3 \quad (293-1600 \text{ K}).
\]

It should be pointed out that the room-temperature dielectric constant for silicon can be calculated from the expression for \( \varepsilon \) 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 1 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 2 and 3, respectively, give the calculated \( dn/dT \) and \( dn/d\lambda \) values based on the first derivatives of eq (22) with respect to \( T \) and \( \lambda \). The corresponding plots are shown in figures 9 and 10.

Uncertainties in the calculated \( dn/dT \) are estimated based on Icenogle's [5] 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 \( \pm 0.15 \times 10^{-4} \text{ K}^{-1} \). 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 [4, 14], 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 \( \lambda \), we have

\[
-\frac{dn}{d\lambda} = \frac{(1/n)A(T)}{\lambda^3} = (1/n)\left(\frac{n^2 - \varepsilon}{\lambda^2}\right),
\]

which leads to

\[
\delta\left(\frac{dn}{d\lambda}\right) \approx \frac{1}{\lambda^3} \cdot 2\delta n/\lambda.
\]

Based on the fact that the spectral dependence of the refractive index from various investigators are essentially parallel, it should be permissible to 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 \( \mu \text{m} \). For wavelengths <2.55 \( \mu \text{m} \), 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 \( \pm 10 \times 10^{-4} \text{ \mu m}^{-1} \) at 2 \( \mu \text{m} \), \( \pm 2.4 \times 10^{-4} \text{ \mu m}^{-1} \) at 2.55 \( \mu \text{m} \), \( \pm 0.6 \times 10^{-4} \text{ \mu m}^{-1} \) at 10 \( \mu \text{m} \), and \( \pm 0.4 \times 10^{-4} \text{ \mu m}^{-1} \) at 14 \( \mu \text{m} \).

It should be noted that calculated values in tables 1, 2, and 3 are given with more digits than warranted merely for the purpose of tabular smoothness. As these values are calculated from an equation, it is highly desirable to give enough digits to show the variation of the variables in the equation and to provide comparison among neighboring entries. These extra digits which are insignificant and not indicative of the accuracy of the values are indicated with an overstrike. Appropriate uncertainties in the recommended values discussed in the text are quoted in the footnotes of the tables.
FIGURE 1. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF SILICON (Wavelength Dependence)
FIGURE 2. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF SILICON (Temperature Dependence)
FIGURE 3. SELECTED EXPERIMENTAL REFRACTIVE INDEX OF SILICON (Wavelength Dependence)
FIGURE 4. AVAILABLE EXPERIMENTAL $dn/dT$ OF SILICON (Wavelength Dependence)

<table>
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<th>Ref.</th>
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<td>[14]</td>
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<td>2</td>
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</table>

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

Data Set | Symbol | $\lambda$(µm) | Ref.
--- | --- | --- | ---
1 | □ | 1.259 | [4]
2 | ○ | 1.364 | [4]
3 | △ | 1.407 | [14]
4 | ▲ | 2.409 | [14]
5 | × | 3.826 | [14]
6 | ◇ | 5.156 | [14]

Calculated
FIGURE 6. VARIATION OF REFRACTIVE INDEX OF SILICON WITH TEMPERATURE AT WAVELENGTH 3 μm [3]
Figure 7. Temperature dependence of the optical energy gap of silicon [7].
**TABLE 1. RECOMMENDED VALUES ON THE REFRACTIVE INDEX OF SILICON**

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*aThe estimated uncertainty in the recommended values is ±0.001.*

Recommended values are given to more digits than warranted merely for the purpose of tabular smoothness. The insignificant digits of the values are indicated by overstrikes.
REFRACTIVE INDEX OF SILICON AND GERMANIUM

FIGURE 8. RECOMMENDED n-λ-T DIAGRAM OF SILICON
**TABLE 2. RECOMMENDED VALUES ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF SILICON**

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*The estimated uncertainty in the recommended values is ±0.05 × 10^-10 K^-1. Recommended values are given to more digits than warranted merely for the purpose of tabular smoothness. The insignificant digits of the values are indicated by overstrikes.*
REFRACTIVE INDEX OF SILICON AND GERMANIUM

FIGURE 9. RECOMMENDED $\frac{dn}{dT}$-$\lambda$-$T$ DIAGRAM OF SILICON
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</table>

*Recommended values are given to more digits than warranted merely for the purpose of tabular smoothness. The insignificant digits of the values are indicated by overstruck. The estimated uncertainties in the recommended values are about $2.2 \times 10^{-6}$ at 2 $\mu m$, $2.4 \times 10^{-6}$ at 2.25 $\mu m$, $2.6 \times 10^{-6}$ at 3 $\mu m$, and $3.0 \times 10^{-6}$ at 14 $\mu m$.\n
FIGURE 10. RECOMMENDED $dn/d\lambda$ CURVE OF SILICON AT 293 K
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 [12], Salzberg and Villa [13], Cardona et al. [5], Rank et al. [38], Lukes [36, 37], Icenogle et al. [5], and Edwin et al. [38] are representatives for the refractive index of germanium in the transparent region between 1.8 and 16 μm.

Briggs [12] measured the refractive index of a germanium specimen of 99.99% purity over the spectral range 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 [13] 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 [39], a polycrystalline sample was measured and they found that there were no significant differences between the results obtained for different crystals.

Cardona et al. [5] 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 region. At a fixed long wavelength, 3 μm, they measured 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 ± 0.4)×10^-4 K^-1, agrees well with those for the dielectric constant measurement at 10 mc/s [40] at low temperatures, but discrepancies occurred at high temperatures where values obtained in reference [40] 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. [35] 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 [36, 37] 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 1.8-5.6 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. [5] made a thorough investigation on the refractive index for germanium over the 98-297 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 ±6×10^-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 λ>5 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. [38] 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 [15] 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 [17] reported his radically different results (shown in figure 11) obtained for a germanium sample of high impurity content. Spitzer et al. [44] 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 [41-58] 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 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 [36, 58, 59]. His $dn/dT$ values were evaluated from his measurements of $n$ given in table A-6 and figure 12.

Although considerable amounts 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 [41]. 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 qualitative attempt was made by Rank et al. [35], who fitted a Cauchy type dispersion relation of the form

$$n = n_0 + \frac{a}{\lambda^2 + b/\lambda^2}$$

(25)

where $\lambda$ is in units of $\mu$m. They presented results for fits on both their own data and for the Brattain and Briggs data with the following constants:

<table>
<thead>
<tr>
<th>Data</th>
<th>$n_0$</th>
<th>$a$, $\mu$m$^2$</th>
<th>$b$, $\mu$m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RBC [43]</td>
<td>4.0385</td>
<td>0.21345</td>
<td>0.5363</td>
</tr>
<tr>
<td>BB [49]</td>
<td>3.9992</td>
<td>0.44647</td>
<td>0.6882</td>
</tr>
</tbody>
</table>

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 [31] 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 $\lambda^4$. They found the mean asymptote of all the materials in the UV region to be at $\lambda_0 = 0.168 \mu$m. Their dispersion relation is based upon a Taylor expansion in $\lambda^4$ which retains only the linear terms. The form is

$$n = A + BL + CL^2 + DL^3 + EL^4$$

(26)

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

- $A = 3.99931$,
- $D = -0.0000060$,
- $B = 0.391707$,
- $E = 0.00000053$,
- $C = 0.16492$.

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 $\epsilon$ and $\lambda_0$, 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 $\mu$m.

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. [38] and Icenogle et al. [5] are uniformly higher than those of Salzberg and Villa [13] in the long wavelength region. Spitzer and Fan [44] observed that the refractive index of an impurity 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 $\lambda$ and $\lambda_s$ presented some difficulties. Cardona et al. [3] observed the relative change of refractive index $\Delta n/n$, at a wavelength of 3 $\mu$m 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 $[6.9 \pm 0.4] \times 10^{-4} K^{-1}$. Icenogle et al. obtained a higher value of $9.9 \times 10^{-4} K^{-1}$ for $(1/n)(dn/dT)$ in the wavelength range 2.554 to 12.1 $\mu$m. It appeared that $\epsilon$ in eq (10) could be determined from the relation $(1/n)(dn/dT) = (2/\lambda_s)(dn/dT)$ using the value of $(1/n)(dn/dT)$ at long wavelengths. The result would be an exponential relation of the form $\epsilon = \epsilon_0 e^{\lambda T}$. However, the constant $(1/n)(dn/dT)$ does not hold for a wide temperature range. Hence, an empirical relation between $\epsilon$ 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 $\epsilon$ and $T$. As $\epsilon$ closely equals $n^2$ at long wavelengths, the best choice in the present case is the refractive indices at 10.27 $\mu$m by Icenogle et al. [5]. However, their results cover only a temperature range from 100 to 295 K. A wider temperature coverage is required to establish a relation between $\epsilon$ and $T$ that is reliable over the temperature region 100–550 K of general interest. As shown in figure 12, the 5.166 $\mu$m curve of Lukes [36] is slightly above and parallel to the extension made from the 10.27 $\mu$m curve. The needed refractive indices at 10.27 $\mu$m 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 $\mu$m and over 100–550 K:

$$n^2(10.27 \mu m, T) = 15.3122 + 1.4571 \times 10^{-3}T + 3.5131 \times 10^{-6}T^2 - 1.2059 \times 10^{-9}T^3.$$  

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:

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

where $E$ is the proportional constant.

Spectral positions of natural absorption peaks in germanium have been studied by a number of investigators. McLean [2] investigated the absorption edge spectrum of germanium and found the optical energy gap at 300 K to be $E_g = 0.663$ eV or $\lambda_0 = 1.8703$ $\mu$m. McLean and Fan's results [8] 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 [9] studied the reflectivity spectrum of germanium and found two additional absorption peaks at $\lambda_0 \sim 0.589$ $\mu$m and $\lambda_0 \sim 0.282$ $\mu$m. The latter corresponds to that predicted by Yu and Cardona [33]. As a summary of these findings, one now has three absorption peaks; namely: $\lambda_0 = 1.8703$ $\mu$m, $\lambda_0 \sim 0.589$ $\mu$m, and $\lambda_0 \sim 0.282$ $\mu$m that are supposed to have significant effects on the refractive index in the transparent region, 1.9–16 $\mu$m.

In this work, the selected data were fitted to an equation similar to eq (10) by including extra terms due to $\lambda_0$ and $\lambda_s$. It was found, however, that introduction of the $\lambda_0$ and $\lambda_s$ terms did not improve the agreement obtained when only the $\lambda_s$ term was included. Furthermore, the coefficients of the $\lambda_0$ and $\lambda_s$ 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 $\mu$m and 100–550 K:

$$n^2(\lambda, T) = \epsilon(T) + \frac{L(T)}{\lambda^2} (A_0 + A_1 T + A_2 T^2),$$  

where

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

$$L(T) = e^{-\lambda_0 [\epsilon(T)]^{1/2}},$$

$\lambda = \text{wavelength in units of } \mu m,$  

$T = \text{temperature in units of K},$  

$A_0 = 2.5381,$  

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

$A_2 = 2.8888 \times 10^{-6}.$

and from reference [60]

\[
\Delta L(T) = -0.098 + 2.626 \times 10^{-6} (T - 100) + 1.463 \\
\times 10^{-6} (T - 100)^2 - 2.221 \times 10^{-11} (T - 100)^3
\]

\[(100 < T < 293),\]

\[
\Delta L(T) = 5.790 \times 10^{-6} (T - 293) + 1.768 \\
\times 10^{-6} (T - 293)^2 - 4.562 \times 10^{-13} (T - 293)^3
\]

\[(293 < T < 1200).\]

It is interesting to point out that the room temperature dielectric constant for germanium can now be calculated from the expression of \(\epsilon\) 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 4 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 5 and 6, respectively, give the calculated \(dn/dT\) and \(dn/d\lambda\) values based on the first derivatives of eq (28) with respect to \(T\) and \(\lambda\). The corresponding plots are shown in figures 19 and 20.

Uncertainties in the calculated \(dn/dT\) values are estimated based on Icenogle's data [5] 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 \(\pm 0.5 \times 10^{-4}\text{K}^{-1}\). 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 [36, 38, 59], 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:

\[\delta (dn/d\lambda) = \pm 25 n/\lambda,\]

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

It should be noted that calculated values in tables 4, 5, and 6 are given with more digits than warranted for the purpose of tabular smoothness. As these values are calculated from an equation, it is desirable to give enough digits to show the variation of the variables in the equation and to provide comparison among neighboring entries. To identify the unwarranted insignificant digits in the values, an overstrike is used. Appropriate uncertainties in the recommended values are discussed in the text and quoted in the footnotes of the tables.
FIGURE 11. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF GERMANIUM (WAVELENGTH DEPENDENCE)
FIGURE 12. AVAILABLE EXPERIMENTAL REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence)
FIGURE 13. SELECTED EXPERIMENTAL REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)
FIGURE 14. AVAILABLE EXPERIMENTAL $dn/dT$ OF GERMANIUM (Wavelength Dependence)
FIGURE 15. AVAILABLE EXPERIMENTAL $\frac{dn}{dT}$ OF GERMANIUM (Temperature Dependence)
FIGURE 16. VARIATION OF REFRACTIVE INDEX OF GERMANIUM WITH TEMPERATURE AT WAVELENGTH 3 \( \mu m \) [3]
FIGURE 17. TEMPERATURE DEPENDENCE OF THE OPTICAL ENERGY GAP OF GERMANIUM [8]
FIGURE 17. TEMPERATURE DEPENDENCE OF THE OPTICAL ENERGY GAP OF GERMANIUM [8]

TABLE 4. RECOMMENDED VALUES ON THE REFRACTIVE INDEX OF GERMANIUM*

<table>
<thead>
<tr>
<th>Temperature, K</th>
<th>( \lambda, \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>4.0580</td>
</tr>
<tr>
<td>150</td>
<td>4.0479</td>
</tr>
<tr>
<td>200</td>
<td>4.0378</td>
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<tr>
<td>250</td>
<td>4.0277</td>
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<td>350</td>
<td>4.0176</td>
</tr>
<tr>
<td>400</td>
<td>4.0075</td>
</tr>
<tr>
<td>450</td>
<td>3.9974</td>
</tr>
<tr>
<td>500</td>
<td>3.9873</td>
</tr>
<tr>
<td>550</td>
<td>3.9772</td>
</tr>
</tbody>
</table>

* THE ESTIMATED UNCERTAINTY IN THE RECOMMENDED VALUES IS \( \pm 2 \times 10^{-4} \). RECOMMENDED VALUES ARE GIVEN TO MORE DIGITS THAN WARRANTED FOR THE PURPOSE OF TABULAR GRANULARITY. THE INSIGNIFICANT DIGITS OF THE VALUES ARE INDICATED BY OVERSTRIKES.
FIGURE 18. RECOMMENDED n-λ-T DIAGRAM OF GERMANIUM
### Table 5: Recommended Values on the Temperature Derivative of Refractive Index of Germanium

<table>
<thead>
<tr>
<th>( \lambda, \mu \mathrm{m} )</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
</tr>
</thead>
</table>
*The estimated uncertainty in the recommended values is ±0.5X10⁻² K⁻¹. Recommended values are given to more digits than warranted merely for the purpose of tabular smoothness. The insignificant digits of the values are indicated by overstrikes.
FIGURE 19. RECOMMENDED $dn/dT - \lambda - T$ DIAGRAM OF GERMANIUM
### Refractive Index of Silicon and Germanium

#### Table 5. Calculated Values on the Wavelength Derivative of Refractive Index of Germanium at 293K *

<table>
<thead>
<tr>
<th>$\lambda$, $\mu m$</th>
<th>$-dn/d\lambda$, $10^{-4}$ $\mu m^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.90</td>
<td>1.17.5</td>
</tr>
<tr>
<td>1.92</td>
<td>1.14.4</td>
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<td>2.10</td>
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<td>2.15</td>
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<td>3.00</td>
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<td>3.40</td>
<td>0.09.2</td>
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<tr>
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<td>0.00.1</td>
</tr>
<tr>
<td>4.00</td>
<td>0.00.0</td>
</tr>
</tbody>
</table>

*Recommended values are given to more digits than warranted merely for the purpose of tabular smoothness. The insignificant digits of the values are indicated by overstrikes. The estimated uncertainties in the recommended values are about $2.5 \times 10^{-4}$ $\mu m^{-1}$ at 2.55 $\mu m$, $1.2 \times 10^{-4}$ $\mu m^{-1}$ at 10 $\mu m$, and $0.7 \times 10^{-4}$ $\mu m^{-1}$ at 18 $\mu m$.

FIGURE 20. RECOMMENDED $dn/d\lambda$ CURVE OF GERMANIUM AT 293 K
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 has 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 [15]. 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} [9]. That of Si is -3\pm 2 \times 10^{-7}kg^{-1}cm^{2} [9].

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, e.g., (22) and (28), are valid for the region 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.

5. Acknowledgments

This work was jointly supported by the Office of Standard Reference Data of the National Bureau of Standards, U.S. Department of Commerce, and by the Defense Logistics Agency of the U.S. Department of Defense. Their support is gratefully acknowledged.

6. References


**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-I. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence)

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| Temperature, T, K; Wavelength, \( \lambda \), \( \mu m \); Refractive Index, \( n \) |

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Specifications and Remarks:
- Deviation angle to within ±1'; data extracted from a figure.
- 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.
- Crystal specimens; no details of source, sample preparation and measurement given; data read from a figure; temperature not given, 298 K assumed.
### TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
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### Table A-1. Experimental Data on the Refractive Index of Silicon
(Wavelength Dependence) (continued)

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<td>Single crystal; ellipsometry method used to determine refractive index; the effect of oxidized film on silicon corrected; error in refractive index about ( \pm 0.007 ).</td>
<td>Philipp, H.R. and Taft, E.A., 1960</td>
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\( T = 298 \text{ K} \)

9 [21] 0.5461 4.050

\( n \)-type, phosphorus doped silicon samples; carrier concentration \( N = \) \( 7.5 \times 10^{19} \) cm\(^{-3} \); polished; refractive index derived from reflectivity measurements; data taken from a figure.

\( T = 298 \text{ K} \)

10 [18] 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

\( T = 298 \text{ K} \)

11 [18] 3.456 2.943
        4.458 2.586
        5.179 2.288
        5.618 2.111
        5.963 1.922

\( n \)-type, phosphorus doped silicon samples; carrier concentration \( N = 7.5 \times 10^{19} \) cm\(^{-3} \); polished; specimen heated at \( 1310 \text{ K} \) for \( 30 \) sec in a vacuum of \( \leq 1 \times 10^{-7} \) torr; refractive index derived from reflectivity measurements.

\( T = 298 \text{ K} \)

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

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<td>Spitzer, W.G., et al., 1964</td>
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<td>Spitzer, W.G., et al., 1964</td>
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<td>Spitzer, W.G., et al., 1964</td>
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<td>7.5 $\times 10^{19}$ 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.</td>
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<td>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.</td>
<td>Bennett, J.M. and Booty, K.J., 1966</td>
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### Table A-1. Experimental Data on the Refractive Index of Silicon (Wavelength Dependence) (continued)

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<td>16 [23]</td>
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<td>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.</td>
<td>Velam, K., Knaußenberger, W., and Luces, F., 1969</td>
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<td>70.392</td>
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<td>Single crystal; obtained from Exotic Materials, Costa Mesa, CA; p &gt; 10 $\Omega$·cm; plate specimen of 1.94067 ± 2.3 x 10$^{-8}$ mm thick; refractive indices measured using interference method; data taken from a figure.</td>
<td>Randall, C.M. and Rawcliffe, R.D., 1967</td>
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<td>Single crystal; obtained from Exotic Materials, Costa Mesa, CA; p &gt; 10 $\Omega$·cm; plate specimen of 6.41495 ± 5 x 10$^{-8}$ mm thick; refractive indices measured using interference method; data taken from a figure.</td>
<td>Randall, C.M. and Rawcliffe, R.D., 1967</td>
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<td>20</td>
<td>(&lt;298 K)</td>
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<td>Amorphous silicon film; deposited on polished silica glass silica by</td>
<td>Grigorovic, H. and Vance, A., 1968</td>
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<td></td>
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<td>vacuum (&lt;1 x 10^{-6} mm Hg) evaporation of pure silicon crystals (n = 10</td>
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## REFRACTIVE INDEX OF SILICON AND GERMANIUM

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

<table>
<thead>
<tr>
<th>Data Set [Ref.]</th>
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<th>n</th>
<th>Specifications and Remarks</th>
<th>Author(s), Year</th>
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<tbody>
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<td>20 (cont.) [26]</td>
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<td>3.966</td>
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<td>Grigorovici, R. and Vancu, A., 1968</td>
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<td>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.</td>
<td>Brodsky, M.H., Title, R.S., Weiner, K., and Pettit, G.D., 1970</td>
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<tr>
<td>22 (T=298 K) [27]</td>
<td>0.93</td>
<td>3.95</td>
<td>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.</td>
<td>Brodsky, M.H., et al., 1970</td>
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<td>1.96</td>
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<tr>
<td>23 (T=298 K) [27]</td>
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<td>3.93</td>
<td>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 7 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.</td>
<td>Brodsky, M.H., et al., 1970</td>
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<td>24 (T=298 K) [27]</td>
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<td>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 7 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.</td>
<td>Brodsky, M.H., et al., 1970</td>
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**TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON**  
(Wavelength Dependence) (continued)

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<th>Data Set [Ref.]</th>
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<th>n</th>
<th>Specifications and Remarks</th>
<th>Author(s), Year</th>
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<td>24(cont.) [27]</td>
<td>0.86</td>
<td>3.92</td>
<td>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.</td>
<td>Brodsky, M.H., Titlo, B.S., Weiser, K., and Pettit, G.D., 1970</td>
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<td>25 (T=298 K) [27]</td>
<td>0.81</td>
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<td>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.</td>
<td>Brodsky, M.H., et al., 1970</td>
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<td>26 (T=298 K) [27]</td>
<td>0.718</td>
<td>3.56</td>
<td>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 1222 K for 2 hours; refractive indices determined from the transmission interference fringes and thickness of the specimen; data taken from a figure.</td>
<td>Brodsky, M.H., et al., 1970</td>
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<tr>
<td>27 (T=297 K) [13]</td>
<td>1.2</td>
<td>3.5196</td>
<td>Silicon wedge specimen; cut from a single crystal rod obtained from Merck and Co.; ultra-high purity p-type; ρ = 1200 ω-cm; orientation &lt;111&gt; along the rod axis and perpendicular to one face of the wedge; wedge angle 11°40'35&quot;; wedge faces 22 mm long by 12.7 mm high; refractive indices determined by autocollimation method; data taken from a table.</td>
<td>Primak, W., 1971</td>
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<tr>
<td>28 (T=297 K) [15]</td>
<td>1.144</td>
<td>3.5295</td>
<td>Silicon wedge specimen; cut from a single crystal rod obtained from Merck and Co.; ultra-high purity p-type; ρ = 1200 ω-cm; orientation &lt;111&gt; along the rod axis and perpendicular to one face of the wedge; wedge angle 11°40'35&quot;;</td>
<td>Primak, W., 1971</td>
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### Table A-1. Experimental Data on the Refractive Index of Silicon (Wavelength Dependence) (continued)

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<td>28(cont.) [15]</td>
<td>1.696</td>
<td>3.4644</td>
<td>wedge faces 22 mm long by 12.7 mm high; refractive indices determined by auto-collimation method; data taken from a table.</td>
<td>Primak, W., 1971</td>
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<td>29 [15]</td>
<td>(T=297 K)</td>
<td>3.5361</td>
<td>Silicon wedge specimen; cut from a single crystal rod obtained from Merck and Co.; ultra-high purity p-type; ( \rho = 1200 , \Omega \cdot \text{cm}; \text{orientation } &lt;111&gt; \text{ along the rod axis and perpendicular to one face of the wedge; wedge angle } 11^\circ 40' 35'' ; )</td>
<td>Primak, W., 1971</td>
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<td>30 [28]</td>
<td>(T=298 K)</td>
<td>4.08</td>
<td>Single crystal; surface polished with diamond dust; refractive index determined by the method of ellipsometry.</td>
<td>Shevchenko, G.K., Rachkovskii, R.R., Kol’tsov, S.I., and Aleskovskii, V.B., 1972.</td>
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<td>Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a figure.</td>
<td>Icenogle, H.W., et al., 1976</td>
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<td>Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a figure.</td>
<td>Icenogle, H.W., et al., 1976</td>
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<td>Icenogle, H.W., et al., 1976</td>
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<td>3.39884</td>
<td>Good optical grade silicon samples; supplied by Exotic Materials, Inc.; prism specimen measured with a modified minimum deviation method; data taken from a figure.</td>
<td>Icenogle, H.W., et al., 1976</td>
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### Table A-1. Experimental Data on the Refractive Index of Silicon (Wavelength Dependence) (continued)

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<th>Data Set</th>
<th>λ (T=298 K)</th>
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<td>Icenogle, H.W., Platt, B.C., and Wolfe, W.C., 1976</td>
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<td>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.</td>
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<td>0.53</td>
<td>4.60</td>
<td>Thin films of thicknesses 0.06-0.350 μm; deposited on quartz substrate in</td>
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### Table A-1. Experimental Data on the Refractive Index of Silicon (Wavelength Dependence) (continued)

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<td>a vacuum of ( 10^{-6} ) Torr; evaporation produced by electron beam bombardment; rate of deposition 0.0002-0.001 ( \mu m ) 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.</td>
<td>Thutupalli, G.K.M. and Tomlin, S.G., 1977</td>
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<td>[29]</td>
<td>0.64</td>
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<td>Single crystal; cut at &lt;111&gt; face and polished with successively finer grades of diamond abrasives and finally with an ( Al_2 O_3 ) polishing powder on a beeswax lap; refractive index determined from normal incident reflectance and transmittance measurements; data taken from a figure.</td>
<td>Thutupalli, G.K.M. and Tomlin, S.G., 1977</td>
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<tr>
<td>[29]</td>
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<td>Single crystal; obtained from the Raytheon Co.; prism specimen of 15°38'29&quot; apex angle; refractive index determined by minimum deviation method; reported uncertainty ( 2 \times 10^{-6} ); the values in this set are much higher than the author's previous measure (data set 3) for a sample obtained from Raytheon sample may be responsible to such discrepancies; data extracted from a table.</td>
<td>Villa, J.L., 1972</td>
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### TABLE A-1. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON (Wavelength Dependence) (continued)

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

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

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(Temperature Dependence) (continued)

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TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
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### REFRACTIVE INDEX OF SILICON AND GERMANIUM

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

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8 (λ=2.409 μm)

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Lukes, F., 1960
## TABLE A-2. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF SILICON
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Specifications and Remarks:
- Single crystal; p-type; $\rho = 380$ ohm-cm;
- Prism specimen of 17°51.4' apex angle;
- Refractive indices for the spectral line $\lambda = 5.156$ μm at various temperatures determined by the minimum deviation method; reported error in $n \approx 0.0004$; data read from a figure.
- Single crystal; $\rho = 15$ Ω-cm; plane-parallel disk specimens of 23 mm in diameter; optical polished; emissivities directly measured by comparison of the...
### Table A-2. Experimental Data on the Refractive Index of Silicon (Temperature Dependence) (continued)

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<td>(\lambda=2.00 \mu m))</td>
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| [30]            | 284 | 3.47| Single crystal; \(\rho = 15 \Omega \cdot cm\); 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...
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# Refractive Index of Silicon and Germanium

## Table A-3. Experimental Data on the Temperature Derivative of Refractive Index of Silicon (Wavelength Dependence)

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<td>Single crystal; p-type; ρ = 380 Ω·cm;</td>
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<td>Lukes, F., 1960</td>
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TABLE A-4. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF SILICON (Temperature Dependence)

[Temperature, \(T, \text{K}\); Wavelength, \(\lambda, \text{\AA}\); Temperature Derivative of Refractive Index, \(\frac{dn}{dT}, 10^{-4}\text{K}^{-1}\)]

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<th>Author(s), Year</th>
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<td>Single crystal; p-type; (\rho = 380\ \Omega\text{-cm};) prism specimen of (17^\circ51.4') apex angle; refractive indices for the line (\lambda = 1.259\text{\AA}) at various temperatures determined using the minimum deviation method and (\frac{dn}{dT}) obtained; data read from a figure.</td>
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<td>Single crystal; p-type; (\rho = 380\ \Omega\text{-cm};) prism specimen of (17^\circ51.4') apex angle; refractive indices for (\lambda = 1.407\text{\AA}) at various temperatures determined using the minimum deviation method and (\frac{dn}{dT}) obtained; data read from a figure.</td>
<td>Lukes, F., 1960</td>
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<td>Lukes, F., 1960</td>
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### Table A-4. Experimental Data on the Temperature Derivative of Refractive Index of Silicon (Temperature Dependence) (continued)

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<td>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.</td>
<td>Lukes, F., 1960</td>
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TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)

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<td>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.</td>
<td>Brattain, W.H., and Briggs, H.B., 1949</td>
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<td>Sample from a standard high back-voltage melt with impurity content estimated at less than 0.01%; prismatic specimen of 17°6'30&quot; angle; index of refraction measured by method of minimum deviation; data extracted from a table.</td>
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<td>Crystal; obtained from RCA Laboratories; p-type 0.1-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.</td>
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<td>Pure crystal; thin plate specimen of 227 μm thick; interference fringe of transmitted radiation observed and refractive index determined; data extracted from a table.</td>
<td>Collins, R.J., 1953</td>
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### Data Set

**5** (T=300 K)  
[42]  
8.66 3.92  
9.4 3.90  
10.2 3.93  
11.22 3.92  
12.35 3.93  

Specifications and Remarks:  
Pure crystal; thin plate specimen of 227 μm thick; interference fringe of transmitted radiation observed and refractive index determined; data extracted from a table.

Author(s), Year:  
Collins, R.J., 1953

**6** (T=297.3 K)  
[35]  
2.00 4.1254  
2.10 4.1145  
2.30 4.0980  
2.40 4.0918  

Specifications and Remarks:  
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 aperture; interference fringe order observed and vacuum refractive index of the plate determined; data taken from a table.

Author(s), Year:  

**7** (T=297 K)  
[43]  
1.8 3.95  
15.2  

Specifications and Remarks:  
Single crystal; \( \rho = 25 \Omega \cdot \text{cm} \); plate specimen of about 7 mm thick; refractive index deduced from reflectance and transmittance measurements; refractive index in the wavelength region between 1.8 and 15.2 μm being a constant 3.95.

Author(s), Year:  
Oswald, F. and Schade, R., 1954

**8** (T=297 K)  
[44]  
2.811 4.027  
3.217 4.027  
5.629 4.027  
4.029 4.014  
7.139 3.959  
10.926 3.662  
12.008 3.595  
12.870 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  

Specifications and Remarks:  
Single crystal, 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.

Author(s), Year:  
Spitzer, W.C. and Fan, H.Y., 1957

**9** (T=297 K)  
[44]  
7.816 3.824  
8.762 3.824  
9.980 3.791  
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  

Specifications and Remarks:  
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.

Author(s), Year:  
Spitzer, W.C. and Fan, H.Y., 1957
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<td>10 [13]</td>
<td>2.0581</td>
<td>4.1016</td>
<td>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.</td>
<td>Salzberg, C.D. and Villa, J.J., 1957</td>
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<td>11 [39]</td>
<td>2.0581</td>
<td>4.1016</td>
<td>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.</td>
<td>Salzberg, C.D. and Villa, J.J., 1958</td>
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## Table A-5. Experimental Data on the Refractive Index of Germanium (Wavelength Dependence) (continued)

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<tr>
<td>13 [45]</td>
<td>0.36</td>
<td>4.13</td>
<td>Specimens of both mechanically polished and etched 6 Ω-cm germanium; optical constants obtained from eellipticity 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.</td>
<td>Archer, R.J., 1958</td>
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<td>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.</td>
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<td>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.</td>
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<td>17 [46]</td>
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<td>Single crystal; etched surfaces; near normal reflectance spectrum</td>
<td>Philipp, H.R.</td>
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<td>between 0.1 and 1.8 μm observed,</td>
<td>and Taft, E.A., 1959</td>
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<td>above 1.77 μm reflectance calculated</td>
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<td>0.148</td>
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<td>from available refractive indices;</td>
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<td>phase angle computed from reflectance</td>
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### Table A-5. Experimental Data on the Refractive Index of Germanium (Wavelength Dependence) (continued)

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<th>$n$</th>
<th>Specifications and Remarks</th>
<th>Author(s), Year</th>
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<td>18</td>
<td>1.513</td>
<td>4.815</td>
<td>Thin film of 1.092 µm thick; deposited on rotating glass substrate at air pressure of less than $4 \times 10^{-5}$ mmHg and rate of deposition of 30-60 Å/sec; refractive indices determined from reflection and interference observation; data taken from a figure.</td>
<td>Huldt, L. and Staflin, T., 1959</td>
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<td>1.607</td>
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<td>19</td>
<td>1.409</td>
<td>4.853</td>
<td>Thin film of 1.010 µm thick; deposited on rotating glass substrate at air pressure of less than $4 \times 10^{-5}$ mmHg and rate of deposition of 30-60 Å/sec; refractive indices determined from reflection and interference observation; data taken from a figure.</td>
<td>Huldt, L. and Staflin, T., 1959</td>
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TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM
(Wavelength Dependence) (continued)

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### Table A-5. Experimental Data on the Refractive Index of Germanium (Wavelength Dependence) (continued)

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

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<td>High purity germanium; prism cut from a single crystal; prism angle: 4(^{\circ}) 21' 13&quot;; ( p = 50 \Omega \cdot \text{cm} ); index of refraction measured by deviation method; data taken from a figure.</td>
<td>Kornfeld, M.I., 1960</td>
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<td>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.</td>
<td>Lukes, F., 1960</td>
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<td>Single crystal; polished specimens of 7 ( \times ) 7 ( \text{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.</td>
<td>Kiseleva, N.K. and Pribytkova, N.N., 1961</td>
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<td>Hertzberger, N. and Salzberg, C.B., 1962</td>
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### TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM  
(Wavelength Dependence) (continued)

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<td>Single crystal; thin plate specimens of 0.5 to 2.0 mm thick cut perpendicular to the &lt;111&gt; axis; refractive indices found to be constant in the region between 23 and 67 μm.</td>
<td>Aronson, J.R., McLinden, H.G., and Gielisse, P.J., 1964</td>
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<td>Single crystal; thin plate specimens of 0.5 to 2.0 mm thick cut perpendicular to the &lt;111&gt; axis; refractive index measured using interference method.</td>
<td>Aronson, J.R., et al., 1964</td>
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<td>Amorphous germanium thin film prepared by evaporation of very pure germanium in a vacuum better than 10⁻² mmHg on a fused quartz substrate at room temperature; refractive index determined from reflection and transmission measurements; data read from a figure.</td>
<td>Tauc, J., Abraham, A., Pajasova, L., Grigorovicí, R., and Vancu, A., 1965</td>
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TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

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<td>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</td>
<td>Potter, R.F., 1966</td>
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### REFRACTIVE INDEX OF SILICON AND GERMANIUM

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

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<td>Gisin, M.A. and Ivanov, V.A., 1967</td>
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<td>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 × 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.</td>
<td>Gisin, M.A. and Ivanov, V.A., 1967</td>
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<td>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 × 10^{-5} Torr; polished</td>
<td>Gisin, M.A. and Ivanov, V.A., 1967</td>
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### Table A-5. Experimental Data on the Refractive Index of Germanium (Wavelength Dependence) (continued)

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<td>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.</td>
<td>Gisi, M.A. and Ivanov, V.A., 1967</td>
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<td>Thin film samples of 0.5-5 $\mu$m thick prepared by thermal evaporation from an electron beam heated source on to unheated substrates in a vacuum of $1 \times 10^{-6}$ Torr; refractive indices determined from the sample thickness and interference fringe order observations; averaged values read from a best fit curve.</td>
<td>Wales, J., Lovitt, G.J., and Hill, J.A., 1967</td>
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<td>Thin film samples of 0.5-5 $\mu$m thick deposited on unheated substrates from an electron beam heated source in a vacuum of $1 \times 10^{-6}$ Torr; refractive indices determined from the sample thickness and interference fringe order observations; averaged values read from a best fit curve.</td>
<td>Wales, J., et al., 1967</td>
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<td>Thin film samples of 0.5-5 $\mu$m thick deposited on unheated substrates from an electron beam heated source in an atmosphere of oxygen at $1 \times 10^{-7}$ Torr; refractive indices determined from the sample thickness and interference order</td>
<td>Wales, J., et al., 1967</td>
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### Reflex Index of Silicon and Germanium

#### Table A-5. Experimental Data on the Refractive Index of Germanium
(Wavelength Dependence) (continued)

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<td>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 10⁻⁴ Torr; refractive indices determined from sample thickness and interference fringe order observations; averaged values read from a best fit curve.</td>
<td>Wales, J., et al., 1967</td>
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<td>Wales, J., et al., 1967</td>
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Wales, J., et al., 1967

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

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<td>58</td>
<td>(T=298 K)</td>
<td>1.300</td>
<td>Thin film samples of 0.5-5 μm thick deposited on substrates at 373-473 K</td>
<td>Wales, J., et al., 1967</td>
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<td>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 order observations; averaged values read from a best fit curve.</td>
<td>Wales, J., et al., 1967</td>
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<td>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; averaged values read from a best fit curve.</td>
<td>Wales, J., et al., 1967</td>
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### Table A-5. Experimental Data on the Refractive Index of Germanium (Wavelength Dependence) (continued)

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<td>Single crystal; $\rho=40$ $\Omega$-cm; $n$-type; specimens with $&lt;111&gt;$ surfaces cleaved by the Gobeli-Allen technique; refractive index determined by ellipsometry method; the average value reported with error $\pm 0.10$.</td>
<td>Knausenberger, W.H. and Vedam, K., 1969</td>
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Amorphous Ge films; vacuum deposited onto rotating substrates of fused quartz, fused silica and KCl; evaporation sources of tungsten boat, Al$_2$O$_3$-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, 0.2138 µm, 0.3576 µm and 0.5371 µm taken from a table.

### Table A-5. Experimental Data on the Refractive Index of Germanium (Wavelength Dependence) (continued)

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<td>Donovan, T.M., Spicer, W.E., Bennett, J.M., and Ashley, E.J., 1970</td>
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<td>Donovan, T.M., et al., 1970</td>
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<td>Jutk, G., 1971</td>
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(Wavelength Dependence) (continued)

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<td>and Lamare, M.,</td>
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Specifications and Remarks:

- **Amorphous germanium; thin film specimen**
- **Evaporation of germanium from a tungsten boat on glass substrate in vacuum of**
  - 10^-6 Torr; substrate held at 673 K
- **During evaporation; refractive indices determined by ellipsometric method**
- **Data taken from a figure.**

- **Single crystal; grown at the Royal Signals and Radar Establishment, Malvern, U.K. using the Czochraski pulling technique; p = 45-53 Ohm-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.
TABLE A-5. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence)  (continued)

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<th>Data Set [Ref.]</th>
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<th>( n )</th>
<th>Specifications and Remarks</th>
<th>Author(s), Year</th>
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<td>72 [38] (T=293 K)</td>
<td>8.00</td>
<td>4.00551</td>
<td>Single crystal; grown at the Royal Signals and Radar Establishment, Malvern, U.K.; using the Czochraski pulling technique; ( \rho = 45-53 \Omega \cdot \text{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.</td>
<td>Edwin, R.P., Dudermel, M.T., and Lamare, M., 1978</td>
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<tr>
<td>73 [38] (T=298 K)</td>
<td>8.00</td>
<td>4.00748</td>
<td>Single crystal; grown at the Royal Signals and Radar Establishment, Malvern, U.K. using the Czochraski pulling technique; ( \rho = 45-53 \Omega \cdot \text{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.</td>
<td>Edwin, R.P., et al., 1978</td>
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</table>

### Table A-6. Experimental Data on the Refractive Index of Germanium (Temperature Dependence)

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<th>Data Set</th>
<th>Temperature, T, K; Wavelength, λ, μm; Refractive Index, n</th>
<th>Specifications and Remarks</th>
<th>Author(s), Year</th>
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<td>(λ=2.00 μm)</td>
<td>High purity single crystal; prism</td>
<td>Lukes, F., 1958</td>
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<tr>
<td>[58]</td>
<td>113.593, 116.291, 202.919, 208.329, 208.338, 228.630, 256.408, 261.111, 273.295, 292.254, 309.848, 323.383, 342.337, 354.522, 370.764, 391.061, 407.332</td>
<td>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.</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(λ=2.00 μm)</td>
<td>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.</td>
<td>Lukes, F., 1958</td>
</tr>
<tr>
<td>3</td>
<td>(λ=2.26 μm)</td>
<td>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.</td>
<td>Lukes, F., 1958</td>
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### TABLE A-6. EXPERIMENTAL DATA ON THE REFRACTIVE INDEX OF GERMANIUM (Temperature Dependence) (continued)

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<td>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.</td>
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<td>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.</td>
<td>Lukes, F., 1958</td>
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<td>Pure germanium crystal; prism angle: $14^\circ 53'$. $p=1.2 \Omega \cdot cm$; minimum deviation method used; data read from a figure.</td>
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# REFRACTIVE INDEX OF SILICON AND GERMANIUM

## Table A-6. Experimental Data on the Refractive Index of Germanium

(Temperature Dependence) (continued)

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### Table A-6. Experimental Data on the Refractive Index of Germanium (Temperature Dependence) (continued)

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### Table A-6: Experimental Data on the Refractive Index of Germanium (Temperature Dependence) (continued)

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Good optical grade germanium samples; supplied by Exotic Materials Inc.; prism specimen; measured with a modified minimum deviation method; data taken from a table.

# Refractive Index of Silicon and Germanium

**Table A-6. Experimental Data on the Refractive Index of Germanium**

(Temperature Dependence) (continued)

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|          |     |         | 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 |
|          | 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 | 3.95734 |                                                                 |                       |
|          | 183 | 3.96090 |                                                                 |                       |
|          | 192 | 3.96390 |                                                                 |                       |
|          | 204 | 3.96808 |                                                                 |                       |
|          | 210 | 3.97028 |                                                                 |                       |
|          | 217 | 3.97296 |                                                                 |                       |
|          | 226 | 3.97587 |                                                                 |                       |
|          | 234 | 3.98896 |                                                                 |                       |
|          | 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)

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<td>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.</td>
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<td>5.36</td>
<td>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.</td>
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<td>0.961</td>
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<td>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.</td>
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TABLE A-7. EXPERIMENTAL DATA ON THE TEMPERATURE DERIVATIVE OF REFRACTIVE INDEX OF GERMANIUM (Wavelength Dependence) (continued)

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<td>Icenogle, H.W., Platt, B.C., and Wolfe, W.L., 1967</td>
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<td>Pure germanium crystal; prism angle of ( 14^{\circ}53.0' ); measurements made by minimum deviation method; data taken from a figure.</td>
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