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Ion Beam Deposition

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1.0 INTRODUCTION

Ion bombardment of surfaces has been used in connection with thin film deposition for decades. The amount and type of ion bombardment greatly influences film structure and composition; this, in turn, determines optical, mechanical and electrical properties of the film. The bombardment can be achieved using a number of techniques, some of which are very simple. However, the highest degree of control of critical parameters (e.g., ion flux, energy, species, and angle of incidence) is provided by broad-beam Kaufman ion sources. This is because the gas discharge of the ion source is separate and removed from the rest of the deposition system. This is not the case with some other ion bombardment techniques used in film deposition. The discussion here is restricted to applications of the broad-beam Kaufman ion source. For discussion of other ion sources see Refs. 1–3.

The following material is consistent with the general nature of this volume in that application, or “how-to,” aspects of ion beams for thin film deposition are emphasized. References are given to more in-depth technical treatments of several topics. For example, Harper et al.,[3] gave
an excellent review of modification of film properties provided by ion bombardment. The first two sections which follow are fairly general, while the section discussing applications is somewhat specific. This is a result of the backgrounds of two of the authors in optical materials. Also, the authors’ approach is that it is more beneficial to discuss a few applications in detail rather than many applications in a cursory manner.

2.0 OVERVIEW OF ION BEAM APPLICATIONS

The general technology of broad-beam ion sources has been discussed adequately in the literature (see, for example, Ref. 1). This section covers a brief description of the construction of ion sources and cites specific examples of operational characteristics that impact the design of processing tasks.

The typical ion source consists of an enclosure containing electrodes, magnetic fields, ion accelerating grids, and emitters suitably arranged to sustain electron-bombardment ionization of a working gas. The arrangement of these components has been widely varied by many experimenters and analytically investigated by even more. The results invariably support the local mythology of what a “good” ion source should be. The many configurations and concepts incorporated in both commercially available and custom-built ion sources tend to overwhelm users upon initial exposure to the technology.

2.1 Categories of Kaufman Ion Sources

The following comments do not deal with the full range of ion source possibilities. They merely attempt to describe some of the design trends in an overview, using details only to illustrate extremes of the trends. Ion sources, like most apparatus, when highly optimized for a given process, tend to sacrifice performance in other areas. This tendency leads to grouping of types of sources that conform to the process parameters of interest.

Sputtering sources, those used to remove the maximum amount of material from a target in the minimum time, are one example. In general, beam uniformity is not of great importance. The source is usually operated at 1 to 2 kV. It is important that the beam strike the target and that the source not produce contaminants. The lower the gas flow rate, the better.
Frequently, operation with reactive gases is desirable—or even necessary—to control stoichiometry. These parameters usually dictate small to moderate diameter (2 to 15 cm) sources operating at close to maximum conditions. When large numbers of substrates need to be coated, larger diameter sources are used, and the source-to-target and target-to-substrate distances are increased. This geometric scaling results in inverse square losses, with a corresponding reduction in coating rate. Linear sources have been applied to this task to partially eliminate the losses associated with increasing distance. The linear sources permit reduced geometries. While the number of workpieces coated is also decreased, there can be a net gain in throughput in a significantly smaller working volume.

Another example is etching sources, which have significantly different characteristics. They generally operate at voltages below 1 kV, with some even optimized for voltages between 50 and 200 eV. Beam uniformity is normally critical, with a typical specification of \( \pm 5\% \) across a significant fraction of the beam. Etching sources are characterized by highly developed grid systems which seek to present a high current-density beam of acceptable flatness to the workpiece. The workpiece is frequently mounted on a fixture which produces a complex, non-integer motion to compensate for the remaining non-uniformities of the beam. Etching sources are frequently required to operate with gases that react with the workpiece to enhance etch rate or selectivity.

Peculiar ion source shapes occasionally appear among etching sources because of the need to be consistent with the geometry of the workpiece or that swept by the fixturing. Beams and sources shaped to segments of circles or annular segments are available. Linear sources are used to sweep, in a push-broom fashion, around cylindrical fixtures or along continuous rolls of material (e.g., webs).

Similar to the etching sources are sources used for cleaning workpieces prior to deposition or used to simultaneously bombard coatings during the deposition process (enhancement sources). These sources usually have fewer uniformity requirements. For example, if approximately 50 Å of material is removed to clean the workpiece, then a large percentage variation in this amount can be tolerated. Relatively small sources can be used for the cleaning task, but they are generally operated at maximum performance to minimize cleaning time. The voltage and current density used for cleaning are sometimes determined by the material to be cleaned. As an example, a web of plastic materials passing under a high performance linear source moves at a rate such that the web is in the beam
for about one second. If the web motion is interrupted for three seconds, the web is melted. Further discussion of ion beam cleaning is given in a later section.

Enhancement sources provide ion bombardment to a surface being coated with material produced by magnetron, thermal, electron-gun, or ion sputter techniques. Enhancement sources are typically operated at low beam energies and current densities. This energy input into the growing film modifies the physical structure and growth characteristics of the film. It is possible to alter the crystalline phase of some films. Enhancement sources are frequently required to operate with reactive gas to control the stoichiometry of the film. Some arrangements permit constant exposure of the substrate to the beam, while other arrangements allow the substrate to pass through the beam occasionally, due to planetary rotation. The effects of the ion bombardment might not be the same for the two situations.

The point of this discussion is to make the reader aware of the wide variety of potential tasks that can be accomplished using broad-beam ion sources, and that the ion sources can be optimized for various tasks. Frequently, the optimization from one specialized task to another can be accomplished by something as simple as a grid change. Other optimization can require extensive hardware changes and include significant variations in control systems and operating procedure.

A good example of major change is the method of producing the ionizing electrons for ion source operation. The most popular method of producing ionizing electrons is by thermionic emission. One method to achieve this is the use of a bare refractory wire as an emitter. Another method makes use of a low work-function material dispersed through a tungsten slug that is heated inside an inert gas-buffered tube. The latter device is known as a hollow cathode. The simple thoriated tungsten wire has given good service as an emitter for many investigators. However, the wire is sputtered by the ions in the discharge, and this limits the cathode lifetime. The wire emitter also presents a problem when operated with reactive gases. In addition, some users find problems with both the heat and photon flux on sensitive workpieces, as well as contamination due to evaporated and sputtered filament material. The hollow-cathode emitter can be used for both the source discharge chamber emitter and the neutralizer emitter to solve these lifetime problems. Use of the hollow cathode does impose heat-up and cool-down constraints prior to venting the work chamber, but for long runs these factors become less critical. The hollow-cathode requires a supply of inert gas, usually argon or xenon, to buffer the
low work-function insert. Any gas may be used in the source discharge chamber, giving wide flexibility to the use of the hollow-cathode ion source.

Radio frequency discharges can be used to produce the ions that are accelerated to produce the beam; this has been under investigation since the early 1960s. Recent advances in efficient RF circuit components have allowed the control and impedance matching problems to be reduced such that reasonably reliable operation can be achieved. While the RF sources eliminate the hot emitter from the chamber, many electronic design, control, and stability problems remain to be investigated.

2.2 Operational Considerations

Ion sources that produce beams using electrostatic acceleration present certain potential problems. The beam is extracted and accelerated by significant DC potentials (200 to 2,000 V typically). The work chamber contains a moderate current ($\geq 1$ A) beam and is filled with a dilute, conducting plasma. Care must be taken to electrostatically shield the high potential leads to the source. Electrical breakdown is possible between closely spaced leads, and this is enhanced by the dilute plasma.

Some ion sources are designed in which gas flow lines are isolated from ground potential near the ion source. Other sources have a conductive gas line at high voltage that passes through an insulator in the vacuum system wall and is electrically isolated outside the chamber. This line is often overlooked as a high voltage electrode.

The pressure inside the gas line goes from a few psi above atmospheric pressure at the gas bottle to approximately $10^{-3}$ torr in the ion source plasma region. Screens and metal wool pads are frequently used to provide large area surfaces on which ions can recombine. This prevents electrical breakdown in the gas feed tubes.

Oxidation can occur if a hot ion source is vented to atmosphere too soon after operation. The oxide films on the various electrodes can become sufficiently insulating to prevent source operation on a subsequent pump down. Similarly, sputtering or etching of materials in a reactive atmosphere can produce insulating coatings. To avoid problems due to this, regular cleaning of the ion source is important. This can be accomplished mechanically, for example, using bead blasting, or chemically, using acids to remove thin film material.
3.0 ION BEAM PROBING

The applications of ion beams to coating discussed below require knowledge of the ion flux at the target. In some applications, such as ion assisted deposition (IAD) in which the target is the substrates being coated, this is very important; knowing just the total beam current is not sufficient. In this section, probe construction and operation are first discussed, and then use of the probe as related to film deposition is discussed. Only applications of the probe to measure particle flux are addressed here.

Probes can also be used to determine charged particle energy. Typically ions from a Kaufman ion source are nearly monoenergetic; they have an energy spread of approximately 10 eV centered about the anode potential (i.e., beam energy) for the dual grid extraction arrangement.\textsuperscript{[3]} Ion energy spread in the beam from a source with a single grid arrangement is somewhat larger.\textsuperscript{[3]} However, because beam energy characteristics are fixed by discharge conditions and are rarely measured by the user, this probe technique will not be discussed in further detail.

The ions and neutralizing electrons in a beam can be considered a weakly ionized plasma, or gas discharge. Plasma probe technology can be applied to monitor the beam conditions. For details, many references on plasma probes are available.\textsuperscript{[4]} Only the relevant technology will be discussed here. A simple arrangement which is widely used is the planar Faraday probe illustrated in Fig. 1(a). The probe is connected to an electrical vacuum feedthrough with a shielded conductor. The shield is connected to the part of the probe which encloses the probe element. Note that the back of the probe element is also shielded to avoid ion current contribution from this region. The probe element diameter is typically 5 to 10 mm, and it is recessed into the shield enclosure by approximately the same amount. This maintains approximately the same sheath dimensions and effective probe area with minor variations in probe bias voltage. Insulators of alumina can be used to separate the probe element and the shield enclosure. This separation should be as small as convenient, with approximately 0.5 mm being typical. An easily constructed, simpler, though perhaps less accurate, version of a probe is shown in Fig. 1(b). In this case, the probe element is mounted on a sheet of insulating material such as mica, and this is fastened to a piece of metal (e.g., Al) plate. Again, the back of the probe and the electrical conductor are shielded to avoid extraneous sources of ion current. The entire probe arrangement,
whichever form is used, should be constructed such that it is easily disassembled for cleaning.

![Diagram of Faraday probe setup](image)

**Figure 1.** Two arrangements of a Faraday probe to monitor ion beam current; (a) more accurate version and (b) simple version. Note, in both arrangements the back side of the probe should be shielded (e.g., with Al foil) to prevent ion current contribution from this region.

Outside the vacuum system, the probe can be biased, and probe current can be measured with a meter connected in series with the arrangement. If the probe is to be used to measure ion current density, and therefore to calculate ion flux, the bias should be approximately -30 V. This potential repels electrons from the beam, and the measured current is primarily due to the ions. If the probe is perpendicular to the beam, then the ion current density is approximately equal to the measured probe current divided by the probe element area. The ion flux ($I'$) is calculated by dividing the current density by the ion charge $q$. For example, if the probe current is 25 μA and the probe element is 1 cm in diameter, the current density and ion flux are given by:

$$ J = I_p / A_p $$

Eq. (1)

$$ J = 25 / \pi (0.5)^2 \mu A/cm^2 $$

$$ = 31.8 \mu A/cm^2 $$
and

\[ \Gamma = \frac{J}{q} \]

Eq. (2)

\[ = 31.8 \times 10^{-6}/1.6 \times 10^{-19} \]

\[ = 19.9 \times 10^{13} \text{ ions/cm}^2\text{-sec} \]

the latter could, for example, be used for comparison with the flux of thin film molecules at the substrate.

As Kaufman discusses,\cite{3} there are two sources of error in the probe current measurements described above. First, ions striking the probe surface can cause secondary electrons to be emitted from the probe. Because the probe is biased negatively, the electrons are repelled, and this constitutes a current which is additive with that of incident ions. Because the probability of secondary electron emission from the metal surfaces involved (e.g., Al, stainless steel, etc.) at the ion energies employed is of the order of 0.1, there is little error introduced by this effect. The second source of error involves secondary (charge exchange) ions produced by the high energy ions of the beam. The probe will collect both types of ions, and therefore give an erroneously high current reading. Unless the background pressure in the vacuum chamber is abnormally high, this effect is generally negligible except at the outer edges of the ion beam. At this point, the density of the secondary ions can be relatively high compared to that of the beam ions, and one might think the extent of the beam is greater than it actually is.

When this arrangement is used while depositing conducting film materials, no special precautions are necessary. The probe element should remain insulated from the rest of the probe body, and the electrical characteristics of the probe element should remain constant. The probe might be moved into the ion beam just prior to substrate cleaning, sputtering, or whatever the application, in order to check the beam condition. The probe would then be moved out of the beam.

When insulating materials are being deposited, care should be exercised to prevent the probe element from becoming coated. This would change the probe characteristics to provide incorrect indications of ion beam current density. During coating, the probe might be moved to an area where it is shielded from coating material, or the probe might have a shield attached. If the beam is to be monitored during coating, some deposition on the probe element is inevitable, and the probe should be later cleaned.
4.0 SUBSTRATE CLEANING WITH ION BEAMS

Substrate condition prior to coating is extremely important for proper film adhesion; in addition, it has an influence on subsequent film growth characteristics. The general topic of substrate cleaning is very diverse and will not be treated here. What is discussed is the application of ion beam apparatus as the final step of cleaning a surface immediately before film deposition. Results of ion beam cleaning and the improved adhesion of films which this can provide, such as Au on BK-7 glass, are discussed in Ref. 5. For a general treatment of substrate cleaning techniques. (See, for example, Ref. 6.)

Bombardment with ions and electrons to clean a surface has been commonly used for many years, primarily by employing a glow discharge in the deposition system. However, with this so-called “glow discharge” technique, one has very little idea of what species is actually bombarding the substrate, or the energy and flux of the bombarding species. Use of the ion beam apparatus to provide the particle bombardment affords more control of the important system parameters such as ion species (reactive or inert), flux, and energy. The same parameters are not only known, they are in large part independently controllable. This, combined with proper beam probing techniques discussed previously, make the process very useful for cleaning and bombardment during early stages of film growth. With a neutralized beam, conducting and insulating substrates can be treated. Ion beam cleaning obviously represents no added equipment to the deposition system if ion assisted deposition (IAD) is employed. See a later section.

The processes which occur on the substrate due to ion and electron bombardment include a number of things. This includes desorption of adsorbed water vapor, hydrocarbons and other gas atoms. Adsorbed gases are very efficiently desorbed at low energies (~300 eV). Chemisorbed species and possible occluded gases are sputtered. If the bombarding ion is an oxygen species, chemical reactions with organic species on the surface can result in compounds which are more volatile and hence more easily removed.[6] For the levels of ion flux and energy employed, and for the small time required for cleaning, the substrate temperature rise is usually negligible, and this has little effect on substrate outgassing. Ion bombardment causes substrate defect production which, in general, is beneficial for subsequent film nucleation and adhesion.
Typically, the level of ion flux at the substrates used during precleaning is several tens of μA/cm². In this application, uniformity of current density is not as important as it is for other applications such as IAD. Because of this, small ion sources are useful provided they have sufficient total beam current. Relatively low energy (~300 eV) ions are preferable to higher energy ions to minimize substrate sputtering, while still being sufficiently energetic to produce the effects mentioned above. A mixture of Ar and O₂ can be used as the gas species in the ion sources. As an example, consider a 30 μA, 300 eV beam from a 2.5 cm diameter ion source which is directed at substrates approximately 30 cm away. At the substrates, depending somewhat upon the vacuum chamber pressure, the peak current density would be approximately 160 μA/cm²; the width of the beam (FWHM beam current density) would be approximately 17 cm. If the deposition chamber dimensions permit, the ion source should be placed farther away to provide a larger, more uniform beam at the substrates. If there is only single-axis rotation of the substrates, the ion source might be placed directly below the center of the substrates; if it is not directly below the substrates, then the beam pattern is simply spread over a larger area. In either case, it might be advantageous to direct the beam off-center of the substrate fixtureing if the fixtureing is much larger than 17 cm in diameter. If the fixtureing involves planetary rotation, then the beam should be directed to a region that will ultimately provide bombardment of all substrates. In this case, the ion beam is obviously not on a particular substrate continuously; it is “time-shared” between all substrates. This, however, does not present the potential problems that are discussed in connection with IAD of substrates in planetary arrangements.

To estimate the time required for cleaning substrates, one should consider the amount of material which is sputtered. This is determined in part by the sputter yield of the substrate material and that of the unknown species on the substrate. Sputter yields for many materials are well characterized for various incident ions and ion energies; typical values range from 0.1 to 3 atoms/ion for inert gas ions of approximately 0.5 to 2 keV energy. If a sputter yield (S) of 0.1 atoms/ion is assumed, the thickness (L) of the layer of material removed in five minutes (t) due to a beam of 50 μA/cm² current density (J) is given by:

\[
L = \frac{SJt}{q}
\]

Eq. (3) \[= (0.1)(50 \times 10^{-6})(27)(300)(10^{-16})/1.6 \times 10^{-19}
\]
\[= 25 \text{ Å} \]
here $V$ is an assumed volume of the sputtered atoms, taken to be 27 Å,$^{[3]}$ and $q$ is the charge of the ion in coulombs. The factor of $10^{-16}$ in the equation is included to express the layer thickness in angstroms. This calculation illustrates how several atomic layers of material can be quickly removed from the substrate to leave it atomically clean. This should actually be considered a maximum estimate of substrate material removal. The adsorbed species on the surface are, in general, much easier to remove and have a large effective sputter yield. If the beam is “time-shared” as described above in connection with planetary fixturing, then one must estimate the fraction of time $F$ the substrates are in the ion beam; in the expression above, $t$ would become $t/F$.

There are four considerations one should be aware of in applying ion bombardment, regardless of the technique, to clean substrates. The first has to do with the influence of ion bombardment on the substrate microroughness. If the substrate is polycrystalline and composed of relatively large crystallites, the microroughness of the substrate might increase significantly if the substrate is ion-bombarded for a very long time. This is due to the crystals in the substrate sputtering at different rates and therefore different amounts being removed, depending upon their orientation to the incident ions. See Fig. 2. For example, Cu substrates have demonstrated an increase in rms roughness from approximately 25 Å to nearly 50 Å when 1200 Å of the substrate was removed using ion beam sputtering.$^{[5]}$ This amount of material removal is somewhat severe in terms of substrate cleaning, but it illustrates the point. On the other hand, amorphous or very small-grained polycrystalline substrates, as well as single crystalline materials, do not present a problem. For example, glass substrates (e.g., fused silica, Zerodur, and BK-7) have been ion-beam milled several microns deep with no noticeable increase in roughness, starting with substrates as smooth as 7 Å rms roughness.$^{[8]}$ Electroless Ni films have been examined in this same manner, and they do not display an increase in roughness with ion milling.

The second consideration when applying ion precleaning is that the stoichiometry of the top few atomic layers of substrates composed of molecular species, can be altered. This is due to the ions preferentially sputtering one atomic species from the top molecules, leaving the surface rich in the other atomic species. The extent of this altered layer production is naturally minimum with minimum ion energy (for energies less than approximately 2 keV) and flux, while the impact of it depends upon the application of the coated substrate. In the case of fused silica and other
glass substrates, the effect is not noticeable in optics used in routine, as well as severe, applications such as high energy laser optics.\textsuperscript{[9]} Similarly, fused silica samples which were ion milled several microns and examined with an ellipsometer displayed no change in optical constants. In this case, the effects of the altered layer were either negligible or exposure to atmosphere made them so. The situation in the case of other substrate materials might not be as favorable as that for glass materials, and one should be aware of potential problems.

![Graph](image)

**Figure 2.** Sputter yield, $S$, of three planes of Cu bombarded by normal-incidence Ar$^+$ ions.\textsuperscript{[7]}

A third consideration when applying ion beam precleaning involves the potential damage to crystalline substrate surfaces such as semiconductor materials. It is very difficult to obtain a clean semiconductor surface and maintain the bulk properties at the surface; atoms in the crystal lattice structure are dislocated due to the ion bombardment. A general guideline is to reduce the ion energy to the lowest level possible if substrate damage is a concern. The dislocation energy of an atom is typically a few tens of eV. The sputter yield of adsorbed molecules should be sufficient at the reduced ion energy to provide the desired cleaning with minimal substrate damage.
A fourth consideration in applying ion precleaning involves contaminating the surface of the substrate being cleaned with the material from the fixture holding the substrate. Slight contamination, especially around the periphery of the substrate, is unavoidable. When possible, the fixturesing should be constructed of material which is compatible with the coating. For example, in deposition of oxides for optical applications in which a high background pressure of O$_2$ is present, the fixturesing might be constructed of Al. In this case, the contaminant from the fixturesing could be present in the form of Al$_2$O$_3$ which is harmless in most cases.

5.0 APPLICATIONS

Two general arrangements are most popular for application of the ion source to thin film coating. First, ions from the source can be directed at a target which is sputtered, and the sputtered material is deposited as a thin film. This is termed ion beam sputter deposition (IBS). Second, ions from the source can be directed to the substrate which is being coated with material generated by some independent technique. This is termed ion assisted deposition (IAD). In both cases, the intent is to provide the thin film adatoms on the substrate with increased energy and therefore more mobility prior to nucleation. This leads to the modifications in film properties mentioned previously. Two or more ion sources can be used simultaneously to provide both IBS and IAD. These two processes are discussed in detail in this section.

5.1 Ion Beam Sputtering

Aspects of ion beam sputtering which are described here first include a brief review of sputtering parameters and results. This is necessary, for example, to describe some of the advantages and disadvantages of ion beam sputtering compared to other forms of sputtering. Detailed treatments of sputtering are given in Refs. 1, 7 and 10. Next, several aspects of ion beam apparatus and other experimental details are described. Last, a summary of film properties provided by ion beam sputtering is given.

Aspects of Sputtering. When an energetic ion or neutral atom strikes a surface, many processes can occur. One of these is the ejection of atoms of the surface target material, and this is known as sputtering. Of primary concern in sputtering is the sputter yield ($S$), in atoms/ion, and the relation of
S to parameters such as ion and target species, ion energy, ion incident angle, and target condition. In addition, it is very important to have an idea of the average ejection energy of sputtered atoms, as this has a significant influence on resulting thin film properties. Similarly, the angular distribution of the sputtered atoms is important in determining film deposition rate and uniformity. The following is a summary of relevant aspects of sputter yield and sputtered particle properties taken from Refs. 1, 7 and 10.

**Sputter Yield**

(a) $S$ has a threshold level of approximately 10 to 30 eV for most ion/target combinations. It increases exponentially with ion energy up to 200 or 300 eV (see Fig. 3) and increases approximately as $E^x$, where $0.5 \leq x \leq 1$ for ion energies up to several keV.\(^{[1]}\) At higher ion energies, $S$ decreases, most likely due to implantation.

(b) $S$ increases for many target elements with increasing mass of rare gas ions. For example, for 500 eV ions incident on Ta, $S$ is 0.01, 0.28, 0.57, 0.87 and 0.88, respectively, for He, Ne, Ar, Kr, and Xe.\(^{[11]}\)

(c) $S$ increases with ion angle of incidence to the target, up to angles of approximately 45 to 60 degrees. The increase can be as great as a factor of two or more; at larger angles of incidence, $S$ decreases. See Fig. 4.\(^{[1]}\)\(^{[10]}\)

(d) $S$ can be different for different crystal orientations of the same material.

**Sputtered Particle Energy**

(a) Average ejection energies increase with incident ion energy up to roughly 0.5 to 1.0 keV, above which the energy of the sputtered particle increases little.

(b) For the same incident ion species, materials with lower sputter yield tend to have higher ejection energies.

(c) For the same target material, average ejection energies tend to increase for heavier bombarding ions.

(d) Average ejection energy tends to increase with ion angle of incidence.

(e) There is not a significant dependence of the sputtered atom ejection energy upon crystal orientation of the target.
Figure 3. Sputter yield, $S$, vs ion energy; (a) shown for several materials with Ar$^+$ bombardment, and (b) for W bombarded by different ion species.$^{10}$ (Reproduced with permission from Maissel and Glang. Handbook of Thin Film Technology, McGraw-Hill, 1970.)

Figure 4. Effect of angle of incidence on sputter yield; $\bigcirc$: gold, O: aluminum, and $\times$: photoresist.$^{30}$ (Reproduced with permission from Vossen and Kern. Thin Film Processor, Academic Press, 1978.)
Angular Distribution of Sputtered Atoms. In general, the angular distribution of sputtered particles is peaked in a forward direction, at an angle roughly comparable to that of the incident ions. A cosine distribution has been used to describe this, although several factors have an influence. In particular, the target condition is very important. For example, the target can be single crystal or polycrystalline, and there will be different effects on the distribution pattern. In addition, the distribution changes in the case of a new target that is being used for the first few hours. A target of solid material will provide a distribution pattern different from that of one made of pressed powder. In addition, if the target is arranged at a different angle with respect to the ion beam, the distribution pattern would be different as well. Energy of the incident ions has been observed to have an effect on the sputtered particle distribution.

From what has been described, it is apparent that the best approach to characterize the distribution pattern in applications in which it is critical is to directly measure it. For example, sample substrates might be located at various positions relative to the target and then coated. Film deposition rate and uniformity could be determined from coating thickness measurements using a spectrophotometer or other types of interferometry.

Advantages/Disadvantages of Ion Beams for Sputtering. In sputter applications, ion beams provide control of ion energy, flux, species, and angle of incidence. These parameters are not only controllable over a wide range, they can be controlled nearly independently of each other. This represents significant advantages compared to other forms of sputtering. In addition, the gas discharge of the ion source is contained and separate from the rest of the deposition system. From the discussion above, it can be seen that having an ion energy of 1 to 2 keV is desirable for higher sputter yield and higher sputtered atom energy. In the case of magnetron sputtering, for example, the incident ion energy is, at most, equal to the energy provided by the cathode fall voltage (typically 600 V), and it could be less due to charge transfer collisions in the region above the cathode. In addition, the ion energy can not be controlled over a wide range, and it is closely coupled to the magnetron discharge current. Being able to arrange the sputter target at an angle to the incident ion beam is advantageous both in terms of sputter yield and sputtered atom energy, as well as allowing flexibility in the experimental arrangement. In the case of magnetron sputtering or other processes in which the sputter target is in
contact with the gas discharge, there is no control of the ion incident angle. Ion beam sputtering allows greater flexibility in target material and composition than in other forms of sputtering. This is discussed below in connection with targets. In addition, the species in the ion beam can be easily and accurately controlled by adjusting the flow of one or more types of gas through the source; reactive (e.g., O₂, N₂ etc.) or inert ion species can be present in practically any ratio desired. This is not the case with other forms of sputtering. The low background pressure present during ion beam sputtering might lead to less gas inclusion compared to other processes. However, the deposition geometry should be such that the substrates are not bombarded with energetic neutralized ions which are reflected from the target. In this case, the incorporation could increase significantly due to a larger sticking coefficient of the energetic atom.

An obvious disadvantage of the application of ion beams in general is the added expense and complexity of the coating process. However, neither of these is severe. Another disadvantage is that it is more difficult to scale the ion beam sputter process compared to magnetron or some other sputter process. Geometries of the ion beam sputter arrangement must sometimes be small in order to provide reasonable deposition rates, and this might be a problem.

Aspects of Ion Beam Sputter Apparatus. Figure 5 illustrates the apparatus used in ion beam sputtering. Two ion sources are shown in the figure; one is used for sputtering and the other is used for bombarding the substrate prior to coating or during deposition (i.e., IAD). Also shown is a probe to characterize the beam in the vicinity of the target, as well as the other shutters typically found in a deposition system.

Vacuum Chamber. Chamber size requirements are influenced little by the addition of a small ion source; more elaborate arrangements such as illustrated in Fig. 5 require a specially designed system. Typical size of the arrangement shown in the figure is roughly 50 cm in diameter. Similarly, vacuum pumping requirements are not influenced greatly by the addition of a small ion source; typical added gas load is 2 to 4 cm³/min for a 2.5 cm diameter ion beam source. A 6-inch diffusion-pumped or cryogenically-pumped system will typically operate in the 10⁻⁵ to low 10⁻⁴ torr region with this gas load. Incorporating large ion sources into a system may require additional pump capability.
Figure 5. Ion beam sputter apparatus. Although the vacuum system shown here is designed specifically for IBS, the same ion beam apparatus could be added to an existing vacuum system.
The arrangement of the sputter target and the substrates is often as illustrated in Fig. 5. A typical separation between the ion source and the target is 30 cm. The target is arranged at an angle of approximately 45 degrees to the ion beam to optimize the sputter process as discussed above. The energetic neutralized ions which are reflected from the target can, in some situations, be detrimental to the film if they are allowed to bombard the substrate. This is the case, for example, when high quality oxide films are being deposited using Ar ions to sputter a target and with an O₂ partial background pressure[12]. To minimize this effect, the substrates are arranged as shown in Fig. 5. Although the neutralized ions do not all reflect in a specular sense, it is believed they are predominantly directed in this direction.

**Ion Sources.** For ion beam sputtering, it is usually desirable to deliver as much ion current to the sputter target as possible, and this dictates the use of large ion sources (e.g., 10 to 15 cm diameter). Wire filament cathodes and neutralizer can be used which are made of W or Ta, and typically 0.010 to 0.015 inches in diameter. Both have lifetime limits of several (one to over ten) hours. Lifetime of the neutralizer is increased if it is placed near the edge of the ion beam and not through the center. This can be tedious to achieve, as the beam profile and, therefore the position of the neutralizer, are somewhat dependent on operating conditions (pressure, beam energy, etc.). Both the cathode and neutralizer lifetime are greatly reduced if a reactive gas is used in the ion source. In addition, the W or Ta material can contaminate the target and be deposited in the film at a low level. In place of the wire cathode, a hollow cathode discharge device can be used to supply electrons to the main discharge of the ion source. Although this operates very well with inert gas, operation with O₂ has not been satisfactory. Similarly, the wire neutralizer can be replaced with an auxiliary discharge device, a plasma bridge neutralizer, to supply neutralizing electrons to the beam. This must remain outside of the beam to avoid being sputtered and contaminating the target material. Another approach is to construct the housing of the plasma bridge neutralizer of a material which is compatible with the target and film.

**Targets.** Target size should be sufficient to insure that none of the beam passes the target and sputters other material. In optical coating arrangements in which large ion sources are used, target size is typically 20 cm wide and 30 cm long. Placement of the target and the influence of this on the distribution of sputtered atoms has been discussed previously.
In the case of optical coatings, elemental targets of Si, Ti, Ta, etc., are often preferred because of the higher sputter yields and therefore large deposition rates provided, compared to targets composed of the oxide materials. In this particular situation, Ar ions are often used to sputter the target; a second ion source, possibly with a single-grid arrangement to provide low energy ions, is often used with O₂ to improve film stoichiometry by IAD. Deposition rates of 1 to 2 Å/sec can be achieved. Similar techniques can be used in the case of nitride film deposition. This arrangement is illustrated in Fig. 5.

In general, there is no restriction placed on a target used in ion beam sputtering; the target can be an insulator since the ion beam can be neutralized. Sputter targets are often water-cooled due to the incident power (e.g., 0.25 A at 1,500 V in vacuum).

A technique which has been used to ion-beam sputter compounds of materials involves placing pieces of one target material on a second target material. The film composition depends on the relative sputter yields, the relative areas of the targets which are sputtered, and the relative sticking coefficients of the atoms at the substrate.

**Properties of Ion Beam Sputtered Films.** Harper has described the properties of thin films deposited by ion beam sputtering. These include superior adhesion and denser film structure, both attributed to the higher energy of the sputtered particles. The improved adhesion was observed for films produced with and without ion precleaning. The superconducting transition temperature, $T_c$, of ion-beam deposited transition materials has been found to increase over bulk values for some metals and decrease for others. The effects were correlated with the size of the sputtering ion used and attributed to the influence on lattice expansion.

More recently, ion-beam sputtered oxides have been found to exhibit optical properties which are superior to those of films of the same material deposited using e-beam evaporation. This is illustrated in Fig. 6 which shows the refractive indices of several film materials deposited using ion-beam sputtering as described above. The total losses (absorbance, scatter, and transmittance) from high reflectance mirrors constructed from these films is 100 parts per million or less, as determined by performance in a ringdown laser arrangement. The films are stable with temperature cycling to 300°C in atmosphere for several hours. The internal stress of ion-beam sputtered films is compressive, and it is generally greater than that of evaporated films of the same material. In the case of some oxide materials, the compressive stress is sufficient to cause film
delamination from the substrate.[12] The amount of film stress changes with the location of the substrates relative to the sputter target. This suggests the dependence might be related to substrate bombardment during film deposition.

![Graph showing refractive index vs. wavelength for TiO$_2$, Nb$_2$O$_5$, and Ta$_2$O$_5$.](image)

**Figure 6.** Values of refractive index obtained from examining thin film materials which were ion-beam sputtered.[12]

5.2 Ion Assisted Deposition

Ion-assisted deposition (IAD) employs an ion source to direct a beam of ions at the substrates during deposition. The source of film material could be an evaporation source or a sputter arrangement, such as the dual ion beam deposition arrangement mentioned in the previous section. An obvious advantage to utilizing IAD is that the process can be easily incorporated into an existing vacuum deposition system.

In this section, we describe the equipment used to deposit thin films using IAD, the advantages inherent in using IAD, and the limitations in applying IAD to deposit thin films. This technique has been employed in the fabrication of multilayer optical coatings, in the deposition of compound thin films at reduced substrate temperature, and to modify film properties during deposition. We review results of employing IAD and illustrate how control of the ion energy and flux can be utilized to tailor the properties of thin films.

**Equipment.** A schematic of a vacuum deposition system configured for IAD is shown in Fig. 7.[9] The operation of the source of thin film material is totally independent from the ion source. The Kaufman ion
source provides a monoenergetic, neutralized ion beam which is directed at the substrates being coated. This configuration has a number of advantages over conventional plasma configurations used to provide ion bombardment of the substrate. Three advantages provided by ion beams include the independence of the bombardment process from the deposition process, the inherent control provided by the ion beam, and the ability to accurately measure all critical deposition parameters. An additional feature concerning IAD is that substrate cleaning can be readily accomplished prior to deposition by controlling the appropriate gas species through the ion source.

As illustrated in Fig. 7, the gas is introduced through the ion source into the deposition chamber. IAD is inherently a low pressure process (10^{-5} to 10^{-4} torr) that permits a great deal of flexibility in deposition configuration. Any number of gas species can be introduced, depending upon the complexity of the gas manifold. Neutral background gas can also be introduced into the vacuum chamber through another inlet if desired.

![Figure 7. Schematic of an IAD deposition system.](image-url)
As described in a previous section, it is essential that the ion beam is properly probed prior to deposition. For some materials, film properties are sensitive to bombarding ion flux levels; examples are given later in this section. As illustrated in Fig. 7, an ion current probe is located just below the substrate. The probe platform is mounted on an aluminum rod that is attached to a rotary vacuum feedthrough. The probe is rotated into position immediately below the substrates to be cleaned or coated. After the ion flux value is measured, the probe is rotated away from the substrate area to minimize coating of the probe. Not shown in Fig. 7 is a shield attached to the probe platform which protects the probe from film material during deposition. This shield prolongs the lifetime of the probe when depositing insulating film materials.

An important parameter in depositing thin films using IAD is the ratio of the ion-to-molecule arrival rates. Proper beam probing allows accurate determination of the ion flux. In the case where substrates are continuously exposed to the ion beam, modification of film properties occurs on a continual basis. One method of determining the flux of arriving thin film molecules is measurement of the film deposition rate using a crystal monitor. In the data presented below, film properties are plotted versus ion beam current density and for a constant deposition rate. Thus the ratio of ion-to-molecule arrival rates is a variable. As illustrated in Fig. 7, the monitor can be located very close to the substrates. The monitor must be calibrated to determine an accurate tooling factor for different film materials and for various ion source conditions.

If the substrate fixtureing involves planetary rotation, the monitor cannot be located immediately adjacent to the substrates. In this arrangement, determining the proper flux of ions and film molecules is more difficult. Usually the substrates are exposed to the ion beam for only a fraction of time, $F$. The effect of the ion bombardment during the fraction of time $F$ may not be the same as if the substrate were bombarded continuously. This might be the case even if the average levels of ion flux are kept constant, for example, by increasing the ion current density by a factor of $1/F$. Therefore, when using IAD with a planetary rotation geometry, care must be exercised in selecting the ion beam parameters which result in the desired thin film properties. This is best achieved by first coating sample substrates with single layer films (if multiple layered structures are ultimately desired). For each film material, optimal ion beam current density and energy can be determined by examining samples deposited under different conditions.
Another important consideration when applying IAD is the respective arrival directions of the bombarding ions and the film molecules. As illustrated in Fig. 7, when employing a fixed-position substrate geometry with an ion source located off-axis, it is important that substrate rotation be employed. The rotation of the substrates is necessary to minimize anisotropic properties in the films due to the different arrival directions of the ions and the molecular species.

Proper selection of the discharge voltage is important. The value should be high enough to sustain an appropriate discharge in the source, but not too high a value, which will cause an increased production of doubly ionized ions. The doubly ionized species will accelerate to twice the beam energy, and this reduces the level of control the operator has over the ion beam parameters. In addition, high values of discharge voltage decrease the lifetime of the cathode filament in the source. For a 10 cm source, cathode filament lifetime for typical IAD conditions (500 eV, 30 \( \mu A/cm^2 \)) operating in oxygen is approximately 4 hours for a 0.015 inch diameter tungsten wire. The lifetime for a 0.020 inch diameter tantalum wire is only 1 to 1.5 hours under similar conditions.

As mentioned in a previous section, it is necessary to provide an equal number of electrons to neutralize the ion beam, especially when bombarding an insulating target. This is often accomplished using a thermionic neutralizer filament which emits the appropriate electron current into the beam. The value of this neutralizer current is made approximately equal to that of the beam current. Note that the ions are not each neutralized, but rather the net charge flux to the target is zero. When using this simple arrangement for beam neutralization, consideration must be given to problems arising due to neutralizer filament sputtering. Another technique for beam neutralization is the use of a plasma bridge neutralizer arrangement (see a previous section).

**Procedures.** The thin film material can be preheated prior to coating and, as illustrated in Fig. 7, a shutter can be employed to shield the chamber from the vapor material. Immediately upon completion of the cleaning process, film deposition can commence. The time between the two processes is limited to the delay, if any, associated with changing the gas species flowing through the ion source.

It is critical that the ion flux is stable and accurately measured before deposition begins. The gas discharge of the ion source should be established and the desired beam parameters (ion energy, flux, and neutralizer
current) set at the ion source power supply. When the ion flux is measured by the probe, an accurate record of its value and all ion source parameters should be made. When the probe is rotated out of position, deposition can commence. During deposition, the beam energy and current must be monitored on the power supply to ensure stable ion source operation. At the completion of deposition, the ion flux should be checked by rotating the probe back to the original measurement position.

**Examples of Applications of IAD to Optical Coatings.** Early work utilizing a separate ion source to bombard evaporated SiO with 5 keV oxygen ions during deposition was examined by Dudonis and Prannevicius.\(^{[14]}\) They investigated the effects of ion flux on film stoichiometry and found that for increasing flux values, the O/Si ratio approached two. They also simultaneously bombarded with oxygen ions during the evaporation of aluminum and measured changes in film resistivity as function of ion flux; resistivity changes for \(10^{17}\) were obtained using the ion bombardment. Changes in resistivity are an extremely sensitive measure of film stoichiometry. Cuomo, et al.,\(^{[15]}\) obtained superconducting NbN films by bombarding evaporated Nb with \(\text{N}_2^+\) during deposition. They also reported a change in stress from tensile to compressive for evaporated Nb films bombarded with 100 to 800 eV \(\text{Ar}^+\) during deposition. Hoffman and Gaerttner\(^{[16]}\) bombarded evaporated Cr films during deposition with 11.5 keV \(\text{Ar}^+\). They reported changes in stress from tensile to compressive and attributed the results to modifications in film microstructure. In these studies, an important parameter affecting film properties was the ion-to-atom arrival rate ratio. This ratio can be used to normalize results from various experiments and is discussed in more detail later in this section.

Recently, IAD has been applied in the production of optical coatings. Netterfield and Martin have studied the effects on the properties of \(\text{ZrO}_2\) and \(\text{CeO}_2\) films bombarded with \(\text{O}_2^+\) and \(\text{Ar}^+\) during deposition.\(^{[17]}-[19]\) They reported increased packing densities, reduced permeability to water and changes in film crystal structure. Bombardment with \(\text{Ar}^+\) produced changes in film stoichiometry. Allen applied IAD to obtain increased values of refractive index in \(\text{TiO}_2\) films.\(^{[20]}\) The increase was larger at 300 eV bombardment than at 500 eV. McNeil, et al.,\(^{[21]}-[22]\) examined the effects of 30 and 500 eV oxygen ion bombardment on the properties of \(\text{TiO}_2\) and \(\text{SiO}_2\) films deposited using TiO and SiO starting materials. They reported improvements in film properties were obtained with 30 eV bombardment in the
case of ambient substrate temperatures. In particular, they obtained films with improved stoichiometry. Al-Jumaily, McNally and McNeil\cite{23}-\cite{25} examined the effects of ion energy and flux on optical scatter and crystalline phase in Cu, TiO$_2$, and SiO$_2$ films. They reported reduction in optical scatter and crystal phase transitions for bombarded films. The modifications in Cu films were obtained with 500 eV Ar$^+$ bombardment. McNally, et al.,\cite{26}\cite{27} reported on the effects of oxygen ion bombardment on the properties of Ta$_2$O$_5$, Al$_2$O$_3$, TiO$_2$, and SiO$_2$ films. Increases in the values of refractive index were reported for 200, 300, 500, and 1,000 eV bombardment. The increase was found to be directly dependent on the ion flux, which is consistent with the comments in a previous section regarding the importance of proper beam probing. Changes in film stoichiometry and crystal phase were also reported.

As a final example of recent IAD work, the deposition of protective coatings on sensitive substrates at low temperatures has been demonstrated.\cite{28} Films of MgF$_2$ were successfully deposited on heavy metal fluoride glass substrates at 100°C temperature. The films were bombarded with 300 eV Ar$^+$ during deposition. Conventionally evaporated MgF$_2$ films are soft when deposited at this substrate temperature, while the IAD MgF$_2$ films were hard and robust. This represents a significant advantage in using IAD to deposit films.

**IAD Results.** Some sample results from applying IAD to produce coatings are given in this section. McNally, et al.,\cite{9} produced Ta$_2$O$_5$ coatings which were electron-beam evaporated at a rate of 0.30 nm sec$^{-1}$ with oxygen backfill pressure of $1.0 \times 10^{-4}$ torr. The coatings were deposited onto heated substrates (275°C), and were bombarded with oxygen ions during deposition. The transmittance spectra for two Ta$_2$O$_5$ coatings are given in Fig. 8. The curve labeled $J = 0$ corresponds to a coating deposited with no ion bombardment; the curve labeled $J = 5$ is for a coating bombardment during deposition with 500 eV O$_2^+$ current density of 5 $\mu$A cm$^{-2}$. The curve for the ion assisted coating contains larger differences in transmittance extrema than the curve for the conventional e-beam evaporated coating. These larger differences indicate a larger value of refractive index ($n$) for the ion assisted coating. Good film stoichiometry was obtained for the ion bombardment conditions employed, as indicated by an absence of measurable absorption at wavelengths for which the film is multiple half-wave in optical thickness down to 340 nm. Examination of the reflectance spectra for these coatings indicated an absence of any refractive index inhomogeneity.
Figure 8. Transmittance spectra of two Ta$_2$O$_5$ coatings, one deposited without ion bombardment ($J = 0$) and the other deposited with ion bombardment ($J = 5$ μA/cm$^2$).
The values of $n$ (at $\lambda = 400$ nm) for Ta$_2$O$_5$ coatings bombarded with 200, 300 and 500 eV oxygen ions are plotted in Fig. 9 as a function of O$_2^+$ current density. The error bars indicate the uncertainty in the index measurements. The values increase from 2.16 for the coating deposited without bombardment to maximum values of 2.25, 2.28 and 2.19 for films bombarded with 500, 300 and 200 eV O$_2^+$, respectively.

![Graph showing refractive index vs. O$_2^+$ current density for Ta$_2$O$_5$ coatings bombarded with different energies.](image)

**Figure 9.** Values of refractive index for Ta$_2$O$_5$ coatings deposited under different levels of O$_2^+$ current density and energy.

The increase in the values of $n$ with increasing O$_2^+$ current density indicates that ion bombardment during deposition modifies the growth of film columnar microstructure resulting in film densification. The results indicate that the coatings bombarded with 300 eV O$_2^+$ had larger values of $n$ than those bombarded with 500 eV O$_2^+$. The results in Fig. 9 indicate that only minor densification occurred for coatings bombarded with 200 eV oxygen ions during deposition. A similar dependence of refractive index on bombarding ion energy has been reported for ion assisted CeO$_2$ films.$^{[19]}$

The current density value (for a fixed ion energy) at which the maximum $n$ occurs is termed the **critical value**. The results in Fig. 9 illustrate that film index values decrease for ion current densities greater than the critical values. The decrease in index may be explained as a result
of degradation in film stoichiometry, creation of closed isolated voids, or oxygen incorporation into the films. The decrease was largest for bombardment with 500 eV ions and least for 200 eV ions in the case of Ta₂O₅. This energy dependent decrease is consistent with the dependence on ion energy of the average ion penetration depth and preferential sputtering yield. Similar results for which the values of refractive index decrease for current densities greater than the critical values have been reported for ion assisted ZrO₂ films\(^{[18]}\) and CeO₂ films\(^{[19]}\).

The coatings bombarded during deposition at oxygen ion current densities up to approximately the critical values exhibit good optical characteristics. For higher levels of bombardment, the optical absorption of the coatings increase. In Fig. 10, values of extinction coefficient (\(k\)) for Ta₂O₅ coatings (300 nm thick) bombarded with 500, 300, and 200 eV oxygen ions are plotted as a function of O₂⁺ current density. The values of \(k\) were calculated at \(\lambda = 400\) nm. The error bars indicate the uncertainty in the measurements. The dashed line across the bottom at \(k = 2.0 \times 10^{-4}\) indicates the level below which the values of \(k\) were too small to be regarded as reliable due to the minimum sensitivity of the measurement technique.

![Extinction Coefficient of Ta₂O₅](image)

**Figure 10.** Values of extinction coefficient of the same Ta₂O₅ coatings represented by Fig. 9.
As illustrated in Fig. 10, film optical absorption increased with higher levels of oxygen bombardment. The most probable mechanism for this is the preferential sputtering of oxygen in the Ta$_2$O$_5$ molecule. Preferential sputtering would result in oxygen-deficient layers continuously integrated into the coatings as deposition occurs. Values of $k$ for coatings bombarded at a fixed current density were the lowest for 200 eV O$_2^+$, higher for 300 eV, and highest for 500 eV O$_2^+$. This result is consistent with increasing preferential sputtering yields for higher energy ions. This damage mechanism has been observed in other IAD films.$^{18}$ This highlights the requirement for proper beam probing to avoid compositional change by preferential sputtering.

The environmental stability of optical coatings is in large part limited by the porosity of the film microstructure. Figures 11 and 12 are the transmittance curves for two Ta$_2$O$_5$ coatings exposed to humidity testing. The spectra in Fig. 11 are for a coating deposited onto a heated silica substrate with no ion bombardment ($J = 0$). The spectra in Fig. 12 are for a coating bombarded during deposition with 300 eV O$_2^+$ at a current density of 20 $\mu$A cm$^{-2}$. The curve labeled “AIR” is the spectrum measured after the coating has been removed from the vacuum chamber and exposed to the ambient atmosphere. The curve labeled “POST HUMIDITY” is the spectrum for the same coating remeasured after exposure to 97% relative humidity at 35°C for 6 hours.

**Figure 11.** Transmittance spectra of a Ta$_2$O$_5$ coating deposited without ion bombardment subjected to humidity test.
Figure 12. Transmittance spectra of a Ta$_2$O$_5$ coating bombarded during deposition with 300 eV O$_2^+$ at $J = 20$ mA cm$^{-2}$ subjected to humidity test.

The curves in Fig. 11 illustrate a spectral shift of 1% to longer wavelengths for the coating deposited without bombardment. The shift is most likely due to water adsorption into the microvoids in the film microstructure. This increases the effective index value of the coating and, in turn, increases the optical thickness ($nt$). Figure 12 is typical of the results obtained for IAD coatings. No spectral shifts within the measurement precision of the spectrophotometer are observed. Similar results have been reported for IAD ZrO$_2$ and TiO$_2$ coatings.$^{[17][18]}$

IAD can affect intrinsic stress in films. Changes in stress for Ta$_2$O$_5$ coatings have been reported.$^{[9]}$ The stress was measured interferometrically. The stress was computed from measured substrate bending, and because film thickness was much less (factor of 1000) than the substrate thickness, the elastic constants of the coating were not required.

Figure 13 illustrates the values of film stress plotted versus oxygen ion current density. The triangles and circles represent stress values for coatings bombarded during deposition with 300 and 500 eV O$_2^+$, respectively. The results indicate film stress was compressive and increased for increasing levels of ion bombardment.
Figure 13. Values of stress of Ta$_2$O$_5$ coatings for films deposited with different levels of O$_2^+$ current density and energy.

There have been a number of studies in which the effects of ion bombardment on stress in metal films were examined. Cuomo, et al.,\textsuperscript{[15]} reported a change in stress from tensile to compressive for evaporated Nb films bombarded with 100 to 800 eV Ar$^+$ during deposition. They attributed the changes in stress to modifications in film microstructure and incorporation of argon. Hirsh and Varga\textsuperscript{[29]} measured stress relief in evaporated Ge films bombarded with 100 to 300 eV Ar$^+$ during deposition. The stress changed toward compressive values. Hoffman and Gaerttner\textsuperscript{[16]} bombarded evaporated Cr films during deposition with 11.5 keV Ar$^+$ They reported changes in stress from tensile to compressive and attributed the results to modification in film microstructure. Thus, the results illustrated in Fig. 13 are consistent with the trend toward increasing compressive stress for increasing ion bombardment.

IAD has also been used to produce Al$_2$O$_3$ optical coatings.\textsuperscript{[9]} The Al$_2$O$_3$ coatings were electron-beam evaporated at a rate of 0.40 nm sec$^{-1}$ with oxygen backfill pressure of $1.0 \times 10^{-4}$ torr. The coatings were deposited onto heated substrates (275°C), and were bombarded with oxygen ions during deposition.
The values of $n$ (at $\lambda = 350$ nm) for $\text{Al}_2\text{O}_3$ coatings bombarded with 300, 500, and 1,000 eV oxygen ions are plotted in Fig. 14 as a function of $\text{O}_2^+$ current density. The values increase from 1.64 for coatings deposited without bombardment to maximum values of 1.70, 1.68, and 1.68 for films bombarded with 100, 500, and 300 eV $\text{O}_2^+$, respectively.

![Graph showing refractive index vs. $\text{O}_2^+$ current density for $\text{Al}_2\text{O}_3$.]

**Figure 14.** Values of refractive index of $\text{Al}_2\text{O}_3$ coatings deposited under different levels of $\text{O}_2^+$ current density and energy.

The increase in the values of $n$ for increasing levels of $\text{O}_2^+$ current density is similar to $\text{Ta}_2\text{O}_5$ results (Fig. 9) and indicates that ion bombardment during deposition results in film densification. The results indicate that the $\text{Al}_2\text{O}_3$ coatings bombarded with 1,000 eV $\text{O}_2^+$ had larger values of $n$ than those bombarded with 500 and 300 eV $\text{O}_2^+$. These results illustrate that the effects of ion bombardment on the values of $n$ are material dependent. The ion energy at which the largest value of $n$ occurred for $\text{Ta}_2\text{O}_5$ was 300 eV, yet for $\text{Al}_2\text{O}_3$ it was 1,000 eV.
The results in Fig. 14 illustrate that values of $n$ decreased for ion current densities larger than the critical values. The decrease was largest for bombardment with 1,000 eV ions and least for 300 eV ions. This energy dependent decrease is consistent with the results for IAD Ta$_2$O$_5$ coatings (Fig. 9).

Attempts to measure the values of extinction coefficient for the Al$_2$O$_3$ coatings (400 nm thick) were limited due to the minimum sensitivity of the measurement equipment. All computed values of $k$ were less than $2.0 \times 10^{-4}$. The low values of $k$ calculated for all the Al$_2$O$_3$ coatings indicate that, for the conditions examined, preferential oxygen sputtering is not a dominant mechanism for Al$_2$O$_3$ as was the case for Ta$_2$O$_5$ (Fig. 10). This result again illustrates that the effects of ion bombardment on film properties are material dependent.

5.3 Application Summary

The two configurations for using ion beams for thin film deposition (Figs. 5, 7) each contain their distinct advantages and disadvantages. Direct comparison of the two configurations to determine which provides the “best” coatings is difficult. The decision as to which configuration to employ must be made with consideration of the end application, the existing deposition system (if any), total costs, and the issues discussed in previous sections. In this section, a discussion summarizing the advantages and disadvantages of IBS and IAD is given with the emphasis on listing information to aid the users in deciding which configuration would better serve their needs.

The improvements in the properties of thin films produced using IBS are detailed in a previous section. Similar improvements in the properties of IAD films are given in a previous section. It appears that each technique results in thin films of similar quality. Thus, a decision based on film quality would need to be made on a case-by-case basis.

A direct advantage of IAD is that the technique is readily implemented with the addition of an ion source apparatus to an existing vacuum deposition system. This offers significant savings in both time and money. On the other hand, IBS may require more modifications to an existing deposition system, or the purchase of a totally dedicated one. Either choice requires a major investment. Another advantage of IAD is the ease in which the technique can be scaled to large geometries. Scaling the IBS process is more limited than the IAD process by the size of ion sources
available. A number of trade-offs among the deposition parameters (deposition rate, uniformity, etc.) exist, and they must be considered before choosing which technique would best achieve the desired results.

6.0 CONCLUDING COMMENTS

In this chapter, a general description and two specific applications of ion beams for thin film coating have been described. A common advantage of ion beam techniques is the degree of flexibility and control provided compared to other techniques that incorporate a gas discharge. Ion beam sources will continue to be incorporated into deposition arrangements and applied to other materials to provide films with improved properties.

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