Citation: Journal of Applied Physics. vol.108, 063514, pp. null - 2219 (2010)

https://doi.org/10.1063/1.3481062

Transmittance and optical constants of Lu films in the 3-1,800 eV spectral range

Sergio García-Cortés, Luis Rodríguez-de Marcos, Juan I. Larruquert*, José A. Aznárez, José A. Méndez

GOLD-Instituto de Física Aplicada-Consejo Superior de Investigaciones Científicas

Serrano 144, 28006 Madrid, Spain

Luca Poletto, Fabio Frassetto

Institute of Photonics and Nanotechnologies-National Council for Research,

via Trasea 7, 35131 Padova, Italy

A. Marco Malvezzi

Dipartimento di Elettronica, Università di Pavia and CNISM, Via Ferrata, 1, I27100 Pavia, Italy

Angelo Giglia, Nicola Mahne

Istituto Officina dei Materiali IOM-CNR Laboratorio TASC, Area Science Park Basovizza, S.S. 14 Km 163.5, 34149 Trieste, Italy

Stefano Nannarone

Dipartimento di Ingegneria dei Materiali e dell Ambiente, Universita di Modena e Reggio Emilia, Via Vignolese 905, I-41100 Modena, Italy

ABSTRACT

The optical constants *n* and *k* of lutetium (Lu) films were obtained in the 3-1,800-eV range from transmittance measurements performed at room temperature. These are the first experimental optical constant data of Lu in the whole range. Thin films of Lu with various thicknesses were deposited by evaporation in ultra high vacuum conditions and their transmittance was measured in situ. Lu films

* Author to whom correspondence should be addressed. Electronic mail: larruquert@ifa.cetef.csic.es; fax number: 34 914117651

were deposited onto grids coated with a thin, C support film. Transmittance measurements were used to obtain the extinction coefficient *k* of Lu films. The refractive index *n* of Lu was calculated with Kramers-Krönig analysis. *k* data were extrapolated both on the high and on the low energy sides by using experimental and calculated *k* values available in the literature. Lu, similar to other lanthanides, has a low-absorption band below the $O_{2,3}$ edge onset; the lowest absorption was measured at ~25.1 eV. Therefore, Lu is a promising material for filters and multilayer coatings in the energy range below the $O_{2,3}$ edge in which most materials have a large absorption. Good consistency of the data was obtained through *f* and inertial sum rules.

Keywords: Extreme Ultraviolet; Far Ultraviolet; Optical constants; Absorption filters; Multilayers; Optical properties of thin films

1. INTRODUCTION

Until recently, lanthanides had not been fully characterized in the extreme ultraviolet (EUV)-soft X-rays. However, an increased interest has grown on these materials with the recent characterization of Yb[1,2], La[3,4], Tb[3,4], Gd[5,4], Nd[5,4], Ce[6], Pr[7], Eu[8], Dy[4], and Tm[9], and of materials with close chemical properties such as Sc[10,11,12,13] and Y[14]. This paper addresses the optical properties of Lu films in the 3-1,800-eV range. The optical properties in this energy range are characterized by the high energy tail of the valence electrons and by the presence of two intense $O_{2,3}$ and $M_{4,5}$ absorption bands, in order of increasing binding energy, and of a weak $N_{4.5}$ band, due to the excitation of 5p, 3d, and 4d electrons, respectively, above the Fermi level.

Almost no previous data on the optical properties of Lu in the UV to soft X-rays has been found for this research. Zimkina et al.[15] performed absorption measurements on Lu thin films and provided data of the product of the absorption coefficient times the film thickness in arbitrary units in the ~60-480 eV range. Unfortunately, this paper cannot be directly taken for absolute reference since the absorption coefficient cannot be deduced. Fischer and Baun[16] obtained M_α and M_β emission spectra of lanthanides and lanthanide oxides, including Lu; they only plotted the data for the oxide but they stated that the spectrum did not show any change between metal and oxide. For other lanthanides they also displayed absorption spectra, which were relatively similar to the emission spectra; however, this comparison was not given for Lu. At higher energies than the present research, Padalia *et al.*[17] obtained absorption spectra of Lu and other lanthanides at $L_{2,3}$ edges.

Other than optical data, Bonnelle *et al.*[18] reported photoelectron spectra of Lu_2O_3 in the valence region and the 4d region. Lang *et al.*[19] reported core-level binding energies of Lu measured by x-ray photoelectron spectroscopy. Colliex et al.[20] measured the energy loss spectra of electrons transmitted

through thin films of Lu and other rare-earth metals and their compounds. For Lu, the authors obtained a main energy-loss peak at 14.9 eV, which they assigned to collective excitations of the upper electron band, and a less intense peak at 41.0 eV, which they assigned to the excitation of the 5p electrons of the metal atom. Onsgaard *et al.*[21] measured the reflection energy-loss spectra of the (001) surface of a Lu single crystal, and they provided the energies of single electron excitation of Lu. Netzer *et al.*[22] presented the electron energy-loss spectra in reflection mode of Lu and the other lanthanides. Manoubi *et al.*[23] determined cross section ratios of rare-earth $M_{4,5}$ to oxygen K for rare-earth oxides including Lu. Henke *et al.*[24] obtained a semi-empirical set of data in the 30-10,000-eV range (later extended to 30,000 eV[25]). Henke compilations could only use the data in arbitrary units of Zimkina et al.[15]. Due to the lack of data on Lu, Henke *et al.* had to use data on Yb at $M_{3,4,5}$ edges, coming from Combley *et al.*[26].

The 5p to nd resonances and the direct 5p photoionization of atomic Lu has been investigated by photoelectron spectroscopy and photoion spectroscopy in combination with monochromatized synchrotron radiation in the vacuum ultraviolet energy region[27,28].

In view of the full lack of data, this paper is aimed at providing accurate optical data on pure Lu films in a broad spectral range. It is organized as follows. A brief description of the experimental techniques used in this research is presented in Section 2. Section 3 presents transmittance data, extinction coefficient of Lu calculated from transmittance, and dispersion obtained using KK analysis; the consistency of the data gathered in this research is also evaluated.

2. Experimental techniques

2.1 SAMPLE PREPARATION

Both Lu film deposition and characterization were performed under ultra high vacuum (UHV) at BEAR beamline of ELETTRA synchrotron (Trieste, Italy). Lu films were deposited onto 5-nm thick C films supported on 117 mesh Ni grids with 88.6% nominal open area (pitch of 216 μm). The procedure for C film preparation was reported elsewhere[12]. Lu films were deposited with a TriCon evaporation source[29], in which a small Ta crucible is bombarded by electrons that impinge on the crucible wall. Lu granules of 99.99 % purity from LTS Chem. Inc. were used. The crucible-sample distance was 200 mm. Deposition rate was ~2.5 nm/min. Film thickness was monitored with a quartz crystal microbalance during deposition. Lu films were deposited onto room-temperature substrates. A witness glass substrate was placed close to the grid-supported C film to get coated simultaneously with a similar Lu film thickness. Reflectance versus the incidence angle was measured on the witness samples at the energy of 100 eV and the angular positions of the minima and maxima were used to calculate the Lu film thickness. Since reflectance measurements were performed far from absorption edges, Henke optical constants[25] could be used in this calculation. Henke data were downloaded from the website of the Center for X-Ray Optics (CXRO) at Lawrence Berkeley National Laboratory[30]. The distance on the surface sample between the area of transmittance measurements and that of reflectance measurements was less than 10 mm.

2.2 EXPERIMENTAL SETUP FOR TRANSMITTANCE MEASUREMENTS

Transmittance measurements were performed at BEAR beamline with vertical exit slits of 100 μm (above 24 eV) and 450 μm (below 24 eV); the monochromator spectral resolution $E/\Delta E$ varied between 500 and 2000, depending on slit widths. The suppression of higher orders was achieved using quartz, LiF, In, Sn, Al, and Si filters at specific ranges below 100 eV, and choosing a plane mirror-to-grating deviation angle in the monochromator setup that minimized the higher-order

contribution at energies above 100 eV. Above 1,200 eV an Ag filter was used. The beam cross section at the sample was about 0.7×1.5 mm^2.

The measurements were performed in the BEAR spectroscopy chamber[31], connected in vacuum to the preparation chamber at a pressure of $\sim3\times10^{-7}$ Pa, where in-situ samples were prepared. Three C substrates were used and their transmittance was measured previously to Lu deposition. Two and four successive Lu coatings of various thicknesses were accumulated upon the first and the second substrate, respectively, without breaking vacuum. The third substrate received only one deposition of a single Lu thickness. Each sample was transferred back and forth between the deposition chamber and the measurement chamber, always under UHV, for the deposition of the successive Lu layers and their characterization. Transmittance measurements were performed onto samples at room temperature. For each film, uniformity evaluations were performed. We estimate that the overall uncertainty in the transmittance measurements is of the order of 2%. At energies above 18 eV, fluctuations of the photon beam during transmittance measurements were recorded with a 100-V biased, Au mesh. These fluctuations were cancelled by normalizing the recorded beam intensity to the mesh current. At energies below 18 eV, fluctuations were cancelled by normalization with respect to the ring current.

3. Results and discussion

3.1 TRANSMITTANCE AND EXTINCTION COEFFICIENT OF Lu

We measured the transmittance of Lu films with the following thicknesses: 24.6, 28.0, 34.5, 44.2, 71.5, 90.0, and 114.0 nm. The transmittance of the Lu films normalized to the transmittance of the uncoated substrate is plotted in Fig. 1. There are two high transmission bands peaked at ~1,486 and ~25 eV, right below Lu M_5 and $O_{2,3}$ edges, respectively. The low-energy band of relatively large transmittance extends within ~20-26-eV. Close transmittance bands have been measured for other

rare earths; hence Lu, as other lanthanides such as La, Ce, Pr, Nd, Eu, Gd, Tb, Dy, Tm, and Yb, is a promising material for transmittance filters or multilayer spacers for the extreme ultraviolet in the ~12-26-eV spectral range, where there has been a lack of low-absorbing materials until recently. The slight oscillations at ~72, ~100, ~285, and ~537 eV are related to data normalization, due to the fact that at these energies there is an abrupt decrease of the signal due to the presence of the Al and Si filters, to carbon contamination of the optics, and to the slight presence of O either at the optics or on the sample, respectively.

If the contribution to transmittance coming from multiple reflections inside the Lu film is negligible, the extinction coefficient *k* (the imaginary part of the complex refractive index) can be calculated from transmittance with the following equation:

$$\ln\left(\frac{T_{fs}}{T_s}\right) \approx A - \left(\frac{4\pi k}{\lambda}\right)\cdot d \qquad (1)$$

where T_s and T_{fs} represent the transmittance of the uncoated substrate and of the substrate coated with a Lu film, respectively; λ is the radiation wavelength in vacuum; *d* stands for the Lu film thickness. Eq. (1) is a straightforward derivation of the well-known Beer-Lambert law. A is a constant for each energy and encompasses the terms that involve reflectance, in the assumption that multiple reflections are negligible.

k of Lu films was calculated by fitting the slope of the logarithm of transmittance versus thickness at each energy using Eq. (1); the data are represented in Fig. 2. The semi-empirical data of Henke[25,30], also plotted in Fig. 2, were calculated with a density of 9.84 g/cm^3. The aforementioned presence of C, Al, Si, and O oscillations at the C K, Al $L_{2,3}$, Si $L_{2,3}$ and O K edges is less significant on *k* than on transmittance because samples of different Lu thicknesses with similar presence of contaminants

(either on the sample or on the light path), or with artifacts coming from normalization at transmittance calculation will tend to cancel out in the calculation of *k* with the slope method.

When reflectance is not negligible, the application of Eq. (1) to calculate *k* through the slope of the log of transmittance versus thickness may result in uncertainties. Furthermore, in the 7.75-17.5 eV range only one sample was available and the slope method could not be used. In order to overcome this, we proceeded in an iterative way. The iterative method was applied in the 3-30-eV range. For the first iteration, initial *k* values were obtained using the slope method, except within the 7.75-17.5 eV range, where initial *k* values were obtained through a direct calculation from transmittance measurements using Eq. 1 and neglecting reflectance (A=0). These values, along with *k* data in the rest of the spectrum, were used to obtain the refractive index *n* (the real part of the complex refractive index) with KK analysis (KK analysis is described in the next sub-section). Once a first set of data {$n(E)$, $k(E)$} was available, the transmittance ratio of the C/Lu bilayer to the single C film was calculated with the usual equations based on Fresnel coefficients. This transmittance ratio was compared with the measured data; the difference between measured and calculated transmittance gave us an estimate to modify *k*. This modified value was a second estimate of *k*, from which a second estimate of *n* was obtained with KK analysis. This procedure can be iterated until the best match to transmittance data is obtained. The optical constants of the single C film at this same range had been previously calculated with a similar procedure starting with *k* obtained from the transmittance of an uncoated C substrate. The *k* data plotted in Fig. 2 were progressively modified from 11 to 3 eV in an attempt to better match literature data below 6 eV, which is explained in the next sub-section.

k values at the $O_{2,3}$ edge and around are presented in Fig. 3. The smallest value of *k* is obtained at ~25.1 eV. This minimum is close to the ones obtained for other rare earths: Ce[6] at 16.1 eV, La[3] at

16.5 eV, Eu[8] at 16.7 eV, Pr[7] at 16.87 eV, Nd[5] at ~ 17 eV, Tb[3] at ~19.5 eV, Gd[5] at ~19.7 eV, Dy[4] at ~20.2 eV, Yb[1,2] at 21.2 eV, Tm[9] at 23 eV, and Sc[10] at 27 eV. As with other lanthanides, optical properties of Lu in this range are promising for its use in transmittance filters or reflective multilayers. However, Lu, as its neighbors in the periodic table, is a reactive material, and this may result in the need to develop a protective layer. $N_{4,5}$ edge for Lu, similar to what was obtained for Yb[2], is much smoother than for other lanthanides. This is probably due to the fact the outer electron shell configuration of the two elements is very similar ([Xe] 4f14 6s2 for Yb and [Xe] 4f14 5d1 6s2 for Lu) and then the oscillation strength of the N edge is very close. This aspect could be further investigated in theoretical literature.

k at the $M_{4,5}$ edge is presented in Fig. 4, along with the semi-empirical data of Henke. At this energy range, the transmittance-versus-energy curves for the different samples are not fully consistent, since they do not have a common shape. The transmittance of the two thinnest films cross at two energies and the same happens with the transmittance of the two thickest films. This is attributed to the small signal available at these energies, which may be masked by scattered radiation of smaller energies, even though we used an Ag filter to reduce this effect. In fact, we extended the measurement range away from the nominal limit of 1,600 eV of the beamline. We did so in order to be able to provide optical constants on the M_{45} edge of Lu, due to the lack of any experimental data in the literature. In the calculation of *k* we decided to use the measurements on all samples since we had no guide to reject any data. We slightly modified k in the 1,690-1,800 eV range in order to smoothly connect with Henke data.

3.2 REFRACTIVE INDEX CALCULATION THROUGH DISPERSION RELATIONS

The refractive index *n* of Lu was calculated using KK dispersion relations:

$$n(E)-1=\frac{2}{\pi}P\int_0^{\infty}\frac{E'k(E')}{E'^2-E^2}dE' \quad (2)$$

where *P* stands for the Cauchy principal value. The application of Eq. (2) to calculate *n* requires the availability of *k* data over the whole spectrum, so that we extended the present data with the available data in the literature and extrapolations. Between 1,800 and $3\cdot10^4$ eV we used Henke data from CXRO's web[24,30]; the two sets of data were coupled with a smooth connection. For even larger energies, the calculations of Chantler et al.[32] were used up to $4.3\cdot10^5$ eV. The extrapolation to infinity was performed by keeping constant the slope of the log-log plot of $k(E)$ of Chantler's data.

At energies smaller than the present ones, no direct data on *k* was found in the literature. We considered the papers of Schüler[33], Weaver and Lynch[34], and Homewood and Trodahl[35]. The three papers gave data on reflectance and optical conductivity (or other functions from which the former ones could be immediately calculated). Unfortunately, even though the three pieces of research must have involved the calculation of also *n* and *k*, these data were not published. Other than the above literature, Pétrakian[36] reported the optical conductivity of Lu films on the 1.6-6.2 eV, from which *k* cannot be calculated. More recently, Saini et al.[37] used a theoretical model to calculate the optical properties of Lu; however, again, they only published optical conductivity data.

Let us see the way how we obtained the small-energy extrapolation starting with the available data. We discarded the data of Weaver and Lynch[34] because their work was performed with single crystals of Lu (versus thin films in the other two papers), so that their samples might have got somewhat oxidized, whereas the samples of Schüler[33] and of Homewood and Trodahl[35] consisted of thin films that were prepared and maintained in UHV. The calculation of *n* and *k* from reflectance and optical conductivity data from Refs. 33 and 35 involved the solution of a 4th order algebraic equation, from which only two of the four solutions could be immediately discarded because they were complex

numbers. The other two solutions looked acceptable in principle. Unfortunately, the data from Refs. 33 and 35 resulted in non-coincident solutions of *n* and *k*, so that we had as many as 4 choices of *k* for our low energy extrapolations. We finally chose a specific solution for each of the two selected papers which better matched each other and better connected with our data, even though this connection was not smooth; unfortunately, the data of Weaver and Lynch[34] resulted in two other solutions which were not coincident with the selected ones from Refs. 33 and 35 and were of no help for the selection of data. The data of Homewood and Trodahl matched better our data than Schüler's data did, and hence the former was initially selected as a continuation of our data[38]. As a help to make the good choice, those data were compared with *n* and *k* data of neighbors in the periodic table: Tm[9] and Yb[2]. In order to enable a smooth connection of our data with Ref. 35, both were modified in the 3-6 eV range. Homewood and Trodahl's data only extended down to 1.5 eV; therefore, Schüler's *k* data were used below this energy down to 0.28 eV. The extrapolation to zero energy was performed by fitting a Drude model on Schüler's data.

The refractive index *n* obtained with Eq. (2) on the *k* data gathered in the whole spectrum was rather different than the data that we calculated from Schüler[33] and Homewood and Trodahl[35] data in the coincidence range. Since we did not have any reason to trust more *k* than *n* data of Refs. 33 and 35, we decided to use both sets of data in our construction of *k* data in the whole spectrum by proceeding in the following way. The refractive index *n* calculated as said above was modified by replacing the 0.28-6 eV range with Schüler'[33] and Homewood and Trodahl's[35] *n* data. The data between 6 and 11 eV were modified to get a smooth connection with the refractive index obtained with Eq. 2. This new and complete set of *n* data was used in an inverse KK analysis:

$$k(E) = -\frac{2E}{\pi} P \int_0^{\infty} \frac{[n(E')-1]}{E'^2 - E^2} dE', \qquad (3)$$

so that a new set of *k* data was obtained. Then we had two sets of *k* data that were similar for energies above 11 eV, but were different below this energy. An average set of *k* data was obtained between the two sets, and the latter was assumed to be a better solution than the first set because it involved both *n* and *k* data (versus only data of *k*) of Lu obtained from the literature.

Fig. 5 displays *k* data of Lu obtained in the present research along with literature data, calculations, and extrapolations that were gathered for KK analysis.

Fig. 6 displays δ=1-*n* calculated with Eq. (2) using the data plotted in Fig. 5; *n* and δ at $O_{2,3}$ and $M_{4,5}$ edges are shown in Figs. 7 and 8, respectively. Only Homewood and Trodahl data[35] or the semi-empirical data of Henke are available for comparison.

3.3 CONSISTENCY OF OPTICAL CONSTANTS

The *f* sum rule relates the number density of electrons to *k* (or to other functions); it provides a guidance to evaluate the global accuracy of *k* data. It is useful to define the effective number of electrons per atom $n_{eff}(E)$ contributing to *k* up to given energy *E*:

$$n_{eff}(E) = \frac{4\varepsilon_0 m}{\pi N_{at} e^2 h^2} \int_0^E E' k(E') dE' \qquad (4)$$

where N_{at} is the atom density, *e* is the electron charge, ε_0 is the permittivity of vacuum, *m* is the electron mass, and *h* is Planck's constant[39]. The *f* sum rule expresses that the high-energy limit of the effective number of electrons must reach Z=71, i.e., the atomic number of Lu. When the relativistic correction on scattering factors is taken into account, the high-energy limit of Eq. (4) is somewhat modified. The following modified Z was adopted here: Z*=69.70[40]. The high-energy limit that we obtained by integrating the data set plotted in Fig. 5 using Eq. (4) was 70.77, which is only a 1.5% larger than the above Z* value. The main contribution to n_{eff} was found to come from the ~1 to 6×10^5

eV range. The small difference with Z^* may come from inaccuracies in the film thickness determination, in the transmittance measurements, and in the *k* data used in the energy extrapolations.

A useful test to evaluate the accuracy of KK analysis is obtained with the inertial sum rule:

$$\int_0^\infty [n(E)-1]dE = 0 \tag{5}$$

which expresses that the average of the refractive index throughout the spectrum is unity. The following parameter is defined to evaluate how close to zero the integral of Eq. (5)[39] is:

$$\zeta = \frac{\int_0^\infty [n(E)-1]dE}{\int_0^\infty |n(E)-1|dE} \tag{6}$$

Shiles et al.[39] suggested that a good value of ζ should stand within ±0.005. An evaluation parameter ζ=-4×10^{-4} was obtained here with the *n* data calculated in this research. Therefore, the inertial sum rule test is well within the above top value, which, along with the above obtained result for the *f* sum rule, suggest good consistency of *n* and *k* data.

CONCLUSIONS

The transmittance of thin films of Lu deposited by evaporation has been measured in situ in the 3-1,800 eV photon energy range under UHV conditions. The extinction coefficient *k* of Lu has been calculated from transmittance measurements in the same spectral range. Lu features an absorption minimum at ~25.1 eV. This relatively low absorption at this spectral range makes Lu a promising candidate for transmittance filters and reflective multilayers. Given the reactivity of Lu, as with other lanthanides, a surface passivation method is expected to be required to prevent surface instability of Lu in contact with atmosphere.

The refractive index *n* of Lu in the same range was obtained with KK analysis over an extended spectral range. A novel way of extending our data with literature data was devised by using both *n* and *k* (versus only *k* data) in our *k* extrapolation; *n* literature data were used to modify the data obtained by KK analysis, which by inverse KK analysis provided a second estimate of *k*, which was averaged with the initial one.

Current data on Lu are the first reported experimental data of both the extinction coefficient and the refractive index in the whole range. The current data encompass Lu $M_{4,5}$, $N_{4,5}$ and $O_{2,3}$ edges.

The evaluation of *f* and inertial sum rules shows good consistency of the optical constants of Lu.

ACKNOWLEDGMENTS

We acknowledge support by the European Community - Research Infrastructure Action under the FP6 "Structuring the European Research Area" Programme (through the Integrated Infrastructure Initiative "Integrating Activity on Synchrotron and Free Electron Laser Science"). This work was also supported by the National Programme for Space Research, Subdirección General de Proyectos de Investigación, Ministerio de Ciencia y Tecnología, project numbers AYA2008-06423-C03-02/ESP and AYA2009-14070. A. M. M. acknowledges the partial support of the Fondo d'Ateneo per la Ricerca (FAR) of Università di Pavia. The technical assistance of J. M. Sánchez-Orejuela is acknowledged. We acknowledge Prof. J. Trodahl for providing us with the optical constants of Lu at small energies.

REFERENCES

1. J. I. Larruquert, J. A. Aznárez, J. A. Méndez, José Calvo-Angós, “Optical properties of Yb films in the far and the extreme ultraviolet”, Appl. Opt. **42**, 4566-4572 (2003).

2. M. Fernández-Perea, J. I. Larruquert, J. A. Aznárez, J. A. Méndez, L. Poletto, D. Garoli, A. M. Malvezzi, A. Giglia, S. Nannarone “Determination of the transmittance and extinction coefficient of Yb films in the 23-1,700-eV range”, J. Opt. Soc. Am. A **24**, 3691-3699 (2007).

3. Yu. Uspenski, J. Seely, N. Popov, I. Artioukov, A. Vinogradov, D. Windt, B. Kjornrattanawanich, “Extreme UV optical constants of rare-earth metals free from effects of air contamination”, in *Soft X-Ray Lasers and Applications VI*, E. E. Fill, ed., Proc. SPIE **5919**, 213-220 (2005).

4. B. Kjornrattanawanich, D. L. Windt, J. A. Bellotti, J. F.Seely, “Measurement of dysprosium optical constants in the 2–830 eV spectral range using a transmittance method, and compilation of the revised optical constants of lanthanum, terbium, neodymium, and gadolinium”, Appl. Opt. **48**, 3084-3093 (2009).

5. B. Kjornrattanawanich, D. L. Windt, Y. A. Uspenskii, J. F. Seely, “Optical constants determination of neodymium and gadolinium in the 3 nm to 100 nm wavelength range”, in *Advances in X-ray/EUV optics, components, and applications*, A. M. Khounsary, C. Morawe, eds., Proc. of SPIE **6317**, 63170U (2006).

6. M. Fernández-Perea, J. I. Larruquert, J. A. Aznárez, J. A. Méndez, L. Poletto, D. Garoli, A. M. Malvezzi, A. Giglia, S. Nannarone “Determination of the transmittance and extinction coefficient of Ce films in the 6-1,200-eV range”, J. Appl. Phys. **103**, 073501-1 to -7 (2008).

7. M. Fernández-Perea M. Vidal-Dasilva, , J. A. Aznárez, J. I. Larruquert, J. A. Méndez, L. Poletto, D. Garoli, A. M. Malvezzi, A. Giglia, S. Nannarone “Determination of the transmittance and extinction coefficient of Pr films in the 4-1,600-eV range”, J. Appl. Phys. **103**, 113515-1 a -7 (2008).

8. M. Fernández-Perea M. Vidal-Dasilva, J. A. Aznárez, J. I. Larruquert, J. A. Méndez, L. Poletto, D. Garoli, A. M. Malvezzi, A. Giglia, S. Nannarone "Determination of the transmittance and extinction coefficient of Eu films in the 8.3-1,400-eV range", J. Appl. Phys. **104**, 123527-1 a -7 (2008).

9. Manuela Vidal-Dasilva, Mónica Fernández-Perea, José A. Aznárez, Juan I. Larruquert, José A. Méndez, Luca Poletto, A. Marco Malvezzi, Angelo Giglia, Stefano Nannarone, "Transmittance and optical constants of Tm films in the 2.75-1,600 eV spectral range", J. Appl. Phys. **105**, 103110 (2009).

10. A. L. Aquila, F. Salmassi, E. M. Gullikson, F. Eriksson, J. Birch, "Measurements of the optical constants of scandium in the 50-1300 eV range", in *Optical constants of materials for UV to x-ray wavelengths*, R. Soufli and J. F. Seely, eds., Proc. of SPIE **5538**, 64-71 (2004).

11. Y. A. Uspenskii, J. F. Seely, N. L. Popov, A. V. Vinogradov, Y. P. Pershin, and V. V. Kondratenko, "Efficient method for the determination of extreme-ultraviolet optical constants in reactive materials: application to scandium and titanium", J. Opt. Soc. Am. A **21**, 298-305 (2004).

12. J. I. Larruquert, J. A. Aznárez, J. A. Méndez, A. M. Malvezzi, L. Poletto, S. Covini, "Optical properties of Sc films in the far and the extreme ultraviolet", Appl. Opt. **43**, 3271-3278 (2004).

13. M. Fernández-Perea, J. I. Larruquert, J. A. Aznárez, J. A. Méndez, L. Poletto, A. M. Malvezzi, A. Giglia, S. Nannarone, "Determination of optical constants of scandium films in the 20-1000 eV range", J. Opt. Soc. Am. A 23, 2880-2887 (2006)

14. B. Sae-Lao, R. Soufli, "Measurements of the refractive index of Yttrium in the 50-1300 eV energy range", Appl. Opt. **41**, 7309-7316 (2002).

15. T. M. Zimkina, V. A. Fomichev, S. A. Gribovskii, I. I. Zhukova, "Anomalies in the character of the x-ray absorption of rare-earth elements of the lanthanide group", Sov. Phys.- Sol. State **9**, 1128-1130 (1967).

16. D. W. Fischer, W. L. Baun, “Self-absorption effects in the soft x-ray M_α and M_β emission spectra of the rare earth elements”, J. Appl. Phys. 38, 4830-4836 (1967).

17. B. D. Padalia, S. N. Gupta, V. P. Vijayavargiya, B. C. Tripathi, “X ray spectroscopic study of 4f heavy rare earth metals”, J. Phys. F **4**, 938-946 (1974).

18. C. Bonnelle, R. C. Karnatak, C. K. Jørgensen, “X-ray and photoelectron spectroscopy for the determination of 4f energies of rare earths”, Chem. Phys. Lett. **14**, 145-149 (1972).

19. W. C. Lang, B. D. Padalia, L. M. Watson, D. J. Fabian, “Reinvestigation of the core levels of pure and oxidised ytterbium and lutetium”, J. Electron Spectrosc. Relat. Phenom. **7**, 357-358 (1975).

20. C. Colliex, M. Gasgnier, P. Trebbia, “Analysis of the electron excitation spectra in heavy rare earth metals, hydrides and oxides”, J. Physique **37**, 397-406 (1976).

21. J. Onsgaard, S. Tougaard, P. Morgen, F. Ryborg, “Scandium and lutetium surfaces studied by reflection electron energy-loss spectroscopy”, J. Electron Spectrosc. Relat. Phenom. **18**, 29-41 (1980).

22. F.P. Netzer, G. Strasser, G. Rosina, “Valence excitations of Rare Earths by Electron Energy Loss Spectroscopy”, Surface Science **152**/**153**, 757-764, (1985).

23. T. Manoubi, C. Colliex, P. Rez, “Quantitative Electron Energy-Loss Spectroscopy on Md5 edges in Rare Earth oxides”, J. Electron Spectrosc. Relat. Phenom. **50**, 1-18 (1990).

24. B.L. Henke, P. Lee, T. J. Tanaka, R. L. Shimabukuro, B. K. Fujikawa, “Low-Energy X-Ray Interaction Coefficients: Photoabsorption, Scattering, and Reflection, E = 100-2000 eV, *Z*=1-94”, At. Data Nucl. Data Tables **27**, 1-144 (1982).

25. B.L. Henke, E.M. Gullikson, and J.C. Davis, “X-ray interactions: photoabsorption, scattering, transmission, and reflection at E=50-30000 eV, Z=1-92”, Atomic Data and Nuclear Data Tables **54**, 181-342 (1993).

26. F. H. Combley, E. Stewardson, J. E. Wilson, “The M x-ray absorption of ^{70}Yb”, J. Phys. B (Proc. Phys. Soc.) **1**, 120-127 (1968).

27. C. Gerth, B. Kanngießer, M. Martins, P. Sladeczek, K. Tiedtke, P. Zimmermann, “Photoelectron and photoion spectroscopy on atomic Lu in the region of the 5p excitation”, Eur. Phys. J. D **5**, 65-69 (1999).

28. Ch Gerth, M Martins, S Brünken, K Godehusen, B Kanngießer, P Zimmermann, “$5p^{-1}$ multiplet structure of atomic Lu studied by photoelectron spectroscopy”, J. Phys. B **32**, L133–L138 (1999).

29. R. Verucchi, S. Nannarone, “Triode electron bombardment evaporation source for ultrahigh vacuum thin film deposition”, Rev. Sci. Instrum. **71**, 3444-3450 (2000).

30. http://www-cxro.lbl.gov/optical_constants/

31. L. Pasquali, A. De Luisa, S. Nannarone, “The UHV Experimental Chamber For Optical Measurements (Reflectivity and Absorption) and Angle Resolved Photoemission of the BEAR Beamline at ELETTRA”, T. Warwick, J. Arthur, H.A. Padmore, J. Stöhr, eds., *AIP Conference Proceedings **705**, 1142-1145 (2004)*

32. C. T. Chantler, K. Olsen, R. A. Dragoset, J. Chang, A. R. Kishore, S. A. Kotochigova, D. S. Zucker, “X-Ray Form Factor, Attenuation and Scattering Tables” (version 2.1), (2005). [Online] Available: http://physics.nist.gov/ffast [2006, May 29]. National Institute of Standards and Technology, Gaithersburg, MD. Originally published as C. T. Chantler, J. Phys. Chem. Ref. Data **29**, 597-1048 (2000); and C. T. Chantler, J. Phys. Chem. Ref. Data **24**, 71-643 (1995).

33. C. Chr. Schüler, “Recent studies on the optical properties of rare-earth metals”, Proc. of the International Colloquium “Optical properties and electronic structure of metals and alloys”, F. Abelès, ed., North-Holland Publishing Company, Amsterdam, The Netherlands, 1966.

34. J. H. Weaver, D. W. Lynch, “Anisotropic optical properties of heavy-rare-earth single crystals”, Phys. Rev. Lett. **34**, 1324-1327 (1975). An Erratum was corrected at J. H. Weaver, D. W. Lynch, “Anisotropic optical properties of heavy-rare-earth single crystals”, Phys. Rev. Lett. **35**, 130 (1975).

35. V. J. Homewood, H. J. Trodahl, “Strain-modulated reflectivity of lutetium”, Phys. Rev. B, **44**, 2920-2922 (1991).

36. J.-P. Pétrakian, “Optical conductivity of rare-earth thin films in relation to their crystalline structure and electronic configuration”, Thin Solid Films **38**, 83-88 (1976).

37. S. M. Saini, N. Singh, T. Nautiyal, S. Auluck, “Optical properties of heavy rare earth metals (Gd-Lu)”, Sol. State Commun. **140**, 125-129 (2006).

38. Once the described calculation and selection process had been performed, in a private communication Prof. J. Trodahl provided us with *n* and *k* data for Lu that they had obtained in their research (Ref. 35). Those data resulted to be coincident with the solution that we had previously calculated and selected.

39. E. Shiles, T. Sasaki, M. Inokuti, D. Y. Smith, “Self-consistency and sum-rule tests in the Kramers-Kronig analysis of optical data: applications to aluminium”, Phys. Rev. B **22**, 1612-1628 (1980).

40. Downloaded from the following web of Physical Reference Data, Physics Laboratory at NIST: http://physics.nist.gov/PhysRefData/FFast/Text/cover.html.

Figure captions

Fig. 1. (color online) The transmittance of Lu films with various thicknesses normalized to the transmittance of the substrate versus the logarithm of photon energy.

Fig. 2. (color online) Log-log plot of the extinction coefficient of Lu as a function of photon energy, along with the data of Homewood and Trodahl[35] and the data of Henke *et al*.[24]

Fig. 3. (color online) The extinction coefficient of Lu as a function of photon energy at the small energy range, along with the data of Homewood and Trodahl[35], and the data of Henke et al.[24]

Fig. 4. (color online) The extinction coefficient of Lu versus photon energy at the $M_{4,5}$ edge, along with the data of Henke *et al.*[24]

Fig. 5. (color online) Log-log plot of *k* data that map a wide spectral range using the current data along with the data of Schüler[33], Homewood and Trodahl[35], Henke *et al.*[24], and Chantler *et al.*[32], and extrapolations in the two extremes.

Fig. 6. (color online) Log-log plot of δ=1-*n* versus photon energy. The data of Henke *et al.*[24] are also represented

Fig. 7. (color online) *n* versus photon energy at the low energy range. The data of Homewood and Trodahl[35] and of Henke et al.[24] are also represented

Fig. 8. (color online) δ=1-*n* versus photon energy at the $M_{4,5}$ edge. Henke data[24] are also represented.

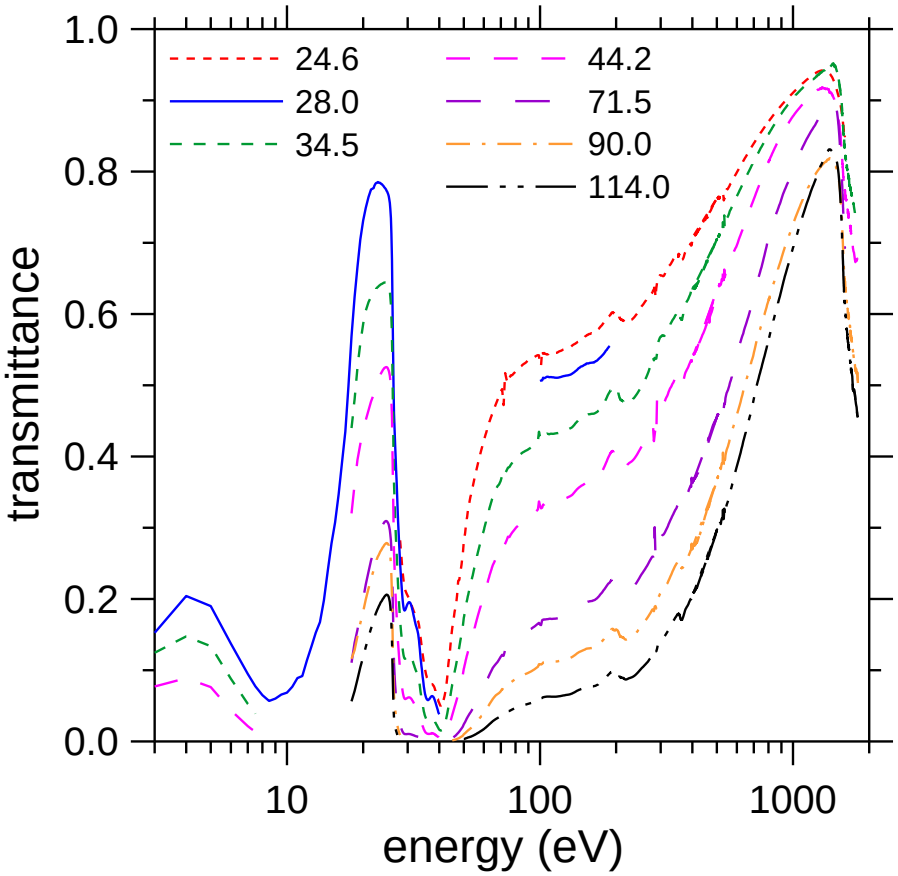
1.0
0.8
0.6
0.4
0.2
0.0
transmittance
10
100
1000
energy (eV)
24.6
28.0
34.5
44.2
71.5
90.0
114.0

Fig 1

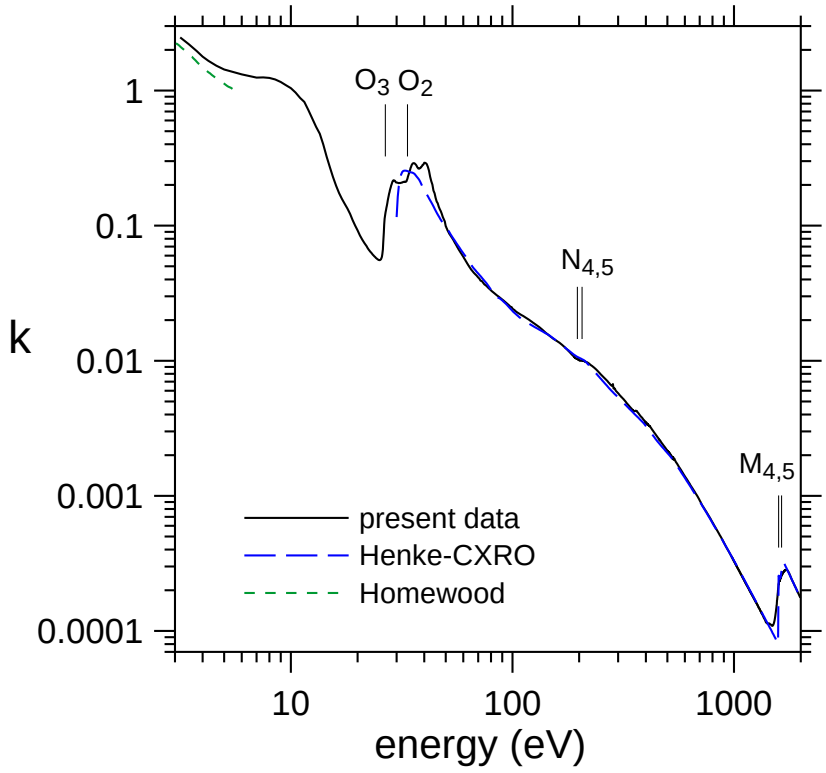
k
1
0.1
0.01
0.001
0.0001
10
100
1000
energy (eV)
O3 O2
N4,5
M4,5
present data
Henke-CXRO
Homewood

Fig 2

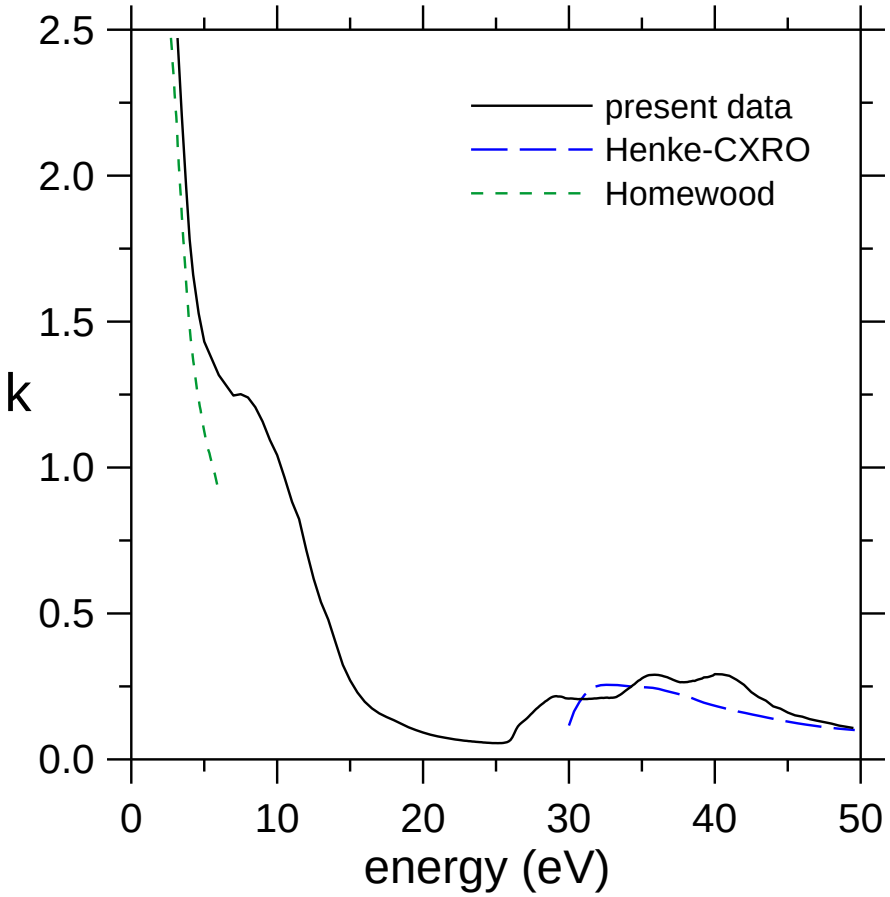
2.5
2.0
1.5
1.0
0.5
0.0
k
0
10
20
30
40
50
energy (eV)
present data
Henke-CXRO
Homewood

Fig 3

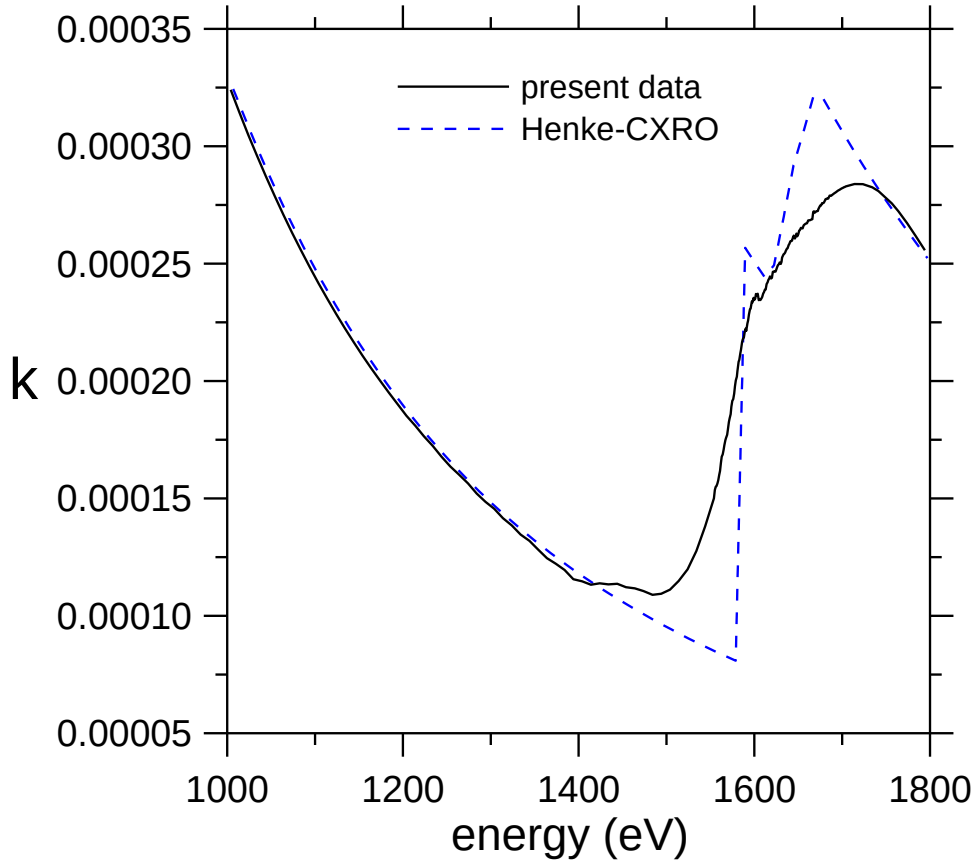
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
k
present data
Henke-CXRO
1000
1200
1400
1600
1800
energy (eV)

Fig 4

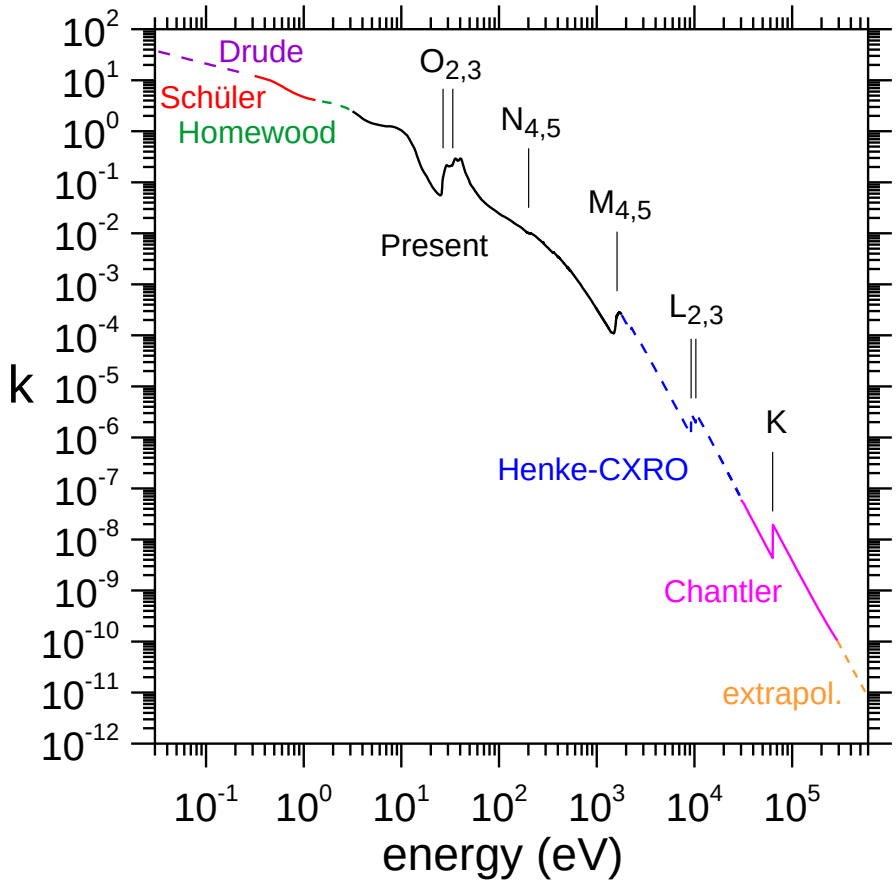
Drude
Schüler
Homewood
Present
Henke-CXRO
Chantler
extrapol.
O2,3
N4,5
M4,5
L2,3
K
k
energy (eV)

Fig 5

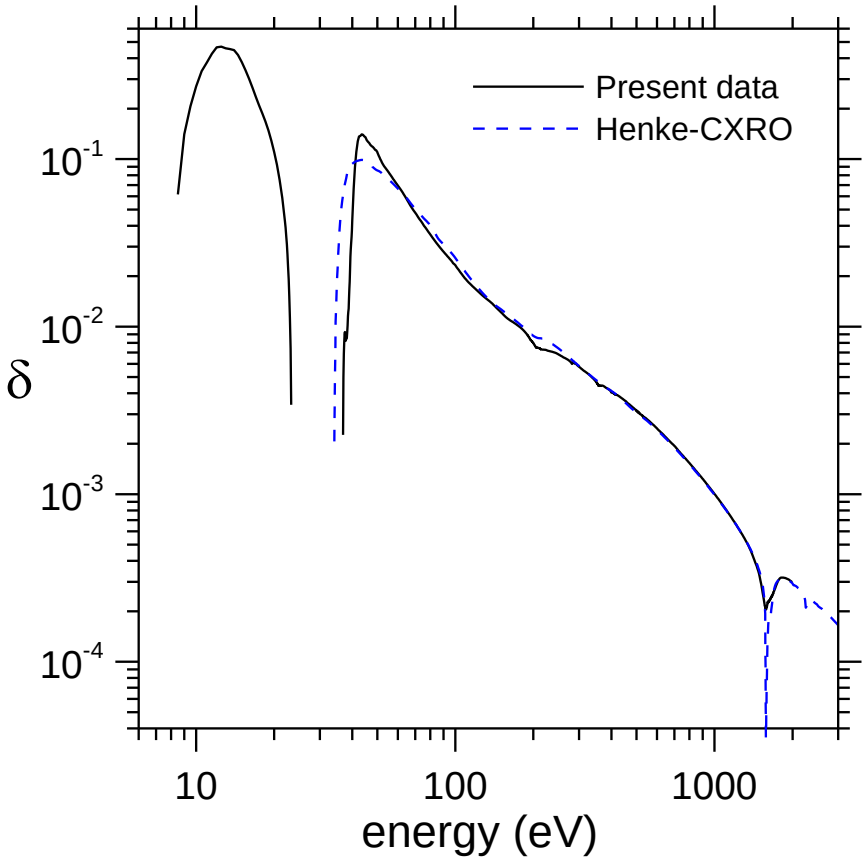
Present data
Henke-CXRO
δ
10^-1
10^-2
10^-3
10^-4
10
100
1000
energy (eV)

Fig 6

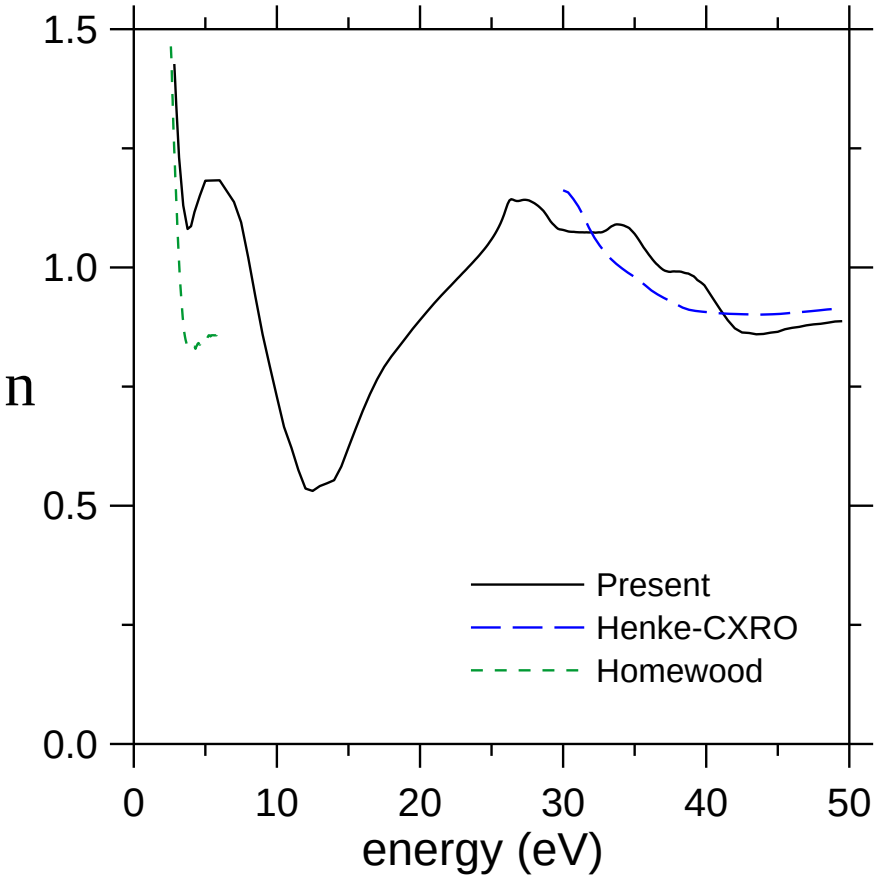
1.5
1.0
0.5
0.0
n
0
10
20
30
40
50
energy (eV)
Present
Henke-CXRO
Homewood

Fig 7

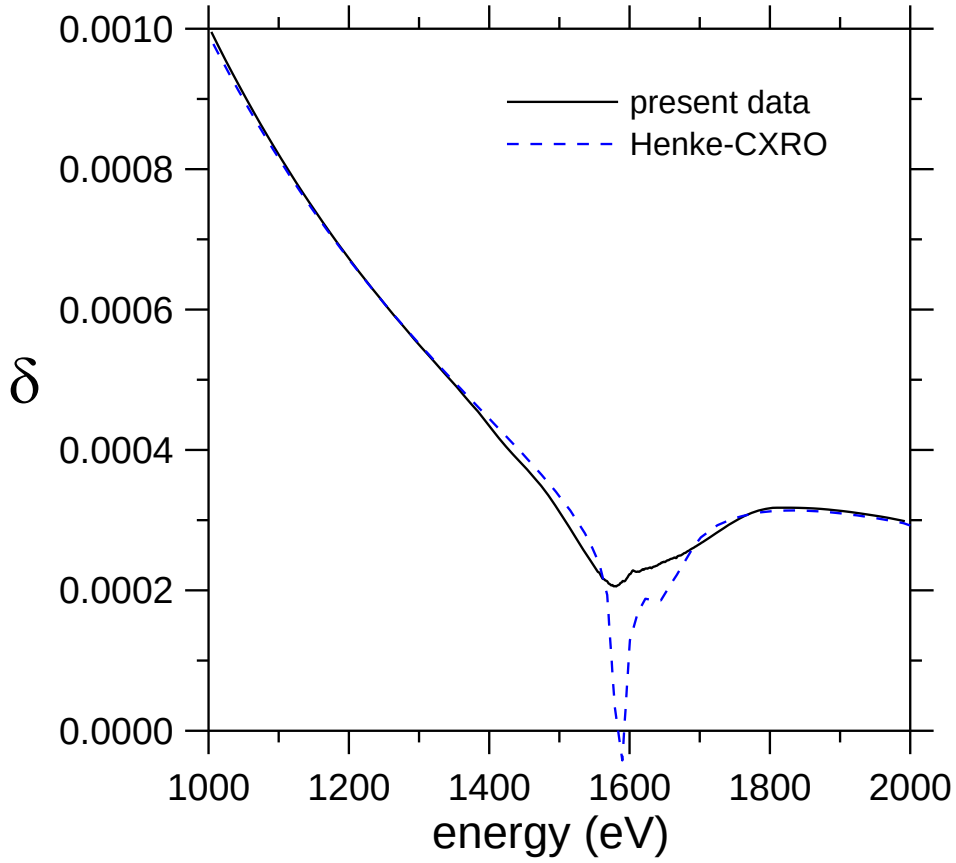
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
δ
1000
1200
1400
1600
1800
2000
energy (eV)
present data
Henke-CXRO

Fig 8