LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

ORNL/OMIS--89/9

DE90 006372

ORNL/OMIS-89/9

Engineering Technology Division
Survivable Optics
Manufacturing and Integration Laboratory (MODIL)

THE OPTICAL PROPERTIES OF BERYLLIUM¹

E. T. Arakawa, T. A. Callcott² and Yun-Ching Chang²
Health and Safety Research Division

Date Published - February 1990

Work Performed for
Producibility and Manufacturing Division
Industry and Operational Interfaces Directorate
Strategic Defense Initiative Organization, Department of Defense
U.S. Department of Energy Interagency Agreement No. 1855-1562-A1

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
Under Contract DE-AC05-84OR21400

¹Research was sponsored jointly by the Optics MODIL under U.S. DOE-DOD Interagency Agreement No. 1855-1561-A1, and by the Office of Health and Environmental Research, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems Inc.

²Also from The University of Tennessee, Physics Department, Knoxville, Tennessee

MASTER

THE OPTICAL PROPERTIES OF BERYLLIUM

E.T. Arakawa, T.A. Callcott[†], and Yun-Ching Chang[†]

Oak Ridge National Laboratory*
Health and Safety Research Division
Oak Ridge, Tennessee

Abstract

We review the published data on the optical properties of beryllium for the spectral region from 0.03 to 300 eV. In the visible and infrared spectral regions, where published data from various authors show very large variations, we have performed experiments that identify the most probable sources of error, and use this information to select the best data from published sources. The effects of surface oxide overlayers have also been studied.

In the far infrared spectral region, where only normal incidence reflectance data are available, and in the extreme ultraviolet, where only transmission data are available, there is insufficient information to fully determine the optical properties at each photon energy. Between 0.06 and 26 eV, however, a normal incidence reflectance curve is fully determined. This curve has been used for a Kramers-Kronig analysis to determine the optical properties in this spectral range.

I. Introduction

Beryllium has many unique properties that make it of both theoretical and practical interest. As a metal, it is strikingly different both from lithium, its neighbor in the periodic table, and the higher Z alkaline earth metals magnesium and calcium, which occupy the same column of the periodic table. The

[†] Also from: The University of Tennessee, Physics Department, Knoxville, Tennessee.

* This research was sponsored jointly by the Office of Health and Environmental Research, U. S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. and by the Optics-MODIL under USDOE-DOE interagency agreement no. 1855-1562-A1.

density of beryllium is not only 3.5 times larger than that of lithium, but is greater than that of both magnesium and calcium. Its compressibility is very low, its Debye temperature is among the highest in the periodic table, its melting temperature is much higher than the other alkaline earths, and its electronic specific heat is very low. These properties, and its hexagonal crystalline structure have generated much theoretical interest in its electronic properties. Several authors have discussed the optical properties of Be expected from theoretical band structure calculations [1-3].

Beryllium also has many properties that recommend it for exotic optical applications. It is relatively light compared with other metals of optical importance, offers a very high specific stiffness (ratio of Young's modulus to density), a low thermal expansion at cryogenic temperatures, a low Z number, high thermal conductivity, and high reflectivity in the infrared. These properties make it particularly attractive for optical components that are intended for use in space.

In view of its many unique properties, it is surprising that no careful survey of the optical properties of Be has yet been published. There appear to be two related reasons for this fact. Few studies have been made and they have produced widely different results, particularly in the visible region of the spectrum, where the methodology and instrumentation is best developed, and results are normally most consistent. The variability of results may be traced to the difficulty of sample preparation. Bulk samples are normally produced by high pressure sintering of microcrystalline powder, which normally results in the incorporation of significant amounts of BeO in the sample, which is concentrated in the grain boundaries between the compressed grains.

For many metals, oxidation problems may be readily overcome by vacuum evaporation, in which the metal evaporates, leaving the more stable oxide behind. In practice, Be is easily evaporated by subliming from the solid state at temperatures of about 900 °C, well below its melting temperature at 1278 °C. In this report, we document that the optical properties measured depend critically on the evaporation procedures used, and that much of the variability of the results reported in the literature can be traced to sample preparation problems.

II. Optical Constants and Methods of Measurement

The response of any isotropic material to a time varying electric field, including optical fields, can be described using two numbers at each frequency. A large number of related quantities are used in the literature to describe this response. We briefly summarize the more common descriptions below. The recently published Handbook of Optical Constants of Solids provides a thorough discussion of the material summarized in this section [4].

n and k - The index of refraction (n) and the absorption coefficient (k), often referred to as the optical constants, are used in the description of a propagating light wave in a solid. n provides a measure of the reduction in wave velocity ($n = c/v$) from c , the velocity of light in vacuum, and k provides a measure of the damping of the wave amplitude.

ϵ_1 , ϵ_2 , and σ - The real (ϵ_1) and imaginary (ϵ_2) parts of the dielectric function (ϵ) appear in the equation relating the displacement vector to the electric field vector in electromagnetic theory $\epsilon = \epsilon^*$, where $\epsilon^* = \epsilon_1 + i\epsilon_2$. ϵ_1 provides a measure of the polarization response (reduction of the applied field due to the polarization) of the medium, and ϵ_2 provides a measure of the number of photons absorbed per unit volume in the medium. ϵ_2 is related to the frequency dependent conductivity $\sigma(\omega)$ by the expression $\sigma = \omega\epsilon_2/4\pi$, ω is related to the wavelength λ by $\omega = \frac{2\pi c}{\lambda}$. $\sigma(\omega)$ provides a measure of the energy deposited in the medium per unit volume.

The above pairs of numbers describing the optical response of a medium are related by the expressions:

- 1) $\epsilon_1 = n^2 - k^2$
- 2) $\epsilon_2 = 4\pi\sigma/\omega = 2nk$

Since two numbers are required to describe the optical response, two independent measurements are required at each frequency. These measurements may be made on either the transmitted or reflected wave. In practice, transmission measurements are used primarily for determining the absorption coefficient k in semi-transparent samples. Measurements of the reflected wave provide a much wider variety of techniques. The description of reflection properties given below uses the notation of O.S. Heavens [5].

When a wave is reflected from a boundary between two media, the ratio of reflected to incident wave amplitude may be written as

$$3) \quad r = \rho \exp(i\beta),$$

where ρ is the magnitude of the amplitude ratio and β is the phase change on reflection. The ordinary measured reflectance R , which is the ratio of wave intensities, is related to r by $R = |r|^2 = \rho^2$. For light incident from a transparent medium of index n_0 onto a plane surface of a material with optical constants n and k , the amplitude reflectance (r) is a function of n and k , as well as the polarization and angle of incidence of the light. The expressions for r are:

$$4) \quad r_s = \frac{n_0 \cos \theta_0 - n^* \cos \theta}{n_0 \cos \theta_0 + n^* \cos \theta}$$

$$5) \quad r_p = \frac{n^* \cos \theta_0 - n \cos \theta}{n^* \cos \theta_0 + n \cos \theta}$$

where the subscripts s and p indicate polarizations perpendicular (s) and parallel (p) to the plane of incidence, and n^* is the complex index of refraction

$$6) \quad n^* = n + ik.$$

θ_0 and θ are the angles of incidence and refraction at the interface related by the complex form of Snell's law

$$7) \quad n^* \sin \theta = n_0 \sin \theta_0.$$

For normal incidence, $\theta_0 = \theta = 0$ and 4) and 5) reduce to the expression

$$8) \quad r = (n_0 - n^*) / (n_0 + n^*).$$

The normal incidence reflectance is thus

$$9) \quad R^0 = |r|^2 = \frac{(n - n_0)^2 + k^2}{(n + n_0)^2 + k^2}.$$

Several strategies are used for measuring the optical constants; some of those useful for metals are described below.

Reflectance and Transmission: The simplest in concept is to measure the transmission and reflection of a semitransparent film. For highly absorbing metal films, this requires the use of very thin films, generally of the order of a few hundred Angstroms, so that problems of film structure, oxidation, and measurement of film thickness present formidable barriers to accurate measurements. None of the reported studies of Be use this approach.

Angular Reflectance $R(\theta)$: The measurement of reflectance for a known polarization over a wide range of angles of incidence provides a very useful means of obtaining n and k for a wide range of absorbing materials, when the reflectance is not too high. In Table I, these measurements are indicated as $R(\theta)$ measurements. This method loses its usefulness for highly reflecting metals when even the normal incidence reflectivity approaches 1, and thus is not appropriate for Be in the far infrared. If the $R(\theta)$ measurements are made for both polarizations over a wide range of angles, highly redundant information is obtained that provides a powerful internal check on the consistency of the n and k values obtained.

Ellipsometry: It is possible to use information contained in changes in the phase angle when light is reflected to obtain n and k . The usual method is to use obliquely incident light that is linearly polarized at 45° to the plane of incidence, so that s and p components are in phase and of equal magnitude. After reflection, the light will, in general, be elliptically polarized. By measuring this ellipticity, both the ratio (ρ_p/ρ_s) of the magnitudes of the two components and the relative phase change ($\beta - \beta_p - \beta_s$) can be measured, from which n and k may be determined. This method can provide useful data on highly reflecting metal films, but is sensitive to the presence of thin oxide overlayers.

Kramers-Kronig Analyses: Though two numbers are required to describe the response of a material to an applied field at a single frequency, the two quantities as functions of frequency are not independent. The Kramers-Kronig (K-K) relations connect the variables $n(\omega)$ and $k(\omega)$, $\epsilon_1(\omega)$ and $\epsilon_2(\omega)$ or $\sigma(\omega)$, and $R(\omega)$ and $\beta(\omega)$. If one of the variables in a pair is known at all frequencies, the other can be determined. And if any pair of variables is known at all frequencies, the optical properties of the material are fully determined. These relations are discussed in detail elsewhere [1].

The most useful of these relations gives the phase change on reflection $\beta(\omega)$ if the normal reflectance is known at all frequencies.

$$10) \quad \beta(\omega) = \frac{-\omega}{\pi} \int_0^{\infty} \frac{[\ln R(\omega') - \ln R(\omega)] d\omega'}{\omega'^2 - \omega^2}$$

The optical constants are then given by

$$11) \quad n = \frac{1 - R}{1 + R - 2\sqrt{R} \cos\beta}, \quad k = \frac{-2\sqrt{R} \sin\beta}{1 + R - 2\sqrt{R} \cos\beta}$$

In the case of Be, measurements of the normal incidence reflectance are available over the full range where R is a strong function of frequency, due to the presence of strong interband transitions which absorb light. At low frequencies in the far infrared, Be behaves as a good free-electron metal with high reflectance, so that the theory of free-electron metals can be used to extend the reflectance values to zero frequency. At photon energies above the plasma energy at 18.4 eV, the reflectance approaches zero as expected for a metal for which the interband oscillator strength has been exhausted. The reflectance versus frequency curves presented in this report are used to perform a Kramers-Kronig analysis that allows us to determine optical constants over the spectral range from 0.02 to 26 eV. The optical constants given in this report as the best available provisional values are derived from this analysis. Some additional information is available from transmission measurements in the vicinity of the Be K-edge at 109 eV that will allow us to determine optical constants with somewhat less accuracy to photon energies of 300 eV.

III. Review of Published Optical Constants of Be

Published studies on the optical properties of Be date from 1936 to the present. These studies are listed in a separate section of the references. [A1-A18] Table I summarizes relevant facts about the more significant studies including photon energy range, sample type, method of measurement, date of publication, and reference number keyed to the reference list at the end of this report.

We will discuss the available experimental data in four spectral regions, beginning at short wavelengths (high photon energy). They are the soft x-ray range (SXR, $\hbar\omega > 50$ eV), the vacuum ultraviolet (VUV, $10\text{eV} < \hbar\omega < 50\text{eV}$), the infrared-visible-ultraviolet (IR-V-UV, $1\text{eV} < \hbar\omega < 10\text{eV}$), and the far infrared (FIR, $\hbar\omega < 1\text{eV}$). These regions are chosen not to match the standard definitions of these regions, which in any case are very vague, but for convenient discussion of the available results.

Normal incidence reflectance data for the three lowest energy spectral regions is shown in Fig. 1. The wide range of results in the available literature is apparent, and will be the subject of further discussion. The reason for the above division into four spectral regions is also apparent. Above 10 eV, the reflectance makes the transition from reflecting to transmitting behavior at the plasmon energy. Between 1 and 10 eV, absorption by interband transitions reduces the reflectance and introduces prominent structure. Below 1 eV, the rising reflectance indicates a transition to free-electron metallic behavior. Each experimental data set is coded with a separate symbol, as listed in Table I. The same symbols are used in this and all subsequent figures. The data sets are also coded with the initials of the authors.

SXR Spectral Region ($> 50\text{eV}$) - In this spectral region, the photon energy is above the plasmon energy (18.4 eV), and most of the interband oscillator strength is exhausted. Consequently, Be is weakly absorbing so that

$n \approx \sqrt{\epsilon_1} \sim 1$ and $\epsilon_2 = 2k \ll 1$. The only important physical process affecting the optical properties is the onset of absorption at the Be K-edge at 109 eV.

The data available in this region are from thin film transmittances that provide a measure of the linear absorption coefficient, $\mu = 4\pi k/\lambda_0$, where λ_0 is the wavelength of the incident radiation. If the thickness of the film is known,

Table I. Summary of experimental information for important experimental studies of the optical properties of Be.

Study (Ref -date)	Range (eV)	Method	Preparation	Identifiers For Figures
Henke (A2-1970)	60-250	Transmission	Evap. film	---
Barstow (A3-1983)	41-705	Transmission	Evap. film	---
LaVilla (A7-1965)	12-28	e Energy loss	Evap. film	---
Toots (A8-1968)	10-26	R(θ)	Evap. film	T-F-M Δ
Seignac (A10-1976)	2-25	R(0) & K-K	Evap. film	S-R *
Hunderi (A11-1974)	0.5-3.4	Ellipsometry	Evap. film	H-M x
Weaver (A12-1973)	0.12-4.5	Abs. & K-K	Single crystal	W-L-R +, $\square$
Shklyarevski (A13-1961)	0.11-1.5	Ellipsometry	Evap. film	S-Y O
Blickensderfer (A15-1977)	0.03-3.1	R(0) only	Polished bulk	B-D-L $\otimes$
Hull (A16-1989)	0.06-4.8	R(0) only	Polished bulk	Hull $\oplus$

Fig. 1. Normal incidence reflectances of Be reported in various published studies. Data sets for Figs. 1-8 are identified in Table I.

k values can be calculated from the transmittances. The available measurements are reported in Refs. A1 - A4. The more modern measurements reported by Henke [A2] and Barstow [A3], are consistent with each other and with theoretical calculations [6]. These values of μ are listed in Table II. Since data are available for only one optical parameter, the optical properties are not fully specified in this spectral region. The optical properties can be established with fair accuracy, however, by using model fits to the high-energy data, plausible extensions into the lower energy spectral regions, and a Kramers-Kronig analysis. These calculations are currently in progress and will be reported in a future report.

VUV Spectral Range (10 -50eV) - In this spectral range, the major feature of the spectrum is the transition from reflecting to transmitting behavior at the plasma energy (18.4 eV). Reflectance data from Seignac and Robin (S-R) [A10] and Toots, Fowler, and Marton (T-F-M) [A8] are plotted in Fig. 1. n and k values for this region are shown in Fig. 2 and ϵ_1 and ϵ_2 in Fig. 3. The function

Table II. Measured linear absorption coefficients for Be in the SXR spectral region.

Energy (eV)	Henke [A2] μ ($\times 10^4$ cm $^{-1}$)	Barstow [A3] μ ($\times 10^4$ cm $^{-1}$)
40.8		5.7 $\pm$ 0.1
48.4		3.67 $\pm$ 0.06
52.3		3.47 $\pm$ 0.05
62.0	3.5	
68.9	2.8	
77.5	2.2	
82.6	1.9	
88.5	1.6	
95.4	1.4	
103.3	1.1	
107.8	1.0	
124.0	26.0	
129.1	24.0	
155.0	16.0	
177.1	12.0	
183.4		9.4 $\pm$ 0.3
200.0	9.1	
221.4	7.1	
277.3		4.2 $\pm$ 0.2
705		0.7 $\pm$ 0.1

Fig. 2. Optical functions n and k in the VUV spectral region.

Fig. 3. Dielectric functions ϵ_1 , ϵ_2 and $\text{Im}(-1/\epsilon)$ in the VUV spectral region.

$\text{Im}(-1/\epsilon)$, which is directly related to the inelastic energy loss by charged particles, is also plotted in Fig. 3. Measures of this function obtained from energy loss data in [A6] and [A7] are in very good agreement with the data of T-F-M. Consequently, we use the T-F-M data to define the optical constants between 14 and 28 eV. Below 14 eV, we use the data of S-R to obtain a smooth transition to the data at lower energies. It may be noted that some errors in the n and k , and ϵ_1 and ϵ_2 values of S-R may be expected near the limits of their experimental data, since they use reflectance data plus a K-K analysis to obtain their optical functions. This method of analysis is least reliable near the end of the experimental range where the effects of extrapolation have the greatest effect on the values obtained for the optical parameters.

IR-V-UV (1 - 10 eV) - In Fig. 1, reflectance data from S-R [A10], Hunderi and Myers (H-M) [A11], Weaver, Lynch, and Rosei (W-L-R) [A12], and Hull [A16] are plotted. The most striking feature of this region is the wide range of reflectances obtained from careful studies in a spectral region where the procedures of optical measurements are usually most reliable.

The two reflectance curves reported by W-L-R for the electric field vector parallel ($E \parallel c$) and perpendicular ($E \perp c$) to the c -axis direction, were obtained on single crystal surfaces prepared by mechanical polishing, with a subsequent chemical etch. We believe that the low reflectances obtained indicate serious problems with the sample composition, or surface structure, and that these results are not characteristic of planar, pure Be surfaces.

The reflectance data of Hull [A16] were taken on the carefully polished surface of a polycrystalline mirror blank prepared by pressure sintering a low oxygen content (<.5%) Be powder. This surface, intended for use as a reflector in the infrared, gives one of the highest reflectances for Be reported to date in the FIR region. However, this surface shows lower reflectance than the best evaporated films in this spectral region.

The highest reflectances reported in the visible were obtained by S-R on Be films prepared by slow evaporation in UHV. Because of the careful UHV preparation techniques used, and because most sample preparation problems will tend to reduce the measured reflectance, our initial assessment was that these data were the best available. A series of experiments, which are detailed in the next section of this report, have confirmed this initial judgement. We have been able to identify film preparation procedures that result in lower reflectances. Thus, we adopt the reflectance values of S-R as the best available

in this spectral region. It should be noted that the reflectance values of H-M are substantially the same in their region of overlap.

Values of n and k , and ϵ_1 and ϵ_2 obtained by S-R and H-M are plotted in Figs. 4 and 5. Though the reflectances are very similar, there are substantial differences in the values of n and k obtained by S-R and H-M. Of particular significance is the crossing in the values of n and k in the spectral region between 1.7 and 3 eV in the data of S-R, which results in the value of ϵ_1 exceeding zero over this range. Our own angular reflectance $R(\theta)$ and ellipsometry measurements on evaporated films in this spectral range consistently confirm the crossing of the n and k values reported by S-R.

The large range of reflectance values observed for samples in the visible and ultraviolet is not unprecedented. An equally large range of reflectances has been reported for aluminum, depending on the method of film preparation (evaporation in UHV or normal vacuum, sputtering or mechanical polishing) [7].

Fig. 4. Optical functions n and k in the IR-V-UV spectral region.

Fig. 5. Dielectric functions ϵ_1 and ϵ_2 in the IR-V-UV spectral region.

It is well known that rough surfaces not only scatter, but can couple incident light to surface plasmon modes and reduce the reflectance [8]. It seems probable that the sensitivity of the reflectance to surface structure, and perhaps to bulk grain size, is related to coupling of light to surface and/or bulk plasmon modes in these samples.

FIR Spectral Region (< 1eV) - In this spectral region, Shklyarevskii and Yarovaya (S-Y) [A13] report a full set of optical constants, and other workers [A15,A16] have obtained normal incidence reflectance data. The reflectances obtained by S-Y are low, which we believe to be evidence for poor film structure. The reflectances of Hull's polished bulk samples [A16] are among the highest reported for this spectral region.

We have measured the optical constants for a number of samples in the transition region from 3 eV to 0.6 eV, and normal incidence reflectance to 0.1 eV, with results to be reported in the following section. In general, it appears that in the FIR, as in the visible region, the best samples have the highest reflectance.

Provisional Optical Response Functions (0.02 - 26 eV)

From the sources described in previous paragraphs, optical measurements are available that span the spectral region up to 26 eV, though only normal incidence reflectance data are available for most of the far infrared (FIR) region.

We have obtained a consistent set of optical response functions for the entire spectral range by assembling a reflectance curve for energies of $0.06 < \hbar\omega < 26$ eV from published results, extending it to 0 and infinite energies using appropriate analytic functions, and performing a Kramers-Kronig (K-K) analysis using equations (10) and (11). The reflectance values used were obtained by drawing a smooth curve through the following data sets:

0.06 $< \hbar\omega < 0.8$ eV, Hull's reflectance data;

0.8 $< \hbar\omega < 5.0$ eV, data from H-M;

1.5 $< \hbar\omega < 14$ eV, data from S-R;

14 $< \hbar\omega < 26$ eV, data from T-F-M.

In regions of overlap, higher reflectance values were favored. These data sets are shown along with the fitted $R(\hbar\omega)$ curve in Fig. 6.

Fig. 6. Reflectance curve used as input for the K-K analysis.

Below 0.06 eV, the reflectance was extrapolated to zero energy using a linear extrapolation of Hull's data. Above 26 eV the reflectance was extrapolated to infinite energy as ω^{-4} , in accordance with the behavior of nearly-free-electron metal above the plasma edge. The numerical integrations in the K-K analysis were performed at 0.01 eV energy intervals; the reflectance is smooth on this energy scale in all spectral regions. The results of this analysis are likely to be least reliable in the FIR spectral region. For example, a change in the measured reflectance of ± 0.005 in this region changes the k values by only a few percent but changes the n values by 20 to 30 percent.

The n and k values derived from the K-K analysis are plotted in Fig. 7 and ϵ_1 and ϵ_2 in Fig. 8. A numerical printout of the optical constants is given in Table III.

Fig. 7. Values of the optical functions n (—) and k (---) determined from the K-K analysis for the photon energy range $0.02 < \hbar\omega < 26$ eV.

Fig. 8. Values of the dielectric functions ϵ_1 (—) and ϵ_2 (---) determined from the K-K analysis for the photon energy range $0.4 < \hbar\omega < 26$ eV.

It should be noted that the optical parameters determined in this analysis are provisional only. We believe that they are the best estimates that can be made from available data, but questions about the effects of surface structure and roughness are by no means resolved. A very careful experimental effort to measure the optical constants of oxide free samples with smooth and well-characterized surfaces will be required in order to obtain a definitive set of optical constants.

Table III. Optical constants for Be

E(eV)	WL(MICRONS)	n	k	R
0.02	6.199E+01	8.61E+01	1.57E+02	9.89E-01
0.04	3.100E+01	3.74E+01	1.10E+02	9.89E-01
0.06	2.066E+01	1.99E+01	7.71E+01	9.88E-01
0.08	1.550E+01	1.46E+01	6.04E+01	9.85E-01
0.10	1.240E+01	1.13E+01	5.01E+01	9.83E-01
0.20	6.199E+00	3.66E+00	2.67E+01	9.80E-01
0.30	4.133E+00	2.43E+00	1.73E+01	9.69E-01
0.40	3.099E+00	2.07E+00	1.26E+01	9.51E-01
0.50	2.480E+00	2.14E+00	9.67E+00	9.17E-01
0.60	2.066E+00	2.41E+00	7.88E+00	8.69E-01
0.70	1.771E+00	2.55E+00	6.64E+00	8.20E-01
0.80	1.550E+00	2.74E+00	5.66E+00	7.62E-01
0.90	1.378E+00	2.87E+00	5.02E+00	7.14E-01
1.00	1.240E+00	3.09E+00	4.51E+00	6.67E-01
1.20	1.033E+00	3.26E+00	3.96E+00	6.15E-01
1.40	8.856E-01	3.35E+00	3.55E+00	5.75E-01
1.60	7.749E-01	3.44E+00	3.35E+00	5.55E-01
1.80	6.888E-01	3.47E+00	3.23E+00	5.44E-01
2.00	6.199E-01	3.46E+00	3.18E+00	5.39E-01
2.20	5.635E-01	3.39E+00	3.17E+00	5.38E-01
2.40	5.166E-01	3.30E+00	3.18E+00	5.38E-01
2.60	4.768E-01	3.19E+00	3.16E+00	5.37E-01
2.80	4.428E-01	3.07E+00	3.16E+00	5.37E-01
3.00	4.133E-01	2.95E+00	3.14E+00	5.37E-01
3.20	3.874E-01	2.84E+00	3.12E+00	5.36E-01
3.40	3.646E-01	2.73E+00	3.10E+00	5.36E-01
3.60	3.444E-01	2.64E+00	3.08E+00	5.36E-01
3.80	3.263E-01	2.55E+00	3.08E+00	5.38E-01
4.00	3.100E-01	2.47E+00	3.08E+00	5.41E-01
4.20	2.952E-01	2.39E+00	3.10E+00	5.47E-01
4.40	2.818E-01	2.30E+00	3.15E+00	5.58E-01
4.60	2.695E-01	2.17E+00	3.22E+00	5.75E-01
4.80	2.583E-01	1.99E+00	3.29E+00	5.97E-01
5.00	2.480E-01	1.78E+00	3.32E+00	6.20E-01
5.20	2.384E-01	1.54E+00	3.30E+00	6.44E-01
5.40	2.296E-01	1.31E+00	3.23E+00	6.68E-01
5.60	2.214E-01	1.08E+00	3.11E+00	6.93E-01
5.80	2.138E-01	8.21E-01	2.90E+00	7.20E-01
6.00	2.066E-01	8.49E-01	2.64E+00	6.73E-01
6.20	2.000E-01	8.44E-01	2.52E+00	6.53E-01
6.40	1.937E-01	8.37E-01	2.42E+00	6.37E-01
6.60	1.878E-01	8.25E-01	2.34E+00	6.26E-01
6.80	1.823E-01	8.05E-01	2.28E+00	6.20E-01
7.00	1.771E-01	7.78E-01	2.23E+00	6.18E-01

E(eV)	WL(MICRONS)	n	k	R (nmol)
7.20	1.722E-01	7.44E-01	2.18E+00	6.19E-01
7.40	1.675E-01	7.07E-01	2.13E+00	6.21E-01
7.60	1.631E-01	6.71E-01	2.08E+00	6.24E-01
7.80	1.589E-01	6.28E-01	2.04E+00	6.30E-01
8.00	1.550E-01	5.88E-01	1.98E+00	6.35E-01
8.20	1.512E-01	5.51E-01	1.92E+00	6.39E-01
8.40	1.476E-01	5.18E-01	1.87E+00	6.42E-01
8.60	1.442E-01	4.90E-01	1.81E+00	6.43E-01
8.80	1.409E-01	4.63E-01	1.75E+00	6.44E-01
9.00	1.378E-01	4.45E-01	1.69E+00	6.41E-01
9.20	1.348E-01	4.27E-01	1.64E+00	6.39E-01
9.40	1.319E-01	4.12E-01	1.59E+00	6.36E-01
9.60	1.291E-01	3.98E-01	1.54E+00	6.33E-01
9.80	1.265E-01	3.85E-01	1.50E+00	6.30E-01
10.00	1.240E-01	3.73E-01	1.45E+00	6.27E-01
10.50	1.181E-01	3.45E-01	1.35E+00	6.20E-01
11.00	1.127E-01	3.24E-01	1.25E+00	6.09E-01
11.50	1.078E-01	3.09E-01	1.16E+00	5.95E-01
12.00	1.033E-01	2.98E-01	1.07E+00	5.80E-01
12.50	9.918E-02	2.87E-01	9.91E-01	5.65E-01
13.00	9.537E-02	2.84E-01	9.13E-01	5.42E-01
13.50	9.184E-02	2.83E-01	8.41E-01	5.19E-01
14.00	8.856E-02	2.84E-01	7.72E-01	4.94E-01
14.50	8.550E-02	2.87E-01	7.07E-01	4.67E-01
15.00	8.265E-02	2.93E-01	6.45E-01	4.38E-01
15.50	7.999E-02	3.00E-01	5.85E-01	4.09E-01
16.00	7.749E-02	3.12E-01	5.27E-01	3.76E-01
16.50	7.514E-02	3.26E-01	4.73E-01	3.42E-01
17.00	7.293E-02	3.42E-01	4.21E-01	3.09E-01
17.50	7.085E-02	3.61E-01	3.72E-01	2.75E-01
18.00	6.888E-02	3.82E-01	3.25E-01	2.42E-01
18.50	6.702E-02	4.07E-01	2.95E-01	2.12E-01
19.00	6.525E-02	4.36E-01	2.70E-01	1.83E-01
19.50	6.358E-02	4.68E-01	2.42E-01	1.54E-01
20.00	6.199E-02	4.96E-01	2.20E-01	1.32E-01
20.50	6.048E-02	5.26E-01	2.03E-01	1.12E-01
21.00	5.904E-02	5.55E-01	1.90E-01	9.54E-02
21.50	5.767E-02	5.83E-01	1.72E-01	8.03E-02
22.00	5.635E-02	6.11E-01	1.60E-01	6.75E-02
22.50	5.510E-02	6.32E-01	1.47E-01	5.85E-02
23.00	5.390E-02	6.53E-01	1.35E-01	5.04E-02
23.50	5.276E-02	6.68E-01	1.22E-01	4.47E-02
24.00	5.166E-02	6.84E-01	1.15E-01	3.97E-02
24.50	5.060E-02	6.97E-01	1.08E-01	3.58E-02
25.00	4.959E-02	7.10E-01	1.02E-01	3.22E-02
25.50	4.862E-02	7.22E-01	9.50E-02	2.90E-02
26.00	4.769E-02	7.34E-01	8.95E-02	2.62E-02

IV. Measurements of Be Optical Properties at ORNL, 1989.

Because of the many ambiguities in the published optical data on Be, we have undertaken a series of measurements to try to understand the source of the differing results reported.

Ellipsometry - We have used ellipsometry to measure the optical functions of several samples provided by the Survivable Optics MODIL at ORNL. The n and k values obtained from a sample prepared by magnetron sputtering a thick film of Be on Si is shown in Fig. 9. Similar measurements were made on samples of thick Be films on glass. The reflectance measurements derived from these values of n and k are plotted in Fig. 10 and compared with the reflectance values from Hull [A16] and S-Y [A13]. The reflectances obtained are very close to Hull's values.

Normal Incidence Reflectance: Dependence on Evaporation Conditions - Because the variation in measured reflectances are greatest in the visible range, normal incidence reflectance measurements were made on a wide range of samples between

Fig. 9. Optical functions n and k and normal incidence reflectance determined from ellipsometry measurements on a Be on Si sample.

Fig. 10. Normal incidence reflectances for Be on Si and Be on glass samples determined from ellipsometry. Other data are from S-Y (o) and Hull (Φ).

4000 Å and 6500 Å. Some of these results are shown in Fig. 11. In this figure the curves, in order of increasing reflectivity, are from W-L-R [A12], rapidly evaporated (~ 30 Å/s) thick films (> 5000 Å) of Be on Au, magnetron-sputtered Be on glass (5-10 Å/s), magnetron-sputtered Be on Si (5-10 Å/s), S-R [A10], and slowly evaporated (< 5 Å/s) thin films (~ 1000 Å) of Be on glass.

For the films prepared with known evaporation rates and thicknesses, thin films prepared by slow evaporation have the highest reflectances. However, these results are preliminary, and clearly other variables such as substrate temperature and vacuum conditions may play important roles in surface conditions.

A study was performed to determine how the reflectance varies with film thickness for very thin, partially transparent, films. It was found that the films have maximum reflectance at thicknesses of a few hundred Å, followed by a reduction of the reflectance by about 10% for increasing film thicknesses. This result may be understood from Fig. 12, in which the calculated reflectance at 5000 Å as a function of film thickness using the optical constants of S-R, and $n_0 = 1.5$ for the glass substrate is plotted. Experimental values of the reflectance are plotted on the same scale. Because relative, rather than absolute

Fig. 11. Normal incidence reflectances of Be for several surfaces in the visible spectral region. Origin of data sets is identified in text.

Fig. 12. Normal incidence reflectance for Be on glass films, as a function of Be film thickness. The solid curve is calculated reflectance and solid symbols are measured values. $\lambda = 5000 \text{ \AA}$.

thicknesses of the films were measured in these experiments, the horizontal axis for the experimental data has been arbitrarily scaled to obtain a good fit between the experimental data and the calculations. The enhanced reflectance at a few hundred Å thickness results from reflection from the film-substrate interface. It should be noted that for constant values of k , greater thicknesses are required at longer wavelengths since the linear absorption coefficient scales inversely with wavelength. For the high reflectance film of Fig. 11, evaporation was continued until the reflectance over the full 4000 - 6500 Å wavelength range reached stable values.

Reflectance With Oxide Overlayers - We have also calculated the effect of a BeO oxide layer on Be as a function of oxide film thickness. The results are illustrated for the FIR spectral region in Fig. 13, which shows the effect of films of thicknesses ranging from 0.025 μm to 25 μm on the reflectance. Thin BeO films have little effect in this region, but thick films effectively suppress the reflectance everywhere except at the Reststrahlen peak of BeO near 10 μm . The optical functions of Be used for these calculations were taken from Table III, and the BeO optical constants from the data of C.A. Worrell [9] and Durig et al. [10]

Fig. 13. Calculated values for normal incidence reflectance of Be with a BeO overlayer as a function of BeO film thickness.

V. Conclusions

This review shows that very little data are available in the FIR-IR ($h\nu < 0.25$ eV) region, and that while more data exist in the UV-Vis-NIR, there are large variations in the results which depend upon sample conditions. We have obtained provisional values of the optical constants from a Kramers-Kronig analysis of the available reflectance data for photon energies $0.02 < h\nu < 26$ eV. Calculations of the effects of oxide layers on the surface of Be show that oxide thicknesses less than $0.25 \mu\text{m}$ have no significant effect on the reflectance. Finally, it is clear that much more research is needed to correlate the various surface preparation conditions with measured reflectances.

Acknowledgments

We would like to thank Linda Dritt from the University of Tennessee Science Alliance Program for helping to make some of the reflectance measurements and C. M. Egert of the Optics MODIL for supplying sputtered beryllium samples.

REFERENCES

1. P.O. Nilsson, G. Arbman, and T. Gustafsson, J. Phys. F-Metal Phys. 4, 1937-1950 (1974).
 2. M. Taut, Phys. Stat. Sol. 77, 165-170 (1976); also Phys. Stat. Sol. 77, 543-550 (1976).
 3. P. Sinha and S. Chatterjee, Indian J. Phys. 52A, 503-510 (1978).
 4. Handbook of Optical Constants of Solids, ed. by E.D. Palik (Acad. Press, Orlando, Fla. and New York, 1985).
 5. O.S. Heavens, Optical Properties of Thin Solid Films, (Dover, New York, 1965).
 6. D.T. Cromer and D. Liberman, Los Alamos Special Rep. LA4403 (Los Alamos National Laboratory, 1973).
 7. D.Y. Smith, E. Shiles and Mitio Inokuti, in Ref. 4 listed above, p. 389. This article summarizes results and provides references to many studies of Al.
 8. R.H. Ritchie and R.E. Wilems, Phys. Rev. 178, 372 (1969); J. Crowell and R.H. Ritchie, JOSA 60, 794 (1970); J.M. Elson and R.H. Ritchie, Phys. Rev. B4, 4129 (1971).
 9. C.A. Worrell, J. Mat. Sci. 21, 781 (1986).
 10. J.R. Durig, R.C. Lord, W. J. Gardner, and L.H. Johnston, JOSA 52, 1078 (1962).
- A. References for the optical properties of Be listed approximately in order of decreasing photon energy.
- A1. R. W. Johnston and D.H. Tomboulion, Phys. Rev. 94, 1585-1589 (1954).
 - A2. B. L. Henke and R. L. Elgin, Adv. X-ray Anal. 13, 639-665 (1970).
 - A3. M. A. Barstow, M. Lewis and R. Peure, JOSA 73, 1220-1222 (1983).
 - A4. B. J. Muldar and J. J. Vrakking, J. Phys. E: Sci. Instrum. 11, 743-744 (1978).
 - A5. O. P. Rustgi, JOSA 55, 630-634 (1965).
 - A6. N. Swanson, JOSA 54, 1130-1134 (1964).
 - A7. P. E. LaVilla and H. Mendlowitz, Appl. Optics 4, 955-960 (1965).

REFERENCES (continued)

- A8. J. Toots, H. A. Fowler and L. Marton, Phys. Rev. 172, 670-676 (1968).
- A9. M. Banning, JOSA 32, 98-102 (1942).
- A10. A. Seignac and S. Robin, Sol. State Commun. 19, 343-345 (1976).
- A11. O. Hunderi and H. P. Myers, J. Phys. F: Metal Phys. 4, 1088-1093 (1974).
- A12. J. H. Weaver, D. W. Lynch, and R. Rosei, Phys. Rev. B7, 3537-3540 (1973).
- A13. I. N. Shklyarevskii and R. G. Yarovaya, Optics and Spectroscopy 11, 355-357 (1960). [Opt. Spekt. 11, 661 (1961)]
- A14. H. M. O'Bryan, JOSA 26, 122-127 (1936).
- A15. R. Blickensderfer, D. K. Deardorff, and R. L. Lincoln, J. of the Less Common Metals 51, 13-23 (1977).
- A16. Anthony B. Hull, Perkin-Elmer/ Applied Optics Operations, Box 3115, Garden Grove, CA, 92641. (private communication).