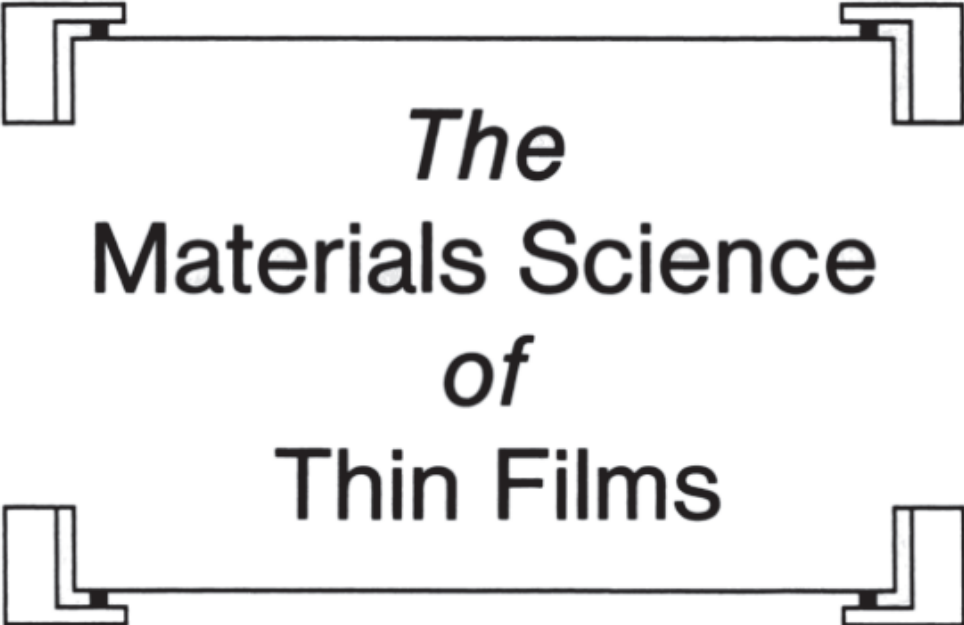


The
MATERIALS
SCIENCE
of THIN FILMS



Milton Ohring

Copyrighted material



The Materials Science *of* Thin Films

Milton Ohring

*Stevens Institute of Technology
Department of Materials Science and Engineering
Hoboken, New Jersey*



Academic Press
San Diego New York Boston
London Sydney Tokyo Toronto

This book is printed on acid-free paper. (∞)

Copyright © 1992 by Academic Press
All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Designed by Elizabeth E. Tustian

ACADEMIC PRESS

A Division of Harcourt Brace & Company
525 B Street, Suite 1900, San Diego, California 92101-4495

United Kingdom Edition published by
ACADEMIC PRESS LIMITED
24-28 Oval Road, London NW1 7DX

Library of Congress Cataloging-in-Publication Data

Ohring, Milton, date.

The materials science of thin films / Milton Ohring.

p. cm.

Includes bibliographical references and index.

ISBN 0-12-524990-X (Alk. paper)

1. Thin films. I. Title.

TA418.9.T45047 1991

620'.44—dc20

91-9664

CIP

Printed in the United States of America
99 00 01 02 03 MV 11 10 9 8 7

equal to 4.34α . Extremely low absorption losses of ~ 1 dB/km are common in silica-based optical fibers. In contrast, a 1-dB loss occurs within a few angstroms of penetration beneath the surface of a metal. This corresponds to a difference of some 12 orders of magnitude in absorption behavior on the part of materials.

Of the total radiation energy incident on an object, a fraction R is reflected from the top surface and a fraction T is transmitted through the bottom surface. The remaining fraction is lost through electronic absorption (A) processes and by scattering (S) at surface and volume imperfections. Surface roughness, internal boundaries, and density fluctuations arising from porosity, pinholes, microcracks, particulate incorporation, and impurities are sources of scattering. Adding the various contributions gives

$$R + T + A + S = 1. \quad (11-4)$$

Of the terms, R is of the greatest interest to us. For light passing through a medium of refractive index n_0 , impinging normally on a transparent film of index n_1 ,

$$R = \left(\frac{n_1 - n_0}{n_1 + n_0} \right)^2. \quad (11-5)$$

If, however, the film is absorbing with index of absorption k_1

$$R = \frac{(n_0 - n_1)^2 + k_1^2}{(n_0 + n_1)^2 + k_1^2}. \quad (11-6)$$

The origins of both formulas will be indicated subsequently.

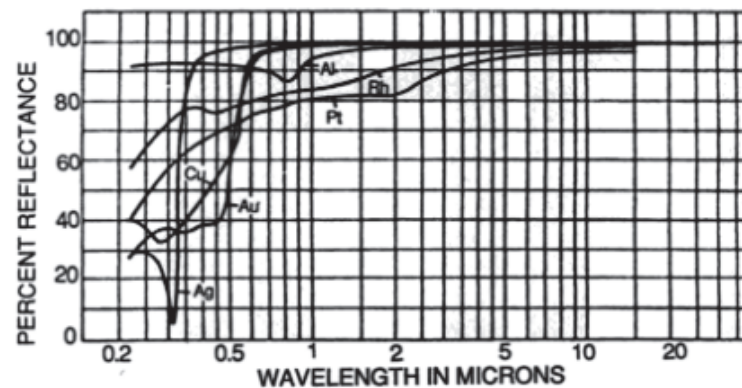
11.2.2. Optical Properties of Metals and Mirrors

The large density of empty, closely spaced electron energy states above the Fermi level in a metal plays an important role in influencing its optical properties. Incident photons over a wide wavelength range are readily absorbed by conduction-band electrons. These excited electrons move to higher energy levels where they undergo collisions with lattice ions, and the extra energy is dissipated in the form of phonons. The lattice is thus heated, and we speak of absorption. Alternatively, if the probability of colliding with an ion is small, the electron will emit a photon as it drops back to a lower energy level. This results in the strongly reflected beam exhibited by metals in the visible and infrared region. The characteristic color of some metals is due to the preferential absorption of some portion of the visible spectrum. In gold, for example, the green portion is absorbed, and the metal assumes the coloration

Table 11-1. Optical Constants of Metal Films Employed for Mirrors

Wavelengths, μ	Silver		Gold		Copper		Aluminum	
	n	k	n	k	n	k	n	k
0.40	0.075	1.93	1.45		0.85		0.40	3.92
0.45	0.055	2.42	1.40	1.88	0.87	2.20	0.49	4.32
0.50	0.050	2.87	0.84	1.84	0.88	2.42	0.62	4.80
0.55	0.055	3.32	0.34	2.37	0.72	2.42	0.76	5.32
0.60	0.060	3.75	0.23	2.97	0.17	3.07	0.97	6.00
0.65	0.070	4.20	0.19	3.50	0.13	3.65	1.24	6.60
0.70	0.075	4.62	0.17	3.97	0.12	4.17	1.55	7.00
0.75	0.080	5.05	0.16	4.42	0.12	4.62	1.80	7.12
0.80	0.090	5.45	0.16	4.84	0.12	5.07	1.99	7.05
0.85	0.100	5.85	0.17	5.30	0.12	5.47	2.08	7.15
0.90	0.105	6.22	0.18	5.72	0.13	5.86	1.96	7.70
0.95	0.110	6.56	0.19	6.10	0.13	6.22	1.75	8.50
2.0	0.48	14.4	0.54	11.2			2.30	16.5
3.0					1.22	17.1		
4.0	1.89	28.7	1.49	22.2			5.97	30.3
6.0	4.15	42.6	3.01	33.0			11.0	42.4
7.0					5.25	40.7		
8.0	7.14	56.1	5.05	43.5			17.0	55.0
10.0	10.69	69.0	7.41	53.4			25.4	67.3

From Ref. 7.

**Figure 11-1.** Reflectance of Al, Ag, Au, Cu, Rh, and Pt mirror coatings from the UV to the IR. (From Ref. 8).

of the reflected red and yellow light. Silver and aluminum reflect all portions of the visible spectrum and therefore appear to have a white color.

Optical constants for the most important mirror-coating metals, Ag, Au, Cu, and Al, are given in Table 11-1. The corresponding reflectivities are plotted as a function of wavelength in Fig. 11-1. A noteworthy feature of the optical

response is the decreased reflectivity in the ultraviolet and, in particular, the abrupt absorption edge exhibited by the noble metals. The absorption is due to interband electron transitions (e.g., $3d \rightarrow 4s$ in Cu). In aluminum, however, and rhodium, to a lesser extent, high reflectance extends into the ultraviolet. In the infrared all metals are very highly reflective. This fact is explained by the Hagen-Rubens relation, which holds when the electron relaxation time is short compared with the period of the incident wave. Physically, electrons can then respond sufficiently rapidly to prevent the external electric field from penetrating the metal.

The optical properties of thin films are somewhat different from those of bulk metals. In ultrathin films ($< 100 \text{ \AA}$ thick) variations in film continuity make the concept of optical constants problematical. In thicker continuous films, n and k values tend to be slightly smaller and larger, respectively, than comparable bulk values. The differences stem largely from variables encountered in evaporation or sputtering, the almost universally employed processes for depositing metal film mirrors. In metals such as Al, which readily getter gases, the reflectivity is sensitive to deposition conditions. Lower operating pressures and higher deposition rates result in purer films with enhanced reflectivities as shown in Fig. 11-2. The reason is due in part to the absence of surface oxides, nitrides, etc., which serve to increase absorption. More noble metals like Rh and Pt are, on the other hand, relatively immune to deposition conditions. Other variables affecting reflectivity include incident angle of

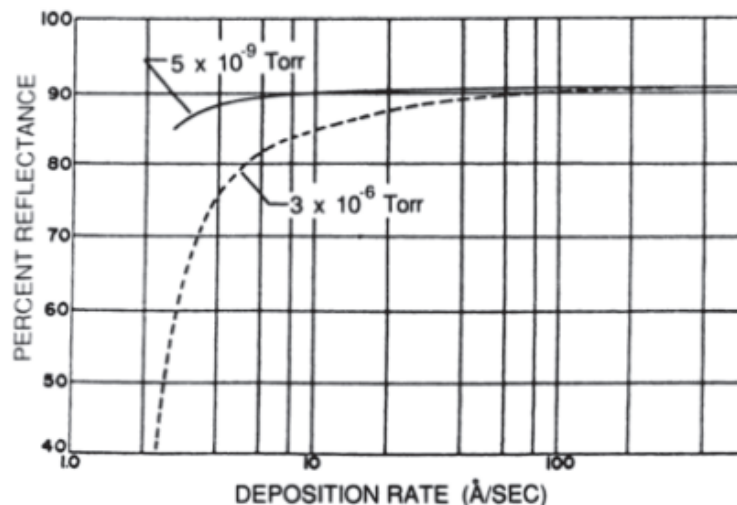


Figure 11-2. Reflectance of Al as a function of deposition rate in high (3×10^{-6} torr) and ultrahigh (5×10^{-9} torr) vacuum. Films were aged 24 h in air and measured at a wavelength of $2000 \text{ \AA}$. (From Ref. 7).