

9j. Work Function and Secondary Emission

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9j-1. Work Function Measurements. The work function ϕ of a substance is given as the difference in energy between the Fermi level (or electrochemical potential) of a solid and the electrostatic surface potential just outside. This is what is generally measured in thermionic (Th) and contact potential (C.P.D.) measurements. The photoelectric "work function" (P.E.), however, is normally taken as the measure of the photoelectric threshold and represents the energy difference between the level of the highest-lying electron at room temperature and the electrostatic surface potential. Although the highest-energy electron of a metal at room temperature is very near the Fermi level, this is not necessarily true for semiconductors. (This fact must be kept in mind when one is comparing photoelectric work functions of semiconductors with those derived from thermionic or contact potential techniques.) Table 9j-1 lists the work functions of elements as determined by *thermionic*, *photoelectric*, and *contact potential* difference methods, while Table 9j-2 gives the thermionic work functions of various compounds used in electron emitter applications.

The thermionic work function ϕ as a rule is obtained by analyzing the emitted current by means of the Richardson equation:

$$J = 120T^2 e^{-\phi/kT}$$

where J is the current density in amp/cm², T is the absolute temperature, k is $8.62 \cdot 10^{-5}$ eV/deg. and ϕ is given in electron volts. ϕ is usually not constant in the temperature range of measurement but for most substances can be expressed in terms of a linear temperature dependence $\phi = \phi_0 + \alpha T$, where ϕ_0 is the temperature-independent component of the work function, and α is the temperature coefficient.

In many thermionic measurements, unfortunately, the work function quoted and subsequently recorded in review articles is the value obtained from the slope of a Richardson plot ($\log J/T^2$ vs. $1/T$), which is just ϕ_0 . If there is an appreciable temperature dependence, this value can be highly erroneous since these measurements are obtained at fairly high temperatures (i.e., 1000 to 2000 K). Consequently, unless the temperature dependence can be determined from the published data by some other method (e.g., from the intercept of the Richardson plot or "Richardson A value") the results are not included in this review. Furthermore, since the linear approximation to the temperature dependence very likely does not hold for all temperatures, the temperature range in which the measurements were made is also included.

Except where specifically noted, the photoelectric work function measurements are carried out at room temperature and therefore require no additional information regarding temperature range. The same is also true of contact potential difference measurements which are normally obtained at room temperature by measuring the difference in electrostatic surface potential between a substance having a known work function value or "standard" (e.g., W, Hg, Ag, etc.), and the substance to be measured.

TABLE 9j-1. WORK FUNCTIONS OF THE ELEMENTS

Element	Work function eV	Technique	Notes	Reference	Year	
Ag.....	$4.31 + 0.1 \times 10^{-4}T$ 1160-1200 K	Th	1	1	1953	
	4.32 1230 K	Th	2	2	1956	
	4.5	P.E.	.....	3	1950
	4.3	P.E.	.....	4	1953
	4.32	C.P.D.	3, 4	5	1951	
	4.3	C.P.D.	4, 5	6	1964	
	4.44	C.P.D.	4, 6	6	1964	
	4.29	C.P.D.	4, 7	6	1964	
	Al.....	4.36	P.E.	7	1936
		4.08	P.E.	8	1936
4.2		P.E.	.....	9	1944
4.24		C.P.D.	3, 4	5	1951	
4.19		C.P.D.	4, 5	10	1957	
4.18		C.P.D.	5, 8	11	1966	
Au.....		$4.25 + 0.15 \times 10^{-4}T$ 1160-1280 K	Th	9	1	1953
	5.1	P.E.	9	12	1961	
	5.4	P.E.	9	13	1966	
	5.45	C.P.D.	9, 10	14	1966	
	5.22	C.P.D.	5, 9, 11	15	1966	
	5.4	C.P.D.	5, 9, 10	13	1966	
	As.....	4.60	P.E.	16	1949
		4.72	P.E.	17	1949
	Ba.....	$2.3 + 5 \times 10^{-4}T$ 1000-1300 K	Th	2	18	1965
		2.49	P.E.	19	1939
2.48		P.E.	.....	20	1940
2.42		C.P.D.	3	21	1935	
2.35		C.P.D.	5	22	1941	
2.66		C.P.D.	6	23	1952	
2.5		C.P.D.	.....	24	1963
B.....		4.4-4.6	P.E.	25	1948
		Be.....	3.67	Th	26	1966
920-1180 K						
3.3	P.E.		.....	27	1934
3.92	P.E.		.....	28	1937
3.89	C.P.D.		12	29	1963	
Bi.....	4.31	P.E.	.....	30	1936
	4.46	P.E.	.....	31	1941
	4.34	P.E.	.....	17	1949
C.....	$4.39 + 1.7 \times 10^{-4}T$ 1300-2200 K	Th	.....	32	1947
	$4.6 + 0.6 \times 10^{-4}T$ 1490-1670 K	Th	1	33	1952	
	4.81	P.E.	.....	34	1926
Ca.....	3.2	P.E.	.....	35	1932
	2.7	P.E.	.....	36	1936
	3.21	P.E.	.....	37	1937
Cd.....	4.07	P.E.	.....	38	1931
	4.099	P.E.	.....	9	1944
	4.0	C.P.D.	13	39	1953	
	4.22	C.P.D.	4, 6	40	1955	
Ce.....	$2.48 + 1.8 \times 10^{-4}T$ 1060-1450 K	Th	2, 4	41	1926	
	2.84	P.E.	.....	35	1932

TABLE 9j-1. WORK FUNCTIONS OF THE ELEMENTS (Continued)

Element	Work function eV	Technique	Notes	Reference	Year
Co.....	$4.4 + 0.9 \times 10^{-4}T$ $\approx 1200-1450$ K	Th	.....	42	1942
	$4.41 + 0.6 \times 10^{-4}T$ 1410-1590 K	Th	1	43	1952
Cr.....	4.12	P.E.	14	44	1931
	4.25	P.E.	15	44	1931
	$4.58 + 0.6 \times 10^{-4}T$ 1450-1600 K	Th	1	43	1952
	≈ 3.9 1100-1400 K	Th	.....	26	1966
Cs.....	4.4	P.E.	.....	12	1961
	≈ 1.86 ~ 500 K	Th	.....	45	1966
Cu.....	2.14	P.E.	.....	46	1964
	1.84	C.P.D.	3, 4	6	1964
	4.5 1160-1280 K	Th	1	1	1953
	4.6 ~ 1350 K	Th	.....	2	1956
	4.4 1100-1300 K	Th	.....	26	1966
	4.76	P.E.	.....	47	1934
	4.80(111)	P.E.	.....	48	1935
	5.61(110)	P.E.	.....	48	1935
	4.60	C.P.D.	3, 4	5	1951
	4.51	C.P.D.	4, 5	10	1957
Er.....	$2.97 + 0.65 \times 10^{-4}T$ 1150-1500 K	Th	.....	48a	1967
	Fe.....	$\phi_{\beta} = 4.48 + 1.3 \times 10^{-4}T$ $\phi_{\gamma} = 4.21 + 3.75 \times 10^{-4}T$ $\approx 1200-1450$ K	Th	42
$4.31 + 0.6 \times 10^{-4}T$ 1410-1610 K		Th	1	43	1952
4.5 1200-1500 K		Th	.....	26	1966
$\phi_{\beta} = 4.62$ $\phi_{\gamma} = 4.68$		P.E.	.....	49	1953
4.16		P.E.	.....	49	1953
Ga.....	3.8	C.P.D.	4, 5	10	1957
	Ge.....	3.8	C.P.D.	16	50	1938
≈ 3.5 ~ 900 K		Th	.....	2	1956
Hf.....	4.11(111)	P.E.	.....	51	1959
	$3.6 + 1.4 \times 10^{-4}T$ 1250-1820 K	Th	.....	52	1957
Hg.....	3.85 $\sim 1000-1700$ K	Th	2	53	1962
	4.52	P.E.	.....	54	1931
Ir.....	4.5	P.E.	.....	55	1934
	$5.3 + 0.2 \times 10^{-4}T$ 1700-2200 K	Th	.....	56	1951
	$5.4 - 0.3 \times 10^{-4}T$ 1590-2320 K	Th	.....	57	1956
K.....	≈ 5.28 1300-2000 K	Th	.....	58	1966
	4.57	C.P.D.	16	50	1938
	2.24	P.E.	.....	59	1932
	2.26	P.E.	.....	60	1937

TABLE 9j-1. WORK FUNCTIONS OF THE ELEMENTS (Continued)

Element	Work function eV	Technique	Notes	Reference	Year
La.....	≈3.0 1200-1500 K	Th	2	41	1926
Li.....	2.42 1.4	P.E. C.P.D.	..... 16	47 50	1934 1938
Mg.....	3.66 3.12	P.E. C.P.D.	..... 13	61 62	1964 1951
Mn.....	3.83 + 1.1 × 10 ⁻⁴ T 1370-1520 K	Th	1	43	1952
Mo.....	3.76 4.38-0.25 × 10 ⁻⁴ T 1410-2110 K	P.E. Th	..... .....	47 52	1934 1957
	4.33 + 0.1 × 10 ⁻⁴ T ~1300-1900 K	Th	.....	63	1962
	4.25 1600 K	Th	.....	64	1966
	4.33-1.52 × 10 ⁻⁴ T 1200-2000 K	Th	.....	58	1966
	4.41 4.20	P.E. C.P.D.	..... 4	63 0	1962 1904
Na.....	2.06 2.29	P.E. P.E.	..... .....	47 28	1934 1937
	2.28	P.E.	.....	20	1940
Nb.....	4.0 1400-2100 K	Th	.....	65	1964
	4.3 2200 K	Th	.....	66	1964
	≈4.19 1050-2100 K	Th	.....	58	1966
	4.33(110) 4.55(335) 4.66(111)	P.E. P.E. P.E.	..... ..... .....	67 67 67	1963 1963 1963
	4.38	C.P.D.	4	68	1964
Nd.....	≈2.95 1150-1450 K	Th	2	41	1926
Ni.....	5.24 + 0.75 × 10 ⁻⁴ T ≈1100 K	Th	.....	69	1949
	4.5 1410-1610 K	Th	1	43	1952
	4.41 1170-1250 K	Th	.....	26	1966
	6.27-1.0 × 10 ⁻³ T 1380-1500 K	Th	.....	26	1966
	5.05 T = 623 K 5.2 T = 1108 K	P.E. P.E.	..... .....	69 69	1949 1949
	4.73	C.P.D.	4, 5	10	1957
	5.22	C.P.D.	10	14	1966
Os.....	5.43-3.9 × 10 ⁻⁴ T 1413-1640 K	Th	.....	58	1966
	≈5.17 ~1500 K(?)	Th	.....	70	1967
	5.93	P.E.	.....	71	1966
Pb.....	3.97 3.49	P.E. C.P.D.	..... 13	72 62	1928 1951
	3.83	C.P.D.	4, 5	73	1956
Pd.....	4.64	C.P.D.	13	39	1953
Pr.....	2.57 + 1.5 × 10 ⁻⁴ T 1120-1410 K	Th	2	41	1926

TABLE 9j-1. WORK FUNCTIONS OF THE ELEMENTS (Continued)

Element	Work function eV	Technique	Notes	Reference	Year
Pt.....	5.3-5.5 ~1600-1900 K(?)	Th	.....	74	1950
	$5.03 + 4.2 \times 10^{-4}T$ 1620-1946 K	Th	.....	26	1966
Rb.....	4.82	C.P.D.	13	39	1953
	2.09	P.E.	.....	59	1932
Re.....	$4.85 + 0.6 \times 10^{-4}T$ 1470-2150 K	Th	.....	75	1963
	$4.7 + 0.75 \times 10^{-4}T$ 1820-2860 K	Th	.....	76	1963
Rh.....	1.8 1600-2200 K	Th	.....	65	1964
	4.96 1325-2250 K	Th	.....	58	1966
	$4.8 + 1.1 \times 10^{-4}T$ ~1500-1900 K(?)	Th	.....	77	1938
Ru.....	$4.9 + 0.2 \times 10^{-4}T$ 1550-1950 K	Th	.....	56	1951
	4.92	P.E.	.....	78	1931
Sb.....	4.52	C.P.D.	16	50	1938
	4.01	P.E.	.....	79	1937
Sc.....	4.6	P.E.	.....	17	1949
	4.14	C.P.D.	16	50	1938
	4.1	C.P.D.	3, 4	6	1964
Se.....	$3.13 + 0.8 \times 10^{-4}T$ 1150-1500 K	Th	.....	48a	1967
	5.11	P.E.	.....	47	1934
Si.....	4.42	C.P.D.	16	50	1938
	$3.59 + 2.3 \times 10^{-4}T$ 1250-1700 K	Th	.....	32	1947
Sm.....	$4.02 + 2.6 \times 10^{-4}T$ 1373-1623 K	Th	.....	80	1953
	5.4(111)	P.E.	.....	81	1962
	3.95 (n type)	C.P.D.	17	82	1947
	4.2 (p type)	C.P.D.	17	82	1947
	4.5 (n or p)	C.P.D.	18	83	1949
Sn.....	≈ 3.15 1150-1600 K	Th	2	41	1926
	3.62	P.E.	.....	72	1928
Sr.....	4.21 liquid	P.E.	.....	84	1929
	4.38 α phase	P.E.	.....	84	1929
	4.50 β phase	P.E.	.....	84	1929
	4.21	C.P.D.	13	85	1952
	4.42	C.P.D.	19	86	1963
Ta.....	$2.3 + 0.5 \times 10^{-4}T$ 850-950 K	Th	20	87	1955
	2.24	P.E.	.....	47	1934
Tl.....	2.74	P.E.	.....	88	1938
	4.35	Th	21	89	1957
	300-1860 K				
	4.25 1100-2200 K	Th	.....	58	1966
	$4.33 + 0.25 \times 10^{-4}T$ 1700-2230 K	Th	.....	90	1966
Tm.....	4.1	P.E.	.....	35	1932
	4.05	P.E.	.....	91	1935
	4.22	C.P.D.	4	6	1964

TABLE 9j-1. WORK FUNCTIONS OF THE ELEMENTS (Continued)

Element	Work function eV	Technique	Notes	Reference	Year
Te.....	5.0	P.E.	.....	92	1953
	4.7	C.P.D.	16	50	1938
Th.....	$3.38 + 0.45 \times 10^{-4}T$ 1250-1800 K	Th	.....	93	1926
	≈ 3.4	P.E.	.....	35	1932
	3.66	P.E.	.....	47	1934
	3.46	C.P.D.	16	50	1938
	3.71	C.P.D.	7	94	1962
	3.44	C.P.D.	3	94	1962
	3.95 + 0.85 × 10 ⁻⁴ T 1370-1520 K	Th	1	43	1952
Ti.....	4.0	Th	.....	65	1964
	1300-1600 K				
	4.45	P.E.	.....	95	1954
	4.14	C.P.D.	16	50	1938
Tl.....	3.68	P.E.	.....	96	1935
	3.84	C.P.D.	16	50	1938
U.....	$3.0 + 2.7 \times 10^{-4}T$ 1250-1400 K	Th	20	96	1959
	3.47	Th	22	96	1959
	1250-1400 K				
	$2.9 + 2.3 \times 10^{-4}T$ 1020-2000 K	Th	20	76	1963
	≈ 3.55 1000-1500 K	Th	22	97	1967
	3.47 (α)	P.E.	.....	98	1962
	3.52 (β)	P.E.	.....	98	1962
	3.39 (γ)	P.E.	.....	98	1962
	3.65 (α)	P.E.	.....	99	1967
	3.59 (β)	P.E.	.....	99	1967
	3.45 (γ)	P.E.	.....	99	1967
	3.19	C.P.D.	3.4	100	1962
	3.63 (α)	C.P.D.	4	97	1967
	3.58 (β)	C.P.D.	4	97	1967
3.53 (γ)	C.P.D.	4	97	1967	
V.....	$4.12 + 0.75 \times 10^{-4}T$ 1410-1540 K	Th	1	43	1952
	3.77	P.E.	.....	47	1934
	4.44	C.P.D.	16	50	1938
	4.52 + 0.6 × 10 ⁻⁴ T 1350-2200 K	Th	.....	101	1950
W.....	$4.5 + 0.15 \times 10^{-4}T$ 1820-2940 K	Th	.....	76	1963
	$4.58 + 0.15 \times 10^{-4}T$ 2100-2600 K	Th	.....	90	1966
	4.52 1150-2200 K	Th	.....	58	1966
	4.6	P.E.	.....	35	1932
	4.565	P.E.	.....	102	1935
	4.49	P.E.	.....	103	1948
Y.....	4.55	C.P.D.	4, 5	10	1957
	$2.95 + 0.2 \times 10^{-4}T$ 1150-1400 K	Th	.....	48a	1967
Zn.....	4.26	P.E.	.....	104	1940
	4.307	P.E.	.....	9	1944
	4.11	C.P.D.	4	105	1940
	4.22	C.P.D.	13	85	1952

TABLE 9j-1. WORK FUNCTIONS OF THE ELEMENTS (Continued)

Element	Work function eV	Technique	Notes	Reference	Year
Zr.....	3.78	Th	.....	106	1951
	$T = ?$				
	3.73	P.E.	.....	35	1932
	4.33	P.E.	.....	95	1954
	3.60	C.P.D.	16	50	1938

However, since the resulting work function values depend on the accuracy with which the work function of the standard is known, the substance used for the standard and its assumed work function are also included.

Some of the earlier work function measurements quoted in other reference works are omitted here, especially where an appreciable number of results on the same subject have been recently published employing more refined experimental techniques. That is not to say, however, that "recentness" is synonymous with "cleanliness"; rather, the most recent studies involving techniques such as low-energy electron diffraction and Auger spectrum analysis serve to show how contaminated "clean" surfaces really are. Consequently, the values listed here merely serve to indicate the measured values of the work functions as they are presently limited by experimental refinement of measuring methods. For some substances which can be easily cleaned they are quite accurate; for others they will most certainly be considered outdated by the next review.

Notes for Table 9j-1

1. Effusion method.
2. Deduced from published results.
3. Film on W substrate.
4. Assuming ϕ for bulk W is 4.54.
5. Film on glass substrate.
6. Film on Ta substrate.
7. Bulk.
8. Assuming ϕ of Au is 5.22.
9. No Hg contamination.
10. Absolute work function value using field-emission-retarding potential method.
11. Assuming ϕ of Al \approx 4.2.
12. From breakdown voltage of metal insulator-metal junction, assuming ϕ of Al = 4.08.
13. Assuming ϕ of Ag = 4.31.
14. Hexagonal crystal structure.
15. Face-centered-cubic structure.
16. Assuming ϕ of Hg = 4.52.
17. Using various oxides, e.g., ϕ of PbO = 4.06.
18. Absolute work function value using photoemission-retarding potential method.
19. From breakdown of metal insulator-metal junction, assuming ϕ of Al = 4.08.
20. Monolayer on W substrate.
21. Also used contact potential shifts of two $\langle 211 \rangle$ Ta crystals to get low-temperature values of ϕ .
22. 15 layers.

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TABLE 9j-2. WORK FUNCTIONS FOR VARIOUS COMPOUNDS

Emissive material	Base metal	Work function	Temperature range, K	Reference	Year
Oxides of:					
Ba.....	Pt	$1.4 + 7 \times 10^{-4}T$	700-950	1	1965
Sr.....	Pt	$1.6 + 7 \times 10^{-4}T$	1000-1180	1	1965
Ca.....	Pt	$1.86 + 7 \times 10^{-4}T$	1080-1380	1	1965
Th.....	W, Ta, Mo	$\sim 2.6 + 2.4 \times 10^{-4}T$	$\sim 1300-2200$	2, 3	1947-8
	Re, Nb	$2.37 + 4 \times 10^{-4}T$	1300-1700	4	1962
Hf.....	W	$2.82 + 4.72 \times 10^{-4}T$	1300-1950	5	1959
Zr.....		3.9	2000	6	1953
Ti.....		3.7	2000	6	1953
Sc.....	W	$3.66 + 2.2 \times 10^{-4}T$	1300-2000	5	1959
Y.....	Re, Nb	$2.9 + 1.6 \times 10^{-4}T$	1300-1700	4	1962
La.....	Ni	$3.0 + .075 \times 10^{-4}T$	$\sim 1000-1100$	7	1959
Ce.....		$2.3 + 4.1 \times 10^{-4}T$	$\sim 1800-2000$	6	1953
Pr.....	W	$2.8 + 5.4 \times 10^{-4}T$	$\sim 1400-1600$	8	1958
Nd.....	W	$2.3 + 4.1 \times 10^{-4}T$	$\sim 1400-1600$	8	1958
Sm.....	W	$2.8 + 5.1 \times 10^{-4}T$	$\sim 1700-1900$	8	1958
Eu.....	W	$2.6 + 6 \times 10^{-4}T$	$\sim 1400-1600$	8	1958
Gd.....	W	$2.1 + 4.5 \times 10^{-4}T$	1100-1600	8	1958
Tb.....	W	$2.1 + 5.4 \times 10^{-4}T$	1400-1600	8	1958
Dy.....	W	$2.1 + 4.16 \times 10^{-4}T$	1100-1600	8	1958
Ho.....	W	$2.3 + 5.1 \times 10^{-4}T$	1350-1950	8	1958
Er.....	W	$2.4 + 4.35 \times 10^{-4}T$	$\sim 1700-1000$	8	1958
Yb.....	W	$2.7 + 2.85 \times 10^{-4}T$	1500-1900	8	1958
Lu.....	W	$2.3 + 6 \times 10^{-4}T$	$\sim 1500-1700$	8	1958
U.....	W	$\sim 3.1 + 2.1 \times 10^{-4}T$	1350-2100	9	1963
Hexaborides of:					
Ca.....	None	$2.86 + 3.3 \times 10^{-4}T$	1100-1400	10	1951
Sr.....	None	$2.67 + 5.82 \times 10^{-4}T$	1250-1459	10	1951
Ba.....	None	$3.45 + 1.74 \times 10^{-4}T$	1250-1650	10	1951
Th.....	None	$2.92 + 4.72 \times 10^{-4}T$	1150-1000	10	1951
Y.....	Ta	$2.2 + 1.8 \times 10^{-4}T$	.....	11	1958
La.....	None	$2.66 + 1.22 \times 10^{-4}T$	1080-1300	10	1951
Ce.....	None	$2.59 + 3.0 \times 10^{-4}T$	1140-1370	10	1951
Pr.....	Ta	$3.46 - 7.9 \times 10^{-4}T$	.....	11	1958
Nd.....	Ta	$3.97 - 1.08 \times 10^{-4}T$	.....	11	1958
Gd.....	Ta	$2.05 + 4.28 \times 10^{-4}T$	.....	11	1958
Dy.....	Ta	$3.53 + 1.37 \times 10^{-4}T$	.....	11	1958
Ho.....	Ta	$3.42 + 1.86 \times 10^{-4}T$	.....	11	1958
Er.....	Ta	$3.37 + 2.15 \times 10^{-4}T$	.....	11	1958
Yb.....	Ta	$3.13 + 3.32 \times 10^{-4}T$	.....	11	1958
Lu.....	Ta	$3.0 + 5.0 \times 10^{-4}T$	.....	11	1958
Tm.....	W	$2.75 + 3.3 \times 10^{-4}T$	1100-1800	12	1904
Carbides of:					
Ta.....	W	$3.14 + 5.2 \times 10^{-4}T$	1400-2300	13	1951
	Ta	$3.17 + 5.4 \times 10^{-4}T$	1600-2250	14	1962
Th.....	Ta	$3.2 + 0.16 \times 10^{-4}T$	1500-2000	6	1953
	W	$3.5 - 1.32 \times 10^{-4}T$	1400-2300	13	1951
Ti.....	W	$3.35 + 1.35 \times 10^{-4}T$	1400-2300	13	1951
Zr.....	W	$2.18 + 5.1 \times 10^{-4}T$	1173-2073	13	1951
	W	$3.24 + 2.0 \times 10^{-4}T$	1300-2000	15	1962
U.....	W	$2.94 + 1.1 \times 10^{-4}T$	1200-2100	16	1960
Si.....	Ta	$3.5 + 0.5 \times 10^{-4}T$	.....	6	1953
Hf.....	W	$3.42 + 1.75 \times 10^{-4}T$	1300-2000	15	1962
V.....	W	3.85	1300-2000	15	1962
Mo.....	None	$5.36 - 4 \times 10^{-4}T$	1400-1650	17	1967

TABLE 9j-2. WORK FUNCTIONS FOR VARIOUS COMPOUNDS (Continued)

Emissive material	Base metal	Work function	Temperature range, K	Reference	Year
Borides of:					
Ta(mono).....	W	$2.89 + 2.14 \times 10^{-4}T$	1400-2100	13	1951
Ta(di).....	W, Ta, C	~ 2.85	1600-1800	18	1962
Ta(di).....	None	4.26	1100-1550	17	1967
Zr(mono).....	W	$4.48 - 4.76 \times 10^{-4}T$	1500-2100	13	1951
Ti(di).....	None	$4.6 - 1.17 \times 10^{-4}T$	1350-1850	19	1957
V(di).....	None	$4.2 + 6.1 \times 10^{-4}T$	1450-1800	19	1957
Nb(di).....	None	$4.0 + 3.65 \times 10^{-4}T$	1500-2000	19	1957
Cr(di).....	None	$4.1 + 3.55 \times 10^{-4}T$	1450-1900	19	1957
Mo(di).....	None	$3.85 + 4.9 \times 10^{-4}T$	1550-2050	19	1957
Hf(di).....	HfC	~ 3.7	2240	20	1963
U(di).....	W	$\sim 3.3 + .2 \times 10^{-4}T$	1300-2100	9	1963
U(tetra).....	W	$\sim 3.4 - .8 \times 10^{-4}T$	1300-2100	9	1963
Y(tetra).....	Ta	$3.2 + 2.5 \times 10^{-4}T$	1530-1890	21	1966
Gd(tetra).....	Ta	$2.5 + 4.0 \times 10^{-4}T$	1500-1750	21	1966
Silicides of:					
Re(di).....	W	$4.02 - 2.67 \times 10^{-4}T$	1200-1400	22	1966
Nb(di).....	W	$4.34 - 5.25 \times 10^{-4}T$	1300-1700	22	1962
Zr(di).....	W	$3.95 - 5.0 \times 10^{-4}T$	1200-1900	22	1962
V(di).....	W	$3.26 - 7.5 \times 10^{-4}T$	1100-1600	22	1962
Cr(mono).....	W	$3.49 - .58 \times 10^{-4}T$	1200-1400	22	1962
Cr(di).....	W	$3.78 - 1.2 \times 10^{-4}T$	1200-1450	22	1962
H(di).....	W	$3.0 + 2.1 \times 10^{-4}T$	1300-2000	9	1963
U(tri).....	W	$3.22 + 1.1 \times 10^{-4}T$	1300-2000	9	1963
W(di).....	None	~ 4.62	1350-1610	17	1967
Ta(di).....	None	~ 4.71	1180-1600	17	1967
Mo(ii).....	None	~ 4.73	~ 1500	17	1967
Nitrides of:					
Zr.....	W	3.96	2000	13	1951
B.....	W	4.0	2000	13	1951
Ti.....	W	3.96	2000	13	1951
U.....	W	$\sim 3.1 + 2.14 \times 10^{-4}T$	1350-2100	9	1963

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9j-2. Secondary Emission Measurements. The secondary emission ratio δ of a material is the number of secondary electrons emitted on the average, per incident primary electron. Secondary electron emission involves three processes: (1) the excitation of electrons in the solid by the incident primary electron beam, (2) the diffusion of the excited electrons to the surface, and (3) the escape of the excited electrons through the surface barrier. The secondary emission ratio of a given surface depends on the primary electron energy, the angle of incidence of the primary electrons with respect to the surface, bulk properties of the material, and most important, the surface conditions. In so far as practicable, yield measurements given here have been selected to be representative of clean surfaces at normal incidence.

The secondary emission ratio increases with primary energy until it reaches a maximum denoted by δ_m in Table 9j-3. The primary energy at which this maximum occurs is listed as $E_{p,max}$. When the primary energy is raised beyond the maximum, electrons are excited increasingly deeper within the material so that many of them are unable to diffuse to the surface. The secondary emission ratio therefore slowly decreases as the primary energy is increased beyond $E_{p,max}$. The voltages for which the secondary emission ratio crosses the $\delta = 1$ line are called the *first* and *second crossover*, respectively, and are designated as E_I and E_{II} in the table.

In general, lower secondary emission ratios are obtained from metals than from insulators. Roughening the surface of a material or increasing its porosity will further decrease the secondary emission ratio since the secondary electrons intercept other parts of the roughened and porous surface and are prevented from escaping into the vacuum. A good example of such a low secondary emission surface is carbon deposited as soot.

The highest secondary emission yields have been previously obtained from alkali halides and various oxides, such as NaBr or MgO. However, certain solid-state concepts have been recently employed to substantially increase the secondary emission ratio. One approach using Cs-treated GaP depends on bending the energy bands near the surface so that the effective electron barrier for escaping secondaries is lowered. The resulting secondary emission ratio for this surface represents an order of magnitude increase over that previously achieved from "natural"-appearing compounds.

A number of reviews of secondary emission have recently been published.¹ Table 9j-3 is taken from the review by Whetten except for a few additions.

¹ See, for example:

R. Kollath, "Handbuch der Physik," vol 21, pp. 232-233, Elektronen-Emission Gasentladungen, Springer-Verlag OHG, Berlin, 1956.

O. Hachenberg and W. Brauer, Secondary Emission from Solids, *Advan. Electron. Electron Phys.* **11**, 413-499 (1959).

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A. J. Dekker, *Solid State Phys.* **6**, 251 (1958).

N. R. Whetten, "Methods of Experimental Physics," vol 4, part A, pp. 69-84, Academic Press, Inc., New York, 1967.

TABLE 9j-3. SECONDARY EMISSION PARAMETERS

Elements	δ_{\max}	$E_{p,\max}$	E_I	E_{II}	References
Ag.....	1.5	800	200	>2000	1, 2, 3
Al.....	1.0	300	300	300	2
Au.....	1.4	800	150	>2000	1, 2, 3
B.....	1.2	150	50	600	5
Ba.....	0.8	400	None	None	2
Be.....	0.5	200	None	None	2, 6, 7, 4
Bi.....	1.2	550	...	.....	8, 9
C (diamond).....	2.8	750	...	>5000	10
(graphite).....	1.0	300	300	300	11
(soot).....	0.45	500	None	None	11
Cd.....	1.1	450	300	700	12, 4
Co.....	1.2	600	200	.....	13, 14
Cs.....	0.7	400	None	None	2, 15
Cu.....	1.3	600	200	1500	1, 12, 2
Fe.....	1.3	400	120	1400	14, 3, 16
Ga.....	1.55	500	75	.....	17
Ge.....	1.15	500	150	900	5, 18, 9
Hg.....	1.3	600	350	>1200	17
K.....	0.7	200	None	None	19, 20
Li.....	0.5	95	None	None	2
Mg.....	0.95	300	None	None	15, 2
Mo.....	1.25	375	150	1200	1, 21, 3, 22, 16
Na.....	0.82	300	None	None	24
Nb.....	1.2	375	150	1050	1, 3
Ni.....	1.3	550	150	>1500	1, 14, 13, 21, 16
Pb.....	1.1	500	250	1000	8, 17
Pd.....	>1.3	>250	120	.....	24
Pt.....	1.8	700	350	3000	3
Rb.....	0.9	350	None	None	19
Sb.....	1.3	600	250	2000	25
Si.....	1.1	250	125	500	5
Sn.....	1.35	500	...	.....	8, 23
Ta.....	1.3	600	250	>2000	1
Th.....	1.1	800	...	.....	2
Ti.....	0.9	280	None	None	11
Tl.....	1.7	650	70	>1500	9
W.....	1.4	650	250	>1500	26, 1, 27, 3
Zr.....	1.1	350	...	.....	11

TABLE 9j-3. SECONDARY EMISSION PARAMETERS (Continued)

Compounds	δ_{max}	$E_{p,max}$	Reference
Alkali halides:			
CsCl.....	6.5	.....	28
KBr(crystal).....	14	1800	29, 30
KCl(crystal).....	12	1600	31, 32
(layer).....	7.5	1200	31, 33
KI(crystal).....	10	1600	29, 32, 30
(layer).....	5.6	.....	28
LiF(crystal).....	8.5	.....	34
(layer).....	5.6	700	28
NaBr(crystal).....	24	1800	35, 32
(layer).....	6.3	.....	28
NaCl(crystal).....	14	1200	36, 30, 29, 32, 34
(layer).....	6.8	600	28, 37
NaF(crystal).....	14	1200	34
(layer).....	5.7	.....	28
NaI(crystal).....	19	1300	34
(layer).....	5.5	.....	28
RbCl(layer).....	5.8	.....	28
Oxides:			
Ag ₂ O.....	1.0	.....	38
Al ₂ O ₃ (layer).....	2-9	.....	39, 40, 36, 2
BaO(layer).....	2.3-4.8	400	40, 2
BeO.....	3.4	2000	40
CaO.....	2.2	500	40
Cu ₂ O.....	1.2	400	28, 41
MgO(crystal).....	20-25	1500	42, 43, 44, 45
(layer).....	3-15	400-1500	40, 46, 47, 42
MoO ₃	1.2	.....	38
SiO ₂ (quartz).....	2.1-4	400	39, 40
SnO ₂	3.2	640	48
Sulfides:			
MoS ₂	1.1	.....	28
PbS.....	1.2	500	31
WS ₂	1.0	.....	28
ZnS.....	1.8	350	40
Others:			
BaF ₂ (layer).....	4.5	.....	28
CaF ₂ (layer).....	3.2	.....	28
BiCs.....	6	1000	31
BiCs.....	1.9	1000	31
GeCs.....	7	700	31
Rb ₂ Sb.....	7.1	450	31
SbCs.....	6	700	31, 50
Mica(natural).....	2.4	350	39
(synthetic).....	2.9	300	51
Glasses.....	2-3	300-450	39, 52
MgF ₂	4.0	400	51
Talc.....	2.3	300	51
Teflon.....	1.7	600	53
ZnSiO ₄	2.6	300	53
GaP + Cs.....	120*	2500*	54
Phosphors:			
P ₁	2.7	750	55
P ₂	3.4	750	55
P ₃	3.9	1000	55
P ₄	3.7	700	55

* Maximum voltage measured was 2500 volts, δ was still rising.

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