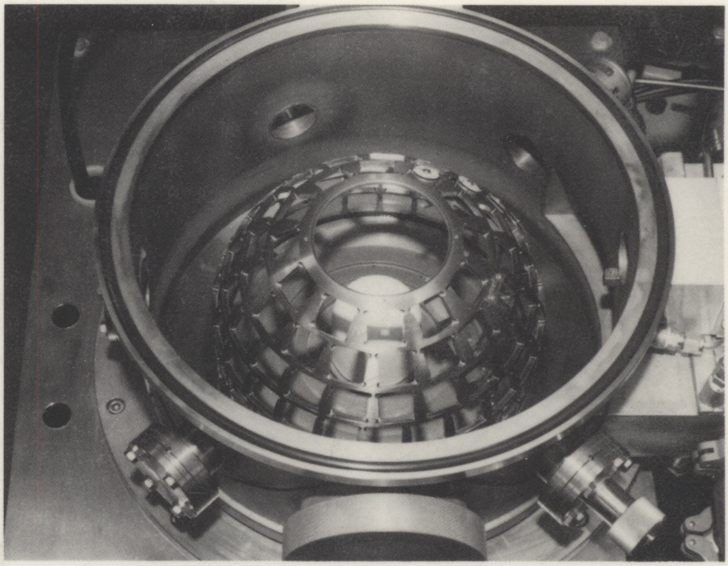
HANDBOOK OF SPUTTER DEPOSITION TECHNOLOGY

Principles, Technology and Applications



by

Kiyotaka Wasa

Shigeru Hayakawa

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Kiyotaka Wasa
Matsushita Electric Industrial Co., Ltd.
Osaka, Japan

Shigeru Hayakawa
Ion Engineering Center Corporation
Osaka, Japan

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Preface

Cathodic sputtering is currently being widely used in the microelectronics industry for the production of silicon integrated circuits. Historically, cathodic sputtering was first observed in the 1800's, but has developed rapidly over the past 20 years for applications for microelectronics and metallurgical coatings. Recently interest has again increased in cathodic sputtering since the novel materials, i.e., high-temperature superconductors, can be synthesized with sputtering under nonthermal equilibrium conditions.

Several books have described sputtering phenomena and applications for a deposition of thin films. For example, two early books, Thin Film Phenomena, by K.L. Chopra (1969) and the Handbook of Thin Film Technology edited by L. Maissel and G. Glang (1970), provided excellent reviews of this field about 20 years ago. Two text books, Sputtering by Particle Bombardment I & II, edited by R. Behrish (1981, 1983), completely review the recent scientific studies on sputtering. More recently, the Handbook of Ion Beam Processing Technology, edited by J.J. Cuomo, S.M. Rossnagel and H.R. Kaufman (1989), and the Handbook of Plasma Processing Technology, edited by S.M. Rossnagel, J.J. Cuomo and W.D. Westwood (1990) review recent developments in plasma and sputtering technology.

However, a concise and organized textbook on sputtering and sputter deposition technology is still desired as a valuable resource for graduate students and workers in the field.

The authors have studied cathodic sputtering and the sputter deposition of thin films for over 25 years. This book is effectively a comprehensive compilation of the author's works on sputtering technology.

The basic processes relating to thin film materials, growth and deposition techniques are covered in Chapters 1 and 2. The basic concepts of physical sputtering are described in Chapter 3, and the experimental systems used for sputtering applications are described in Chapter 4. A wide range of applications of thin films and deposition technology are described in Chapter

5. The extensive review of physics of the thin film growth in Chapter 2 was contributed by K.L. Chopra (Indian Institute of Technology) to whom I am very grateful. Most of the basic data on the sputtering in Chapter 3 were provided by Professor G.K. Wehner (University of Minnesota). Since the preparation and characterization of sputtered films are both vital parts of sputtering research, Chapter 5 is devoted to these topics, including the author's original works on the sputtering deposition as well as his recent studies on the thin film processing of high-temperature superconductors. The microfabrication of electronic devices and IC's by sputter deposition and related technology is discussed in Chapter 6. In Chapter 7 future directions for sputtering technology are listed. This textbook is intended for use as a reference and research book for graduate students, scientists, and engineers.

I am grateful to Professor G.K. Wehner, who has in his original research on sputtering provided the framework for studies in the field. I am also grateful to Professor R.F. Bunshah (University of California, Los Angeles) and Dr. S.M. Rossnagel (IBM Thomas J. Watson Research Center) for their valuable discussions on this manuscript. I am also grateful to G. Narita (Vice President Executive Editor, Noyes Publications) for his continuous aid and support for the publication of this book. Thanks are due to H. Shano, Y. Wasa and K. Hirochi for typing the manuscripts and preparing most of the illustrations. I acknowledge the assistance of my colleagues in Materials Science Laboratory of Central Research Laboratories, Matsushita Electric Ind. Co. Ltd. I thank A. Tanii, President of Matsushita Electric Ind. Co. Ltd. for his continuous encouragement and support. Finally, this book could not be published without the constant help and understanding of my wife, Setsuko Wasa.

Osaka, Japan
October 1991

Kiyotaka Wasa

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THIN FILM MATERIALS AND DEVICES

Thin solid films are fabricated by the deposition of individual atoms on a substrate. Their thicknesses are typically less than several microns. Historically Bunsen and Grove first obtained thin metal films in a vacuum system in 1852.

Thin films are now widely used for making electronic devices, optical coatings and decorative parts. Thin films are also necessary for the development of novel optical devices, as well as such areas as hard coatings and wear resistant films. By variations in the deposition process, as well as modifications of the film properties during deposition, a range of unusual properties can be obtained which are not possible with bulk materials.

Thin film materials and deposition processes have been reviewed in several publications (1). Among the earlier publications, the "Handbook of Thin Film Technology", edited by Maissel and Glang, is notable although more than 20 years has passed since the book was published and many new and exciting developments have occurred in the intervening years.

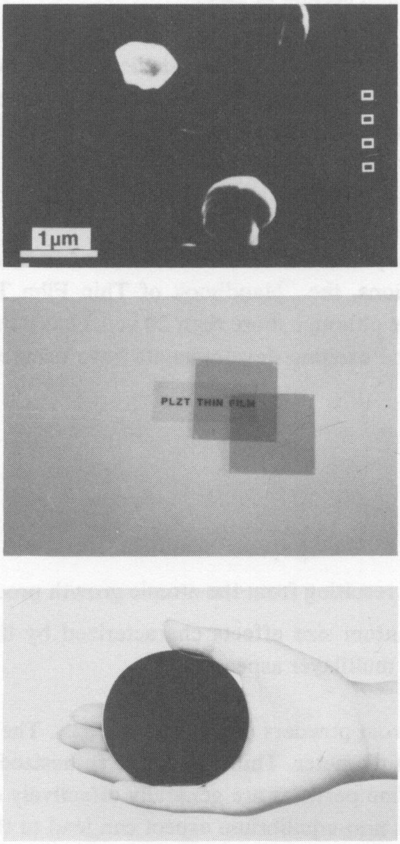
1.1 THIN FILM MATERIALS

Thin film materials will exhibit the following special features:

1. Unique material properties resulting from the atomic growth process.
2. Size effects, including quantum size effects characterized by the thickness, crystalline orientation, and multilayer aspects.

Bulk materials are often sintered from powders of source materials. The particle size of these powders is of the order 1μ in diameter. Thin films are synthesized from atoms or small groups of atoms. These ultrafine particles are generally effectively quenched on substrates during film growth, and this non-equilibrium aspect can lead to the formation of exotic materials. A variety of abnormal crystal phases have been reported in thin films. A typical example is the tetragonal Ta reported by Read (2). An amorphous phase can also be observed in thin films which is not characteristic of the bulk material. Other structures found in the growth of thin films are a island structure of ultra-thin layers or a fiber structure.

Recent progress in thin film growth technology enables one to make novel thin film materials including diamonds and high temperature oxide superconductors. Bulk diamonds are conventionally synthesized at high pressure (≃50,000 psi) and high temperature (2000°C). The deposition of diamonds from energetic carbon ions (≃10 – 100eV) enables the growth of the diamond crystallites and/or diamond films at room temperature (3). Thin films of high temperature superconductors are indispensable not only for making thin film superconducting devices but also for studying fundamental aspects of these new superconductors (1). Figure 1.1 shows some photographs of novel thin film materials.



(a) Diamond crystals prepared at room temperature.

(b) Electro-optic thin films of compound $(Pb,La)(Zr,Ti)O_3$.

(c) High T_c superconducting films on a Si wafer

Figure 1.1: Novel thin materials prepared by cathodic sputtering.

One must also consider that due to abnormal structure accompanied by size effects, thin films may show different features in terms of mechanical strength, carrier transportation, superconducting transitions, magnetic properties, and optical properties. For instance, thin films may be characterized by a strong internal stress of $10^9 - 10^{10}$dynes/cm and a number of lattice defects. The density of the lattice defects can be more than 10^{11} dislocations/cm^2. These lattice defects have the effect of increasing the elastic strength. The strengths obtained in thin films can be up to 200 times as large as those found in corresponding bulk material. Thermal stress arising from the thermal expansion of thin films has been shown to increase the critical temperature of superconducting films (5).

	Increase of resistivity, ρ in metal, $\rho_F/\rho_B \simeq (4/3)(\gamma \ln(1/\gamma))^{-1}$.
SIZE EFFECTS	Reduced TCR, α, in metal, $\alpha_F/\alpha_B \simeq (\ln(1/\gamma))^{-1}$.
$\gamma = t/l << 1$,	Reduced mobility, μ, in metal $\mu_F/\mu_B \simeq (\ln(1/\gamma))^{-1}$.
t: film thickness	Anomalous skin effect at high frequencies in metal.
	Reduced thermal conductivity, K, in metal, $K_F/K_B \simeq (3/4)(\gamma \ln(1/\gamma))$.
l: mean free path of electrons	Enhanced thermoelectric power, S, in metal, $S_F/S_B \simeq 1 + (2/3)(\ln\gamma - 1.42/\ln\gamma - 0.42)$.
	Reduced mobility in semiconductor, $\mu_F/\mu_B \simeq (1 + 1/\gamma)^{-1}$.
	Quantum size effects in semiconductors and semimetal, at t < 1, DeBroglie wavelength: thickness-dependant oscillatory variation of resistivity, Hall coefficient, Hall mobility and magnetoresistance. Galvanomagnetic surface effects on Hall effect and magnetoresistance due to surface scattering.

Table 1.1: Interesting phenomena expected in thin film materials. Electron transport phenomena (F = film, B = bulk).

FIELD EFFECTS	Conductance change in semiconductor surface by means of electric field, Insulated-gate thin film transistor (TFT).
SPACE CHARGE LIMITED CURRENT (SCLC)	SCLC through insulator, J: $J = 10^{-13} \mu d E V^2 / t^3$ (A/cm^2) (one-carrier trap-free SCLS) μd, drift mobility of charge carriers, E, dielectric constant, V, applied voltage
TUNNELING EFFECTS	Tunnel current through thin insulating films, voltage-controlled negative resistance in tunnel diode. Tunnel emission from metal, hot electron triode of metal-base transistor. Electroluminescence, photoemission of electrons. Tunnel spectroscopy. --- Tunnel current between island structure in ultra thin films.
MAGNETICS	Increase in magnetic anisotropy. The anisotropies originate in a shape anisotropy, magnetocrystalline anisotropy, strain-magnetostriction anisotropy, uniaxial shape-anisotropy. Increase in magnetization and permeability in amorphous structure, and/or layered structure.

Table 1.1: (continued) Interesting phenomena expected in thin film materials.

SUPERCON-DUCTIVITY	Superconductivity-enhancement: increase of critical temperature, T_c, in metal with decreasing thickness, t, $\Delta T_c \simeq A/t - B/t^2$, and/or crystallite size. Stress effects: tensile stress increases T_c, compressive stress decreases T_c in metal. Proximity effects in superimposed films: decrease of T_c in metal caused by contact of normal metal. Reduced transition temperature, T_s, $(T_s/T_c)^2 = 1 - 1/(0.2 + 0.8ts)$, ts, ratio of thickness of superconducting films and a critical thickness below which no superconductivity is observed for a constant thickness of normal metal films. Increase of critical magnetic field, H_c, at parallel field, $H_{CF}/H_{CB} \simeq \sqrt{24}\ \lambda/t$, λ, penetration depth, due to G-L theory. at transverse field, $H_{CF}/H_{CB} = \sqrt{2}\ K$, K, Ginzburg-Landau parameter. Reduced critical current, J_C, $J_{CF}/J_{CB} \simeq \tanh(t/2\lambda)$. Supercurrent tunneling through thin barrier, Josephson junction, and Tunnel spectroscopy.

Table 1.1: (continued) Interesting phenomena expected in thin film materials.

1.2 THIN FILM DEVICES

Since the latter part of the 1950's thin films have been extensively studied in relation to their applications for making electronic devices. In the early 1960's Weimer proposed thin film transistors (TFT) composed of CdS semiconducting films. He succeeded in making a 256-stage thin-film transistor decoder, driven by two 16-stage shift resistors, for television scanning, and associated photoconductors, capacitors, and resistors (7). Although these thin film devices were considered as the best development of both the science and technology of thin films for an integrated microelectronic circuit, the poor stability observed in TFT's was an impediment to practical use. Thus, in the 1960's thin film devices for practical use were limited to passive devices such as thin film resistors and capacitors. However, several novel thin film devices were proposed, including man-made superlattices (8), thin film surface acoustic wave (SAW) devices (9), and thin film integrated optics (10).

In the 1970's a wide variety of thin film devices were developed. Of these, one of the most interesting areas is a thin film amorphous silicon (a-Si) technology proposed by Spear (11). This technology achieved low temperature doping of impurities into a-Si devices and suggested the possibility of making a-Si active devices such as a-Si TFT and a-Si solar cells (12-13). In the 1980's rapid progress was made in a-Si technology. Amorphous Si solar cells have been produced for an electronic calculator although the energy conversion efficiency is 5 to 7% and is lower than that of crystalline Si solar cells. This efficiency, however, has recently been improved (14).

In the middle of the 1980's high quality a-Si technology has led to the production of a liquid crystal television with a-Si TFT. Other interesting thin film devices recently produced are ZnO thin film SAW filters for a color television (15). The SAW devices act as a solid state band pass filter, which cannot be replaced by a Si-integrated circuit, and are composed of a layered structure of ZnO thin piezoelectric film on a glass substrate. The high quality growth techniques available for ZnO thin films have made possible the large scale production of these devices. This type of thin film device is used in a higher frequency region of GHz band for CATV and satellite TV.

Silicon Carbide (SiC) thin film high temperature sensors (16) are another attractive thin film device produced in the 1980's. They suggest the possibility of high accuracy, low temperature synthesis of high melting point materials by thin film growth processes.

Magnetic heads having a narrow magnetic gap for video tape recording systems and for computer disk applications are produced by thin film processing. In the production of the magnetic gap, a non-magnetic spacer has been formed from glass material. Prior to the use of thin film technology, the spacer manufacturing process was quite complex. For instance, magnetic head core material is first immersed in a mixed solution of finely-crushed glass, then taken out and subjected to centrifugation so that a homogeneous glass layer is deposited on the opposing gap surfaces of the core members. After forming a glass film on the core surfaces by firing the deposited glass layer, the two opposing gap