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Publication Date

1973-09-01

Submitted to
J. Electr. Spectrosc.

LBL-1971
Preprint C.2

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CHARACTERISTIC ENERGY LOSS STRUCTURE OF SOLIDS FROM X-RAY PHOTOEMISSION SPECTRA*

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ABSTRACT

Energy loss peaks in x-ray photoemission spectra of nine metals are presented. In each case the loss structure can be entirely accounted for in terms of extrinsic plasmons. Spectra from the free electron-like metals, Al, Li, and Na under ultra-high vacuum (10^{-11} Torr) conditions show intense bulk plasmons and surface plasmons. Systematic variations in the characteristic energy losses are reported for the series Ag to Te. In addition to losses that may be attributed to plasma oscillations of the 5s5p bands, with $N = 1$ and 2 electrons, respectively, both Ag and Cd show additional high-energy losses that may arise through 4d-shell participation, with $N = 11$ and 12.

INTRODUCTION

X-ray photoemission from solids can be conceptually decomposed into a three-step process: 1. excitation of an electron from the ground state to a free-electron-like state of high kinetic energy within the solid; 2. passage of this photoelectron to the surface of the solid; 3. escape of the electron from the solid. Conservation of energy requires that the measured kinetic energy of the photoelectron be equal to the x-ray photon energy minus the total energy expended in steps 1-3. In practice XPS spectra are usually corrected by

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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subtracting structure associated with steps 2 and 3, and structure associated with step 1 is then related to the eigenvalue spectrum of the system. This paper deals instead with the spectral structure that results from energy-loss phenomena during steps 2 and 3 of the photoemission process. Our objective is to relate the low-energy loss structure observed in XPS studies of nine clean metals to characteristic energy losses obtained by other methods.

Let us consider, for example, the comparison between XPS and electron scattering spectra. The secondary-electron energy spectrum of monoenergetic electrons reflected from a solid surface exhibits inelastic loss structure similar to that observed in XPS spectra. Figure 1a, after Seah^{1a}, shows the secondary electron energy spectrum of silver bombarded with 250 eV electrons incident at 30° from the normal. For convenience this spectrum is divided into three regions. Region III contains the elastically scattered electrons and those which have lost a few hundredths of an electron volt to phonons. Region II is composed of those electrons which have suffered characteristic energy losses by producing collective excitations, intraband transitions, or interband transitions of the lattice electrons. Characteristic energy loss peaks usually occur between 2 eV and 50 eV below the elastically scattered peak. The electrons in region I (not shown) are mostly secondary electrons (see Figure 1 of Reference 1b). They have low energy and are produced by a cascade process. Thus after passing through the solid the initially monoenergetic beam of electrons has a very broad energy distribution with considerable structure. As the kinetic energy of the incident electron beam increases, the ratio R of elastically scattered to inelastically scattered electrons decreases. At x-ray photoelectron energies R is much smaller than unity.

In general XPS results are more complex than those from electron reflection measurements, because there are as many primary electron energies in XPS as there are orbitals of different energy. The spectral distribution from all orbitals are superimposed in the XPS spectrum. For comparison with Seah's results, the Ag 3d spectrum is given in Figure 1b, with its characteristic energy-loss structure on an expanded scale. The structure in this spectrum is a superposition of the Ag $3d_{3/2}$ and Ag $3d_{5/2}$ levels and their loss structure. The loss peaks P_2 , P_3 , P_6 , and part of P_5 of the Ag $3d_{3/2}$ photoelectrons are very similar to those observed for the electron scattering experiment (Figure 1a). Similar agreement between XPS loss energies and those obtained by other methods was found for the other metals we studied, as indicated below.

Before discussing individual results we should comment on the distinction between extrinsic and intrinsic plasmons. An electron passing through a solid can create extrinsic plasmons by coupling between its longitudinal electric field and electron density fluctuations. Many plasmon resonance energies have been determined by measuring the energy losses of electrons reflected from solid surfaces or transmitted through thin films². Almost all structure observed in the spectra reported below can in fact be attributed to this type of plasmon energy loss. In addition to extrinsic plasmons, many-body calculations³ predict intrinsic plasmon structure resulting from plasmons coupled to core electrons. This type of plasmon excitation is intrinsic to the photoemission of a core electron that is coupled with the surrounding plasma rather than to a free electron passing through a plasma. The total spectral density in this model consists of a sharp quasiparticle peak with a broader plasmon satellite structure at a higher "binding" energy. The plasmon structure is

predicted to be 50 to 100% as intense as the quasiparticle peak. In the results reported below, structure resulting from intrinsic plasmon resonances is not a priori distinguishable from the extrinsic structure that arises from a free electron passing through a solid-state plasma. However, no strong evidence for intrinsic plasmon structure was found in this work.

Experimental procedures have been described elsewhere^{4,5,6}. The Li and Na samples were evaporated metal films, while the other samples were single crystals. Monochromatized Al $K\alpha_{12}$ x-rays (1486.6 eV) were used throughout, and the samples were studied with the spectrometer either in the high vacuum (HV) mode, $p \sim 5 \times 10^{-9}$ Torr, or in the ultrahigh vacuum (UHV) mode, $p \sim 5 \times 10^{-11}$ Torr. The loss structures of Al, Li, and Na are discussed in the next section and those of Ag, Cd, In, Sn, Sb, and Te in the following section.

FREE ELECTRON-LIKE METALS: ALUMINUM, LITHIUM, AND SODIUM

The x-ray photoemission spectrum of the Al 2s core level is shown in Figure 2a. The high binding energy shoulder on the Al 2s metal peak is attributed to surface oxide. Spaced at even intervals of 15.7(2) eV are five orders of bulk plasmon losses P_1 through P_5 . The electron reflection measurements of Powell and Swan yielded a value of 15.3 eV⁷. The sum of the area under the five loss peaks is over 75% that of the Al 2s metal peak. The absence of the surface plasmon peak at 10.4 eV is consistent with the surface's being slightly oxidized⁷. We note that in XPS experiments plasmons of all scattering angles are observed. Dispersion therefore leads to peaks that are asymmetrically broadened toward higher binding energy. The mean peak positions are therefore shifted to slightly higher binding energies than obtained from experiments in

which the scattering angle is zero. The reflection results of Powell, Swan, and Robins^{7,8} should compare well with XPS results because the geometry of their experiments should yield similar dispersion effects.

We were unable to keep Al clean in the HV mode of operation (see footnotes 4 and 6). A surface oxide formed immediately after argon ion bombardment. Preliminary results for Al obtained in the UHV mode of operation are shown in Figure 2b for a single crystal which was annealed in situ and argon-etched. A surface plasmon, labeled S, is now present and the aluminum oxide peak has disappeared. Eight bulk loss peaks associated with the Al 2s level are clearly distinguishable (P_6 to P_8 are not shown). The peak parameters are given in Table 1. The total area of the loss peaks is greater than 175% the area of the zero-loss peak.

The spectra of the Na 1s and Li 1s levels and characteristic energy loss structure have been previously reported and discussed⁹. Derived peak parameters and assignments are listed for completeness in Tables 2 and 3. The relative intensities of the loss peaks have been determined after subtracting a structureless background from under these peaks. The intensities given in Tables 2 and 3 are only accurate to about $\pm 20\%$. As indicated earlier⁹, the bulk plasmon loss energies in both Na and Li agree well with values obtained by other methods. Thus it appears that core-level XPS lines in free-electron metals with clean surfaces can generally be expected to show both surface and bulk plasmon structure, with multiple-loss peaks from the latter. The interpretation of spectra should be straightforward.

PLASMON LOSSES OF THE 4d5s5p ELEMENTS Ag TO Te

In some materials interband and intraband transitions lying close in energy to the free electron plasma resonance energy $\hbar\omega_p$ result in a shift of the measured plasmon energy from this value. The resulting plasmons are termed hybrid resonances. The dielectric theory of energy losses is used to treat this somewhat more complicated phenomenon². Effects of this type were observed for the elements discussed below. The XPS plasmon structures for Ag to Te are shown in Figures 1 and 3-11. The peak parameters are given in Tables 4 to 9 and are summarized in Table 10.

Silver

Silver gave the weakest loss structure of all the elements reported here (Figure 1b). However, it had the narrowest loss peak (1 eV). The bulk plasmon resonance energy is shifted from the free electron value of 9 eV to 3.78 eV by an interband transition ($4d \rightarrow E_F$) that begins at 3.9 eV². In the XPS valence-band spectrum of silver (Figure 12) the low binding energy edge of the 4d band is just 3.9 eV below the Fermi level E_F , which is consistent with the above interpretation. This separation between the d-band edge and the Fermi level is denoted ΔE_{IB} in Figure 13.

The loss at 3.9 eV is assigned to the unresolved bulk and surface plasmon losses of Ag which have been measured by optical experiments to lie at 3.9 and 3.78 eV, respectively². The width of the bulk loss has been determined optically to be 0.08 eV FWHM¹⁰. The 1 eV width of the loss peak reported here is obviously determined by the width of the primary 3d photoelectron energy distribution (1 eV). Optical reflectivity data¹¹ indicates that the

loss structure at 7.8 eV is also attributable to conduction-electron oscillations. We also observed peaks at 18.8 eV and 24.9 eV which can be compared with peaks at 17.2 and 25.0 eV from electron loss experiments¹².

Cadmium

Four loss peaks at 7, 9.3, 13.9, and 19 eV were observed. We interpret the peaks at 7 and 9.3 eV as the surface and bulk loss, respectively. Light emission from electron-bombarded Cd yielded a sharp (0.8 eV), intense peak at 9.1 eV¹³. This resulted from the decay of bulk plasmons. Surface plasmons have a very small probability relative to bulk plasmons of decaying by light emission¹³. The systematics illustrated in Figure 13 also support our interpretation of the 7 and 9.3 eV peaks. The peaks at 13.9 eV and 19.0 eV can be compared with the peaks at 15.2 eV and 23.4 eV which have been observed in electron reflection measurements¹².

Indium, Tin, Antimony, and Tellurium

Indium exhibits four loss peaks at 8.6, 11.7, 19.8, and 23 eV. The electron reflection spectrum showed peaks at 8.7, 11.3, 20, and 22.7 eV¹⁴. The first correspond to a surface plasmon loss, the second to a bulk plasmon loss; the third is from electrons that have suffered both a bulk and surface loss, and the fourth and fifth are from electrons that suffer two and three bulk losses. The results for Sn, Sb, and Te can be also interpreted solely in terms of bulk and surface losses. Table 10 lists these assignments and the corresponding electron reflection results.

Systematics

The systematic variation of the plasmon structure for Ag to Te is illustrated in Figure 13. The interband transition ($4d \rightarrow E_F$) energy ΔE_{IB} is a strong function of atomic number, varying from 3.9 eV in Ag to 39 eV in Te. The free electron plasmon energy,

$$\hbar\omega_p = \hbar \left(\frac{4\pi n e^2}{m} \right)^{1/2}, \quad (1)$$

varies smoothly from 9 eV in Ag where N , the number of valence electrons, is 1 to 15.6 eV in Te ($N = 6$). Here n is the number density of the electron plasma and m is the free electron mass. The measured bulk plasmon energy ΔE_B rises smoothly from 3.9 eV in Ag to 17.6 eV in Te. The difference ($\hbar\omega_p - \Delta E_B$) decreases from Ag to Sn, changes sign between Sn and Sb then increases slightly in magnitude in Te. The surface plasmon energy ΔE_S obeys the expected free-electron relation

$$\Delta E_B = \sqrt{2} \Delta E_S,$$

to within an error of ± 0.05 in the coefficient. The intensities (areas) relative to the parent, zero-loss peak for the bulk plasmon (I_B) and surface plasmon (I_S) are shown as histograms in Figure 13. The intensity I_B of the bulk plasmon loss increases smoothly from a minimum of 2% in Ag to a value of about 28% in Sn, Sb, and Te. The surface plasmon intensity showed more varied behavior. This is not unexpected because I_S is much more sensitive to surface conditions than I_B .⁷

For Ag and Cd, in which interband transitions play an important role, the characteristic loss structure cannot be completely explained by combinations of one surface and one bulk loss alone. We thought it might be possible, however, to relate the observed losses at energies above 10 eV to those at 7.8 eV (Ag) and 9.3 eV (Cd) by assuming that the number of valence electrons participating in these higher-energy plasma oscillations is increased over the number that participate in the low-energy oscillations by 10, the number of electrons in the filled 4d shell. To test this hypothesis we parameterized expression (1) to

$$\hbar\omega_p = C\sqrt{n} \quad , \quad (2)$$

which retains the $\sqrt{n}$ dependence of the bulk plasma oscillations. Adjusting C to reproduce the 7.8 eV (Ag) and 9.3 eV (Cd) losses for $n = 1$ and $n = 2$ respectively, we obtained for $n = 11$ and $n = 12$, values for the loss energies that are in fair agreement with the observed (but otherwise unexplained) losses around 20 eV in the two metals (Table 11).

The above interpretation is supported by other data. In Ag, the real part of the dielectric constant, ϵ_1 , crosses through zero near 7.8 eV and exhibits a local minimum at 25 eV¹⁵. In addition, the imaginary part, ϵ_2 , is small (~ 0.7) at 25 eV¹⁵. Both observations support our description of the 25 eV loss in Ag as plasmonlike. The necessary adjustment of C in Equation (2) implies an effective electron mass, m_{eff} , for these collective excitations. The agreement between $\hbar\omega_p$ as calculated from (2) and the experimental values could be further improved, by taking the difference in effective mass for s- and d-electrons into account.

Reducing the bulk plasmon energies calculated above by a factor of $1/\sqrt{2}$ we obtain energies that are consistent with an interpretation of the losses at 18.8 eV and 13.9 eV as surface plasmons. This interpretation is supported for Ag by a recent investigation by Pratesi and Rovida¹⁶, who find that the loss peak at 18 eV is surface sensitive, a condition commonly observed for surface plasmons.

CONCLUSIONS

The XPS characteristic loss structure of Ag to Te and Al, Li, and Na can be entirely accounted for by excitations similar to those observed in electron reflection experiments. The structure can be assigned to bulk and surface plasmon excitations. The bulk plasmon loss intensities and energies vary systematically from Ag to Te. The surface loss energies are $\approx^{-1/2}$ as large as the respective bulk losses. High-energy losses in Ag and Cd may arise from 4d-shell participation.

FOOTNOTES AND REFERENCES

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TABLE 1

Al 2s CHARACTERISTIC ENERGY LOSSES, FROM UHV DATA

Peak	Al 2s	S	P ₁	P ₂	P ₃	P ₄	P ₅
Binding energy (eV)	118.4(2)	128.8(2)	134.0(2)	149.8(4)	165.2(4)	180.6(4)	196.1(6)
Separation from Al 2s (eV)	--	10.4	15.6	31.4	46.8	62.2	77.7
Bulk losses (eV)	--	--	15.6	15.8	15.4	15.4	15.5
Relative intensity	100	14	74	56	24	6.8	--
FWHM (eV)	1.1	~ 3.8	3.4	6.1	6.2	4.7	--

TABLE 2

Li 1s CHARACTERISTIC ENERGY LOSSES

Peak	1s	P _S	P ₁	P ₂
Binding energy (eV)	54.8(1)	59.8(5)	62.3(5)	69.6(5)
Separation from 1s (eV)	0	5.0	7.5	14.8
Relative intensity	100	16	65	48
FWHM (eV)	1.2	1.0	1.3	1.9

TABLE 3

Na 1s CHARACTERISTIC ENERGY LOSSES

Peak	1s	P _S	P ₁	P ₂	P ₃	P ₄	P ₅
Binding energy (eV)	1071.7(1)	1075.7(3)	1077.5(3)	1089.1(3)	1089.2(3)	1095.1(4)	1101.0(4)
Separation from 1s (eV)	0	4.0	5.8	11.6	17.5	23.4	29.3
Relative Intensity	100	9	85	71	35	21	3
FWHM (eV)	2.0	~ 2	2.7	4.5	4.5	~ 5	--

TABLE 4

Ag $3d_{3/2}$ AND Ag $3d_{5/2}$ CHARACTERISTIC ENERGY LOSSES^a

Peak	$3d_{5/2}$	P_1	$3d_{3/2}$	P_2	P_3	P_4	P_5^b	P_6
Binding energy (eV)	368.4(1)	372.3(1)	374.5(1)	378.4(1)	382.3(5)	387.2(2)	393.2(5)	399.4(5)
Separation from $3d_{5/2}$ (eV)	0	<u>3.9</u>	6.1	10	13.9	<u>18.8</u>	<u>24.8</u>	31.0
Separation from $3d_{3/2}$ (eV)	--	--	0	<u>3.9</u>	<u>7.8</u>	12.7	<u>18.7</u>	<u>24.9</u>
Intensity relative to $3d_{5/2}$	100	<u>2.5</u>	78	1.2	1.5	<u>0.3</u>	<u>1.8</u>	1.0
Intensity relative to $3d_{3/2}$	--	--	100	<u>1.6</u>	<u>1.9</u>	0.4	<u>2.2</u>	<u>1.2</u>
FWHM (eV)	1.0	1.0	1.0	1.0	2.5	1.5	(4.7)	3.5

^a Loss structure is interpreted as arising from primary peaks according to rows in which entries are underlined.

^b P_5 is interpreted as the superposition of 18.7 eV loss from $3d_{3/2}$ and 24.8 eV loss from $3d_{5/2}$.

Intensities of P_4 and P_6 indicate relative intensities of these two components of P_5 .

TABLE 5
ENERGY LOSSES IN Cd

Cd 4d Characteristic Energy Losses					
Peak	4d	P ₁	P ₂	P ₃	P ₄
Binding energy (eV)	11.0(1)	18.0(5)	20.3(5)	24.9(5)	30.0(5)
Separation from 4d (eV)	0	7.0	9.3	13.9	19.0
Relative intensity	100	4.2	11.5	2.3	2.2
FWHM (eV)	1.8	1.8	2.5	~ 3	~ 3

Cd 3d _{3/2} and Cd 3d _{5/2} Characteristic Energy Losses							
Peak	3d _{5/2}	3d _{3/2}	P ₁	P ₂	P ₃	P ₄	P ₅
Binding energy (eV)	405.4(1)	412.1(1)	414.7(2)	418.8(2)	421.4(2)	425.9(5)	432.6(5)
Separation from 3d _{5/2} (eV)	0	6.7	<u>9.3</u>	13.4	16.0	<u>20.5</u>	27.2
Separation from 3d _{3/2} (eV)	--	0	2.6	<u>6.7</u>	<u>9.3</u>	13.8	<u>20.5</u>
Intensity relative to 3d _{5/2}	100	73	<u>14</u>	6.7	8	<u>4.7</u>	3.3
Intensity relative to 3d _{3/2}	--	100	19	<u>9</u>	<u>11</u>	6.4	<u>4.5</u>
FWHM	1.4	1.4	1.6	2.1	2.2	~ 5	~ 5

TABLE 6

ENERGY LOSSES IN In

In 4d Characteristic Energy Losses					
Peak	4d	P ₁	P ₂	P ₃	P ₄
Binding energy (eV)	17.1(1)	25.7(3)	28.8(3)	36.9(5)	40.1(5)
Separation from 4d (eV)	0	8.6	11.7	19.8	23.0
Relative intensity	100	6	23	4	5
FWHM (eV)	1.7	2.5	2.6	~ 4	~ 4

In 3d _{3/2} and In 3d _{5/2} Characteristic Energy Losses								
Peak	3d _{5/2}	3d _{3/2}	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆
Binding energy (eV)	444.2(2)	451.7(2)	456.0(2)	460.0(2)	463.6(2)	467.5(5)	475.0(10)	486.5(10)
Separation from 3d _{5/2} (eV)	0	7.5	<u>11.8</u>	15.8	19.4	<u>23.3</u>	30.8	42.3
Separation from 3d _{3/2} (eV)	--	0	4.3	<u>8.3</u>	<u>11.9</u>	15.8	<u>23.3</u>	<u>34.8</u>
Intensity relative to 3d _{5/2}	100	63	<u>16</u>	1	19	<u>1</u>	2.6	1
Intensity relative to 3d _{3/2}	--	100	25	<u>1.7</u>	<u>29</u>	1.7	<u>4.2</u>	<u>1.7</u>
FWHM (eV)	1.3	1.3	1.5	1.5	2.0	1.5	~ 3	~ 3

TABLE 7

ENERGY LOSSES IN Sn

Sn 4d Characteristic Energy Losses					
Peak	4d	P ₁	P ₂	P ₃	P ₄
Binding energy (eV)	24.1(1)	34.4(2)	38.2(2)	52.1(5)	65.8(5)
Separation from 4d (eV)	0	10.3	14.1	28.0	41.7
Relative intensity	100	10	30	9	2.2
FWHM (eV)	1.8	3.5	~ 4	~ 5	~ 5

Sn 3d _{3/2} and Sn 3d _{5/2} Characteristic Energy Losses								
Peak	3d _{5/2}	3d _{3/2}	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆
Binding energy (eV)	485.0(2)	493.4(2)	499.4(2)	507.6(2)	513.0(5)	522(1)	529(1)	536(2)
Separation from 3d _{5/2} (eV)	0	8.4	<u>14.4</u>	19.6	<u>28</u>	37	<u>44</u>	51
Separation from 3d _{3/2} (eV)	--	0	6.0	<u>14.2</u>	19.6	<u>28.6</u>	35.6	<u>42.6</u>
Intensity relative to 3d _{5/2}	100	76	<u>27</u>	24	<u>13</u>	8	<u>0.3</u>	0.3
Intensity relative to 3d _{3/2}	--	100	36	<u>31</u>	17	<u>10.5</u>	0.4	<u>0.4</u>
FWHM (eV)	1.3	1.3	2.5	2.5	~ 5	~ 5	--	--

TABLE 8

ENERGY LOSSES IN Sb

Sb 4d Characteristic Energy Losses				
Peak	4d	P ₁	P ₂	P ₃
Binding energy (eV)	32.8(1)	44(1)	48.6(5)	64.5(20)
Separation from 4d (eV)	0	11.2	15.8	31.7
Relative intensity	100	6.7	27	9.9
FWHM (eV)	2.0	~ 4	5.5	~ 6

Sb 3d _{3/2} and Sb 3d _{5/2} Characteristic Energy Losses						
Peak	3d _{5/2}	3d _{3/2}	P ₁	P ₂	P ₃	P ₄
Binding energy (eV)	526.5(2)	537.5(2)	542.5(2)	553.5(2)	562(2)	571(2)
Separation from 3d _{5/2} (eV)	0	11	<u>16</u>	27	<u>35.5</u>	44.5
Separation from 3d _{3/2} (eV)	--	0	5	<u>16</u>	24.5	<u>33.5</u>
Intensity relative to 3d _{5/2}	100	77	<u>30</u>	25	~ <u>2</u>	~ 2
Intensity relative to 3d _{3/2}	--	100	39	<u>32</u>	~ 3	~ <u>3</u>
FWHM (eV)	1.0	1.0	2.0	2.0	--	--

TABLE 9

ENERGY LOSSES IN Te

Te $3d_{3/2}$ and $3d_{5/2}$ Characteristic Energy Losses				
Peak	$3d_{5/2}$	$3d_{3/2}$	P_1	P_2
Binding energy (eV)	572.5(2)	582.8(2)	590.1(4)	600.4(4)
Separation from $3d_{5/2}$ (eV)	0	10.3	17.6	27.9
Separation from $3d_{3/2}$ (eV)	--	0	7.3	17.6
Intensity relative to $3d_{5/2}$	100	68	<u>16</u>	<u>14</u>
Intensity relative to $3d_{3/2}$	--	100	23	<u>21</u>
FWHM (eV)	1.6	1.6	~ 5	~ 5

TABLE 10

	Energy (eV)			Intensity %			FWHM of CEL (FWHM of zero loss peak)			Energy (eV) of CEL's from Litera- ture Ref.		Assign- ment	$\hbar\omega_p$	ΔE_{IB}
	3d _{3/2}	3d _{5/2}	4d	3d _{3/2}	3d _{5/2}	4d	3d _{3/2}	3d _{5/2}	4d					
Ag	3.9	3.9	--	1.6	2.5	--	1	1	--	3.78	2	Bulk	9	3.9
	7.8	r	--	1.9	r	--	2.5	r	--	7.3	8	--		
	18.7	18.8	--	0.5	0.3	--	1.5	1.5	--	17.2	8	Surface		
	24.9	24.8	--	1.2	1.5	--	3.5	3.5	--	25.0	8	Bulk		
Cd	6.7	r	7.0	9	r	4.2	1.5	r	1	7.8	12	Surface		
	9.3	9.3	9.3	11	14	11.5	1.6	1.1	1.4	9.1	13	Bulk	11.3	10.0
	r	r	13.9	r	r	2.3	r	r	1.8	15.2	12	Surface		
	20.5	20.5	19	4.5	4.7	2.2	3.6	3.6	1.8	23.4	12	Bulk		
In	8.3	r	8.6	1.7	r	6	1.2	r	1.5	8.7	14	Surface		
	11.9	11.8	11.7	29	16	23	1.5	1.2	1.5	11.3	14	Bulk	12.5	16.5
	r	r	19.8	r	r	4	r	r	2.3	20.0	14	Bulk + Surface		
	23.3	23.3	23.0	4.2	1	5	2.3	1.2	2.3	22.7	14	2 × Bulk		
	34.8	--	--	1.7	--	--	2.3	--	--	--		3 × Bulk		
Sn	r	r	10.3	r	r	10	r	r	1.9	10.4	12	Surface		
	14.2	14.4	14.1	31	27	30	1.9	1.9	2.2	14.1	12	Bulk	14.3	23.5
	28.6	28.0	28.0	10.5	13	9	3.8	3.8	2.8	27.8	12	2 × Bulk		
	42.6	44	41.7	0.4	0.3	2.2	--	--	2.8	41.9	12	3 × Bulk		

(continued)

TABLE 10

	Energy (eV)			Intensity %			FWHM of CEL (FWHM of zero loss peak)			Energy (eV) of CEL's from Litera- ture Ref.		Assign- ment	$\hbar\omega_p$	ΔE_{IB}
	$3d_{3/2}$	$3d_{5/2}$	$4d$	$3d_{3/2}$	$3d_{5/2}$	$4d$	$3d_{3/2}$	$3d_{5/2}$	$4d$					
Sb	r	r	11.0	r	r	6.7	r	r	2	11.3	12	Surface		
	16.0	16.0	15.8	32	30	27	2	2	2.8	15.9	12	Bulk	15.0	31.0
	33.5	35.5	31.7	3	2	9.9	--	--	3	32.5	12	2 × Bulk		
Te	17.6	17.6	--	21	16	--	3.1	3.1	--	17.9	14	Bulk	15.6	39.0
r - not resolved.														

TABLE 11

MEASURED AND CALCULATED PLASMON ENERGIES FOR Ag AND Cd

	Energies of loss peak below main peak (eV)	Adj. bulk plasmon (eV)	Number of electrons	Energy of surface plasmon (eV)
Ag	7.8	<u>7.8</u>	n = 1	
	18.8			18.3
	24.9	25.9	n = 11	
Cd	9.3	<u>9.3</u>	n = 2	
	13.9			16.1
	19.0	22.7	n = 12	

FIGURE CAPTIONS

Fig. 1a. Characteristic electron energy loss spectra for (111) surface of silver under bombardment by 250 eV electrons incident at 30° , from Figure 1 of Reference 1a. See Figure 1 of Reference 1b for complete secondary electron energy spectrum.

Fig. 1b. Photoemission spectrum of Ag 3d level and its characteristic loss structure.

Fig. 2a. Photoemission spectrum of Al 2s level and its characteristic loss structure (HV). Note oxide satellite on 2s peak.

Fig. 2b. Photoemission spectrum of Al 2s level and its characteristic loss structure (UHV).

Fig. 3. Photoemission spectrum of Cd 4d level and its characteristic loss structure.

Fig. 4. Photoemission spectrum of Cd 3d level and its characteristic loss structure.

Fig. 5. Photoemission spectrum of In 4d level and its characteristic loss structure.

Fig. 6. Photoemission spectrum of In 3d level and its characteristic loss structure.

Fig. 7. Photoemission spectrum of Sn 4d level and its characteristic loss structure.

Fig. 8. Photoemission spectrum of Sn 3d level and its characteristic loss structure.

Fig. 9. Photoemission spectrum of Sb 4d level and its characteristic loss structure.

Fig. 10. Photoemission spectrum of Sb 3d level and its characteristic loss structure.

Fig. 11. Photoemission spectrum of Te 3d level and its characteristic loss structure.

Fig. 12. Photoemission spectrum of Ag valence bands.

Fig. 13. Systematic of plasmon losses in Ag, Cd, In, Sn, Sb, and Te. ΔE_{IB} is the onset-interband-transition energy ($4d \rightarrow E_F$), ΔE_B is the measured bulk plasmon energy, ΔE_S is the measured surface plasmon energy, $\hbar\omega_p$ is the calculated free electron bulk plasmon energy, and I_B and I_S are the intensity of the bulk and surface plasmon intensity respectively relative to the zero-loss peak.

XBL 739-4010

Fig. 1

XBL 739-1175

Fig. 2

XBL 7211-7415

Fig. 3

Fig. 4

XBL 7211-7414

Fig. 5

XBL 7211-7413

Fig. 6

XBL 7211-7412

Fig. 7

XBL 7244-7444

Fig. 8

XBL 7211-7410

Fig. 9

XBL 7211-7409

Fig. 10

XBL 7211-7408

XBL 7241-7407

Fig. 11

Fig. 12

XBL 7211-7418

XBL7211-4394

Fig. 13

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